SPATIALLY DISTRIBUTED SIMULATION OF AN IRRIGATION SYSTEM

A THESIS

Submitted in fulfilment of the requirements for the award of the degree of

DOCTOR OF PHILOSOPHY

in

WATER RESOURCES DEVELOPMENT

By

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ROORKEE

CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled **"SPATIALLY DISTRIBUTED SIMULATION OF AN IRRIGATION SYSTEM"** in fulfilment of the requirement for the award of the Degree of Doctor of Philosophy and submitted in the Water Resources Development Training Centre of the Indian Institute of Technology Roorkee, Roorkee is an authentic record of my own work carried out during a period from April, 1997 to December, 2003 under the supervision of **Prof. U. C. Chaube**, Professor, WRDTC, Indian Institute of Technology, Roorkee, and **Dr. S. K. Jain**, Scientist "F", National Institute of Hydrology, Roorkee.

The matter presented in this thesis has not been submitted by me for the award of any other degree of this or any other Institute/ University.

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ABSTRACT

Success of an irrigation system depends on efficient water management. The National Water Policy of India (revised in April 2002) states, "Certain problems and weaknesses in planning and implementation have affected a large number of water resources projects all over the country. Problems of water logging and soil salinity have emerged in some irrigation commands. Complex issues of equity and social justice in regard to water distribution are required to be addressed. The development and over-exploitation of groundwater resources in certain parts of the country have raised the concern and need for judicious and scientific resource management and conservation." 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. Available literature does not indicate the existence of a spatially distributed simulation model that can integrate various processes of irrigation management from micro-scale (field level) to macro-scale (overall command) and provide a comprehensive analysis.

The objective of this study is to develop a geo-simulation scheme 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 scheme will help the irrigation manager for judicious operation of a canal network on the basis of current state of the system.

Irrigation management requires huge volume of data pertaining to hydrological, hydro-geological, hydro-meteorological, soil, agronomic, and cropping pattern parameters. With the availability of remote sensing technology and Geographic Information System (GIS) tools, it is now possible to gather instant observations over large areas and to integrate and manage multi-disciplinary data. In this study, remote sensing data are used to find the actual cropping pattern in command area and to delineate canal network layout. GIS is used to store, analyze, and retrieve multi-disciplinary data. GIS is also used to link spatial data with the simulation scheme to depict effect of various operation scenarios on the performance of irrigation system.

The developed scheme 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. 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) is linked to the scheme.

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 command area is divided into square grids of uniform size and soil moisture accounting is carried out for each grid. Each grid is assigned a specific crop (based on remote sensing analysis), specific soil (based on soil survey map) and specific rainfall input (based on Thiessen polygons of rainfall stations). The effective soil depth at the grid is taken as the average root depth of the crop during a week. Water holding properties at the grid depend on soil characteristics while crop characteristics and climatic conditions govern the crop water demands. SWBM analysis is carried out at daily or weekly time step.

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. The canal system is considered as a network of links (segments) joined together at nodes. CNSM first computes various system details for each canal segment, such as fill-time, groundwater potential etc. Using irrigable area of each canal segment, grid-wise irrigation demands are transferred to the canal segment. The canal segment demands are then integrated upwards towards canal head through the network duly accounting for the seepage losses and capacity constraints. Operation run-time and discharge in each canal segment are worked out. 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.

To analyze its performance and utilisation, the developed 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. Through this case study, the generation, storage, and retrieval of spatial database in GIS environment is demonstrated. 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. The year 1998 happened to be a wet year and to analyze the effect of different allocation policies on the system performance, scarcity conditions with regard to rainfall and canal water supply have been artificially assumed. It is found that under assumed scarcity conditions in one crop season, considerable amount of energy (27 million Kilowatt-hour) can be saved under similar conditions of water supply to existing crops by judiciously operating the canal system. Maps corresponding to irrigation demands, groundwater recharge, water stress conditions in crops, various canal operation details, such as discharge and run-time etc. and performance indicators 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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MANMOHAN KUMAR GOEL

CONTENTS

LIST OF TABLES

* * *

LIST OF FIGURES

* * *

NOTATIONS

RD_t	-	Root depth of crop on t^{th} day/week after planting (mm)
RD_s	-	Starting minimum root depth of crop (mm)
RD_m	-	Maximum root depth of a crop (mm)
t_m	-	Duration of full development of root zone (days/week)
RET	-	Reference crop evapo-transpiration (mm)
AET	-	Actual crop evapo-transpiration (mm)
ETC_t	-	Potential crop evapotranspiration (mm)
G_a	-	Apparent specific gravity of the soil
WDS	-	Equivalent water depth at saturation (mm)
WDFC	-	Equivalent water depth at field capacity (mm)
WDO	-	Equivalent water depth at wilting point (mm)
WDS	-	Equivalent water depth at saturation (mm)
V	-	Volume of soil mass (m^3)
η	-	Porosity of soil (%)
H	-	Depth of root zone (mm)
w_{fc}	-	Water content of soil at field capacity expressed as percent on dry weight basis
w_{pwp}	-	Water content of soil at permanent wilting point expressed as percent on dry weight basis
UL	-	Upper limit of desirable water depth in a grid (mm)
D_{max}	-	Maximum standing water depth required by crop (mm)
LL	-	Lower limit of readily available water (mm)
p	-	fraction of available water utilized by the plant without any stress
WD_t	-	Equivalent soil water depth in root zone at the end of t^{th} time step (mm)
WD_{t-1}	-	Equivalent soil water depth in root zone at the beginning of t^{th} time step (mm)
RF_t	-	Rainfall depth occurring on t^{th} time step (mm)
IRR_t	-	Depth of irrigation applied on the t^{th} time step (mm)
$OLFI_t$	-	Overland flow coming into a grid from adjacent higher elevation grid on t^{th} time step (mm)

$DPER_t$	-	Deep percolation loss (also called recharge to ground water) going out of root zone on t^{th} time step (mm)
$OLFO_t$	-	Overland flow going out of a grid on t^{th} time step (mm)
Kc_t	-	crop coefficient at time (t) depending on growth stage
Ks_t	-	stress coefficient at time (t) representing severity of stress conditions
K	-	Saturated hydraulic conductivity of soil (m/day)
SWR	-	Supplementary water requirement at a grid (m^3)
WDR	-	Water depth required to be maintained at a grid (mm)
f_{ik}	-	Frequency corresponding to transition from i^{th} state to k^{th} state of rainfall
P_{ij}	-	Cumulative transition probability corresponding to transition from i^{th} state to any one state up to j^{th} state
id	-	Identity of a canal segment
FC_{eff}	-	Conveyance efficiency of field channels under a segment 'id' (%)
$AEFF_{id}$	-	Water application efficiency in the fields under a segment 'id' (%)
C_{eff}	-	Conveyance efficiency of a canal segment 'id' (%)
DDI	-	Demand distribution index
$TWRCN_{id}$	-	Canal water demand in a segment 'id' corresponding to irrigation demands in various grids under its command (does not include canal seepage) (m^3)
AGW_{id}	-	Average groundwater depth under a segment 'id' (mm)
$GCAP_{id}$	-	Groundwater availability under a segment 'id' (m^3)
PPP_{id}	-	Average pumping capacity of pumps under segment 'id' (in horsepower)
EFF	-	Average pump efficiency EFF
NOP_{id}	-	Number of pumps installed under a segment 'id'
$POWS_{id}$	-	Availability of power supply under a segment 'id' (hr)
$TWGCN_{id}$	-	Groundwater demand under a canal segment 'id' (m^3)
$NOPR_{id}$	-	Additional pumps required under segment 'id'
IR_{id}	-	An indicator presenting the cause of canal water deficiency at any segment
$IPRIO_{id}$	-	Priority of a segment 'id'
CAP_{id}	-	Discharge capacity of canal segment 'id' (cumec)

$ALEN_{id}$	-	Length of segment 'id' (m)
$BEDW_{id}$	-	Bed width of canal segment 'id' (m)
$WDEPT_{id}$	-	Water depth at FRL in segment 'id' (m)
SL_{id}	-	Side slope of canal setion,
VEL_{id}	-	Flow velocity in a canal segment (m/sec)
FIL_{id}	-	Time required for water to flow through a segment 'id'
$RUNTIM_{id}$	-	Time required to run a segment 'id' to meet its demands (sec)
$FILTIM_{id}$	-	Time required for flow to reach a canal segment from nearest running segment and fill it (sec)
IDS_{id}	-	Node at downstream of segment 'id'
IUS_{id}	-	Node at upstream of segment 'id'
$WRSN(IDS)_{id}$		Total water demand (m3) at the downstream node of segment 'id'
$REQDIS_{id}$	-	Discharge required in segment 'id'
$CSEEP_{id}$	-	Canal seepage losses (m^3) in segment 'id'
$SEEPR_{id}$	-	Seepage rate in a segment 'id' per unit of wetted perimeter
$TWSCN_{id}$	-	Total canal water demand at segment 'id', including seepage loss
$AWAV_{id}$	-	Additional water available at a segment 'id'
$WAV(IDS)_{id}$	-	Water available at downstream node of segment 'id'
$WAVS_{id}$	-	Canal water available for a segment 'id'
$WAVF_{id}$	-	Water available for meeting free demands at a segment 'id'
$RUNTIMP_{id}$	-	Run-time due to priority demands in downstream network (sec)
$REQDISP_{id}$	-	Required discharge due to d/s priority demands (cumec)
$TWSCNP_{id}$	-	Total canal water requirement due to priority demands (m^3), including seepage losses
K_{xx}, K_{yy}, K_{zz}	-	hydraulic conductivity along major axes (L/T)
h	-	potentiometric head in m
W	-	volumetric flux per unit volume. It represents sources and/or sinks of water $[T^{-1}]$
S_s	-	specific storage of the porous material $[L^{-1}]$ and

Q_D	-	volume of water delivered (m^3)
Q_R	-	volume of water required in a segment in a week (m^3)
$L(\lambda)$	-	Radiance corresponding to a digital number 'Q'
L_{min} and L_{max}	-	Minimum and maximum radiance values of a sensor
R_n	-	net radiation at the crop surface (MJ per m^2 per day)
G	-	Soil heat flux density in MJ per m^2 per day
T	-	Mean daily air temperature at 2 m height in °C
u_2	-	Wind speed at 2 m height in m/s
e_s	-	saturation vapour pressure in kPa
e_a	-	actual vapour pressure in kPa
Δ	-	slope of vapour pressure curve in kPa per °C
γ	-	psychrometric constant in kPa per °C

* * *

CHAPTER - 1

INTRODUCTION

1.1 GENERAL

Nature seldom provides adequate amount of water to meet crop requirements at the desired place and time. Modern agriculture practices are based on the development of surface and groundwater irrigation facilities and their scientific management. Availability of irrigation water continues to be the first and foremost requirement for promoting technologically superior agriculture. It is rightly said, "Agriculture sustains life whereas irrigation sustains agriculture". From just 8 million hectares (M ha) in the year 1800, irrigated area across the world increased five-fold to 40 M ha in 1900, to 100 M ha in 1950 and to just over 255 M ha by the year 1995. With almost one-fifth of that area (50.1 M ha net irrigated area), India has the highest irrigated land in the world (Postel, 1999).

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. 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).

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]. In spite of such large investments and phenomenal growth of irrigation potential, the performance of several irrigation systems in India has not been encouraging. The poor performance as reflected in low crop yields, low irrigation efficiency, increased waterlogging and salinity, and low utilization of irrigation potential can be mostly attributed to managerial deficiencies in operation and management practices and lack of proper development of on-farm systems. Singh (1985) provides a realistic 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.

Recent studies in India have indicated that there is considerable rise of groundwater table in a number of irrigation command areas due to improper water management. 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.

Irrigation projects (systems) in India are classified according to source of water (surface water or groundwater) and according to the size of culturable command area (CCA). Major projects (more than 10,000 ha of CCA) and medium projects (between 2000 to 10,000 ha of CCA) generally have river storage or diversion as the source of irrigation water whereas minor irrigation projects (less than 2000 ha of CCA) are based on water lifting from river or shallow/deep aquifers. 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.

1.2 NEED OF THE PRESENT STUDY

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 the 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 resources 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. ET demand of the climate depends on various climatic factors, such as temperature, humidity, sunshine and wind speed, which vary each day. 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. The variable directly related to water table depth is groundwater potential, which also varies spatially and temporally. 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.

1.2.1 Use of remote sensing data

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)]. Advances in remote sensing technology have led to considerable saving in time and money spent in data collection and data input.

As stated in section 1.1, the crop type may change from field to field and from year to year because of smaller land holdings, especially in developing countries. By using multi-spectral satellite data at different times, prevailing cropping pattern and extent of waterlogged and saline areas in a command can be mapped. Using such information, suitable decisions for irrigation management can be taken.

1.2.2 Use of Geographic Information System

Information is vital in reducing uncertainty, evaluating alternative courses of action and revealing new avenues. Availability of right information at the right time to the right person and at the right cost is a crucial factor in decision-making. Irrigation management requires large amount of data pertaining to hydrological, hydro-geological, hydro-meteorological, soil, agronomic, and cropping pattern parameters in command areas. It is also required to continuously update some information (rainfall, ET demand, canal water supply, groundwater depth etc.) for real-time management. A spatially distributed model for irrigation management requires data on various variables and parameters such as existing cropping pattern, soil characteristics, rainfall, groundwater depth, canal irrigable areas, etc. These data need to be efficiently stored, analyzed, and retrieved in a user-friendly and interactive environment.

The conventional procedures of storing, handling and updating records are slow, unsystematic, occupy large space and require huge manpower. Further, such records are difficult to update. The advent of Geographic Information System (GIS) tools has made it possible to prepare dynamic resource maps for large areas. A GIS is a computer-based system designed to store, process and analyze geo-referenced spatial data and their attributes. GIS can assist in water resources management by efficiently handling spatial and temporal information of water resources in a command.

GIS, along with a simulation model, can be used to assist in i) allocation planning, ii) spatial analysis of water distribution for performance evaluation, and iii) communication between irrigation managers and users. Irrigation managers, working in GIS environment, can get comprehensive information in real-time for developing water distribution plans in a command area.

1.2.3 Need of a Geo-simulation model

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. Though a number of irrigation system models have been developed in the past (such as SIMIS, CAMSIS, INCA, OMIS, IOS etc.), the literature lacks a comprehensive model integrating various processes of irrigation management from micro-scale (field level) to macro-scale (overall command). A model is required that can incorporate spatial variability of different data related to the process 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. With this need in view, a geo-simulation scheme for analysing an irrigation system is developed in the present study.

1.3 OBJECTIVES 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 scheme that can be used for any command area;
e) to develop computationally efficient scheme;
f) to display the results in form of maps for easy visualization, thereby allowing the irrigation managers and the users (affected by the operation decisions) to participate in the decision-making process.

It is envisaged that the developed scheme will 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. Flow chart of the scheme presenting the methodology in brief is shown in Figure -- 1.1.

1.4 ORGANISATION OF THE THESIS

This research work consists of development of a geo-simulation scheme and its application for an irrigation command for a crop season. The work is presented in eight chapters as follows:

Chapter-1: General introduction of the investigation and its need in present context is described.

Chapter-2: The review of literature is presented focussing particularly on three different aspects: a) the soil water balance applications, b) irrigation water allocation models, and c) use of remote sensing data and GIS for command area studies. Based on the literature review, conclusions with regard to the need for this study are arrived at.

Chapter-3: This chapter describes the development of distributed soil water balance model (SWBM) for estimation of irrigation demands, stress conditions and recharge in the command area.

Chapter-4: The distributed canal network simulation model (CNSM) for allocation of available surface and groundwater in the command area is explained in this chapter.

Chapter-5: This chapter briefly describes the existing groundwater behaviour model that is linked to the proposed scheme and the development of various sub-models of the scheme, which are used to generate database and link various models. The overall operation scheme is also presented in this chapter.

Chapter-6: Proposed scheme requires extensive database, which is obtained from remote sensing observations, topographic information, and field information. This chapter explains the development of database for the case study of Lakhaoti command area under the Madhya Ganga Canal System, Uttar Pradesh State, India for the application of proposed scheme.

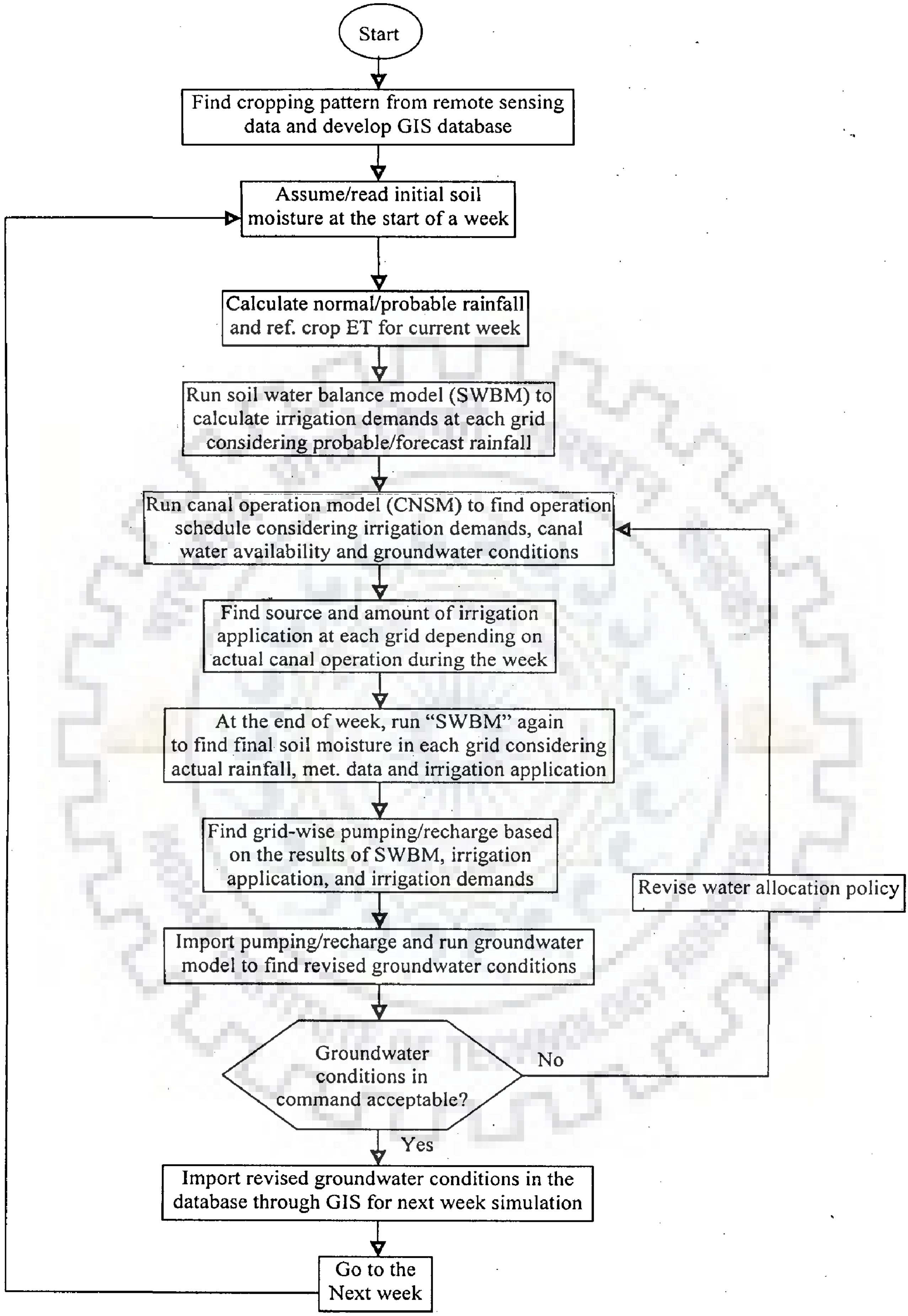

Figure – 1.1: Flow chart describing the developed scheme

Chapter-7: In this chapter, first the results of SWBM and CNSM are illustrated independently. Then, the proposed scheme is validated for the Kharif season (wet season from June to October) of the year 1998. Then, assuming certain scarcity conditions in the command, different water allocation policies are analysed and their performance is compared.

Chapter-8: The conclusions based on the study are presented and scope for further work is described.

* * *

CHAPTER - 2
LITERATURE REVIEW

2.1 GENERAL

Irrigation is the largest consumer of fresh water. Seckler et al. (1998) have estimated that around 70% of water used world-wide each year produces 30 to 40% of the world's food crops on 17% of arable land. There could be several objectives of irrigation management as stated by Hüygen et al. (1995), "Maximize net return, minimize irrigation costs, maximize yield, optimally distribute a limited water supply, minimize groundwater pollution...". In developing countries, demand for water resources is rapidly increasing in all sectors. With limited availability, considerable improvements in efficiency of water use are urgently required. In several developing countries, available water resources are already under considerable stress and there is general realization that traditionally low efficiency of water use by irrigated agriculture can no longer be accepted (FAO, 1994).

Poor management of irrigation water delivery system is one of the principal reasons for low water use efficiency in irrigation. Inadequate and often unreliable water deliveries in the main system result in reduced yields and reduced incomes for the farmers as well as reduced utilisation of created potential. In addition, a range of environmental problems, such as waterlogging, leaching of agro-chemicals and consequent pollution of surface and groundwater, soil salinization etc. are linked to inefficient water use.

Irrigation managers have to take decisions in real-time on how best to allocate the available water to meet spatially distributed demands in a command area. Various data are collected to support decision-making processes. However, all available information may not be utilized in decision making for a variety of reasons –database management is unscientific and inefficient or mathematical tools are not used to utilize and integrate the multi-disciplinary information for arriving at some meaningful conclusion. Considerable efforts have been put in the development of software for improved irrigation water management and a large number of models are now in existence (Lenselink and Jurriens, 1992). Wurbs (1994) presents a comprehensive review of computer models for water resources planning and management. Mujumdar (2002) has summarized mathematical tools for irrigation water management.

In this chapter, review of important studies related to irrigation water management is presented. Soil water balance of cropped area is a dynamic process influenced by the water supply, crop and soil properties, climatological variables and topography. First, studies related to development and application of soil water balance models (SWBM) are discussed. Numerous irrigation water delivery models have been reported in the literature. More than 100 irrigation and hydrology related software have been cited at the internet site – IRRISOFT (http://www.wiz.uni-kassel.de/kww/irrisoft/irrisoft_i.html) which contains a database of software and corresponding links. Second, some important irrigation management and delivery models, relevant for this study, are reviewed. Next, applications of remote sensing and GIS techniques in agricultural systems are reviewed. Finally, based on the survey of literature, research problem for the present study is formulated.

2.2 SOIL WATER BALANCE MODELING

All aspects of irrigation management, especially irrigation scheduling, require an understanding of the soil water balance in root zone as it affects plant growth directly by influencing plant water potential and indirectly through its influence on soil aeration, soil temperature and nutrient mobility (Phene et al. 1990). A (SWBM) can be used to compute and maintain a continuous record of soil moisture, actual evapotranspiration, percolation, and runoff.

Soil moisture can be measured in-situ or estimated using either soil water balance approach or remote observations. Commonly used direct measures include: gravimetric determination, neutron probe, time domain reflectometry, tensiometer, and gypsum block (Swartwood and Remer 1992). These measurements are site specific and, therefore, need many observations to properly characterize an area. This can be a laborious and expensive procedure if spatial variation is to be accounted for over a large area. Methodologies to assess crop water requirement, such as one introduced by FAO (1977), make it possible to routinely estimate actual evapo-transpiration (AET) from climatic data, using a crop coefficient combined with reference evapo-transpiration (RET). This approach follows a meteorologically imposed evapo-transpiration (ET) demand. The irrigation requirements are determined in accordance with other terms of soil water balance equation. Irrigation scheduling models based on ET have been used worldwide (Jensen et al. 1971).

The aim of soil water balance modeling is to predict the water content in the root zone of soil by means of a water conservation equation. Different processes making up the soil water balance are rainfall and irrigation input, AET, infiltration into the soil, redistribution of infiltrated water into the root zone of crops, percolation of water out of the root zone, and runoff. Ideally, these processes are best represented by physics-based models of soil water flow (Molz 1980). Feddes et al. (1988) have reviewed the principles underlying water dynamics in unsaturated zone and presented the overview of simulation modeling of soil water flow and general principles of modeling water balance of cropped soils. Feddes (1988) also provides the state-of-the-art on modeling and simulation techniques in hydrologic systems related to agricultural development.

There are broadly two types of soil water balance models: a) based on simple book-keeping procedure, and b) the dynamic simulation models based on the physics of unsaturated flow in soils. The first type of models have moderate data requirement, such as storage properties of soils, crop properties, and climate data. Second type of models, in addition, require transmission characteristics of soils. The physics-based models describe different hydrological components in great detail. For large area studies, physics-based models become very complicated, require huge data and extensive computational time. Therefore, simple water balance models based on empirical observations of soil-water-plant responses have been preferred in field applications and large area studies (Rao 1998). Simple SWBM with various degree of sophistication have been used in a number of studies, either explicitly or included in simulation models. Itier et al. (1996) have given a detailed account of various components of soil water balance model, their applicability and limitations. Daily soil water balance equation can be written in the form:

$$WD(i) = WD(i-1) + RF(i) + IRR(i) - ET_c(i) - OLF(i) - DP(i) \qquad ...(2.1)$$

where WD(i) is the water depth equivalent to soil moisture in the crop root zone at the end of i^{th} day in mm, WD(i-1) is the water depth equivalent to soil moisture in the root zone at the beginning of i^{th} day in mm, RF(i) is the rainfall on i^{th} day in mm, IRR(i) is the depth of irrigation application on i^{th} day in mm, $ET_c(i)$ is the actual crop ET on i^{th} day in mm, OLF(i) is the runoff going out of the area on i^{th} day in mm, and DP(i) is the deep percolation below the root zone on i^{th} day in mm. Of the various terms on the right hand side, the rainfall and the irrigation application can be found by field measurements, crop ET depends on the RET (which is a function of climatic factors such as temperature, humidity, wind speed, and sunshine), growth stage of crop and soil moisture status in the root zone. Deep percolation occurs when the infiltrated water is in excess of the available storage capacity of the soil in the root zone and percolation rate depends on the hydraulic conductivity of the soil beneath the root zone and its moisture content. Generation of runoff from the agricultural field is a function of the infiltration capacity of soil at the time of storm, rainfall intensity, slope, and the land use. For the sake of application of soil water balance approach, different studies [Rao (1987), Porwal and Rao (1988), Mohan Rao et al. (1990), Hess (1996) etc.] have made various simplifying assumptions. Some common assumptions are:

a) Soil medium is homogeneous,
b) Uniform extraction of moisture by plant roots in the root zone and uniform distribution of moisture in the root zone,
c) Unsaturated zone below the root zone remains at field capacity and acts as passive pathway for drainage of excess moisture,
d) Water table is deep and groundwater contribution is neglected,
e) Complete drainage of soil water in excess of field capacity of root zone.

The studies reviewed in this section can be grouped in three categories: a) studies which mainly deal with the approach for soil water balance modeling, b) studies which use soil water balance as one component of a broader model of irrigation water management, and c) studies which consider spatial distribution of various components of soil water balance utilizing the concepts of GIS. Review of some relevant studies is presented in tabular form (Table – 2.1) for easy comparison. In the table, RF refers to rainfall, IRR refers to irrigation application, AET is the actual crop ET, PET is the potential ET, and DP is deep percolation. Studies reported from S. No. 1 to 5 describe the approach for soil water balance modeling. Studies from S. No. 6 to 14 demonstrate the application of soil water balance approach for various purposes such as irrigation scheduling, effective rainfall estimation, recharge estimation etc., while rest of the studies describe the application of soil water balance model in GIS environment.

Table – 2.1: Review of some soil water balance studies

S. No.	Reference	Purpose of SWBM	Input for SWBM	Output of SWBM	Remarks
1.	Rao (1987)	Simple conceptual SWBM is proposed for finding AET and soil moisture at the end of a week.	Daily RF, pan evaporation and coefficient, soil properties, depletion factors for cotton and its other properties, initial soil moisture.	Average soil moisture in the field at weekly time step.	The study concludes that simple conceptual SWBM, even with lumped input variables like rainfall & irrigation, provide useful information about the dynamics of soil moisture which can be linked to larger computer based irrigation models.
2.	Porwal and Rao (1988)	Presented a simple conceptual model for daily soil water balance at field level.	Crop and soil properties, daily RF, PET, and IRR.	Soil moisture at the end of each day, AET, runoff.	The model calculates field runoff based on SCS method for each storm and effective rainfall is calculated by subtracting runoff from rainfall. Thus precedence is given to runoff over the infiltration and percolation processes. In agricultural fields having gentle slopes and moderate infiltration rates with surface storage, runoff may be marginal.
3.	Phien (1983)	Developed a model "RAINFED" to simulate soil water balance for management of rain-fed agriculture.	Soil and crop properties, daily RF, PET.	AET, crop water demands, effective rainfall, and drainage requirement.	The purpose of SWBM is to develop strategies for deciding planting dates for making best use of rainfall.
4.	Piper et al. (1989)	To calculate irrigation demands and return flows in a basin.	Daily RF, RET, crop and soil properties.	Field water demands.	The authors prefer to use SWBM to find irrigation demands rather than using the concept of effective rainfall.

S. No.	Reference	Purpose of SWBM	Input for SWBM	Output of SWBM	Remarks
5.	Panigrahi et al. (2003)	To simulate soil water balance in root zone of mustard crop under rain-fed and irrigation condition.	Daily RF, RET, crop and soil properties, IRR.	Simulated soil water content at daily time step.	Maximum effective soil depth is divided in two parts: active up to actual root growth and passive beyond the active depth. Deep percolation is considered as the water in excess of storage capacity of active zone. Borg and Grimes method of root depth estimation compared well with actual observations. Runoff was estimated using SCS method combined with soil moisture accounting. The results compare fairly well with measurements.
6.	Hess (1996)	To compute the soil moisture deficit for irrigation scheduling.	Daily RF, IRR, PET, crop and soil properties.	Soil water deficit at the end of each day.	The model assumes no groundwater contribution and no runoff generation. The author points out that main source of error lies in estimation of input data, particularly irrigation and precipitation amounts, and human error in data entry.
7.	Hill and Allen (1996)	To develop irrigation calendars to suggest best dates of irrigation for several planting dates, soil types, and initial soil moisture.	Daily RF, IRR, PET, crop and soil properties.	Soil water status at the end of each day.	The calendars provide simplified, and easy to adopt scheduling guidance to farmers for irrigation application.
8.	Pereira and Teixeira (1994)	To analyse irrigation schedule under various options of water delivery.	Daily, decadaily, or monthly effective rainfall, PET, crop and soil details, IRR.	AET which is linked to the crop yield.	Using soil water balance approach, separate models (ISAREG and IRRICEP) have been reported for simulating soil moisture for row crops and rice crops respectively.
9.	Prajamwong et al. (1997)	To compute the field water demands for input to a larger simulation model (CADSM) to study various management options.	Statistically generated daily weather data, statistically generated fields, crop type and stage, crop and soil properties, ground water contribution, salinity level.	AET which is linked to crop production function	SWBM is used as a tool. AET from SWBM is linked to crop production function to find effect of various management policies. As reported, the model is not suited to large-scale irrigation systems. Statistically derived field information may not represent the actual conditions.
10.	Bhirud et al. (1990)	To compute AET and relate it to crop production function for comparing different water-delivery schedules	Initial moisture content, daily RF, PET, Kc, crop root depth, soil properties, IRR. Root growth is taken as linear function of time.	AET which is linked to crop production function	SWBM is used as tool to evaluate performance of various delivery schedules. The model does not account for spatial variation of crop, soil, and rainfall in modeling soil moisture and does not consider overland flow generation.
11.	Rao (1998)	To validate grouping of water storage properties of soils.	Daily RF, IRR, PET, crop and soil properties. SCS method is used to find runoff.	Soil moisture at different time steps is compared with field observations	SWBM is used as a tool to validate the FC and PWP values of different soil types suggested in the study. The model considers lumped parameters in the irrigation command and uses empirical SCS method to compute runoff.

S. No.	Reference	Purpose of SWBM	Input for SWBM	Output of SWBM	Remarks
12.	Patwardhan et al. (1990)	To estimate the effective rainfall and compare the accuracy of other methods	Daily RF, IRR, runoff, PET, DP, Interception.	Effective rainfall given by (RF-Interception-runoff-DP)	Study concludes that physically based SWBM is te best method of finding effective rainfall than either USDA-SCS method of Hershfield's method.
13.	Mohan et al. (1996)	To compute effective rainfall for rice crop and compare it with other specified empirical methods.	Daily and weekly PET, RF, IRR, initial moisture content, crop coefficients for rice.	Effective rainfall estimates.	The SWBM is considered as standard for comparing other methods (specified by Dastane (1974) and USDA-SCS method). The method is tested for a small area.
14.	Finch (1998)	To find the relative sensitivity of different parameters of soil water balance for groundwater recharge estimation.	Daily PET, RF, canopy interception, fractional proportion of rainfall assigned to runoff and flow bypassing soil store, root distribution at various depths, soil properties	Recharge	Some empirical parameters, like fractional proportion of rainfall for runoff and bypass flow have been considered. The study concludes that soil characteristics and root depth variation are important input to soil water model.
15.	Zelt and Dugan (1993)	To estimate spatial distribution of different variables of hydrologic system such as AET, recharge, runoff, irrigation demands etc.	Monthly PET, RF, initial moisture content, soil properties in form of infiltration curve coefficients, vegetation properties such as root zone, consumptive water demand coefficients, irrigation thresholds.	Spatial distribution of recharge, AET, runoff, irrigation demands.	The study uses SWBM to derive regional hydrologic variables for the great plains of US considering coarse spatial (25 mile) and temporal (monthly) resolution.
16.	Arnold et al. (1998)	To compute the surface runoff, lateral flow, AET, groundwater flow etc. for a conceptual model (SWAT).	Soil and land use properties, daily RF, snow-melt, PET and calculated runoff, AET, and percolation, and return flow.	Soil water content at the end of a day, surface runoff, AET, GW flow and lateral flow.	The model is used to assist water managers in assessing impact of management on water supplies and non-point source pollution in watersheds and large basins. It is a spatially distributed model.
17.	Frankenberger et al. (1999)	To simulate the hydrology for small watersheds having shallow sloping soils.	Daily RF, PET, soil characteristics, geology, vegetation characteristics, digital elevation model etc.	Spatially variable soil moisture, AET, overland flow, and interflow.	The model application is restricted to watersheds with sloping shallow soils. The study highlights the utility of GIS for soil moisture modeling.

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In addition, a number of applications of soil water balance approach are reported in literature. Singh and Kumar (1983) have analysed the process of plant water uptake for simulating soil water dynamics in root zone. Jain and Murty (1985) have developed a mathematical model for simulating soil water content in the root zone by taking into consideration physical properties of soil, crop and climatic parameters. Water uptake by plants is simulated using two different sink terms and the governing differential equation of unsaturated flow of water is solved numerically. The model predicts daily moisture profile for irrigation scheduling. Koch et al. (1987) have presented a soil moisture model based on sharp wetting front approximation that describes the processes of redistribution of soil moisture profile, drainage and ET from the root zone. The authors conclude that uncertainty in soil parameters, root zone depth, and timing of irrigation affect model performance. Mohan Rao et al. (1990) have presented a method of estimating ground water recharge based on the soil moisture accounting (SMA) model. The authors have taken field capacity as a flow parameter and have also compared the results of SMA model with a distributed model based on the finite difference solution of the Richard's equation. The results have shown reasonable agreement between the seasonal totals of groundwater recharge as predicted by both models though daily values differ considerably. Gini and Bras (1991) have developed a lumped parameter mathematical model for simulation of water allocation and salt movement in the root zone. The model simulates with the unsaturated and saturated soil zones and their interaction through capillary rise and percolation. Shih and Jordan (1992) have investigated the use of mid-infrared (MIR) satellite data for assessing four qualitative surface soil-moisture conditions (water/very wet, wet, moist, and dry). Integration of MIR data with land-use through GIS is seen as a useful technique for high-resolution regional soil moisture assessment.

Hatcho and Sagardoy (1994) have detailed four scheduling methods of SIMIS (Scheme Irrigation Management Information System) software, one of which (optimal method) calculates irrigation demands on the basis of soil water balance at weekly time step. Krogt (1994) have used the soil water balance at daily time step to find the demands in the irrigation area for input to OMIS (Operational Management of Irrigation Systems) model. Lamacq and Wallender (1994) have used the soil water simulation model to calculate the daily soil water storage and corresponding evapo-transpiration and deep percolation. Based on the simulated values for different operation schedules, the authors suggest a water allocation policy that provide incentives to the growers for optimising scheduling. Bailey and Spackman (1996) have reported a distributed irrigation scheduling system (IRRIGUIDE) which takes into account the spatial and temporal variation of soil, climate, and crop growth for producing estimates of actual evapotranspiration and soil moisture deficit for individual fields. Griffiths and Wooding (1996) have reported the results of multi-temporal synthetic aperture radar (SAR) data from ERS-1 satellite for monitoring soil moisture at a test site. It is concluded that for bare soil, a good correlation can be achieved between remote observation and soil moisture while for grassland and agricultural fields, the relationship is not strong enough to be utilized for practical applications. Belmonte et al. (1999) have developed a GIS based procedure to better manage an aquifer system using soil water balance approach. The system integrates information from different sources for estimating spatial and temporal distribution of water extractions needed for crops which is used in aquifer modeling. Rajkumar et al. (1999) have developed a controlled water saving method for paddy cultivation using soil water balance approach. The authors use rainfall, RET, and irrigation as input to soil water balance and obtain percolation and AET at weekly time step. Ines et al. (2001) have described a physically based agro-hydrological model (SWAP) which simulates the relation between soil, water, weather and plant using Richard's equation. Using the soil water balance approach, Raes et al. (2002) have developed irrigation charts based on the climate of the region, crop and soil characteristics, irrigation method and local irrigation practices. The developed charts guide the farmers in their day-to-day decisions with regard to the adjustment of irrigation intervals in accordance with actual weather conditions throughout the crop season. Mishra et al. (2002) have reported an optimisation-simulation routine for improving canal water delivery.

The review of various studies utilizing soil water balance approach shows that the method has been extensively used for various applications in irrigated agriculture and it is well recognized that this approach plays an important role in the management of irrigation water. Since a soil water balance model represents the physical processes of water distribution in agricultural fields and the data required for model application are readily available, some authors have used the model directly without any calibration. Some studies have used the distributed approach (using Richard's equation) to find moisture status in root zone while some studies recommend the use of book-keeping procedure for large area studies. In some studies, the whole of rainfall and irrigation application is taken to be infiltrating in the soil column while some studies estimate the runoff using USDA-SCS method. It has also been recognized in some studies that the model parameters, e.g. soil properties, crop types etc. do vary spatially but due to the lack of spatial data, model application is cited considering lumped parameters. It is only in late 90s that GIS capabilities have been utilized for incorporating spatial variation. Itier et al. (1996) highlight the need to develop such remote techniques for soil water modeling that are able to perform spatially integrated measurements to overcome the problem related to spatial variability. The authors further stress that there is a need to develop models that take into account water fluxes that have generally been neglected (capillary rise, seepage, and runoff).

Advanced systems, which take advantage of the remote sensing information and GIS based analytical tools, are currently being developed. With the advancement of remote sensing technology, it is now possible to predict actual cropping pattern in a command area at the scale of individual fields. Using the remote sensing input with a GIS platform, a book-keeping of the soil moisture variation in a command area can be maintained at the field-level.

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.

Before reviewing the literature, various classifications of irrigation system models (FAO, 1994) are briefly described. 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. The model links the hydrology of stream aquifer system to an economic model of agricultural production together with a network model of flows in river reaches, link canals and irrigation canal. 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 the 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), but operational decision support systems are more rare. 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 both 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 generally applicable computer model package [Operational Management of Irrigation Systems (OMIS)] for irrigation system management (Krogt, 1993). OMIS is a generalized model that can simulate different irrigation systems and aims to be a supporting tool for the irrigation system manager. 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, the model calculates the overall and sub-area water demands for selected cropping patterns using historical rainfall for assessing the adequacy of water supply and 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 vs. 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) evapotranspiration (ETM) module; (b) irrigation requirement (IRM) module; and (c) system operation (SOM) module. ETM calculates the crop evapotranspiration 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, either capacity constraint is not considered or it 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. Performance evaluation includes reports on seasonal performance compared with targets.

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 modeling system for optimising the canal releases to meet the crop water demands within existing infrastructure. Besides the MIKE 11 and MIKE SHE modeling systems for the 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. Modeling 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 usually 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 in the water supply available 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 modeling 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 modeling 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 carried out in any 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.

Comparative Review

For easy comprehension of different models with respect to objectives, type of model, allocation scenarios analyzed etc., some details of the discussed models along with remarks are presented in tabular form below:

Table – 2.2: Review of some irrigation scheduling and delivery models

Model	Objective	Type of model	GIS based	Remarks
CROPWAT (FAO)	To calculate crop water requirements for developing irrigation schedules.	Simulation at daily, weekly, or monthly time steps.	No	CROPWAT is an irrigation scheduling model that gives demands for a given combination of crop, soil and climate but does not consider spatial variation in an irrigation command. The results of the model are input to a water delivery model for operation analysis of the canal system.
OMIS (Delft Hydraulics)	A supporting tool for irrigation manager for simulating a canal network for pre-season planning, in-season operation or post-season evaluation.	Simulation at daily time step.	Yes	The model is a useful tool for irrigation manager. In case of deficiency, supply to unauthorized crops is first cut followed by policy of proportionate supply. The use of GIS is limited to input of some digitised maps of canal network and irrigation areas and output in form of maps. It is reported to provide interface of OMIS with remote sensing images and introduction of detailed water accounting module, detailed crop water module, and improved hydraulic module. Groundwater conditions are not accounted for in allocation process.
IMSOP	To simulate the operation of irrigation delivery networks and assist in day-to-day operation	Simulation at daily and weekly time step	No	The model acts as a robust tool for canal operation simulation. Capacity constraint is satisfied through proportionate reduction. However, it does not account for the spatial variation of different variables that affect the irrigation demand. Further, the allocation options are limited and it is not possible to simulate a number of scenarios and select one giving best performance. Groundwater conditions are not accounted for in allocation process.
INCA (ODU, Wallingford)	To act as a generalized database and analysis system for use by irrigation management.	Simulation	No	Provides strong management tool to the managers with graphical presentation of information. Makin and Skutsch (1994) points out that it is planned to introduce GIS for visualization of spatial distribution of model results. It is also planned to introduce an optimization algorithm for optimization of water allocations. Groundwater conditions are not accounted for in allocation process.
IOS (Danish Hydraulic Institute)	To optimise canal releases for meeting crop water demands within existing infrastructure.	Optimization at time step of two weeks.	Yes	IOS is a versatile system that analyses the hydraulic analysis in the canal system and hydrological analysis in the command area in great detail. However, it is not possible to analyse various operation scenarios using this model as the sole aim of optimization is to minimize various penalty functions.
CAMSIS	To analyze various operation scenarios and aid in the day-to-day management of irrigation systems.	Simulation at weekly, 10-daily, or bi-weekly time step.	No	CAMSIS is one of the few simulation models that can simulate a number of allocation scenarios for analysing the behaviour of a canal system. However, geographical variability of various variables is not yet taken into consideration. Groundwater conditions are not accounted for in allocation process.

Model	Objective	Type of model	GIS based	Remarks
SIMIS (FAO)	A DSS for managing irrigation systems.	Simulation at daily, ten-daily, and monthly time step.	Yes	SIMIS is a user-friendly software with modular structure. Many inputs and outputs can be graphically displayed. All the geo-referenced information can be visualized through a GIS. Three water delivery criteria have been incorporated. Groundwater conditions are not accounted for in allocation process.
RIWAP	To estimate water demands at tertiary and secondary levels of irrigation system.	Simulation at weekly time step.	No	RIWAP is a real-time irrigation scheduling model whose results are input to a water delivery model for operation analysis of the canal system.
MIOS	For real-time decision-making under deficit irrigation in a multiple crop irrigation.	Optimization at fortnightly time step.	No	MIOS is a dynamic programming based optimization model with option of selecting a specified strategy among four allocation strategies. Groundwater conditions are not accounted for in allocation process.

The review of a number of canal water delivery models (most of which are main system level, steady state, simulation models) shows that computer simulation of irrigation systems has been attempted with the objective to assist in some aspects of management of irrigation systems. However, different modeling systems have different capabilities and some of them address only specific aspects of the delivery system operation. For example, spatial distribution of some variables is considered only by a few of the discussed models, while some models have the provision of simulating alternative operation scenarios. Groundwater condition in the command is an important function that can affect the policy of irrigation system operation. Most of the models do not consider the groundwater situation in the command while allocating canal water for satisfying irrigation demands. Murray-Rust and Vander Velde (1994) analysed the management options of canal and groundwater in Punjab province, Pakistan and inferred that groundwater is an integral part of irrigated agricultural environment. Sahni (1997) demonstrates the necessity of integrated use of surface and groundwater for sustained irrigation use in India. So, while formulating plans for optimum use of canal water, there is a need to consider groundwater conditions also in the modelling approach.

2.4 REMOTE SENSING & GIS APPLICATIONS IN IRRIGATED AGRICULTURE

For the formulation and implementation of a water distribution plan, detailed information on spatial variation of existing cropping pattern, soil characteristics, surface topography, groundwater conditions etc. is a prerequisite. These data and information need to be analysed, stored and retrieved efficiently in a user-friendly environment. It is also required to frequently update the information for real-time operation and management of water distribution system.

Conventional procedure of storing, handling and updating irrigation data in the form of field/village maps and reports has several drawbacks. It is a slow process, usually unsystematic, occupies large space and requires large manpower for data management. With the advent of remote sensing and GIS tools, it has become possible to prepare dynamic resource maps at various levels of accuracy. Remote sensing provides multi-spectral and multi-temporal synoptic coverage, while GIS provides facilities to integrate and analyse multi-disciplinary data.

2.4.1 Remote sensing applications

Remote sensing implies sensing from a distance. Each satellite image is considered as representing a spatial distribution of energy coming from the earth's surface in one or several wavelength ranges of the electromagnetic spectrum. By using multi-spectral satellite data suitably, different ground features can be differentiated and thematic maps can be prepared. Satellite remote sensing measurements have been used to provide regular information on agricultural and hydrological conditions of the land surface for vast areas and have played vital role in developing and monitoring water management plans.

The usefulness of remote sensing techniques to obtain information on land use, irrigated area, biomass development, crop type, crop yield, crop water requirements, salinity, and water logging etc. has been demonstrated in various investigations. Such information is potentially useful in water distribution planning, performance diagnosis, and impact assessment. Bastiaanssen et al. (2000) have presented the utility of remote sensing deliverables for various applications (see Table – 2.3).

Remote sensing has several advantages over field measurements. First, remote sensing covers a wide area such as entire river basins/command areas whereas field measurements are often confined to a small pilot area because of the expense and logistical constraints. Second, the information is collected in a systematic way which

Table – 2.3: Utility of remote sensing output for water management (after Bastiaanssen et al. 2000)

Remote sensing deliverables	Water use/ productivity	Performance diagnosis	Strategic planning	Water rights	Operations	Impact assessment
Land use	√		√			
Irrigated area	√	√	√	√	√	√
Crop type	√	√		√	√	√
Crop yield	√	√	√			√
Daily ET		√			√	
Seasonal ET	√	√		√		√
Crop stress		√			√	
Salinity		√				√
Historical data		√	√	√		√

allows time series and comparison between schemes. Third, the information can be spatially represented and analysed through geographic information systems, revealing information that is often not apparent from field measurements represented in tabular form.

Comprehensive reviews on remote sensing applications for agricultural water management are presented by Wolters et al. (1991), Veerlapati-Govardhan (1993), Vidal and Sagardoy (1995), Bastiaanssen (1998), Bastiaanssen et al. (2000), and Ambast et al. (2002). Vidal (2000) has presented the applications and methodological guide of remote sensing and GIS in irrigation and drainage. Before analysing the applications of remote sensing in irrigated agriculture, a brief presentation of characteristics of some currently available satellite/sensors and their suitability for various applications is also discussed here.

2.4.1.1 Satellite systems

Several satellites are now in earth orbit and are designated for measuring certain terrestrial processes. Each satellite has its own characteristics in terms of return period, local overpass time, pixel size and number of spectral bands etc. A fleet of different sensors (sensor is a radiometer that measures electromagnetic radiation in small and finite part of the spectrum) is required to make a range of applications feasible. Some sensors/satellites have only a few bands (IKONOS and IRS-1C/1D have 4 narrow spectral bands and 1 wide band) whereas others have many more bands that enable them to measure in a broader part of the spectrum (MODIS has 36 narrow spectral bands). Visible bands are found in the range between 0.4 and 0.7 μm. The blue band has the lowest wavelength (0.41 to 0.50 μm), followed by the green (0.51 to 0.60 μm) and red band (0.61 to 0.70 μm). The near-infrared bands measure in 0.71 to 1.5 μm range while thermal-infrared band measure between 8 to 15 μm region. Information on basic characteristics of some satellite systems is provided by Bos et al. (2001) which is presented in Table - 2.4.

Table – 2.4: Basic characteristics of some currently available satellites (after Bos et al. 2001)

Platform	Sensor	Spatial resolution (m)		Temporal resolution (days)	Image dimensions (km)	Price (US$/km^2)
		Pan	Spectral			
IKONOS-1	-	1	4	3	15	39
SPIN-2	-	2 & 10	-	On request	40	30
SPOT-4	XS	10	20	26	60	1.14
IRS-1C/1D	WIFS	-	1100	5	806	0.001
IRS-1C/1D	LISS	6	23.5	24	141	0.25
LANDSAT	ETM	15	30	16	185	0.018
TERRA	ASTER	-	15, 30	4 to 16	60	Free
TERRA	MODIS	250, 500	1000	1	2330	Free
NOAA	AVHRR	-	1100	0.5	2800	Free
CBERS-2	-	-	80, 160	26	120	0.007

Panchromatic satellite data currently have spatial resolutions of 1 m (IKONOS), 2 m (SPIN), 6 m (IRS) and 10 m (SPOT) and these data are valuable to deduce the location of roads, canals, ditches, boundaries of individual fields, and for describing cartographical changes due to construction and encroachment of built-up areas or deserts. Crop identification at small farm plots (< 0.5 ha) can be done with multi-spectral images of sensors/satellites such as TM, IRS, and SPOT. NOAA-AVHRR is providing remote sensing data on a regular basis at 1.1 km spatial resolution at low costs which makes it suitable for land use determinations of large areas. This sensor allows fast delineation of a basin into major agro-ecosystems (Kite, 1995), though small-scale activities such as the cultivation of various crop types can not be captured with AVHRR images. Bastiaanssen et al. (2000) and Bos et al. (2001) have also provided an account of utilisation of various sensors/satellites. A gist of use of various sensors for different aspects of agricultural management is given in Table – 2.5.

Table – 2.5: Suitability of current sensors/satellites for agricultural management

Purpose	*LANDSAT-TM*	SPOT	IRS	IKONOS	SPIN	TERRA-ASTER	TERRA-MODIS	NOAA-AVHRR	ERS-SAR
Cartographic information		√	√	√	√				
Irrigation/drainage Canals		√	√	√	√				
Micro-scale salinity/waterlogging		√	√	√	√				
Irrigated area	√	√	√			√	√	√	
Cropping pattern	√	√	√			√			√
Land use	√	√	√			√	√	√	
Leaf area index	√	√	√			√	√	√	
Crop coefficient	√	√	√						
Surface roughness									√
Crop yield	√	√	√				√	√	
Potential evapo-transpiration	√	√	√			√	√	√	
Actual evapo-transpiration	√					√	√	√	
Surface moisture									√
Root-zone moisture	√					√	√	√	
Soil salinity	√	√	√	√		√			√
Water logging	√	√	√	√		√			√

There are a variety of available packages for image processing of satellite data (Bos et al. 2001), ranging from low-cost and simple (MapInfo, IDRISI, ER-Mapper, PCI) to complete and simple (ILWIS, GRASS) and professional and expensive (Erdas-Imagine, IDL-Envi, ArcView-spatial analyst).

2.4.1.2 Major applications of remote sensing in irrigation

Advent of remote sensing technology and its great potential use in the field of agriculture have opened new possibilities of improving agricultural statistic system as it offers accelerated, repetitive and spatial–temporal synoptic view in different windows of electromagnetic spectrum. In last few years, remote sensing technology has been increasingly considered for evolving an objective, possibly cheaper and faster methodology for obtaining geographic information on various physical variables. In agriculture, possible applications of remote sensing are in the estimation of land use, irrigated area, crop identification and crop yield estimation, crop stress determination, soil moisture assessment, and estimation of crop ET. Potential applications of remote sensing in irrigation studies are briefly described below:

a) Identification of irrigated areas

Determination of irrigated area using spectral observations provided by MSS, TM, SPOT, LISS etc. has achieved a semi-operational status (Menenti, 2000). The simplest way to discriminate crops and irrigated area is by relying on reflectance spectra (0.4 through 2.5 μm) as there is significant spectral contrast between crops and soils in irrigated and non-irrigated areas. Determination of yearly changes in irrigated areas can be a major remote sensing contribution for better irrigation management.

One of the earliest publications on use of satellite technology to distinguish irrigated areas from non-irrigated areas (in India) is by Thiruvengadachari (1981). Some other works related to estimation of irrigated area using remote sensing include [Nageswara Rao and Mohan Kumar (1994); and Vidal and Baqri (1995)]. An average accuracy varying between 85 to 90% have been reported in various studies.

b) Cropping pattern

Irrigation water allocation is based on information about the irrigated area, crop types, and near-surface meteorological conditions that determine crop water demands. Actual irrigated area may deviate from the original estimates of irrigation command areas. Cropping patterns have been found to change over the years under the influence of price mechanism, infrastructure development, waterlogging, water scarcity, field irrigation and agricultural technology adaptation by farmers etc. Remote sensing has shown great potential in agricultural mapping and monitoring due to its advantages over traditional methods in terms of cost effectiveness and timeliness in the availability of information over larger areas (Murthy et al., 1996). SPOT, IRS and Landsat multi-spectral data can be used for classifying cropped fields and the type of crop with an overall accuracy of about 85% (Bos et al. 2001).

Cropping patterns often comprise many crops which differ in terms of sowing date and phenology. Temporal evolution of amount and colour of foliage is a useful feature for crop discrimination, so multi-temporal sequences of satellite images can be used to measure spectral reflectance at different growth stages. Menenti (2000) describes a procedure to discriminate crops by increasing the number of attributes using spectral reflectance of multi-temporal data.

Some other works on crop identification based on remote sensing data include Waddington and Lamb (1990), Zuluaga (1990), Tennakoon et al. (1992), Ahmed et al. (1996), and Thiruvengadachari et al. (1997). Based on the studies reported in literature, Bastiaanssen (1998) has worked out an average accuracy of 86% for crop identification using remote sensing data.

c) *Crop water stress*

Spectral reflectance of leaves is very sensitive to water absorption. Continuing water stress leads to observable changes in spectral reflectance of crops. Measurement of spectral reflectance in 0.4 to 12 μm region can be used to study land surface heat balance to obtain estimates of actual evaporation and other indicators of soil water availability. Radiometric temperature provides a measure of difference between actual and maximum transpiration which is related to crop water stress. This, however, applies to a relatively homogeneous canopy.

The feasibility of a remote sensing method to determine quantity and type of crop stress by means of multi-temporal Landsat-TM data has been demonstrated by Azzali and Menenti (1989). Various stress indicators, such as Crop Water Stress Index (CWSI) by Jackson et al. (1981) and Water Deficit Index (WDI) by Moran et al. (1994) have been specified. A significant amount of research has been focussed on this subject but the scope for truly operational use of airborne or space-borne sensors is constrained by the need for timely acquisition of observations, rapid distribution and actual use for irrigation management (Menenti, 2000).

d) *Soil salinity*

Statistics about the extent of salt affected soils and the evolution of salinity with time are scarce. A simple combination of multi-spectral bands provides qualitative information about soil salinity, though a quantitative interpretation into salinity classes requires extensive field data. Maps of salt affected areas have been produced using

Landsat MSS and TM imagery by Joshi and Sahai (1993). For large single-cropped (wheat or maize) irrigated areas affected by salinity, reasonable correlations (with 60% accuracy) have been found between soil electric conductivity and spectral reflectance in visual bands by Brena et al. (1993).

Vidal and Sagardoy (1995) have presented the state-of-art in salinity mapping and conclude that highly saline areas can be separated from non-salinized areas using remotely sensed data. Most of the published investigations based on remote sensing distinguish only three to four classes of soil salinity. Ambast et al. (1999) have presented an approach to quantify physical appearance through biophysical parameters of salt-affected crops (such as surface albedo, fractional vegetation coverage, leaf area index, evaporative fraction etc.). Bastiaanssen et al. (2000) have stated that current sensors and interpretation algorithms do not allow the detection of intermediate to medium salinity levels.

e) Soil moisture

Spectral reflectance throughout the whole spectrum is low if water is standing at or near the land surface. A tendency of lower reflectance at increasing wavelength is usually witnessed for open water bodies which makes the classification of ponding layers relatively easy and reliable. Soil moisture can be determined in two manners:

- by means of a radar beam which penetrates through the vegetation and is scattered back after penetrating a few cm into the soil,
- root zone soil moisture as inversely related from the surface energy balance, which describes the moisture content related to root water uptake.

Optical remote sensing is sensitive primarily to the total amount of green vegetation while microwave remote sensing is sensitive to soil moisture, soil type, and salinity. Microwave techniques can provide estimates of near-surface soil water content [Engman and Chauhan (1995), Nojuki and Enthekabi (1996), Schmugge (1999)]. However, active and passive microwave instruments probe only a small soil depth, so their use for irrigation water management is limited as many crops root up to 1 to 2 m depth. van Oevelen et al. (1996) have demonstrated that by combining microwave data at different wavelength ranges, it is possible to estimate integrated soil moisture over a depth of 17 cm. Engman (2000) has described remote sensing applications for soil moisture mapping but concludes that its operational use will remain uncertain for some years.

f) Crop evapo-transpiration

Close dependence of surface temperature on actual evapo-transpiration makes thermal remote sensing suitable for crop consumptive use studies. A review on evapo-transpiration algorithms using remotely sensed data is given by Kustas and Norman (1996). Bastiaanssen et al. (1998) and Bastiaanssen (2000) have recently develop Surface Energy Balance Algorithm for Land (SEBAL) for determining actual crop evapo-transpiration for heterogeneous terrain. SEBAL does not require ancillary information on land use or crop type. The model uses NOAA satellite data and can be applied for diverse agro-ecosystems. Results have shown that the error at a 1 Ha scale varies between 10 to 20% and that the uncertainty diminishes with increasing scale.

g) Crop yield

In last few years, different approaches to compute crop yield using remote sensing data have been developed. Simple empirical relationships with spectral vegetation indices (spectral index that identifies the presence of chlorophyll) or the leaf-area index (LAI) have been derived. However, these relationships need to be calibrated with ground data sets for every season (Wiegand et al., 1994).

Single date Normalized Difference Vegetation Index images acquired during heading stage of grain crops have shown to be closely related to crop yield [Murthy et al. (1996), Thiruvengadachari and Sakthivadivel (1997)]. However, data from crop cutting experiments are found to be necessary to validate these types of statistical relationships [Thiruvengadachari et al. (1997) and Ambast et al. (1999)].

h) Performance assessment of irrigation schemes

Performance assessment is an essential component of effective irrigation management. Regular feedback of information from the field into decision-making can substantially improve the performance of water delivery services. However, obtaining repeated objective evaluations about actual field conditions is difficult. Remote sensing provides viable solutions in some situations, allowing repeated sampling of field conditions in units as small as 100 ha. By regularly monitoring field wetness indicators, irrigation manager can modify decisions based on field moisture depletion and evaporation deficit.

Menenti et al. (1989) have described the determination, mapping and interpretation of three performance indicators (equity, adequacy, and effectiveness) with Landsat TM data and ancillary geo-referenced data. Thiruvengadachari and Sakthivadivel (1997) have obtained similar indicators for four irrigation schemes in India. The performance of Bhakra Irrigation System in Haryana, India has been assessed using remote sensing [Bastiaanssen et al. (1999b), Sakthivadivel et al. (1999)]. The authors presented spatial variations in land and water productivity through linkage with field observations and a hydrological model in GIS environment. It is demonstrated that while productivity remains at reasonable levels, sustainability is in question with build up of salts, and rapid rise in groundwater levels in some areas and fall in other areas.

Bastiaanssen et al. (2001) have presented a remote sensing based approach to find spatial and temporal performance indicators of irrigation management, such as crop water deficit, relative evapo-transpiration, relative soil wetness and biomass yield over irrigation supply. The potential and actual evapo-transpiration estimates are obtained from NOAA satellite data. However, the authors indicate that such coarse resolution data (1.1 km) is a limitation for plot scale studies while high resolution satellites do not provide data in time for operational purposes.

i) Miscellaneous other applications

In a number of countries, irrigation fees are assessed on the basis of irrigated area and/or crop type and these data are typically based on statements made by farmers to either Irrigation Authority or Revenue Service. Sometimes, the reliability of this information is not very high. Satellite data provide reliable and cost-effective estimates of cropped area (Menenti, 2000).

Bausch (1995) has demonstrated that estimates of crop coefficients can be obtained for maize crop using spectral reflectance. Michael and Bastiaanssen (2000) have also reported remote sensing procedure to determine spatially distributed regional scale crop coefficients. However, the authors iterate that approach needs to be tested for arid climates and for larger irrigation areas with uncertain cropping pattern.

The integration of hydrological simulation models with remotely sensed data is a rapidly growing area of research and applications. D'Urso et al. (1992) has mapped crop water requirements in a large irrigation district by combining analysis of Landsat TM images with a calculation of reference evapo-transpiration. The results are used in combination with a regional hydrological model to describe the interaction between surface irrigation and groundwater system.

To summarize, irrigation systems have received considerable attention for a broad range of remote sensing applications. Several inherent features of irrigated lands such as flat or gentle slope, significant contrast between irrigated and non-irrigated areas, serious water management problems tend to establish areas with open water and salt deposits which are clearly identifiable with simple techniques, and multi-spectral multi-temporal attributes of satellite data have led to the possibility of remote sensing applications. This potential is yet to be fully utilised. Daily remote sensing observations are available at relatively low spatial resolution (NOAA-AVHRR, TERRA-MODIS), which can be used for large irrigation schemes. The scope of remotely sensed data can be significantly enhanced through integration with other types and sources of data in a GIS environment. In the next section, utility of GIS for managing spatial database for efficient use of irrigation water is discussed.

2.4.2 GIS Applications

Large amount of multi-disciplinary information pertaining to hydrological, hydro-geological, hydro-meteorological, soil, agronomic, and cropping pattern parameters are involved for irrigation management in a command area. Further, if the database is to handle spatial information, such as satellite imagery and thematic information of various important components of irrigation system, then the amount of data becomes enormous, particularly if the data pertains to a large geographical region.

To handle such vast data, there is a need of efficient system by which data types can be stored, retrieved, manipulated, analysed and displayed according to the requirement. This is the purpose of GIS.

A GIS is a computer-based system designed to store, process and analyse geo-referenced spatial data and their corresponding attribute information. It has provided the planners with an inexpensive, rapid and flexible tool for combining earth related facts to create decision alternatives. GIS can assist in water resources management by efficiently handling spatial and temporal information of hydrology and water resources in a command area. Various distributed information relevant to irrigation management include maps depicting topography; soil type; cropping pattern, irrigation and road network; groundwater table; irrigable areas; water bodies cities, towns, villages, and forests etc. The GIS capability to integrate spatial data from different sources, with diverse formats, structures, projections or resolution levels, constitute the main characteristic of these systems, thus providing needed aid for those models that incorporate information in which spatial data has a relevant role (Goodchild, 1993). Salmah et al. (1994) have highlighted the building up of databases within a GIS for efficient water management.

The growth of GIS has greatly enhanced the opportunity to integrate conventional and remote sensing data to form the basis for development of digital expert systems (Kontoes et al. 1993). Remote sensing provides multi-spectral synoptic coverage for the area of interest, while the GIS provides the facilities to integrate and analyse multi-disciplinary data. The capability of GIS to express the information in form of maps and pictures can make the user more informed and can involve them in decision-making activities (Bradley, 1993).

The use of water management strategies in irrigation is to prevent over-application of water while minimizing yield loss due to water shortage or drought stress (Evans et al. 1991). Landuse and cropping pattern of the command area for various cropping seasons are one of the important information for proper irrigation planning and management. Such information is extracted from satellite images and existing records and stored in GIS along with data layers of soil characteristics, weather conditions, ground water availability etc. All these data layers determine and affect the irrigation water requirement and operation of water delivery system. Integrating these data layers along with analytical models can provide a framework for decision support system (DSS) that can be explicitly designed to support decision-making process for complex irrigation problems. Singh (1995) has described modeling approach for integrated water management with use of remote sensing and geographic information system and the future perspective. Rowshon et al. (2003) have developed a GIS-based computer program for spatial and temporal distribution of irrigation supply for large-scale rice irrigation project in Malaysia.

To summarize, integration of remote sensing and various other spatial ground inputs can be very effectively organized and analysed in GIS environment to find the optimum irrigation water delivery schedules.

2.5 PROBLEM DEFINITION

Poor performance of canal irrigation systems is a matter of growing concern in developing countries, particularly in South-Asian countries, where the need to enhance the agricultural productivity is coupled with decreasing availability of water for agriculture owing to rapid industrialisation and ever-increasing municipal needs (Biswas 1994; Lenton 1994). In an extensive analysis of canal irrigation management, Chambers (1988) has emphasized the need for appropriate and reliable methods of calculating target water releases and their timing (scheduling) coupled with operational practices to achieve target deliveries. ASCE Task Committee (1993) has observed that in the absence of application of any scientific decision support system for the management of large-scale irrigation systems in Asian region, water allocations generally ignore crop water demands with respect to time and quantity leading to poor performance of irrigation projects.

The impact of irrigation on soil water balance, vegetation and shallow groundwater bodies within the irrigated perimeter is significant. Because of poor enforcement of equity in irrigation water distribution, preference for the cheaper canal water (as compared to groundwater use), and location advantage to head-reach farmers, excess canal water is used in the head-reaches of command areas while the tail-ends are deprived of even basic irrigation facilities. On account of excess irrigation, groundwater table rises in the head-reaches of a command and the area, sometimes, get waterlogged as has happened in several canal irrigation projects in India. Govardhan (1993) has mentioned that 18% of 25 major command areas in 13 states in India have become waterlogged. Continued waterlogging results in salinity development. In the tail-ends, due to continuous withdrawal, groundwater table keeps declining making it further difficult to sustain agriculture.

Further, irrigation command areas in developing countries like India, usually have a large number of subsistence holdings due to continuous fragmentation of land holdings over centuries of traditional agricultural practices. Because of these small land holdings, spatial heterogeneity within the command area prevails in terms of cropping pattern, agronomic and irrigation practices, water availability and utilization. Often, gross simplifying assumptions, such as fixed cropping pattern, uniform soil properties, normal average rainfall over the command, normal evapo-transpiration demands, average groundwater potential in the area, average irrigation practices etc. are made in planning and implementation of irrigation projects leading to significant differences with respect to ground situation. There is a need to consider all such spatial and temporal variations while developing an irrigation water distribution plan.

A number of models and decision support systems (as reviewed in Section 2.3) have been developed in the past to prepare water distribution plan in accordance with some specified criteria/objective function. However, it is realised that if, in addition to the crop water demands and canal water availability, groundwater conditions in the command are also taken into account while developing the canal water distribution plan, then considerable savings in terms of energy requirement for pumping groundwater can be made and a plan with higher sustainability can be prepared.

Based on the literature survey, the problem for the present study can be defined as: ***"To develop a simulation model for analysing the operation of a canal network in real-time (weekly) under the prevailing conditions of water demand, water supply, and groundwater position in a command area incorporating physical constraints and taking into consideration the geographical variability of various parameters and processes and to demonstrate the model application for an irrigation system".***

* * *

CHAPTER – 3

DISTRIBUTED SOIL WATER BALANCE MODEL

3.1 GENERAL

Water balance of cropped area is influenced by crop and soil properties, meteorological variables and topography. Knowledge of water content in the root zone of crops is crucial for several applications in agriculture. In this chapter, soil water content in the root zone of crops is simulated to estimate the irrigation demands, crop water stress, and groundwater recharge. Soil water balance approach is used to estimate the water content at different time periods. The developed soil water balance model (SWBM) incorporates spatial variability of crop, soil, rainfall, and topography in the interaction of soil-water-plant system.

In this chapter, first the concepts of soil water balance approach are described. Then, the model developed for the purpose, its assumptions, input data requirements, computational steps, and output are described. Subsequently, the use of model results in the proposed geo-simulation scheme is discussed. Estimation of probable/forecast rainfall for week of canal operational planning. A statistical approach to forecast the rainfall for the forthcoming week is described.

3.2 A DISTRIBUTED SOIL WATER BALANCE MODEL

Soil water balance equation is a mathematical statement of law of conservation of mass as applied to the hydrologic cycle. It states that in a specified period of time, all water entering a specified volume must either go into storage within its boundaries, be consumed therein, or be exported therefrom either on the surface or underground. The water balance approach allows an irrigation planner to compute a continuous record of soil moisture, actual evapo-transpiration (AET), ground water recharge, and surface runoff.

There are broadly two types of soil water balance models: one based on the simple book keeping procedures; and second, the dynamic simulation models based on the physics of unsaturated flow in soils. First type of models has moderate data requirement, such as, storage properties of soils, crop properties, and weather conditions. Second type of models, in addition, requires transmission characteristics of soils and needs to satisfy some basic assumptions of uniformity and isotropy of soil medium. Such models describe different hydrological components in great detail. However, for large area studies, they become very complicated and require huge data and extensive computational time. Therefore, simple water balance models have been preferred in field applications and large area studies (Rao, 1998).

In this study, water balance approach has been adopted to estimate the spatial and temporal variation of root zone soil moisture in a command area in real-time. Based on the measurable variation of different parameters that affect the root zone soil moisture, a command area is divided into square grids of uniform size as shown in Figure – 3.1. Spatial crop variation is incorporated in the model through the analysis of remote sensing data for crop type discrimination. GIS tools are used to account for the spatial variation of other related parameters, such as soil type, rainfall, topography, and groundwater depth. Using the remote sensing input with a GIS platform, a book keeping of soil moisture is maintained for each grid and for each time step in the

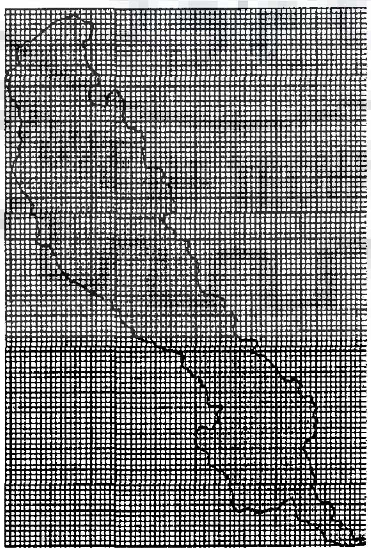


Figure - 3.1: Representation of a command area in grid form

command area. The basic concepts of the model are similar to those used by others [Phien (1983), Rao (1988), Piper et al. (1989) etc.]. However, the present model is capable of being used as a distributed parameter model with a wider potential usage. Different aspects of the distributed soil water balance model are discussed in the following.

3.2.1 Effective soil depth

Effective soil depth at a grid during a day/week is taken as the average crop root depth during that period. The root depth of a crop increases in the initial stages of development till it attains a maximum value. Different crops have different values of maximum root depth and time to reach maximum root depth. Such information about the crops prevalent in a region can be obtained from the field records. Doorenbos and Pruitt (1977) have also given such values for a number of crops. Canadell et al. (1996) have also compiled information on maximum rooting depths for a wide range of vegetation types. Root growth with time is simulated either by a linear model [Eq. (3.1)] or a sigmoidal model [Eq. (3.2)] as proposed by Borg and Grimes (1986). The value of root depth on any day (t) is given by:

$$RD_t = RD_s + (RD_m - RD_s).\frac{t}{t_m} \qquad ...(3.1)$$

$$RD_t = RD_m\left[0.5 + 0.5\sin\left\{3.03\left(\frac{t}{t_m}\right) - 1.47\right\}\right] \qquad ...(3.2)$$

where RD_t is the root depth of crop on t^{th} day after planting, RD_s is the starting root depth [taken as 15 cm since soil evaporation can occur from top 15 cm soil layer (Rao (1987) and Panigrahi and Panda (2003)], RD_m is the maximum root depth, and t_m is the duration of full development of the root zone (days).

3.2.2 Spatial variability of inputs

Components of soil water balance vary spatially as well as temporally. Soil type governs the water holding properties of soil, such as field capacity and permanent wilting point, and its transmission properties, such as hydraulic conductivity. Crop type governs the root development at any time which directly affects the effective soil depth. Rainfall may vary substantially over large command areas thus affecting the soil water balance and irrigation demands in different parts. Topographical variation from place to place may affect the movement of overland flow and depth of water table in a command. Position of water table with respect to crop root zone may affect the water availability to the plants and percolation out of the root zone.

Spatial information in a command may be categorized as static, semi-static, and dynamic. Static information does not change appreciably with time (soil and topographic variation), semi-static information remains constant for a considerable time span but may change over longer durations (cropping pattern, groundwater conditions) while dynamic information change rapidly from day-to-day or week-to-week (rainfall, reference evapo-transpiration (RET) etc.).

Each grid in the command is assigned a specific crop type (based on remote sensing analysis), specific soil type (based on soil survey map of the command) and specific rainfall input (based on Thiessen polygons of the rainfall observation stations in/around the command). Grid-wise information on surface elevation, flow direction, groundwater depth etc. is derived using the GIS.

3.2.3 Time step size

During crop growth period, irrigation applications are made in irrigation intervals of 7 days, 10 days, or 15 days. Weekly time step is considered reasonable for demand estimation in the present study. However, estimation of various components of soil water balance such as overland flow, deep percolation etc. may not be accurate if variation of rainfall and AET within a week is not considered. To account for such variability, water balance models at daily time step have also been used in the literature. In this study, option is provided to carry out the analysis at daily or weekly time step.

3.2.4 Equivalent soil water depth

Conversion of water content (w) in percent on dry weight basis into equivalent water depth is required as various components of SWBM, such as rainfall, RET, deep percolation etc. are expressed as water depth. Consider a soil reservoir (Figure – 3.2) of surface area 'A' sq. m and soil depth 'H' meter.

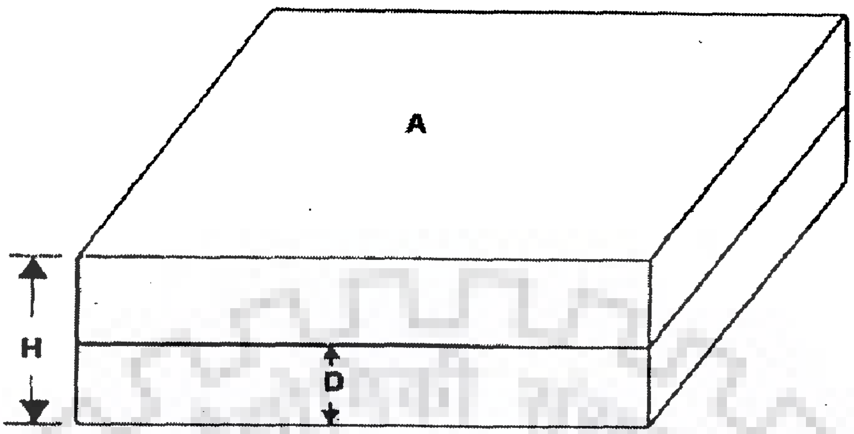


Figure – 3.2: A grid representing soil reservoir

Let 'G_a' be the apparent specific gravity of the soil (a dimensionless parameter equal to bulk density of soil in gm/cc) and 'D' be the equivalent water depth in mm corresponding to water content of 'w' percent on dry weight basis. Then,

w = weight of water/weight of soil solids = W_{water}/W_{solid} * 100 ...(3.3)

W_{water} = Volume of water * specific gravity of water = (A.D/1000) * 1

W_{solid} = Volume of soil * apparent specific gravity of soil = (A.H) * G_a

Therefore, $$w = \frac{A.D}{1000.A.H.G_a}.100$$

and $$D = 10.w.G_a.H \quad \text{...(3.4)}$$

Definition sketch of equivalent water depths corresponding to specific water contents (saturation, field capacity, wilting point etc.) that are useful in SWBM is presented in Figure – 3.3 and these are discussed below.

a) Water depth at saturation (WDS)

In saturated soil, all the pore spaces are filled with water. Water depth at saturation (WDS) represents the water depth equivalent to water content at saturation in mm. Let 'η' represent the porosity of the soil (volume of voids per unit volume of soil) and 'w_s' represent the water content of saturated soil in percent on dry weight

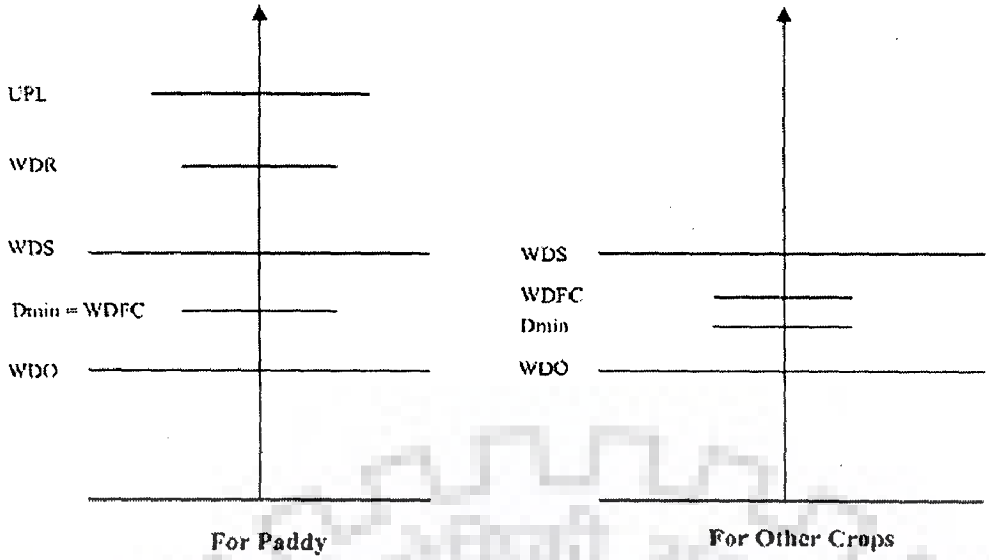


Figure - 3.3: Definition sketch of equivalent water depths of specific moisture contents

basis. Then, equation (3.4) can be written as:

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

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

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

$$= 10.\, \eta .\, H \qquad \ldots(3.5)$$

where 'V' represents the total volume of the soil reservoir. Since the specific gravity of water is 1, therefore, W_{water} is equal to V_{water}.

b) Water depth at field capacity (WDFC)

It is defined as the water content that is held in soil against the force of gravity. This water depth depends on the soil characteristics. Water content at field capacity in terms of depth of water in mm is given by:

$$WDFC = 10 * w_{fc} * G_A * H \qquad \ldots(3.6)$$

where 'w_{fc}' is the water content of soil at field capacity expressed as percent on dry weight basis.

c) Water depth at permanent wilting point (WDO)

It is the water content in the soil when the plants can no longer extract water for evapo-transpiration purpose and get permanently wilted. This condition affects the yield of crops. The equivalent depth of water at permanent wilting point (also called wilting coefficient) in mm is given by:

$$WDO = 10 * w_{pwp} * G_A * H \qquad \ldots(3.7)$$

where 'w_{pwp}' is water content of soil at permanent wilting point expressed in percent on dry weight basis.

d) Upper limit of water depth (UL)

This limit represents the maximum water depth that can be stored in a grid and excess water beyond UL in a time step will move away as overland flow. UL represents the sum of water depth at saturation and the standing water requirement for the crop, if any. UL can be represented as:

$$UL = WDS + D_{max} \qquad \ldots(3.8)$$

where 'D_{max}' is maximum standing water depth required by the crop at any time. For example, paddy crop needs standing water during major part of its growth period.

e) Lower limit of water depth (LL)

When soil water content reaches near the permanent wilting point, then water is not easily extracted by the plants. Hence the term 'readily available water is used which refers to that portion of the total available water (FC–PWP) that can be easily extracted by the plants. Lower limit of water depth (LL) represents the lower bound of the readily available moisture and indicates the level at which the crop just starts to respond to the shortage of the soil moisture. A plot showing the variation of ratio of actual to reference crop evapo-transpiration with soil water content (Shuttleworth, 1993) is shown in Figure – 3.4.

Let 'p' represents the fraction of available water utilized by the plant without any stress. Then, LL in equivalent water depth in mm is given by:

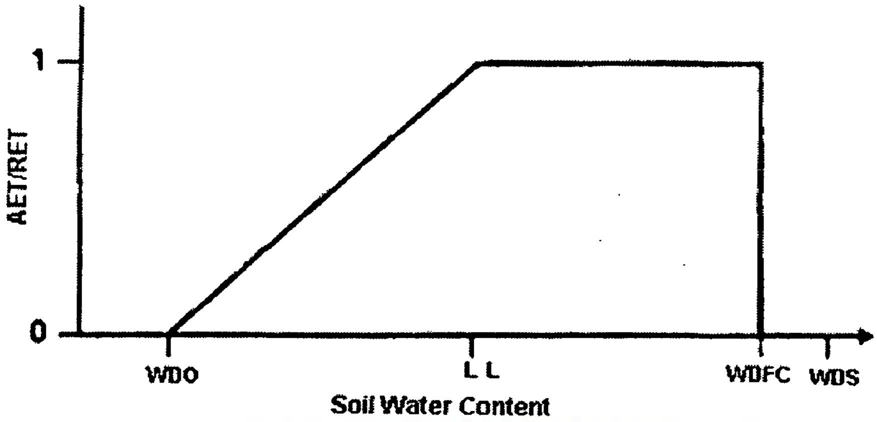


Figure – 3.4: Variation of actual crop evapo-transpiration with soil water content

For Paddy: $LL = WDFC$ ...(3.9)

For other crops: $LL = 10 * [FC - p * (FC-PWP)] * G_A * H$

or $LL = WDFC\,(1- p) + WDO * p$ ...(3.10)

Does it not also depend on the Crop growth stage?

'p' depends on the type of crop and RET demand and its values for various crops are given in FAO (1977). It is recommended by the authors that for RET values smaller than 3 mm/day, the given 'p' value may be increased by 30% and for RET higher than 8 mm/day, the given 'p' value may be reduced by 30%.

3.2.5 Soil water balance equation

For water management simulations in irrigated agriculture, it is necessary to have models that predict the behaviour of soil moisture. The schematic sketch of various components of soil water balance is presented in Figure – 3.5.

For a grid with attributes of a specific crop type, soil type, rainfall, and irrigation supply, at a particular location, the soil water balance equation for a day (t) can be written in the following form:

$$WD_t = WD_{t-1} + RF_t + IRR_t + OLFI_t - AET_t - DPER_t - OLFO_t \quad ...(3.11)$$

where:

WD_t is the equivalent soil water depth in root zone at the end of t^{th} day (mm),

WD_{t-1} is the equivalent soil water depth in root zone at the end of $(t-1)^{th}$ day or at the beginning of t^{th} day (mm),

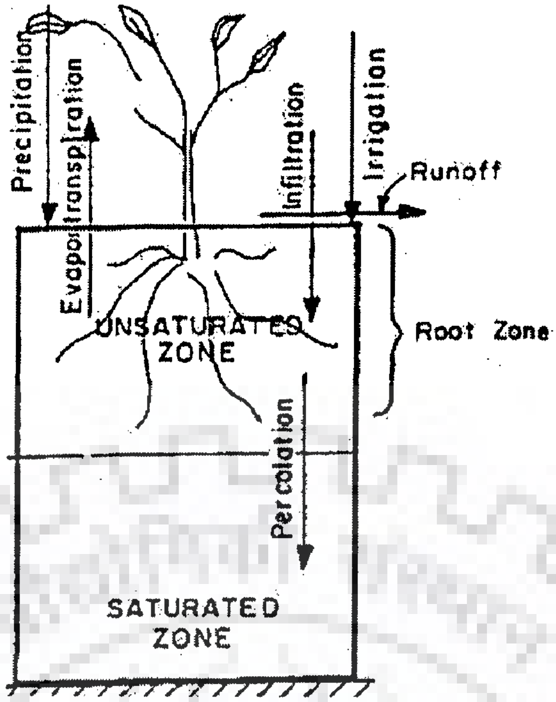


Figure – 3.5 Schematic diagram showing various components of soil water balance

RF_t is the rainfall occurring over the grid on t^{th} day (mm),

IRR_t is the depth of irrigation water applied on the t^{th} day (mm),

$OLFI_t$ is the overland inflow to the grid from adjacent higher elevation grid on t^{th} day (mm),

AET_t is the actual crop evapo-transpiration on t^{th} day (mm),

$DPER_t$ is the deep percolation loss going out of root zone on t^{th} day (mm), and

$OLFO_t$ is the overland flow going out of the current grid on t^{th} day (mm).

How does the net overland flow (contribute to soil moisture in the root zone)

The estimation of various components of the soil water balance equation is discussed in the following:

a) Initial water content (WD_{t-1})

It is the water content available in the root zone at the beginning of time step. At the start of the simulation, an initial value has to be assumed based on the antecedent moisture conditions in the command area. For example, if the water balance simulation is started after the wet season or after a storm event, the initial soil water can reasonably be assumed to be at field capacity.

After the initiation of the water balance algorithm, the residual moisture in the root zone at the end of a day/week becomes the initial moisture for the next day/ week. If the water table is within the effective soil depth in a grid, the water available due to groundwater will affect the water content in the grid.

b) Irrigation input (IRR_t)

Irrigation input is the irrigation water applied to a grid. Irrigation input from canals is estimated by knowing the amount of water supplied in a canal segment during a time step, the crop grids associated with the canal segment, their water demands against which supply is made, and field channel efficiency and water application efficiency. The amount of irrigation application in each grid is approximated by proportioning the canal water supply in the ratio of demands in each grid after accounting for the field channel and application losses.

c) Crop evapo-transpiration (AET_t)

Reference crop evapo-transpiration (RET_t) at any time (t) is an important input for irrigation demand simulation. Daily RET_t can be computed based on the weather data, i.e. temperature, humidity, sunshine, and wind speed. A number of procedures, such as empirical, pan evaporation based, radiation based, and methods based on physical laws governing the process (Penman's method, Penman-Montieth method) are available for calculation of RET_t. After computing RET_t, the potential crop evapo-transpiration ($PAET_t$) is calculated on the basis of known crop coefficient 'Kc_t' of the crop at time (t) in following way:

$$PAET_t = Kc_t * RET_t \qquad \text{...(3.12)}$$

Actual crop evapo-transpiration occurs at potential rate when sufficient water is available in the root zone of crop. Based on the water content in the root zone, the crop condition may lie in any of the three states: Normal, Stress, or Wilt. Normal conditions occur when the soil water depth in root zone lies at or above the lower limit of readily available moisture (LL). Under normal conditions, the AET_t is equal to the $PAET_t$. Stress conditions occur when the soil moisture depth lies below the LL and above the permanent wilting point (WDO). Under stress conditions, the growth of the crop is affected by water deficiency and AET_t is less than $PAET_t$. Wilt conditions occur when the water content reaches at or below WDO. Under wilt conditions, the AET_t becomes 0. Based on the actual water content in the root zone and stress condition of crop, the AET_t is worked out. The stress coefficient 'Ks_t' represents the severity of stress condition in the grid on the tth day. There exist several formulae for computing 'Ks_t' (Boonyatharokul and Walker, 1979). The popular linear form is used in the present study. Three conditions of moisture depth are possible:

i) If $WD_t \geq LL$, then $Ks_t = 1$ ...(3.13)

ii) If $WDO < WD_t < LL$, then $Ks_t = 1 - [\{LL - WD_t\}/\{LL - WDO\}]$ ...(3.14)

iii) If $WD_t < WDO$, then $Ks_t = 0$ ...(3.15)

Actual crop evapo-transpiration 'AET_t' is calculated as:

$$AET_t = Ks_t * PAET_t \quad ...(3.16)$$

For crops other than Paddy, AET is affected not only by the water deficit conditions but also by the surplus conditions in the root zone. It approaches towards zero for water contents nearing saturation. Therefore, if the water table is present at shallow depth or within the effective soil zone in a grid such that the effective soil depth gets saturated, then it may restrict the free drainage of excess water (above field capacity) out of the root zone and also affect the AET. To account for this effect, a linear variation of AET from field capacity to saturation is assumed such that at field capacity, AET equals RET and at saturation, AET reduces to zero.

d) Deep percolation ($DPER_t$)

Deep percolation is assumed to occur when the water content in the effective soil depth increases beyond field capacity (WDFC). The water content above the field capacity drains out of the root zone as deep percolation. However, maximum value of deep percolation is limited by the hydraulic conductivity (K) of the underlying soil at prevalent water content. The value of deep percolation is computed as:

If $WD_t \leq WDFC$, $DPER_t = 0$ ...(3.17)

If $WD_t > WDFC$, $DPER_t$ = function of (K, $WD_t - WDFC$) ...(3.18)

For ponded crops that need standing water depth (such as paddy), moisture content is kept above the equivalent depth at saturation in the field. For such crops, higher initial values of hydraulic conductivity of the underneath soil stabilize to lower values after a hard pan is formed below the crop roots. Phien (1983) used a value of 3 mm/day for sandy loam soil and 1 mm for clay soil. CWC and INCID (1995) suggests that percolation rate for paddy field may vary from 3 to 16 mm/day depending upon the type of soil and the time elapsed after the introduction of irrigation.

If the groundwater table lies very near or within the effective soil zone, it may restrict the deep percolation of excess water from the effective soil zone. To account for this effect, deep percolation is restricted to the water depth equivalent to the water content which saturate the soil column below the root zone up to the water table. If the groundwater table lies within the root zone, deep percolation is assumed to be zero.

e) Overland flow ($OLFI_t$ & $OLFO_t$)

Overland flow ($OLFO_t$) is generated at a grid when the water depth [after accounting for all inputs (rainfall, irrigation, and incoming overland flow) and after deducting for crop evapo-transpiration and deep percolation] exceeds the upper limit (UL) of water depth. The balance flow (in excess of UL) will move in the form of overland flow from one grid to the other in the direction of steepest descent. For water content below UL in a grid, $OLFO_t$ is taken to be zero. The overland flow generated at a grid that moves to adjacent lower elevation grid is calculated as:

$$OLFO_t = WD_{t-1} + RF_t + IRR_t + OLFI_t - ETC_t - DPER_t - UL \qquad ...(3.19)$$

$OLFO_t$ generated at a grid flows down to adjacent lower elevation grid where it becomes the incoming overland flow ($OLFI_t$). Using the digital elevation model of an area, the elevation of each grid and the flow direction is specified.

3.2.6 Assumptions of the model

Basic objective of the model described herein is to simulate the soil water content in the crop root zone at different time periods. Following simplifying assumptions are incorporated in the simulation:

1) *Soil medium is homogeneous over the root zone and within the grid.* Root zone depths for the cultivated crops are small (less than 2 m), and the grid size is also taken to be small. Therefore, the assumption of uniformity of soil in root zone within the grid will hold true in most of the instances.
2) *Overland flow is generated after satisfying storage and transmission characteristics of soil.* A number of researchers [Rao (1987), Phien (1983), Piper et al. (1989), Bhirud et al. (1990) etc.] have taken effective rainfall to be equal to the total rainfall if it is within the limitations of storage and transmission characteristics of soil. Rainfall is assumed to occur at uniform rate during the time step. This may become a gross simplifying assumption over weekly or fortnightly time step.
3) *Water is uniformly distributed and withdrawn in the root zone.* Entire root zone is taken as a single unit with the aim of finding average water content in it. Root distribution and root water uptake are also considered uniform.
4) *Effective depth of root zone is constant for a week.* This assumption is justified in consideration of the root development process and weekly time step.
5) *Any water above field capacity in the root zone is treated as deep percolation (up to maximum limit governed by hydraulic conductivity).*
6) *Gravity is the only dominant force for the movement of soil water.* Since the agricultural fields have minor slopes and moderate infiltration rates, the flow of water in root zone is assumed to be mainly guided by the gravity forces unless an underneath restrictive layer blocks the vertical movement of flow. For this reason, subsurface horizontal flow in the root zone is not considered in this model.
7) *Unsaturated zone in between the root zone and water table remains at field capacity and acts as a passive pathway for drainage of excess water.* Below the root zone in a crop grid, there exists no mechanism to extract soil water, except for deep percolation which occurs only when the water content exceeds field capacity.

3.2.7 Computational steps of model

Stepwise computation procedure of the SWBM followed in this study for a time step 't' is described below:

a) Equivalent water depths

Based on the crop type at a grid and its growth stage, the effective soil depth is determined. Then, based on the soil type, equivalent water depths corresponding to saturation, field capacity, and permanent wilting point are determined. Knowing the crop type and its water requirements, upper limit (UPL, above which water depth will move as overland flow) and lower limit (LL, below which crop stress will occur) are fixed. For the first time step, initial water content in the root zone is assumed while for subsequent steps, water content at the end of previous time step becomes the initial water content.

b) Total available water

Total water available in a grid is calculated by adding the rainfall amount (RF_t), irrigation application (IRR_t), and overland inflow ($OLFI_t$) to the soil water storage at the start of t^{th} period. Total available equivalent water depth (WD_A) becomes:

$$WD_A = WD_{t-1} + RF_t + IRR_t + OLFI_t \qquad \text{...(3.20)}$$

c) Actual crop evapo-transpiration

Initially, it is assumed that actual crop evapo-transpiration occurs at potential rate ($PETC_t$) and is obtained by multiplying reference crop evapo-transpiration with crop factor (depending on growth stage of crop). Remaining water content (WD_{AE}) after evapo-transpiration consumption will be:

$$WD_{AE} = WD_A - PETC_t \qquad \text{...(3.20a)}$$

However, actual crop evapo-transpiration will be less than the potential crop evapo-transpiration if WD_A or WD_{AE} happen to fall below LL. Different combinations of WD_A and WD_{AE} are possible which are as follows:

i) ***If*** $\boldsymbol{WD_A \geq LL}$ ***and*** $\boldsymbol{WD_{AE} \geq LL}$, then $AET_t = PETC_t$ ...(3.20b)

ii) ***If $WD_A \geq LL$ and $WD_{AE} < LL$***, then actual crop evapo-transpiration will be less than $PETC_t$. Water available up to LL will be consumed at potential rate and rest of the crop evapo-transpiration will occur at stressed rate. Coefficient of stress (Ks_t) is 1 at LL and 0 at WDO. Based on the position of WD_{AE}, Ks_t is worked out as:

$$Ks_t = \frac{WD_{AE} - WDO}{LL - WDO} \qquad \text{...(3.20c)}$$

Since stress decreases from 1 to the value Ks_t, average stress coefficient is worked out as $(1+Ks_t)*0.5$ and the actual crop evapo-transpiration is worked out as:

$$AET_t = (WD_A - LL) + [PETC_t - (WD_A - LL)] * (1 + Ks_t) * 0.5 \qquad \text{...(3.20d)}$$

iii) ***If $WD_A < LL$ and $WD_{AE} < LL$***, then the stress coefficients (K_{s1} and K_{s2}) corresponding to initial and final condition respectively are worked out [by using equation (3.20c) except that WD_{AE} is replaced by WD_A for the initial condition]. Average stress coefficient ($Ks_t = (Ks_1+Ks_2)*0.5$] is calculated and multiplied by the potential crop evapo-transpiration to get the AET_t.

After calculating the revised value of AET_t, the remaining water depth (WD_{AE}) after crop evapo-transpiration consumption is calculated again by replacing $PETC_t$ in equation (3.20a) by AET_t. The calculations are repeated till WD_{AE} stabilizes.

$$WD_{AE} = WD_A - AET_t \qquad \text{...(3.21)}$$

d) Deep percolation

The water content that can be held by the soil particles in the root zone is given by WDFC. If the WD_{AE} is less than WDFC, then the deep percolation ($DPER_t$) will be 0. However, if WD_{AE} exceeds WDFC, then excess moisture above WDFC will flow out as deep percolation from the root zone. The maximum rate of deep percolation is limited by the hydraulic conductivity of the soil. Hydraulic conductivity varies with moisture content of soil. In present case, average value of hydraulic conductivity in-between field capacity and saturation is assumed. The water content in the root zone after crop evapo-transpiration and deep percolation is given by:

$$WD_{AEP} = WD_{AE} - DPER_t \qquad \text{...(3.22)}$$

e) Overland flow

If the soil water available in the grid, after accounting for AET_t and $DPER_t$, exceeds the upper limit (UL) of water depth, then saturation excess overland flow ($OLFO_t$) will be generated and can be calculated by:

If $WD_{AEP} \leq UL$, then $\quad OLFO_t = 0 \quad$ ...(3.22a)

If $WD_{AEP} > UL$, then $\quad OLFO_t = WD_{AEP} - UL \quad$ ...(3.22b)

and $\quad WD_t = WD_{AEP} - OLFO_t \quad$ ...(3.23)

where WD_t is the water depth in a grid at the end of t^{th} time step. For the movement of overland flow, calculations are started from the highest elevation grids (which has no incoming overland flow) in the command and then step-by-step, subsequent lower elevation grids are considered. The overland flow generated from the higher elevation grids is moved to the adjoining lower elevation grids based on the direction of steepest descent. Water balance accounting for those grids that receive overland flow is carried out again.

After making the water balance computations for all the grids for t^{th} time step, the water content of each grid is carried over to the next time step and the calculations are repeated for the $(t+1)^{th}$ time step with new set of input data. This way, the water balance accounting is carried out for all the time steps and the water content in the root zone at the end of a week is found out. This information is utilized to find the supplementary irrigation demands in the grid.

3.3 ASSESSMENT OF SUPPLEMENTARY WATER REQUIREMENT

The proposed SWBM keeps continuous account of the various mass balance components of unsaturated zone and estimates the equivalent water depth 'WD_t' in each grid at the end of week (t). Supplementary water requirement (SWR) represents the water depth required to increase the water content up to some specified target (WDR). Selection of WDR is done with care as it directly affects the SWR. Improper selection of WDR can lead to:

i) wastage of irrigation water due to percolation,

ii) reduced rainfall efficiency by wasting rainfall into percolation, and

iii) the need for increased canal capacity.

To minimize water wastage due to deep percolation, the target water content for the non-paddy crops is selected equal to the field capacity. For paddy crop, WDR is selected as the upper limit of water content. Thus, WDR is computed as:

For paddy, $WDR_t = UL$ ...(3.24a)

For other crops, $WDR_t = WDFC$ ...(3.24b)

Supplementary water requirement (SWR_t) for the t^{th} week is computed as:

$$SWR_t = WDR_t - WD_t \quad \text{...(3.25)}$$

To increase the scope of applicability of the proposed model, SWR_t can be computed based on several alternate scheduling criteria as discussed below:

a) Weekly irrigation

Under this operation schedule, soil water content is maintained at some target level every week. Target level represents the percentage of readily available water that is to be maintained. It varies between UL and LL and can be specified by the user. Target level of 100% refers to maintaining UL. In case of scarcity of canal water, irrigation demands corresponding to different target levels can be worked out.

b) Irrigation at stress

This irrigation scheduling criteria is the conventional criteria used in practice. Under this schedule, irrigation water is supplied when the water depth reaches very close (but slightly higher) to the lower limit of readily available moisture (LL). The irrigation demand, SWR_t is computed to increase the soil moisture up to the field capacity limit. This criterion needs higher irrigation demands and requires increased canal capacity due to high variation in discharge.

c) Irrigation at fixed intervals

This scheduling criteria is based on the conventional rotational supply system and is suitable for conventionally operated canal systems. Irrigation water is applied at fixed interval (as in Warabandi system in India) and the demand is calculated up to the irrigation day (rotation day) using the soil water balance procedure.

3.4 SOFTWARE FOR DISTRIBUTED SWBM

A computer program is developed (SWBM) to carry out the water balance computations in the root zone of crops. The program performs grid-wise analysis using the raster as well as attribute data and calculates the final water content at the end of a week. Various features of the program are described below.

3.4.1 Selection of time step

The program performs water balance accounting for a specified week. The specification of week numbers has been standardized. The first week starts from the 1st of January every year and it corresponds to the period from 1st to 7th January. Then subsequently, the second, third ... weeks follow. Since a normal year has 365 days, it can be divided into 52 full weeks with one day remaining. So, the extra day is merged with the last week (52nd week) of the year and the daily simulation for this week is carried out for eight days from 24th December to 31st December. Similarly, a leap year contains 29 days in February. Hence for a leap year, the 9th week (corresponding to period from 26th February to 4th March) contains 8 days rather than 7 days. The week number, for which simulation is carried out, is specified at the start of program. Data files containing the rainfall at various stations for the week and reference crop evapo-transpiration are also specified.

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 daily time step, the water balance computation is performed for each day of the week considering daily rainfall and reference crop evapo-transpiration values. Final water content in each grid at the end of a day is stored in a temporary file and is taken as initial moisture content at the beginning of next day. The calculations are performed for all the days of the specified week and the soil moisture status at the end of the last day of the week is given as one output.

3.4.2 Input data requirement

Various types of spatial and attribute information are integrated by the program to carry out the water balance analysis of the command area. These include raster based distributed information such as crop map, soil map etc., attribute information such as properties of crops and soils, and real-time information coming from the field such as rainfall, reference evapo-transpiration, actual canal network operation. The details of various data that are input to the model are as follows:

3.4.2.1 Spatially distributed data

Spatially distributed information about the command area is obtained as geo-referenced maps either from the remote sensing analysis or from the digitization of topographic maps and field survey records in GIS. Different types of distributed information used by the SWBM are described below.

a) Crop map

Crop type may vary from field to field in the command area. To find the actual cropping pattern in a command, remote sensing data are analyzed and the crop type at each grid is identified. Various crop types are represented with different digital numbers (crop identifiers) such as 1 for sugarcane, 2 for maize, 3 for rice etc.

b) Soil type map

Soil type does not vary from field to field but may vary over large distances in the command area. If the soil survey map of the command is available, the same can be digitized in GIS and converted to grid-based raster format. Different numeric identifiers are specified for different soil types.

c) Thiessen polygon map

Based on the location of different raingauge stations in/around the command area, Thiessen polygon map is prepared, digitized and rasterized in GIS, and different numeric identifiers are specified for different raingauge stations (and corresponding polygons). Numeric value at a grid represents the raingauge to which it is attached.

d) Digital elevation map

A digital elevation map represents the elevations at all grids in an area. After digitizing the contours and spot levels for an area, interpolation can be carried out in a GIS to find elevations at the intermediate grids. This information is used to find flow direction and groundwater depth at each grid in the area.

e) Flow direction map

Flow direction map can be generated in GIS by using the digital elevation map to find the direction of steepest descent at each grid. A 3x3 window is moved over the digital elevation map and the direction of steepest descent is assigned as the flow direction to the central grid of the window. Various flow directions are represented with different digital numbers as shown in Figure – 3.6.

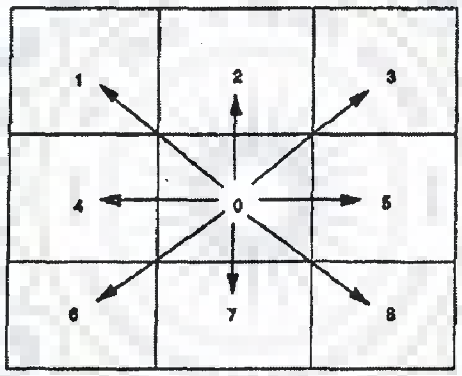


Figure – 3.6: Digital representation of flow directions

f) Groundwater depth map

If the water table rises within to the root zone, then its position affects the water content in a grid and the occurrence of deep percolation. By knowing the position of groundwater observation wells in an area and their water levels, a groundwater surface can be generated in a GIS by kriging/interpolation. By subtracting the groundwater surface from digital elevation map, the water table depth at each grid is found.

g) Irrigation application data

Amount of irrigation water application is an important input to the soil water balance equation. This information is difficult to obtain for individual grids. Therefore, an approximate method, based on weekly canal system operation, is used to find irrigation application map. The method is described under section 3.2.5 (b). Irrigation application is calculated in a separate sub-program that uses the actual canal operation during the week and estimated grid-wise irrigation demands.

h) Initial moisture content

If it is the first week of simulation, then some initial soil water content in each grid has to be assumed based on the antecedent weather conditions. Otherwise, the water content at the end of the previous week becomes the initial water content for the current week. The water content at the end of each week is stored in a separate file for use in the subsequent week.

i) Map containing other information

Other information that is relevant to the agricultural command area include layout of the canal system, irrigable area of different canal segments, extent of villages and water bodies, and the extent of area provided with surface/subsurface drains. Information about different canals and their irrigable areas are used to find the irrigation water application map. If surface drains are provided in a canal command, then overland flow movement from grid-to-grid in that part of the command is neglected. Similarly, if sub-surface drains are provided in a part of the command at some specified depth from the surface, then minimum depth of groundwater table in that region is taken as the depth of sub-surface drains. Grids representing village/water bodies are ignored for the computation of soil water balance. All these information are represented in a single file (generated in GIS) with different identifiers specifying different themes. For example, different canal segments and their irrigable commands are represented by values from, say 1 to 225, all village grids are represented by number 250, all permanent and temporary water body grids are represented by numbers 301 and 302 respectively etc.

Various distributed information obtained either from the remote sensing analysis or GIS analysis are converted to the ASCII format which is used by the

SWBM written in *FORTRAN* language.

3.4.2.2 Attribute data

Various attribute information are attached to different types of crops and soils in agricultural command area. The information useful in SWBM is as follows:

a) Crop attributes

Various crop details that are specified for each crop type in the command are: identification number, maximum root depth (mm), time to reach maximum root depth (weeks), fraction of available water that is readily consumed by the crop without stress (p), water depth required for land preparation before planting the crop (mm), time of land preparation (week), starting week of crop (standardized week number), total number of weeks for which crop remains in the field, depth of standing water requirement (mm), time of standing water requirement (weeks), bund height around the crop field (mm), an identifier to specify whether the crop is carried over from one year to another (1 for Yes and 0 for No), and weekly crop coefficients. For paddy crop, in addition to the mentioned attributes, information about the initial percolation rate, final percolation rate (after the formation of hard pan), and the time to change from initial to final conditions are also specified.

b) Soil attributes

Various soil parameters that are useful in soil water accounting are specified for each soil type in the command. These are: soil identification number, specific gravity, porosity, field capacity, permanent wilting point, and averaged hydraulic conductivity between field capacity and saturation.

3.4.2.3 Dynamic data

Dynamic information that change daily/weekly include the rainfall at different raingauge stations, reference crop evapo-transpiration, canal water supply and initial water content at the start of a week.

Depending on the time step of analysis, either daily rainfall for all days of the week or the weekly rainfall data are specified for all raingauge stations in/around the command area and stored in a separate file. Based on the daily weather data, such as temperature, relative humidity, radiation, and wind speed, reference crop evapo-transpiration can be estimated. Various methods of estimating evapo-transpiration are Penman method, Penman-Monteith method, Hargreaves method, Christiansen method etc. Reference crop evapo-transpiration using weather data is calculated in a separate programming module. Penman-Monteith method is the most preferred method (FAO, 1998). Reference evapo-transpiration for all days of a week or weekly sum is stored in a separate file. Canal water supply data are used to derive the irrigation application. For each canal segment, average discharge passed during a week and the canal run-time are obtained from field and stored in a file along with the identity of canal segment. Irrigation application is calculated in a separate programming module.

3.4.2.4 Processing of distributed data

To decrease the dimensions of the computer program, the redundant grids lying outside of the command area are removed using two programming modules – DIMENSION and IMAGE. Further, the information of four distributed variables (crop, soil, Thiessen polygon, and flow direction) is merged in a single code using a programming module - *CODE*. A description of these modules is given in Chapter-5.

3.4.3 Operation of computer program

The flow chart of SWBM is given in Figure – 3.7. As soon as the program is invoked, it prompts to enter the simulation week, time step of analysis, and information about the initial water content in the command. Then, the program reads various data files one by one and the data type being read is displayed on the screen. While reading distributed data, the row number being read at any time is displayed on the screen.

After reading the data files, water balance computations are initially started for all agricultural grid in the command assuming no movement of overland flow (if any). Movement of overland flow is started after knowing the locations of overland flow generation from the highest observed elevation down to the lower elevations. First, the grid code is decoded to find the crop type, soil type, associated raingauge station, and flow direction at a grid. Other spatial data for the grid, such as rainfall, irrigation water application, and groundwater depth are also recalled from the database. Based on the day/week of simulation and the crop type at the grid, the program identifies whether the crop is present during the simulation week or not. If present, then the growth stage of crop and its root depth are calculated. Based on the effective soil depth and crop and soil properties, equivalent water depths for specific water contents, actual crop evapo-transpiration, deep percolation, and overland flow are estimated.

After computing individual water balance for each grid, movement of overland flow from grid-to-grid is computed. Elevations of all those grids, at which overland flow is generated (donor grids), are compared. The identity of all grids to which the overland flow is contributed (receiver grids) is also found out. The movement of overland flow is started from the highest elevation grid and the flow from all the donor grids at highest elevation is moved to lower elevation receiver grids using the established identity. Water balance computations are revised for all receiver grids in light of the incoming overland flow. Then, overland flow movement computations are made for the next lower elevation donor grids (where overland flow is generated). The computations are repeated till the lowest elevation in the command is reached or there remains no overland flow to be moved.

3.4.4 Output of the model

Four output files are generated by the program: a) final water depth at the end of the week, b) supplementary irrigation demand, c) stress condition, and d) deep percolation. These are discussed below.

a) Final water depth

Final water depth is the equivalent depth of water content in the effective soil zone at the end of simulation week. It is carried forward to the subsequent week as initial water depth for soil water balance computations.

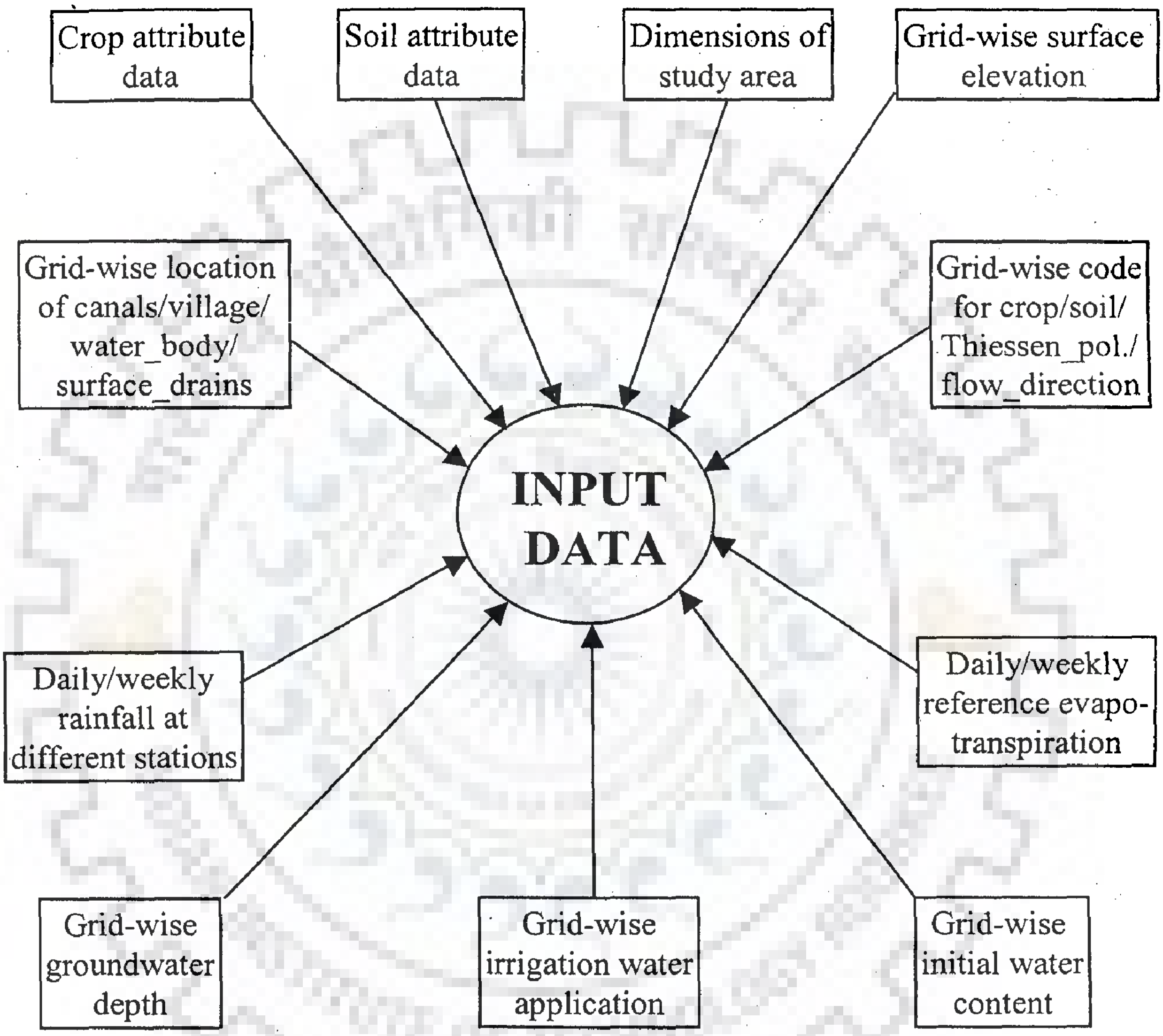
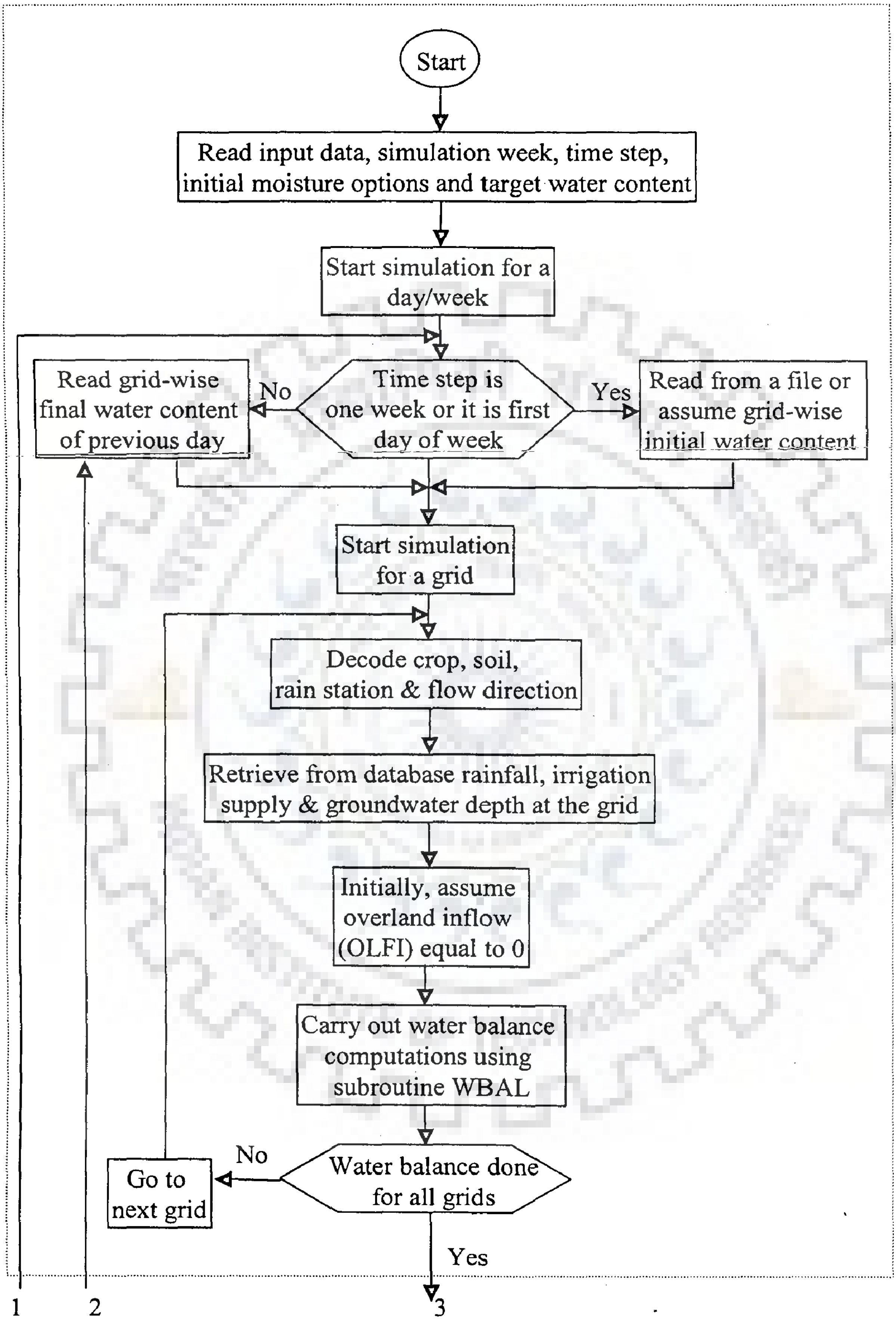
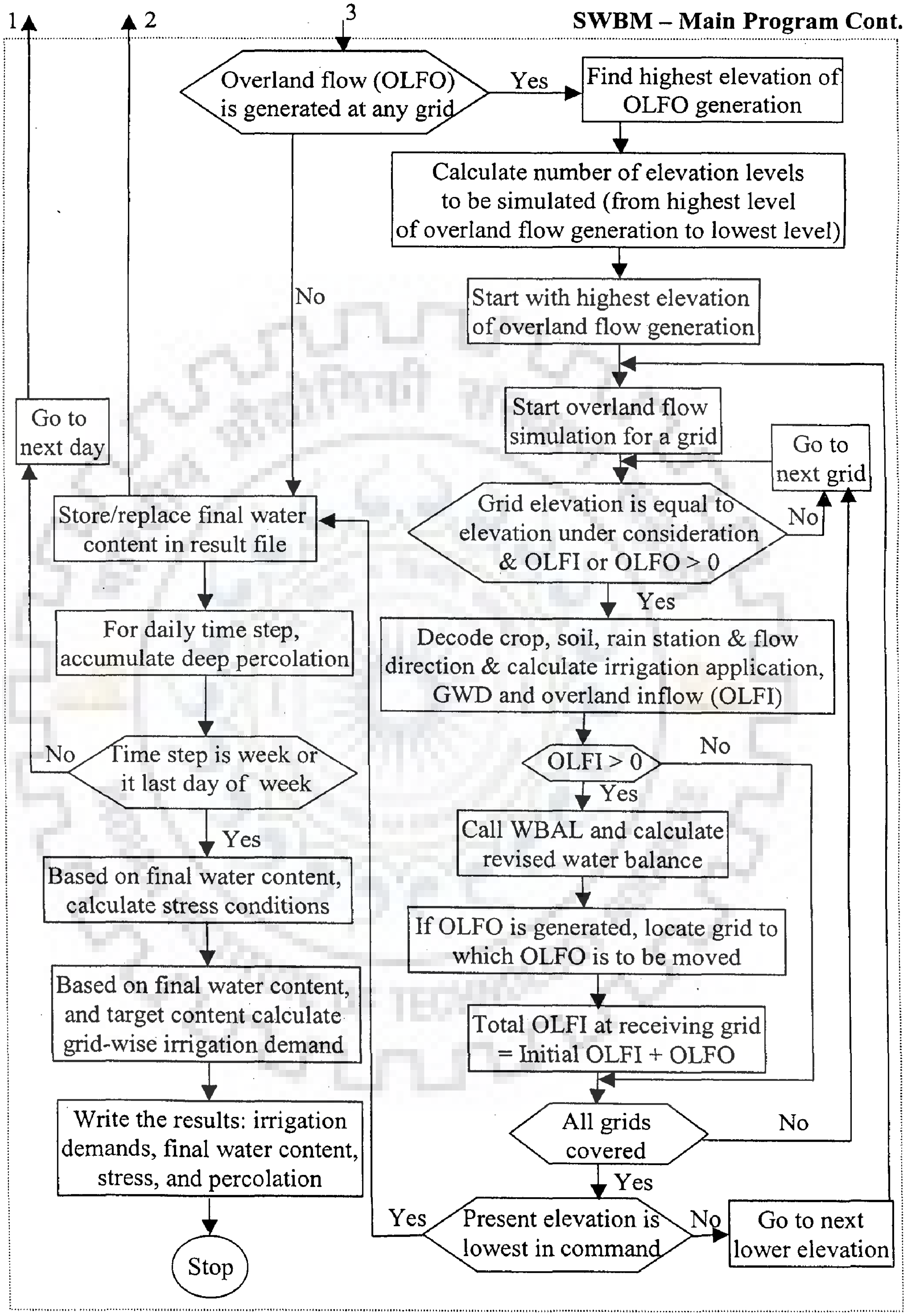
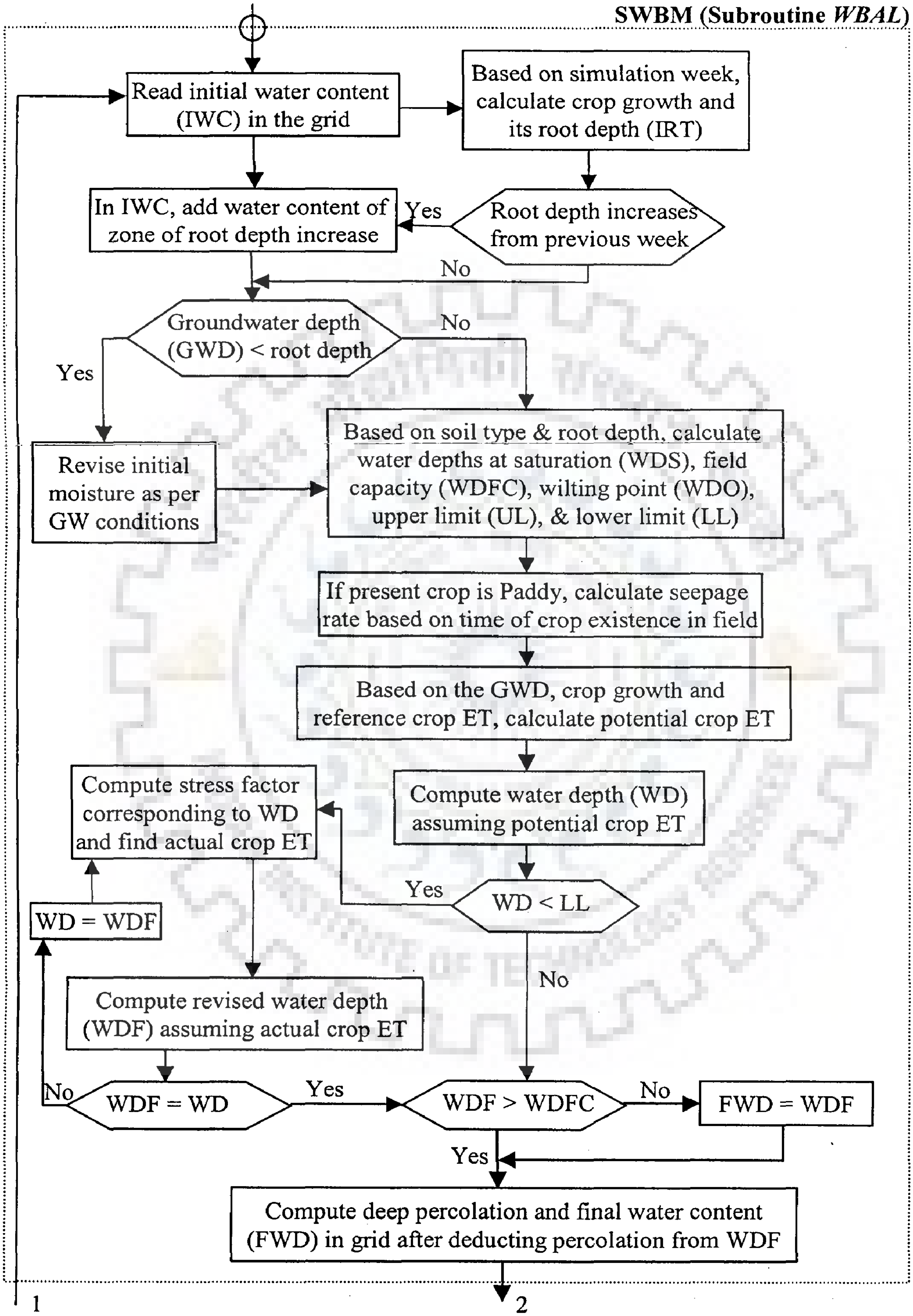
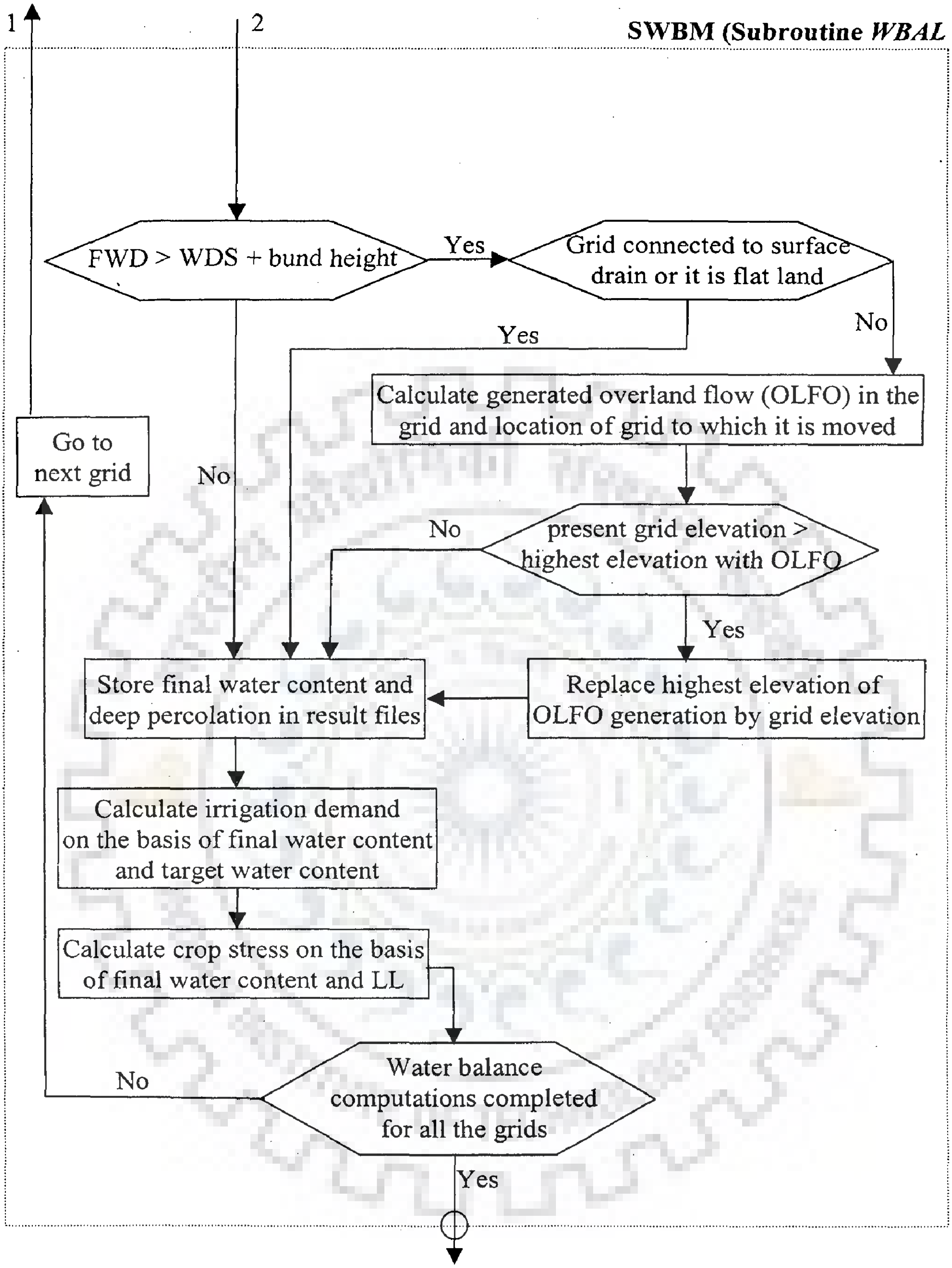


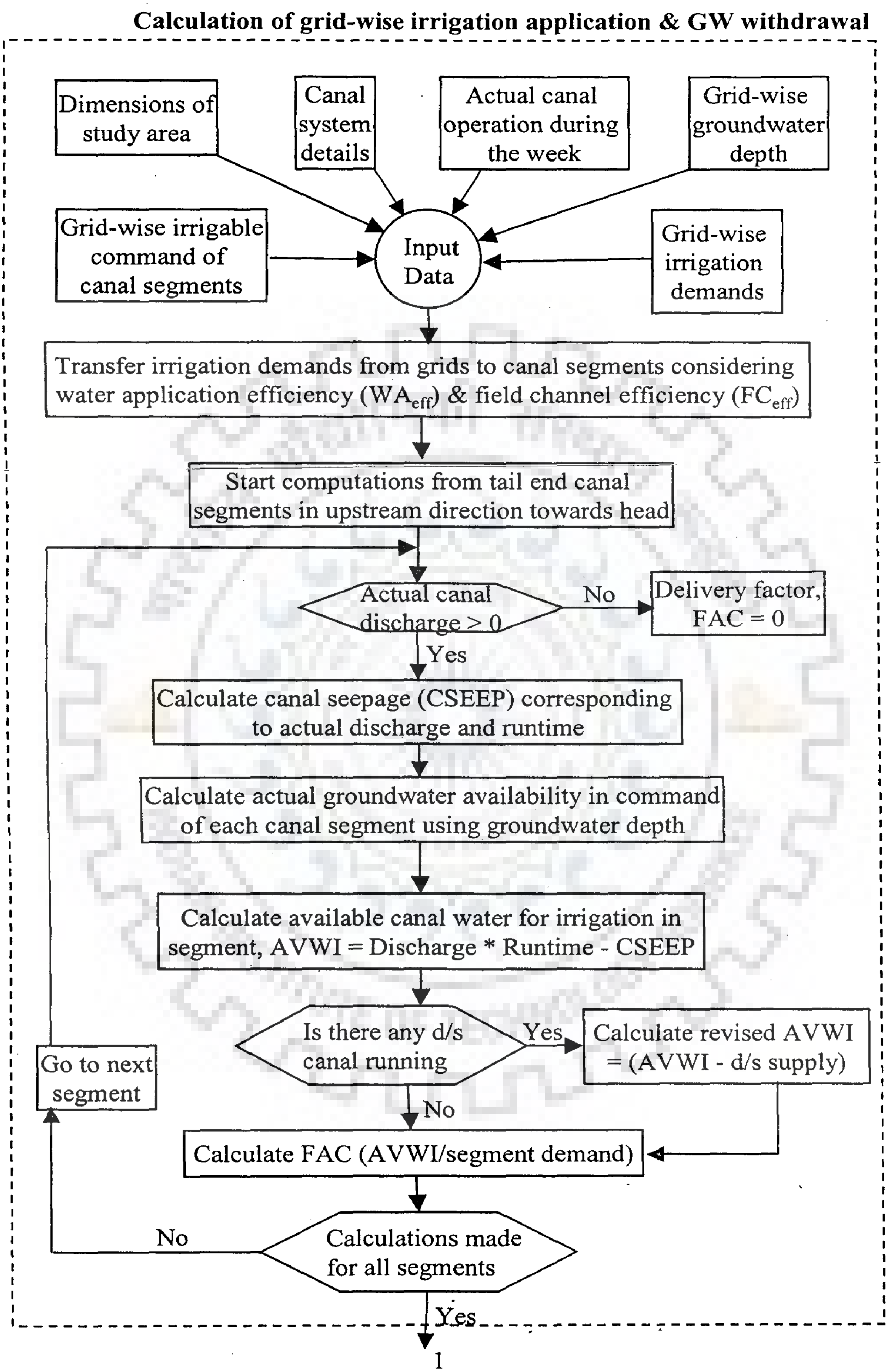
Figure – 3.7: Flow chart of SWBM

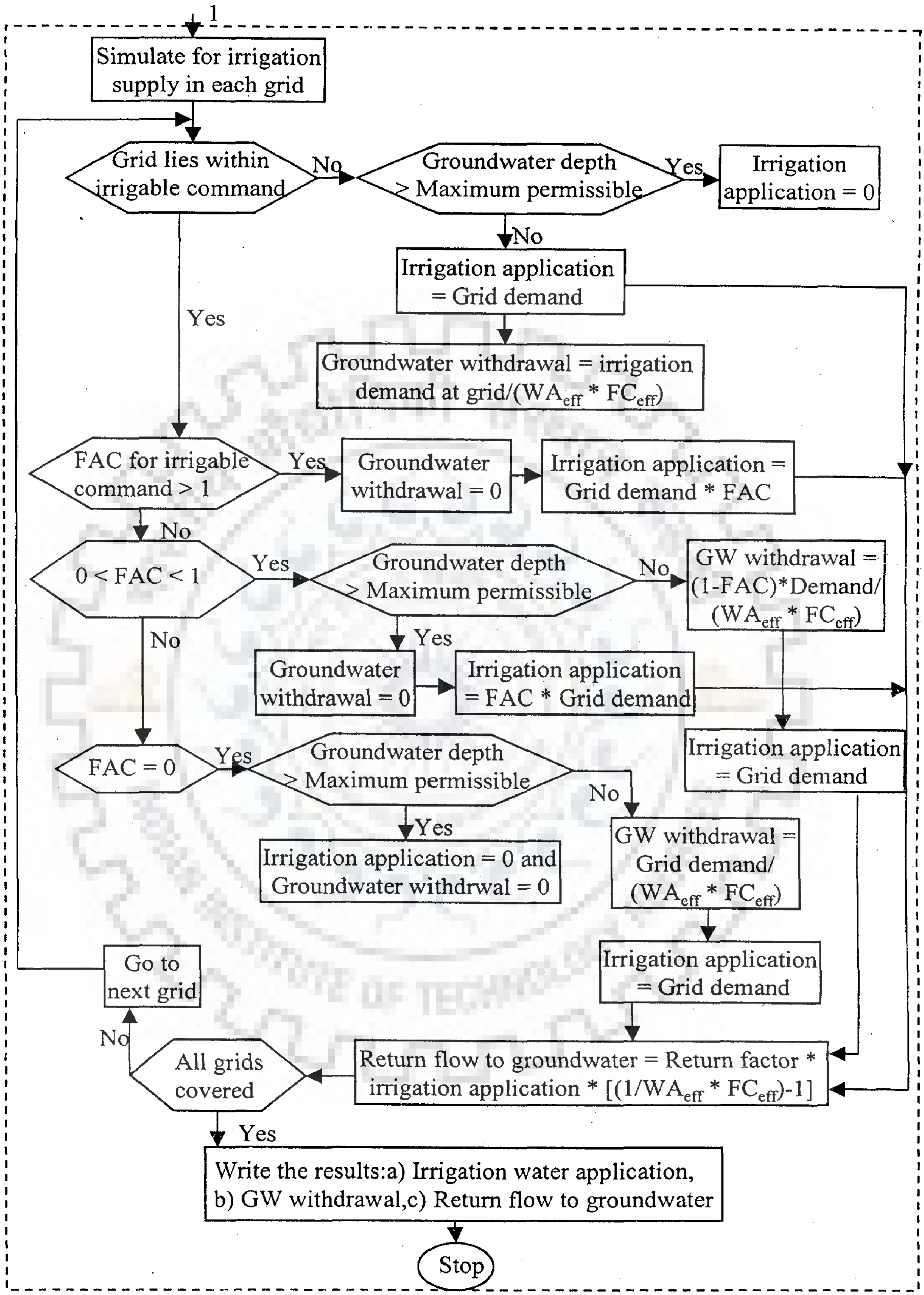

Start
Read input data, simulation week, time step, initial moisture options and target water content
Start simulation for a day/week
Read grid-wise final water content of previous day
No
Time step is one week or it is first day of week
Yes
Read from a file or assume grid-wise initial water content
Start simulation for a grid
Decode crop, soil, rain station & flow direction
Retrieve from database rainfall, irrigation supply & groundwater depth at the grid
Initially, assume overland inflow (OLFI) equal to 0
Carry out water balance computations using subroutine WBAL
Go to next grid
No
Water balance done for all grids
Yes
1
2
3


1
2
3
Overland flow (OLFO) is generated at any grid
Yes
Find highest elevation of OLFO generation
Calculate number of elevation levels to be simulated (from highest level of overland flow generation to lowest level)
Start with highest elevation of overland flow generation
No
Start overland flow simulation for a grid
Go to next grid
Go to next day
Grid elevation is equal to elevation under consideration & OLFI or OLFO > 0
No
Store/replace final water content in result file
Yes
Decode crop, soil, rain station & flow direction & calculate irrigation application, GWD and overland inflow (OLFI)
For daily time step, accumulate deep percolation
OLFI > 0
No
Yes
No
Time step is week or it last day of week
Call WBAL and calculate revised water balance
Yes
Based on final water content, calculate stress conditions
If OLFO is generated, locate grid to which OLFO is to be moved
Based on final water content, and target content calculate grid-wise irrigation demand
Total OLFI at receiving grid = Initial OLFI + OLFO
All grids covered
No
Write the results: irrigation demands, final water content, stress, and percolation
Yes
Yes
Present elevation is lowest in command
No
Go to next lower elevation
Stop


SWBM (Subroutine *WBAL*)
Read initial water content (IWC) in the grid
Based on simulation week, calculate crop growth and its root depth (IRT)
In IWC, add water content of zone of root depth increase
Yes
Root depth increases from previous week
No
Groundwater depth (GWD) < root depth
No
Yes
Revise initial moisture as per GW conditions
Based on soil type & root depth, calculate water depths at saturation (WDS), field capacity (WDFC), wilting point (WDO), upper limit (UL), & lower limit (LL)
If present crop is Paddy, calculate seepage rate based on time of crop existence in field
Based on the GWD, crop growth and reference crop ET, calculate potential crop ET
Compute stress factor corresponding to WD and find actual crop ET
Compute water depth (WD) assuming potential crop ET
Yes
WD < LL
WD = WDF
No
Compute revised water depth (WDF) assuming actual crop ET
No
WDF = WD
Yes
WDF > WDFC
No
FWD = WDF
Yes
Compute deep percolation and final water content (FWD) in grid after deducting percolation from WDF
1
2


1
2
FWD > WDS + bund height
Yes
Grid connected to surface drain or it is flat land
Yes
No
Calculate generated overland flow (OLFO) in the grid and location of grid to which it is moved
Go to next grid
No
No
present grid elevation > highest elevation with OLFO
Yes
Store final water content and deep percolation in result files
Replace highest elevation of OLFO generation by grid elevation
Calculate irrigation demand on the basis of final water content and target water content
Calculate crop stress on the basis of final water content and LL
No
Water balance computations completed for all the grids
Yes


Calculation of grid-wise irrigation application & GW withdrawal
Dimensions of study area
Canal system details
Actual canal operation during the week
Grid-wise groundwater depth
Grid-wise irrigable command of canal segments
Input Data
Grid-wise irrigation demands
Transfer irrigation demands from grids to canal segments considering water application efficiency (WAeff) & field channel efficiency (FCeff)
Start computations from tail end canal segments in upstream direction towards head
Actual canal discharge > 0
No
Delivery factor, FAC = 0
Yes
Calculate canal seepage (CSEEP) corresponding to actual discharge and runtime
Calculate actual groundwater availability in command of each canal segment using groundwater depth
Calculate available canal water for irrigation in segment, AVWI = Discharge * Runtime - CSEEP
Is there any d/s canal running
Yes
Calculate revised AVWI = (AVWI - d/s supply)
Go to next segment
No
Calculate FAC (AVWI/segment demand)
No
Calculations made for all segments
Yes
1


1
Simulate for irrigation supply in each grid
Grid lies within irrigable command
No
Groundwater depth > Maximum permissible
Yes
Irrigation application = 0
No
Irrigation application = Grid demand
Groundwater withdrawal = irrigation demand at grid/(WA_eff * FC_eff)
Yes
FAC for irrigable command > 1
Yes
Groundwater withdrawal = 0
Irrigation application = Grid demand * FAC
No
0 < FAC < 1
Yes
Groundwater depth > Maximum permissible
No
GW withdrawal = (1-FAC)*Demand/ (WA_eff * FC_eff)
Yes
Groundwater withdrawal = 0
Irrigation application = FAC * Grid demand
No
Irrigation application = Grid demand
FAC = 0
Yes
Groundwater depth > Maximum permissible
No
Yes
Irrigation application = 0 and Groundwater withdrwal = 0
GW withdrawal = Grid demand/ (WA_eff * FC_eff)
Irrigation application = Grid demand
Go to next grid
No
All grids covered
Return flow to groundwater = Return factor * irrigation application * [(1/WA_eff * FC_eff)-1]
Yes
Write the results:a) Irrigation water application, b) GW withdrawal,c) Return flow to groundwater
Stop

b) Supplementary irrigation demand

Supplementary irrigation demand at a grid is worked out by subtracting the final water depth at the end of week from the target depth. The target water depth can be decided on the basis of adopted scheduling criteria as discussed under section 3.3. Knowing the water application efficiency, field channel conveyance efficiency, and the irrigable command of each segment, the grid-wise supplementary irrigation demands can be transferred to the canal segments. This information is used by the canal operator for deciding the quantity of water supply in a canal segment.

c) Stress condition

As stated earlier in section 3.2.5 (c), three different water conditions are assumed to occur in a crop – normal, stress, and wilt. The information about stress conditions in a command can guide the irrigation manager in deciding the priority areas for allocation of available water so that the crop loss/damage can be minimized.

d) Deep percolation

Spatial distribution of deep percolation in the command is used to simulate the groundwater table.

All the four result files represent grid-wise distributed information in the command area in ASCII format. These result files are converted to map form by using the *IMAGE* module and output of SWBM can be displayed in GIS system for easy comprehension and decision-making.

3.5 PROPOSED USAGE OF SWBM

In the operation scheme adopted in this study, SWBM is utilized in two steps for each week. First, it is used at the beginning of the week to forecast the spatially distributed irrigation demands in the command area, given the probable/forecast rainfall and reference evapo-transpiration for the week. Based on the forecast demands and water availability, the operation of canal system is planned.

After the week has passed and the actual rainfall, reference evapo-transpiration, and canal operation during the week become known, the SWBM is run again to find the final water content at the end of the week. This information is used to provide the initial moisture conditions in the command for the subsequent week simulation.

3.6 RAINFALL GENERATION PROCEDURE

Precipitation data constitutes an important input for studying demand simulation. Because of the wide variability of rainfall distribution in space and time, accurate forecasting of rainfall is very difficult. However, for forecasting the probable daily rainfall for the forthcoming period, statistical approaches are usually adopted which utilize the historical observations.

As discussed in section 3.5, SWBM is first utilized at the beginning of a week to forecast the irrigation demands in the command area based on probable/forecast rainfall at different gauging stations. To obtain probable rainfall for the coming week, following two methods are considered in the present study.

3.6.1 Statistical analysis

In this approach, rainfall corresponding to different probability levels is derived from the historical record at a raingauge station. Daily/weekly rainfall of past years is arranged in descending order and the rainfall corresponding to different probability is worked out. If sufficient length of record (say 25 years or more) are available, then a distribution can also be fitted to the data and values corresponding to different probabilities can be obtained from the fitted distribution.

3.6.2 Markov chain model

Markov chain model is applied for stochastic simulation and sequential generation of daily rainfall series based on the historical data of observed rainfall. In this study, a computer program is developed to generate the daily rainfall data for the subsequent week. Since the simulation period is short, first order Markov Chain model is assumed to be applicable. The rainfall generation procedure is standard and is widely discussed in the literature. It is briefly summarized in the following:

1. Input the historical daily rainfall record of the week.

2. Convert the historical rainfall data into 'M' states.
3. Work out the transition probability matrix (M, M) for transition from one state to another based on the occurrence frequency.
4. Work out the cumulative probability matrix based on:

$$P_{ij} = \frac{\sum_{k=1}^{k=j} f_{ik}}{\sum_{k=1}^{k=M} fik} \qquad \text{for } i = 1, 2, \ldots M \qquad \ldots(3.26)$$

where f_{ik} is the frequency corresponding to transition from i^{th} state to k^{th} state and P_{ij} is the cumulative transition probability corresponding to transition from i^{th} state to any one state up to j^{th} state.

The resulting transition probability matrix provides the computational scheme for transition from any rainfall state in one particular day to the next day.

5. Synthesize the daily rainfall state by using the Monte-Carlo simulation technique, based on generating a random number as follows:
   a. Compute the transition probability matrix of size (M, M).
   b. Generate a random number between 0 and 1.
   c. Initial rainfall state is calculated according to the actual rainfall state at the beginning of the week. Alternatively, it can be generated by generating the random number.
   d. Generate a new random number.
   e. To generate a state on the N^{th} day ($2 \leq N \leq 7$), random number is compared to the transition probability corresponding to the transition from the state 'i' on $(n-1)^{th}$ day (which is known) to the state 'j', 'j+1', ... M. For each state 'j' (starting from j = 1 onwards) the random number is compared with the cumulative probability (P_{ij}) for the conversion from state 'i' to state 'j'. If the random number is less than or equal to P_{ij} for the state 'j', then 'j' is the output resulting state on the N^{th} day.
   f. Convert the generated rainfall state into the amount of rainfall by taking the mid-value of the rainfall corresponding to the generated state.
   g. Repeat from steps 5d for the generation of next day rainfall in the week.

3.7 CHAPTER CLOSURE

The variability of different parameters involved in agriculture process makes the use of complex models unrealistic in field. The widespread availability of digital geographic data has opened new opportunities for developing distributed models in irrigation water management. The use of remote sensing and GIS allows information about multiple spatial variables to be converted to common coordinate system for analysis.

In this chapter, a conceptual continuous time distributed soil water balance model is developed. The model uses different spatial variables related to water balance of cropped areas, such as cropping pattern, soil map, rainfall, topography, canal irrigable areas and groundwater conditions. Attribute information of existing crops and soils and dynamic information of rainfall, reference evapo-transpiration, and actual canal operation are integrated with the spatial variables to evaluate the spatial distribution of soil water conditions and irrigation demands in the crop root zone, crop stress conditions, and deep percolation in the command area. Various irrigation-related processes simulated by the model include actual crop evapo-transpiration, overland flow generation and movement, deep percolation, and groundwater contribution.

Information about irrigation demands and stress conditions in the command can assist the irrigation manager in the canal network operation while information about deep percolation can be used to simulate the groundwater conditions. Since the model uses the GIS database, it is possible to modify the spatial data and simulate for the revised conditions. For example, it is possible to change the cropping pattern in a part or whole of the command and then simulate the system. Effect of changing crop attributes, such as sowing dates, can also be visualized. Irrigation demands can be worked out for maintaining various levels of water content. The presentation of results in the form of maps makes it easy for the irrigation manager and users to visualize and comprehend the integrated situation in the command.

Database development for the SWBM for the case study of Lakhaoti command area under the Madhya Ganga Canal System, U.P. State, India, is described in Chapter-6 and the results are illustrated in Chapter-7. The results of SWBM are used to analyze the operation of canal network. In the next chapter, a simulation model is developed that links the irrigation demands, worked out by SWBM, with the operation of a canal network.

* * *

CHAPTER - 4
CANAL NETWORK SIMULATION MODEL

4.1 GENERAL

The objective of effective water management in an irrigation system is to ensure its distribution at proper times and in adequate quantities throughout the command area. The water supplied into a main canal is distributed amongst different branches, distributaries and minors in accordance with their demands while satisfying various system constraints. This distribution is easy when the available supply equals or exceeds the demand. However, when the canal head supply is insufficient to feed the entire canal network simultaneously, some judicious operation criteria need to be adopted for making optimum use of the available water.

This chapter is devoted to the development of a distributed canal network simulation model. First, the need for development of such a model is established. Then, the terminology used in the model, the approach adopted, and the assumptions are discussed. For realistic simulation, the model considers spatial variation of a number of input variables and parameters. Subsequently, input data requirements, computational steps and flow chart, and outputs of the model are presented. Finally, the usage of developed model in the proposed geo-simulation scheme (to be discussed in Chapter-5) is elaborated.

4.2 NEED OF CANAL NETWORK SIMULATION MODEL (CNSM)

Irrigation water must be utilized in a judicious manner as irrational use of this developed resource not only amounts to wasteful expenditure but also leads to deterioration of agricultural land. Several examples exist on irrational use of canal water and consequent land degradation as discussed in Chapter-1.

The prevalent practice of planning/operating canal irrigation without consideration of groundwater behavior has often resulted in waterlogging and salinity problems in command areas. Because of their locational advantage, head-reach farmers make excessive use of canal water thus, depriving tail-end farmers of their share of canal water which have to develop groundwater to sustain their crops. Higher recharge of groundwater in head-reaches due to excessive seepage and operational loss from canals, field channels, and irrigated fields builds up the water table in these areas. In the tail-reaches, if withdrawal from groundwater exceeds recharge, the water table keeps declining making it further difficult to extract groundwater. Thus, an hydrologic imbalance is created in the irrigation system which is neither healthy for the head-reaches nor for the tail-reaches. Further, spatial heterogeneity within an agricultural command prevails in terms of cropping pattern, soil properties, agro-climate, irrigation practices, groundwater conditions and utilization potential etc. Canal system characteristics vary along the network. Often, simplifying assumptions, such as fixed irrigation demands, average and uniform physical system characteristics etc. are usually made in planning and operation of irrigation projects leading to discrepancies with respect to ground situation.

A number of canal operation models (described in Chapter-2) have been developed in the past with varying degree of success in simulating ground realities. There is a need to develop a computer-based model that accounts for geographic distribution of characteristics and variables related to irrigation water distribution and makes allocation of the available water resources to satisfy distributed irrigation demands and maintain desired groundwater conditions in a command area. It is also required to simulate various scenarios of canal operation so that their impact on the system performance can be visualized and appropriate operation policy can be derived. The presentation of model is required in a form which is easy to comprehend and interpret.

With this need in view, a simulation model is developed for analyzing the weekly operation of a canal system. The model simulates canal operation scenarios under five different policies. Using the model, spatial distribution of performance indicators can also be visualized. The model can assist the irrigation manager in preparing a flexible water distribution plan for the command area. Various features of the simulation model are described below.

4.3 DEVELOPMENT OF CNSM

The objective of developing CNSM is to simulate the weekly operation of a canal network for satisfying the prevailing irrigation demands of existing crops by judicious use of canal water and groundwater. The grid-wise real-time irrigation demands (that change as per the actual rainfall, weather, and irrigation application), as estimated by the SWBM (Chapter-3) are used by the model. Canal water availability is also reviewed every week. The proposed operation is based on the estimated irrigation demands, canal water and groundwater availability, and prevailing groundwater conditions in the command area during a week. In the proposed approach, priority is assigned to utilize canal water to the extent possible provided that groundwater conditions permit. This results in least requirement of power for pumping groundwater.

Another major objective of developing CNSM is to account for the spatial variation of canal system characteristics and the spatial and temporal variation of irrigation demands and groundwater conditions in the command area. The approach takes advantage of the GIS for database generation, processing, and display of results.

4.3.1 Definition of terms used

Irrigation water distribution network comprises of the main canal, branch canals, distributaries, minors, canal outlets, watercourses and field channels. In this study, the canal system up to minor level is considered as a network of links joined together at nodes. Various terms used in the model are explained below with an illustrative example as shown in Figure -- 4.1.

a) Canal segment

A canal segment represents a link in the canal network. For the intermediate part of network, a segment is the portion of canal in-between two diversion links. For the tail-end of a canal, it represents the portion of canal after the last diversion up to

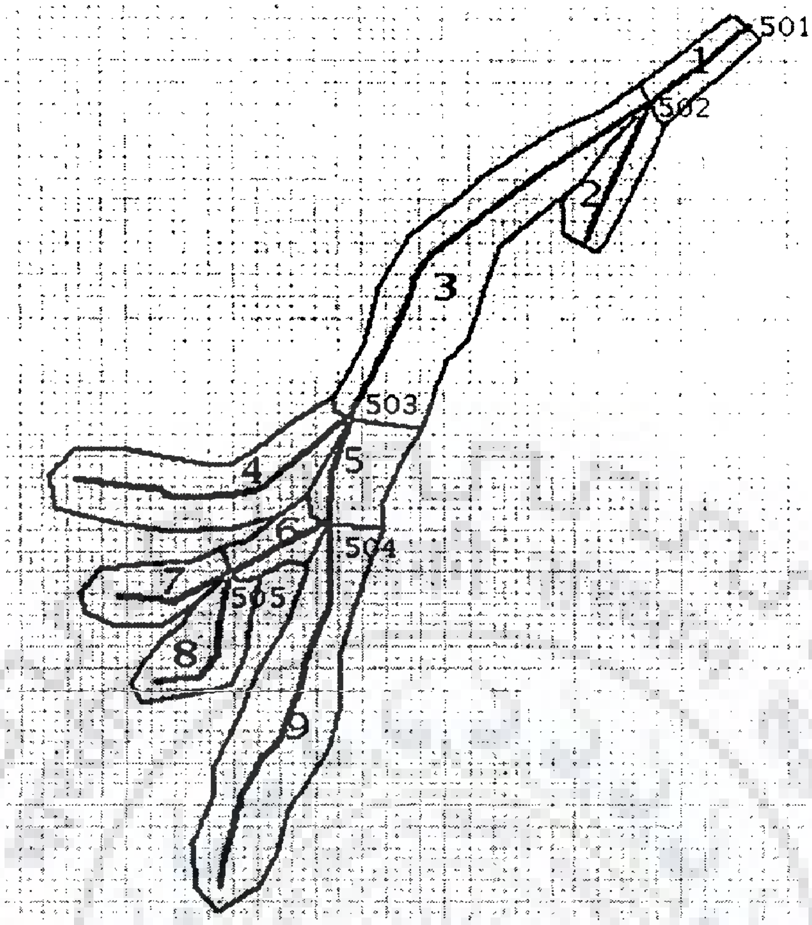


Figure – 4.1: Illustrative example of a canal network

canal end. Each canal segment is allocated a unique numerical identity as shown in Figure – 4.1. Though the segment numbers 1, 3, 5, and 9 represent same distributary, yet they are considered as different canal segments. Canal characteristics, such as discharge capacity, cross section, conveyance efficiency, application and field channel efficiency, seepage rate etc. are assumed uniform in a segment. In the model, the number range 1 to 500 is reserved for the specification of canal segments.

b) System node identification

Various canal segments are connected to each other at junctions called "Nodes". These are also allocated unique numeric identities starting from 501. Range 501 – 1000 is reserved in the model for specifying junction nodes. In Figure – 4.1, the canal system head is represented by node number 501. Other junction nodes in the network are 502, 503, 504, and 505. If a segment represents tail-end of a canal with no downstream network, then its downstream node is given an identity of 1000.

c) Irrigable command of segment

A canal segment is considered to have a number of outlets through which canal water is distributed in its command area. Irrigable area under the direct command of a canal segment is termed as the irrigable command of segment. It does not include the irrigable area of the network lying downstream of the segment. In Figure – 4.1, periphery of the irrigable command areas of different canal segments is shown. For the area lying outside of the periphery, it is not possible to supply canal water.

d) Grid identification number

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

e) Free and intermediate segments

The last segment of a canal that does not have any downstream network is considered as a free segment while a segment with canals bifurcating from its lower node is taken as the intermediate segment. In Figure – 4.1, segments 2, 4, 7, 8, and 9 are free segments while 1, 3, 5, and 6 are intermediate segments. A free segment is operated to meet its own demands only while an intermediate segment is required to supply water for meeting its own demands (of local irrigable area) and the demands of the downstream network.

f) Segment priority

Segment priority refers to the importance of a particular segment with regard to supply of canal water. In real field situation, it is possible that some area in the command needs to be given canal water urgently either because of crop stress or various socio-political reasons. 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 (if any) is distributed among other normal priority segments in accordance with some specified criteria. This concept provides a lot of flexibility to the irrigation manager in analyzing the network operation.

g) Augmentation supply to a segment

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 provision is made in the model to account for the additional availability of water at intermediate locations in the canal network. Using this option, the operator can visualize the effect of augmentation supply on the performance of canal system.

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

Fill-time of a canal segment is the time required for the water to travel from the nearest running canal segment (at the end of previous week) to the current segment and fill it. Run-time is the maximum time required to operate a canal segment for meeting irrigation demands in its irrigable command (including losses in canal segment, field channels, and water application). Maximum possible run-time available to a canal segment is computed by subtracting its fill-time (in hours) from 168 (duration of a week in hours). In Figure – 4.1, assume that segment 1 and 3 are running at the end of previous week. Let the fill-time of segment 7 (time required for the water to travel from node 502 to tail end of segment 7) be 24 hours. Then, the maximum possible run-time for segment 7 will be 144 hours.

i) Groundwater depth in a segment

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

j) Groundwater availability in a segment

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

4.3.2 Approach adopted in CNSM

The approach adopted in CNSM takes into account actual irrigation demands, probable canal water supply during the week, and prevailing groundwater conditions in the command area for deriving operation plan of a canal network. The objective is to use the canal water to the extent possible and to maintain the groundwater table in the desirable range in all the segment command areas. System constraints that have been considered in the model include canal water availability, conveyance capacity of canal segments, and groundwater availability. Five alternate operation policies have been considered for allocation of surface water and groundwater and three methods of computing canal seepage have been specified. The approach is briefly described in the following sections.

4.3.2.1 Transfer of spatial demands to canal network

Grid-wise irrigation demands, as worked out by the SWBM, are transferred to the canal segments using information on irrigable areas, field channel efficiency (FC_{eff}), and water application efficiency (WA_{eff}) under each segment. Irrigation demands of all grids under the irrigable area of a segment are accumulated, converted to volume units, and divided by the WA_{eff} and FC_{eff} to get the gross irrigation demands in canal segment. To meet these demands, the run-time of canal segment is calculated using conveyance capacity and assuming no canal seepage loss. Based on the run-time and specified canal seepage estimation procedure, canal seepage is calculated. Seepage loss is added to the irrigation demands and run-time and seepage is calculated again. This procedure is repeated till the run-time value converges. The calculations of water requirement are routed upstream through the network up to the canal head after giving due consideration to the conveyance capacity of each segment and its maximum available run-time during the week. If the conveyance capacity is a constraint at some segment, then groundwater requirement at that segment is worked out.

4.3.2.2 Capacity constraint satisfaction

After accumulating the water demands up to canal head, groundwater demands at various intermediate segments (due to capacity constraint) are first settled. To settle the capacity constraint, demands of one or more downstream segments for canal water need to be curtailed. Different authors have specified different methods to satisfy capacity constraint. Krogt (1993) has reported that in case of limited supply, water supply to unauthorized crops is curtailed first followed by proportionate reduction. Malano et al. (1993) have reported that in the IMSOP package, either the capacity constraint is not considered or the flow is reduced proportionately. In this model, three methods of satisfying capacity constraint are simulated: a) head-reach priority, b) tail-reach priority, and c) based on groundwater depth.

Under head-reach priority, canal water demands of free segments lying farthest from the constrained segment are curtailed (provided they have sufficient groundwater potential) till the capacity constraint at segment under consideration is settled. Under tail-reach priority, canal water demands of free segments lying nearest to the constrained segment are curtailed. In the method based on groundwater depth, canal water demands of free segments lying downstream of the constrained segment and having least groundwater depth are curtailed. Calculations proceed upstream from tail end till capacity constraint in all segments is satisfied.

4.3.2.3 Distribution/Allocation policy

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

a) Policy 1 - Head-reach priority

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

b) Policy 2 – Conjunctive utilisation of water

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

There polices are rather subjective;

system and the revised demands at head are found. The process is iterated till the deficit at the system head reduces to zero.

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

c) Policy 3 – Proportionate supply

Under this policy, the available canal water at a system node is distributed proportionately among different segments (meeting at a node) in proportion to their demands. Thus, this policy tries to equitably distribute the deficit among different canal segments. The canal water demands of irrigable command areas of segments are also proportionately curtailed.

d) Policy 4 - Tail-reach priority

Under this policy, the canal water 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 in full. Using this policy, the operator can visualize the extent of the downstream canal system that can be satisfied for the available canal water. Since the groundwater depth in the tail reach of a command is generally high as compared to the head reach, this policy also tries to equalize the groundwater regime in the command area. However, the canal seepage losses in this policy are very high and the irrigation demand satisfaction from canal water is minimum of all the four specified policies.

d) Policy 5 – Conjunctive use with minimum energy demand

As already mentioned in Policy-2, a lot of water is wasted through seepage in taking the canal water to areas with deeper water table resulting in increased use of groundwater. At the same time, since groundwater is extracted in shallow water table areas, energy required for pumping groundwater can be conserved. Under Policy-5, an optimization is performed through successive model iteration to find the canal-run configuration corresponding to least energy demand for pumping groundwater.

For finding the canal-run configuration corresponding to minimum energy demand, first the Policy-2 is applied and the canal operation configuration corresponding to conjunctive use is found out. Corresponding energy requirement in the irrigation system for pumping groundwater is also calculated. Now, the canal water demands of the segment having maximum distance from the head are curtailed and the canal water demands of one upstream segment having least depth of pumping (among the curtailed upstream segments during the allocation under Policy-2) are restored. Energy demand for the new configuration is computed and stored along with the canal operation configuration. This way, the most distant segment demands are curtailed and upstream segment demands are restored and the process is iterated till the canal head is reached. The configuration that requires minimum energy for pumping groundwater becomes the recommendation of Policy-5.

Option is included in the model to select any one of the five allocation policies and simulate the network operation. Before resuming the allocation analysis, an index known as "Demand Distribution Index" is determined by the model. The purpose of the index is given below.

4.3.2.4 Demand Distribution Index

Demand distribution index (DDI) is related to the spatial distribution of irrigation demands in the command area. DDI is calculated as the ratio of total length of those canal segments that have canal water demands to the total length of the canal network over which water has to be conveyed (from the canal head) to satisfy these demands. In Figure – 4.1, let irrigation demands exist only in segment 8 having a length of 2803 m. To meet its demands, a canal length of 17142 m (Segment 1+3+5+6+8) needs to be run. So the DDI becomes 2803/17142 = 0.1635.

In a particular week, it may so happen that due to the occurrence of rainfall, irrigation demands exist only in some particular segments of the command and water has to be conveyed over a large length of canal network to supply water to these segments, which may not be economical. To account for such situation, DDI is computed by the model. If DDI falls short of some specified minimum, the canal system is not operated.

4.3.3 Assumptions of the model

The main objective of the proposed model is to simulate the operation of a canal network considering spatial irrigation demands and prevailing groundwater conditions in the command area. Following simplifying assumptions are made:

1) *The characteristics of a canal segment are uniform.* The canal system is divided into a number of segments and various characteristics (such as discharge capacity, bed width, water depth, seepage rate, conveyance efficiency etc.) of each segment are input to the model. These characteristics in actual condition may vary from one part of the segment to another particularly if segment size (length and its command area) is large.
2) *Maximum benefits from irrigation system can be achieved if adequate soil moisture is maintained in the root zone of existing crops during each week of crop growth period.* The physical objective of maintaining soil moisture in the root zone has been considered without going into the details of crop and water prices.
3) *Piority use of canal water.* In the developed model, canal water is used to the extent possible. Groundwater is pumped either in waterlogged areas, or in case of scarcity of canal water or canal capacity constraint.

4.3.4 Input data requirement

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

a) Crop type map

The crop map is used to define the critical depth of water table (waterlogging condition) for a canal segment. By knowing crop types in the irrigable command of a segment, the maximum critical water table depth for the segment is found out. If the average water table depth in the irrigable command is within the specified critical depth, then the segment is treated as waterlogged.

b) Layout of irrigable command areas

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

c) Irrigation demands

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

d) Groundwater depth map

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

Various distributed information obtained from remote sensing or GIS analysis are converted to ASCII format for use by CNSM, written in *FORTRAN* language.

e) Canal system characteristics

Canal characteristics vary from one part of the network to another. To account for such variations, the canal network is divided into a number of segments (links) joined together at nodes. Various characteristics that are specified for each canal segment include: numeric identity, discharge capacity (CAP) in cumec, length (ALEN) in m, bed width (BEDW) in m, water depth (WDEPT) in m, side slope (V:H::1:z), irrigable area in ha, conveyance efficiency (CEFF) in percent, application efficiency (AEFF) in the irrigable command, field channel efficiency (FCEFF) in the irrigable command, seepage rate (SEEPR) in cumec/million sq. m of wetted area, code (ISCOD) for specifying the method for canal seepage estimation (1 – conveyance efficiency, 2 – empirical formula, 3 – seepage rate), priority (IPRIO) of segment (0 – normal, 1 – high), number of tube wells (NOP) operating in the irrigable command, average power of pumping plants (PPP) in horse power, number of hours for which power supply (POWS) is available in the irrigable command, and the source of power commonly used in the irrigable command (1–power supply, 2–generator sets). Canal cross-sections are assumed to be trapezoidal. Data that define the linkage of various segments in the network include: upstream and downstream node numbers of each segment, total number of nodes located downstream to each segment, total number of segments bifurcating from the downstream node of each segment, and their identity.

f) Canals running at the end of previous week

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

4.3.5 Computational steps of model

The model schematization is presented through the flow chart in Figure – 4.2. Main parts of the flow chart include: the main program, canal operation subroutine COPR, a section for satisfying capacity constraint, sections for various allocation policies, and result section. Various steps of model 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.

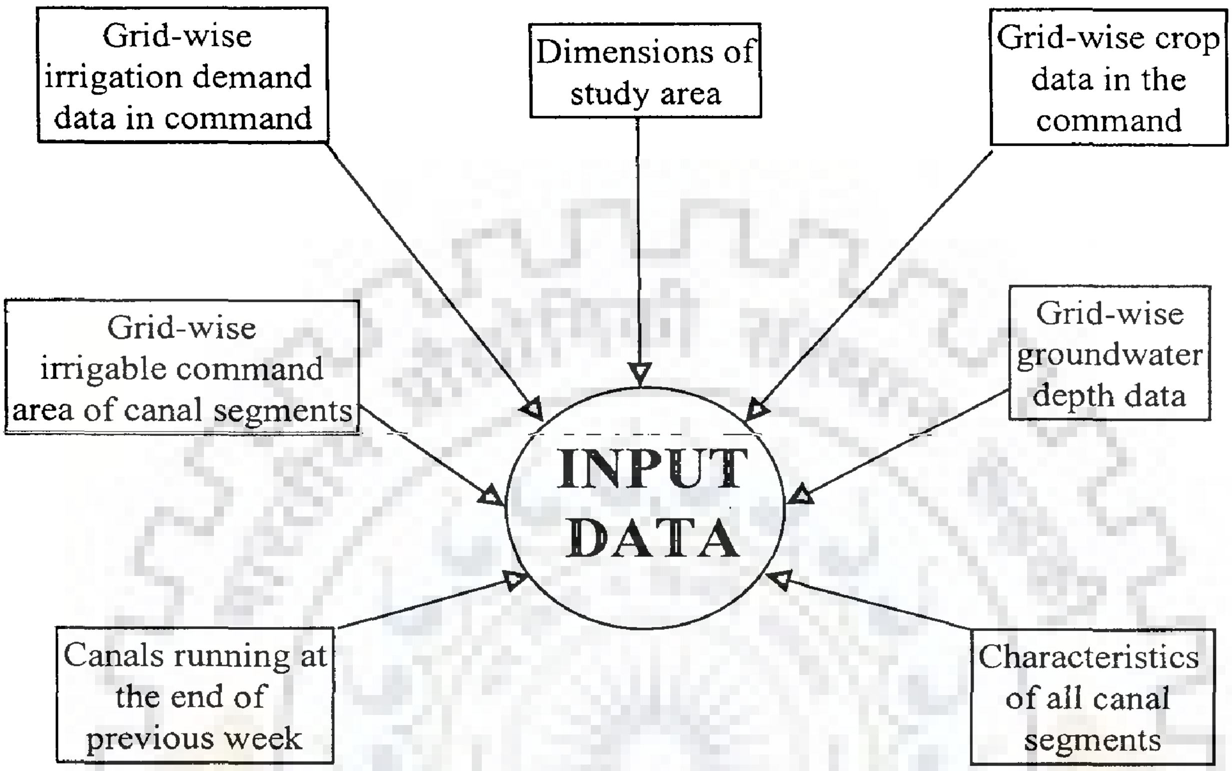
b) Transfer of irrigation demands from grids to canal segments

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.

$$WR_{ij} = SWR(i,j) * 24 * 24/1000 \quad \ldots(4.1)$$

$$(WDG_{ij})_{id} = \frac{WR_{ij}}{AEFF_{id} * FCEFF_{id}} \quad \ldots(4.2)$$

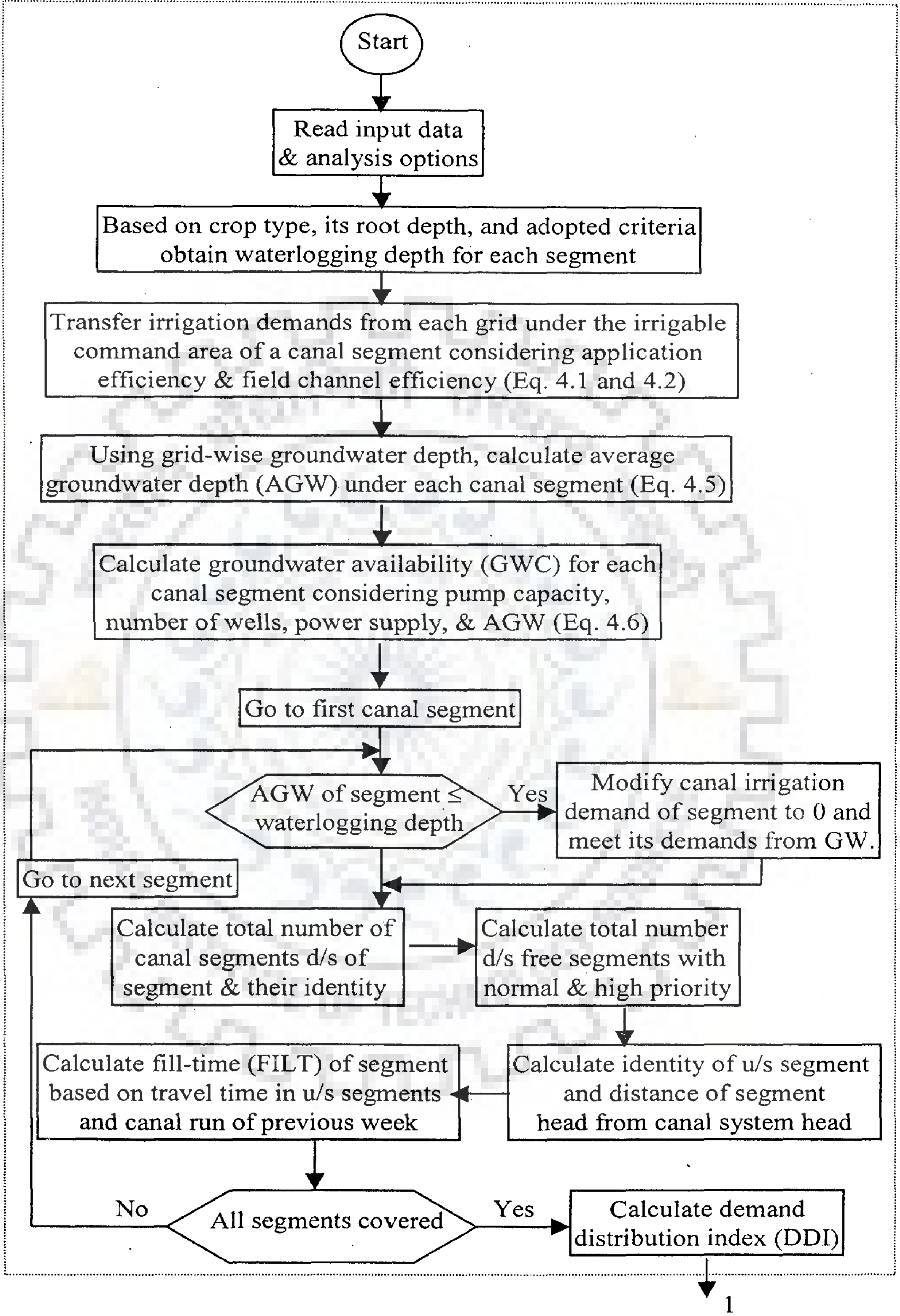
Water demands of all grids that lie under the local command of a canal segment are added to get the total irrigation demands WD_{id} at the canal segment. Initially, it is assumed that all demand are met from canal water. Therefore, canal water demand ($TWRCN_{id}$) in a segment is taken as:



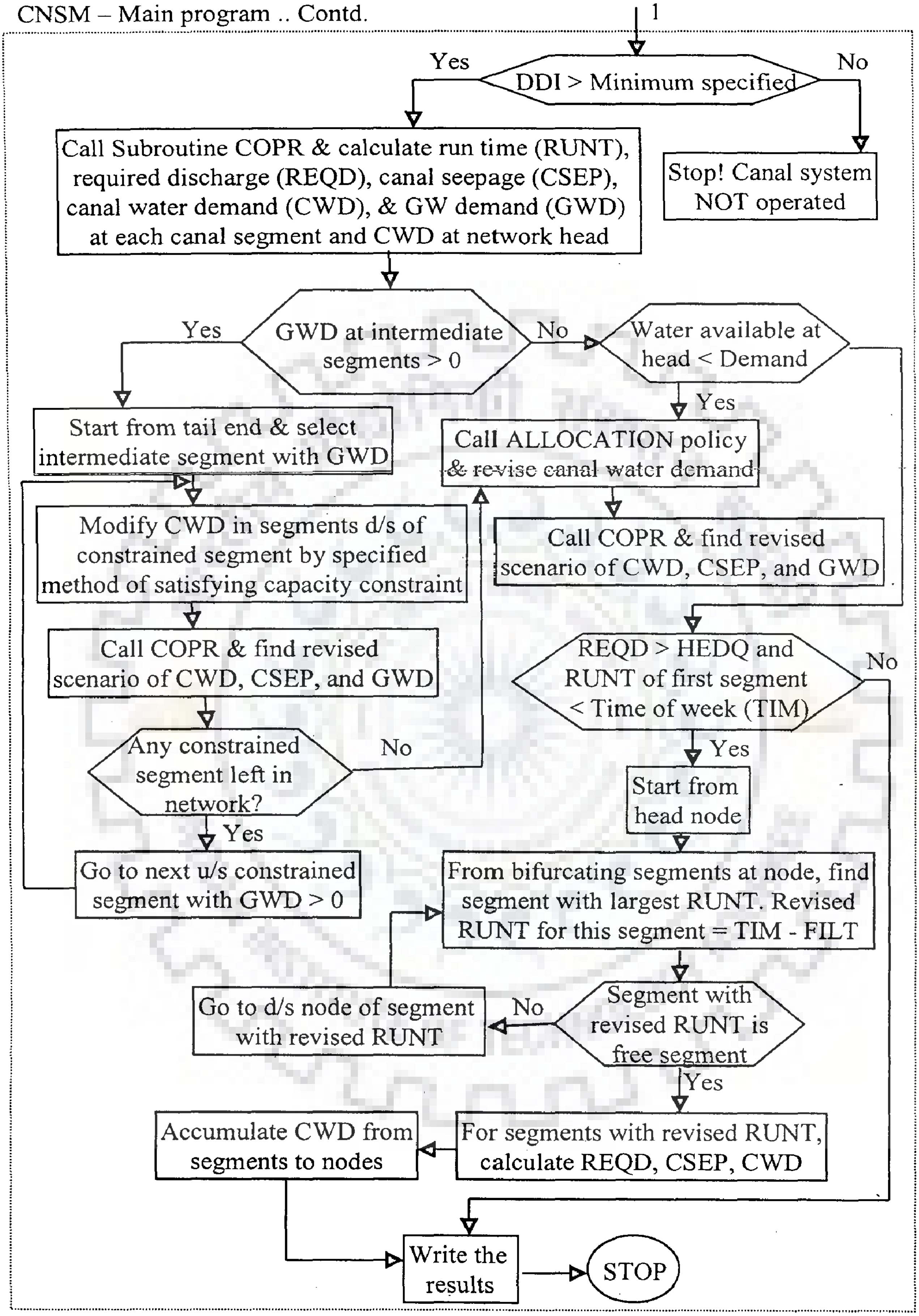
Various Analysis Options:

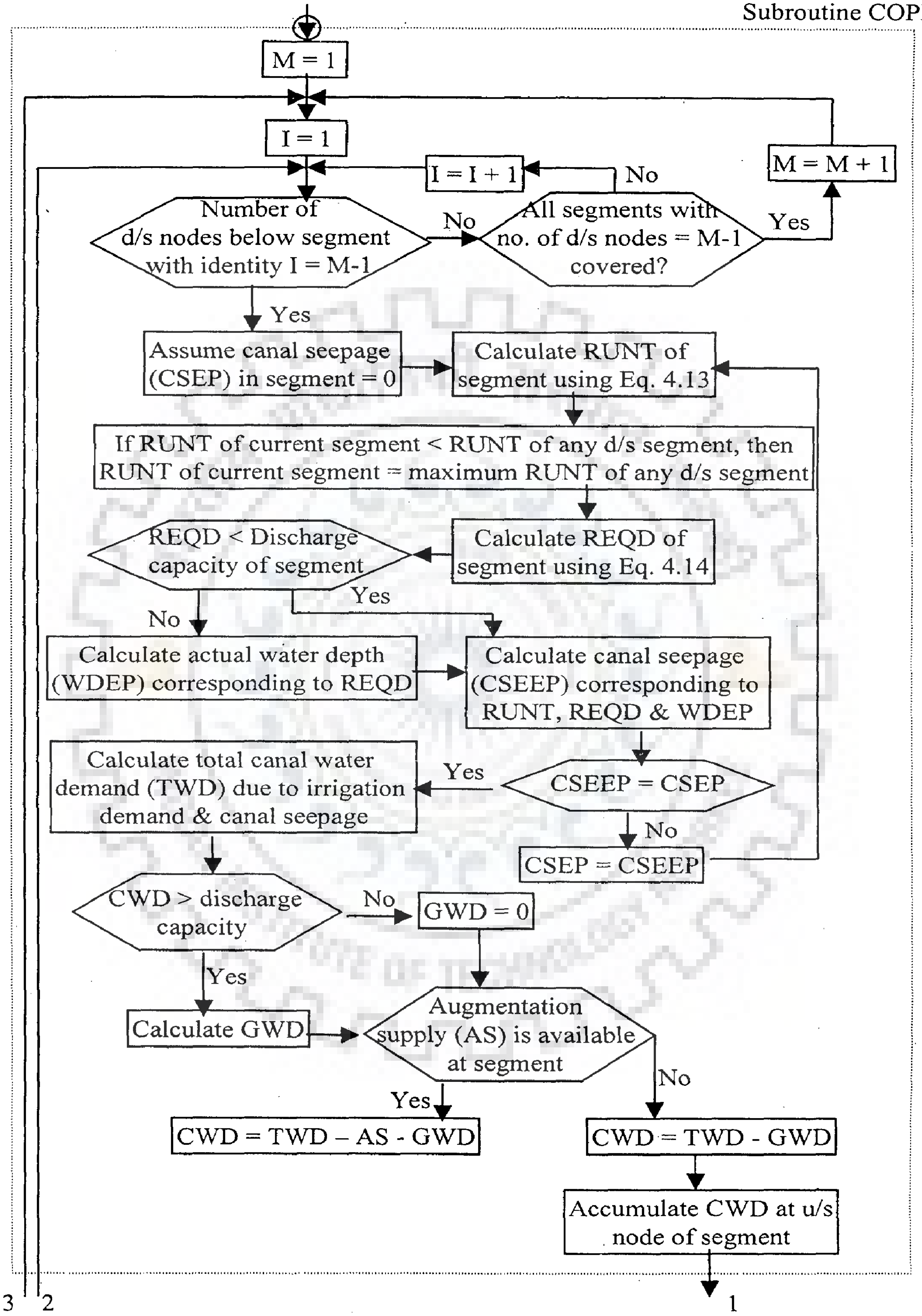
a) Available discharge (cumec) at canal head (HEDQ).
b) Method of satisfying capacity constraint [head-reach priority(1)/ min. pumping depth (2)/tail-end priority(3)]
c) Allocation policy [head-reach priority (1)/conjunctive use (2)/ proportionate supply (3)/tail-end priority(4)/conjunctive use with minimum energy demand (5)]
d) Number of segments with augmentation supply.
e) Canal segments of augmentation supply & corresponding supply rate (cumec).

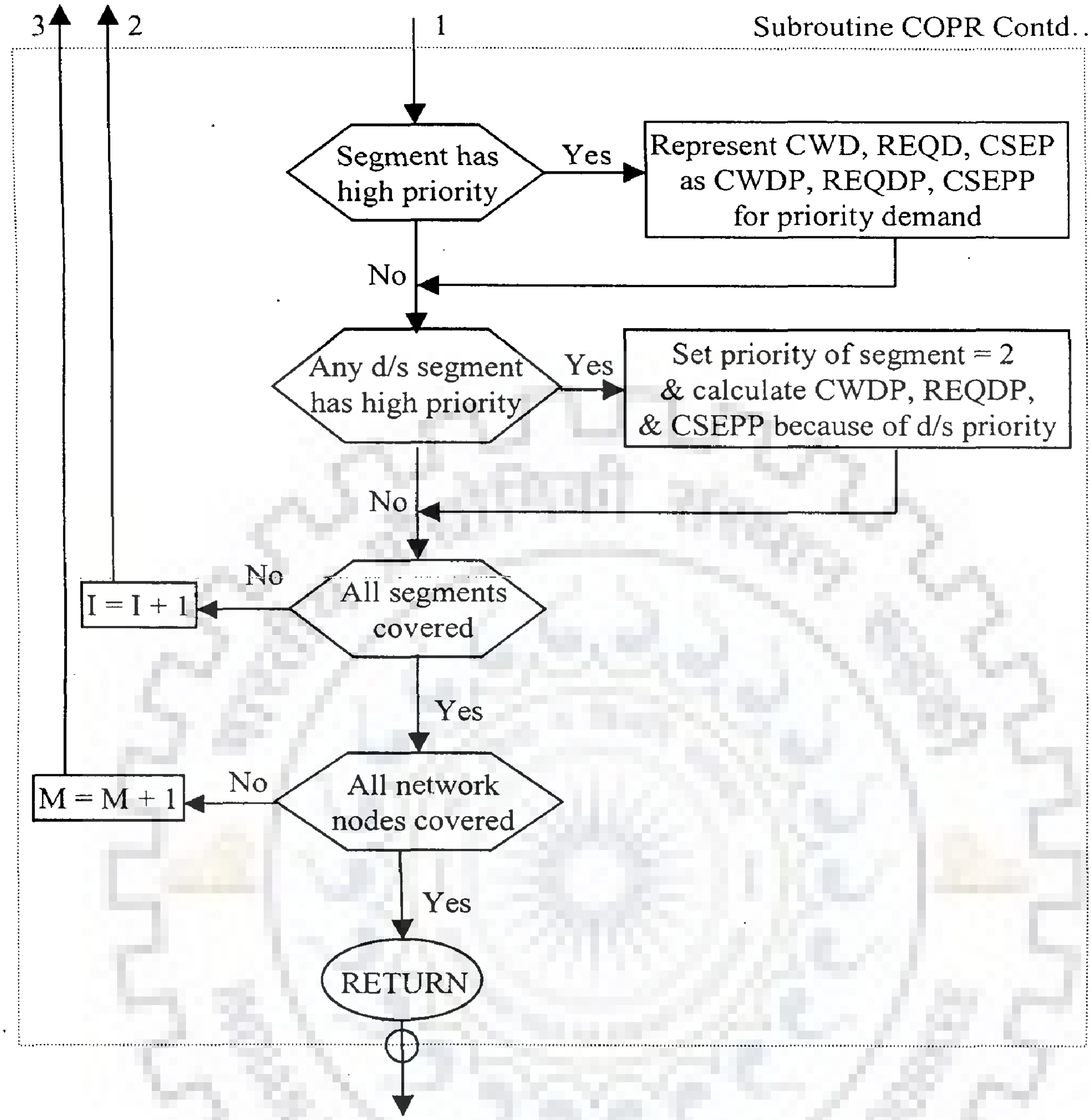
Figure – 4.2: Flow chart of CNSM


Start
Read input data & analysis options
Based on crop type, its root depth, and adopted criteria obtain waterlogging depth for each segment
Transfer irrigation demands from each grid under the irrigable command area of a canal segment considering application efficiency & field channel efficiency (Eq. 4.1 and 4.2)
Using grid-wise groundwater depth, calculate average groundwater depth (AGW) under each canal segment (Eq. 4.5)
Calculate groundwater availability (GWC) for each canal segment considering pump capacity, number of wells, power supply, & AGW (Eq. 4.6)
Go to first canal segment
AGW of segment ≤ waterlogging depth
Yes
Modify canal irrigation demand of segment to 0 and meet its demands from GW.
Go to next segment
Calculate total number of canal segments d/s of segment & their identity
Calculate total number d/s free segments with normal & high priority
Calculate identity of u/s segment and distance of segment head from canal system head
Calculate fill-time (FILT) of segment based on travel time in u/s segments and canal run of previous week
No
All segments covered
Yes
Calculate demand distribution index (DDI)
1

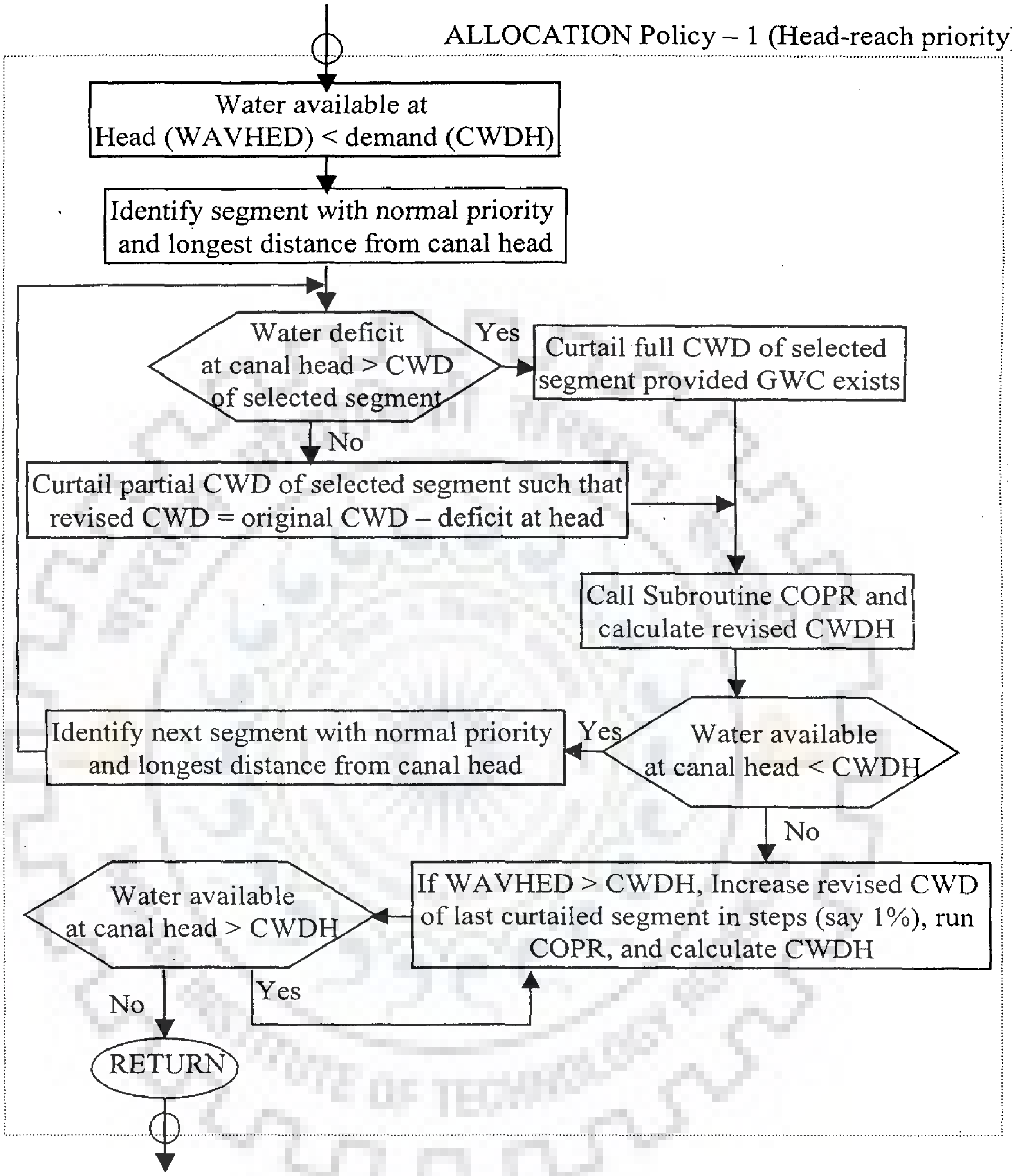
CNSM – Main program .. Contd.

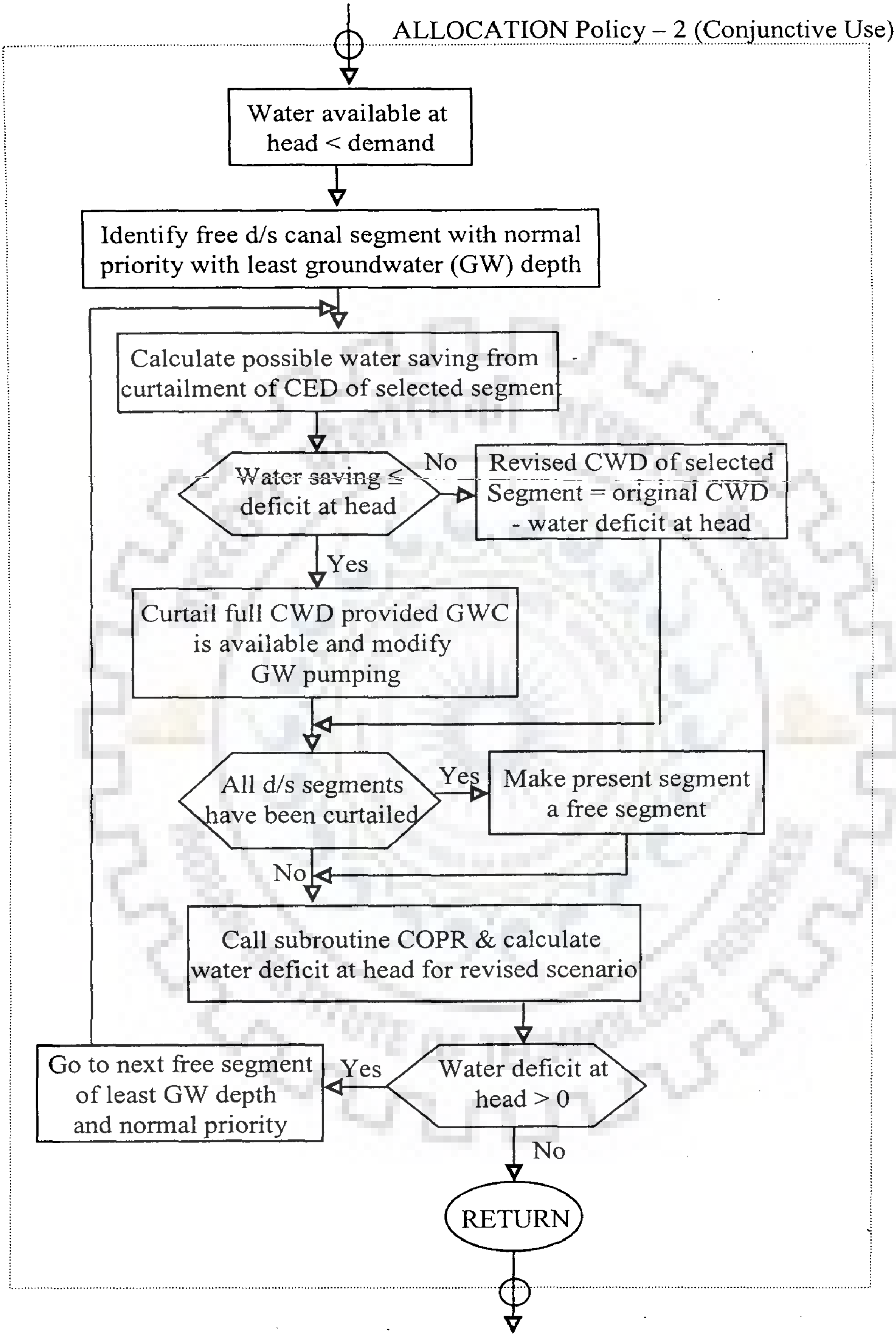


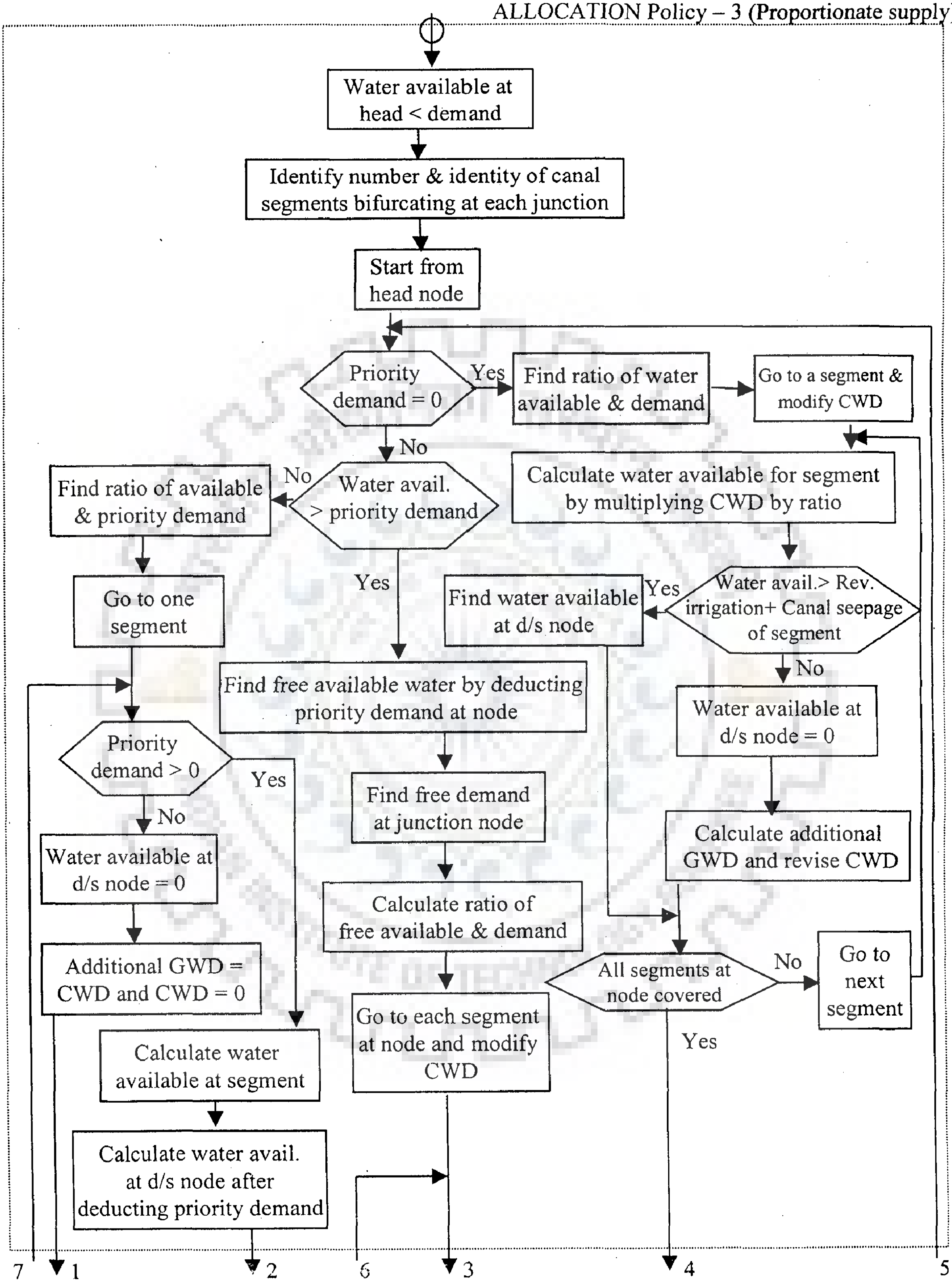

M = 1
I = 1
I = I + 1
No
M = M + 1
Number of d/s nodes below segment with identity I = M-1
No
All segments with no. of d/s nodes = M-1 covered?
Yes
Yes
Assume canal seepage (CSEP) in segment = 0
Calculate RUNT of segment using Eq. 4.13
If RUNT of current segment < RUNT of any d/s segment, then RUNT of current segment = maximum RUNT of any d/s segment
REQD < Discharge capacity of segment
Calculate REQD of segment using Eq. 4.14
Yes
No
Calculate actual water depth (WDEP) corresponding to REQD
Calculate canal seepage (CSEEP) corresponding to RUNT, REQD & WDEP
Calculate total canal water demand (TWD) due to irrigation demand & canal seepage
Yes
CSEEP = CSEP
No
CSEP = CSEEP
CWD > discharge capacity
No
GWD = 0
Yes
Calculate GWD
Augmentation supply (AS) is available at segment
Yes
No
CWD = TWD – AS - GWD
CWD = TWD - GWD
Accumulate CWD at u/s node of segment
3
2
1

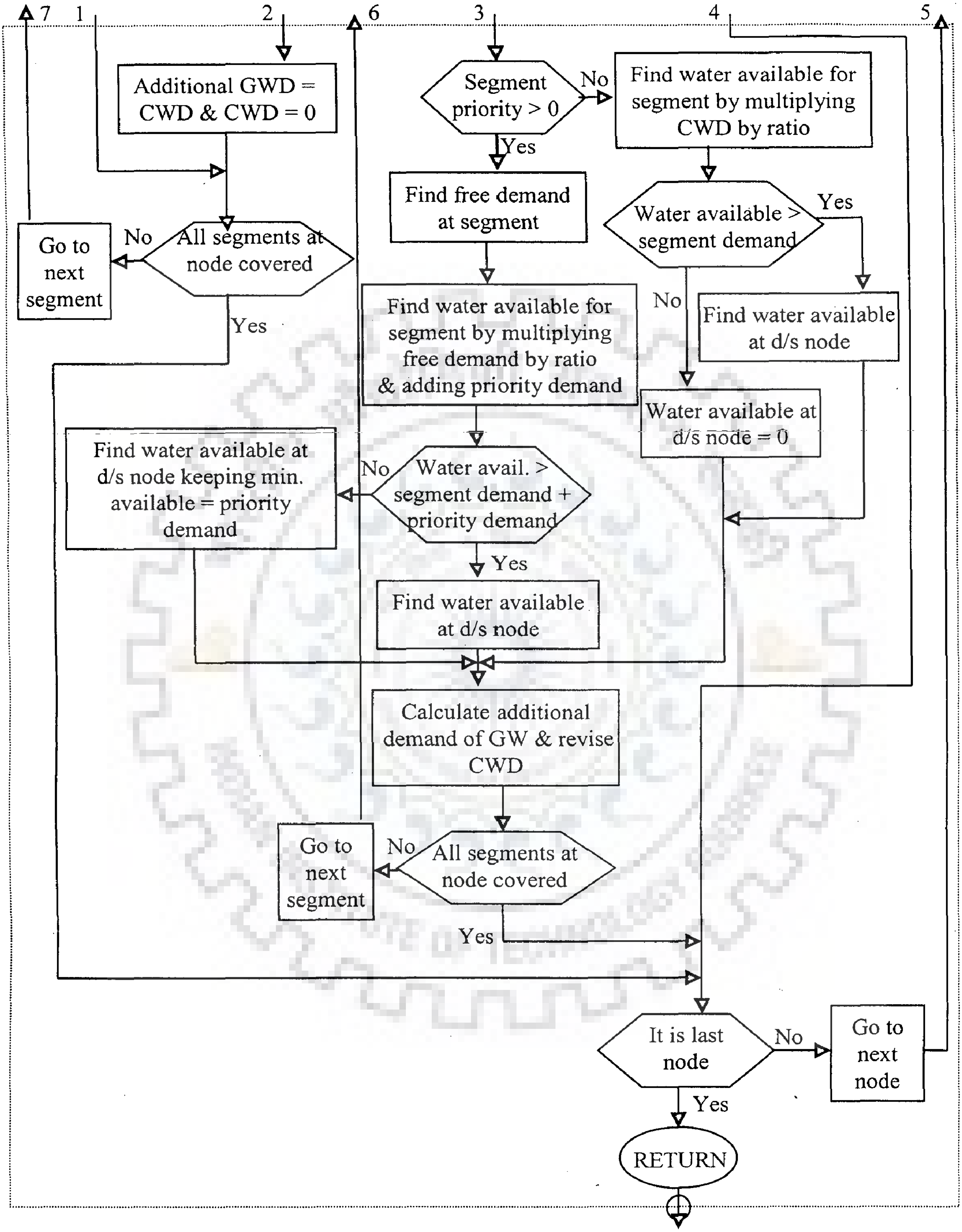

3
2
1
Segment has high priority
Yes
Represent CWD, REQD, CSEP as CWDP, REQDP, CSEPP for priority demand
No
Any d/s segment has high priority
Yes
Set priority of segment = 2 & calculate CWDP, REQDP, & CSEPP because of d/s priority
No
I = I + 1
No
All segments covered
Yes
M = M + 1
No
All network nodes covered
Yes
RETURN

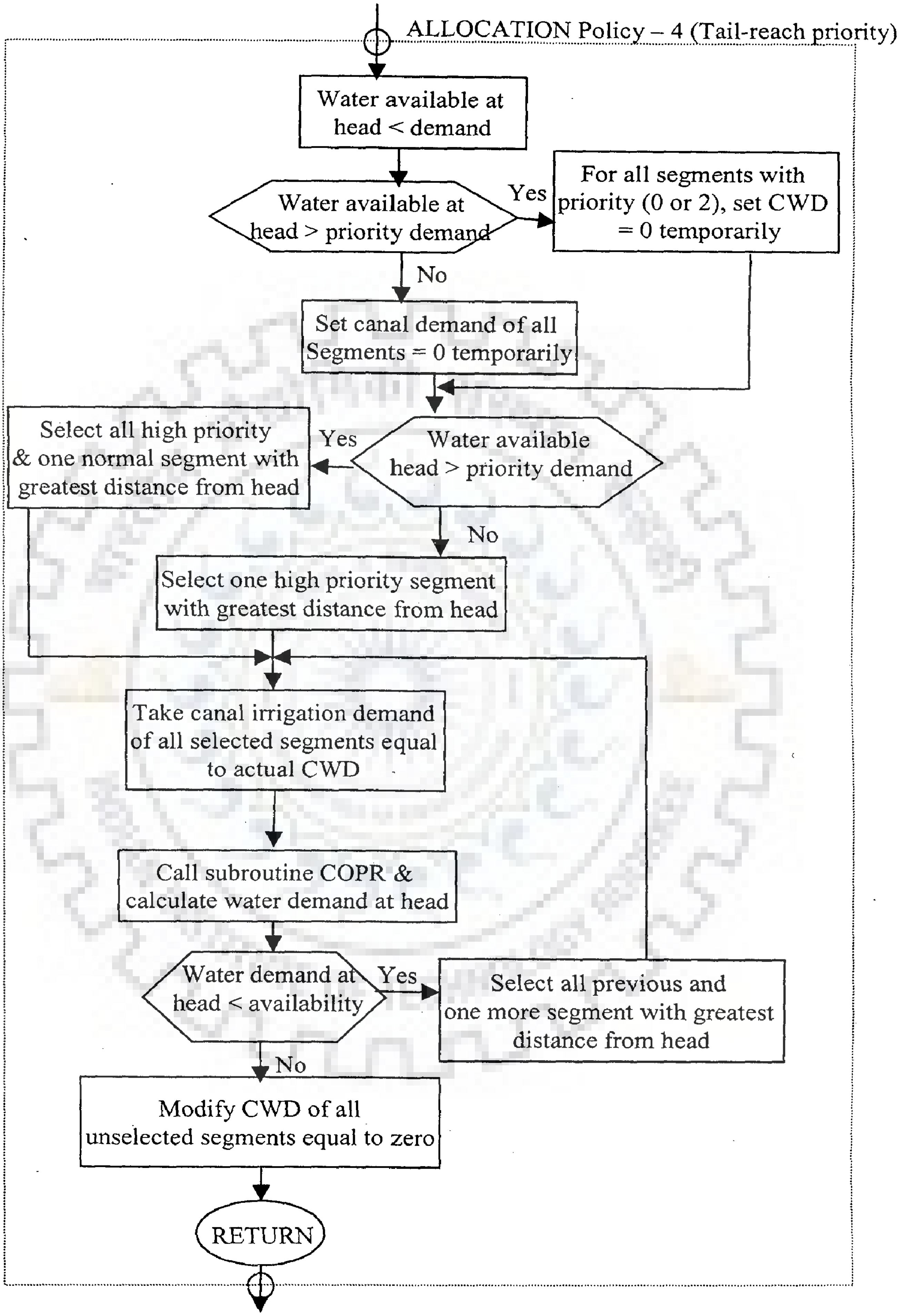
ALLOCATION Policy – 1 (Head-reach priority)

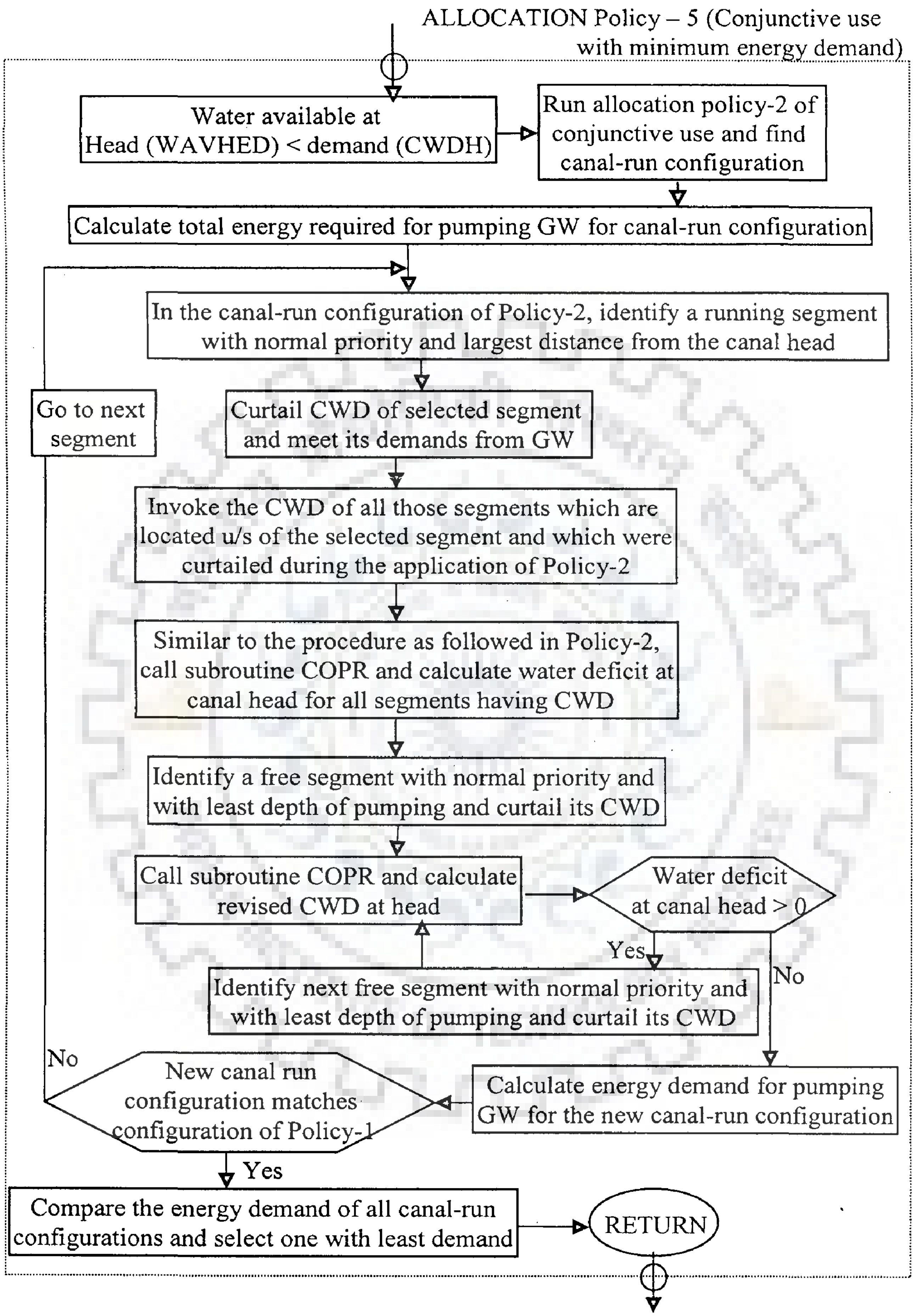



ALLOCATION Policy – 2 (Conjunctive Use)
Water available at head < demand
Identify free d/s canal segment with normal priority with least groundwater (GW) depth
Calculate possible water saving from curtailment of CED of selected segment
Water saving ≤ deficit at head
No
Revised CWD of selected Segment = original CWD - water deficit at head
Yes
Curtail full CWD provided GWC is available and modify GW pumping
All d/s segments have been curtailed
Yes
Make present segment a free segment
No
Call subroutine COPR & calculate water deficit at head for revised scenario
Go to next free segment of least GW depth and normal priority
Yes
Water deficit at head > 0
No
RETURN


Water available at head < demand
Identify number & identity of canal segments bifurcating at each junction
Start from head node
Priority demand = 0
Yes
Find ratio of water available & demand
Go to a segment & modify CWD
No
Water avail. > priority demand
No
Find ratio of available & priority demand
Calculate water available for segment by multiplying CWD by ratio
Go to one segment
Yes
Find water available at d/s node
Yes
Water avail.> Rev. irrigation+ Canal seepage of segment
No
Find free available water by deducting priority demand at node
Water available at d/s node = 0
Priority demand > 0
Yes
No
Find free demand at junction node
Calculate additional GWD and revise CWD
Water available at d/s node = 0
Calculate ratio of free available & demand
Additional GWD = CWD and CWD = 0
All segments at node covered
No
Go to next segment
Go to each segment at node and modify CWD
Yes
Calculate water available at segment
Calculate water avail. at d/s node after deducting priority demand
7
1
2
6
3
4
5


7
1
2
6
3
4
5
Additional GWD = CWD & CWD = 0
Segment priority > 0
No
Yes
Find water available for segment by multiplying CWD by ratio
Find free demand at segment
Water available > segment demand
Yes
No
All segments at node covered
Go to next segment
Find water available for segment by multiplying free demand by ratio & adding priority demand
Find water available at d/s node
Water available at d/s node = 0
Find water available at d/s node keeping min. available = priority demand
Water avail. > segment demand + priority demand
Find water available at d/s node
Calculate additional demand of GW & revise CWD
All segments at node covered
Go to next segment
It is last node
Go to next node
RETURN


ALLOCATION Policy – 4 (Tail-reach priority)
Water available at head < demand
Water available at head > priority demand
Yes
For all segments with priority (0 or 2), set CWD = 0 temporarily
No
Set canal demand of all Segments = 0 temporarily
Select all high priority & one normal segment with greatest distance from head
Yes
Water available head > priority demand
No
Select one high priority segment with greatest distance from head
Take canal irrigation demand of all selected segments equal to actual CWD
Call subroutine COPR & calculate water demand at head
Water demand at head < availability
Yes
Select all previous and one more segment with greatest distance from head
No
Modify CWD of all unselected segments equal to zero
RETURN


ALLOCATION Policy – 5 (Conjunctive use with minimum energy demand)
Water available at Head (WAVHED) < demand (CWDH)
Run allocation policy-2 of conjunctive use and find canal-run configuration
Calculate total energy required for pumping GW for canal-run configuration
In the canal-run configuration of Policy-2, identify a running segment with normal priority and largest distance from the canal head
Go to next segment
Curtail CWD of selected segment and meet its demands from GW
Invoke the CWD of all those segments which are located u/s of the selected segment and which were curtailed during the application of Policy-2
Similar to the procedure as followed in Policy-2, call subroutine COPR and calculate water deficit at canal head for all segments having CWD
Identify a free segment with normal priority and with least depth of pumping and curtail its CWD
Call subroutine COPR and calculate revised CWD at head
Water deficit at canal head > 0
Yes
No
Identify next free segment with normal priority and with least depth of pumping and curtail its CWD
No
New canal run configuration matches configuration of Policy-1
Calculate energy demand for pumping GW for the new canal-run configuration
Yes
Compare the energy demand of all canal-run configurations and select one with least demand
RETURN

$$WD_{id} = \sum(WDG_{ij})_{id} \quad \ldots(4.3)$$

$$TWRCN_{id} = WD_{id} \quad \ldots(4.4)$$

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.

$$AGW_{id} = TGW_{id} / NGCA_{id} \quad \ldots(4.5)$$

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:

$$GCAP_{id} = \frac{2.7 * PPP_{id} * NOP_{id} * POWS_{id} * EFF}{AGW_{id}} \quad \ldots(4.6)$$

d) Identification of waterlogging and revision of demand

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

$$TWRCN_{id} = 0 \quad \ldots(4.7)$$

$$TWGCN_{id} = Minimum\ of\ [WD_{id}, GCAP_{id}] \quad \ldots(4.8)$$

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

$$NOPR_{id} = \frac{[WD_{id} - TWGCN_{id}] * AGW_{id}}{2.7 * PPP_{id} * POWS_{id} * EFF} \quad \ldots(4.9)$$

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:

$$VEL_{id} = \frac{CAP_{id}}{\left[(BEDW_{id} + SL_{id} * WDEPT_{id}) * WDEPT_{id}\right]} \quad \ldots(4.10)$$

$$FIL_{id} = {ALEN_{id}}/{VEL_{id}} \quad \ldots(4.11)$$

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:

$$DDI = AL/BL \quad \text{...(4.12)}$$

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:

$$RUNTIM_{id} = \frac{(TWRCN_{id} + CANSEP + WRSN(IDS)_{id})}{CAP_{id}} \quad \text{...(4.13)}$$

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:

$$REQDIS_{id} = \frac{(TWRCN_{id} + CANSEP + WRSN(IDS_{id}))}{RUNTIM_{id}} \quad \text{...(4.14)}$$

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 the actual value of wetted perimeter and water depth is calculated before calculating the canal seepage. It is assumed that Manning's formula holds good for flow calculation in a canal section. As shown in Figure – 4.3, let 'y' be actual water depth corresponding to discharge $REQDIS_{id}$ and 'H' be the maximum water depth corresponding to discharge capacity CAP_{id}. Let 'B' be the bed width of the segment. Then,

$$REQDIS_{id} = CAP_{id} * \frac{(B+zy)*y*\left[\frac{(B+zy)*y}{B+2y\sqrt{1+z^2}}\right]^{2/3}}{(B+zH)*H*\left[\frac{(B+zH)*H}{B+2H\sqrt{1+z^2}}\right]^{2/3}} \qquad ...(4.15)$$

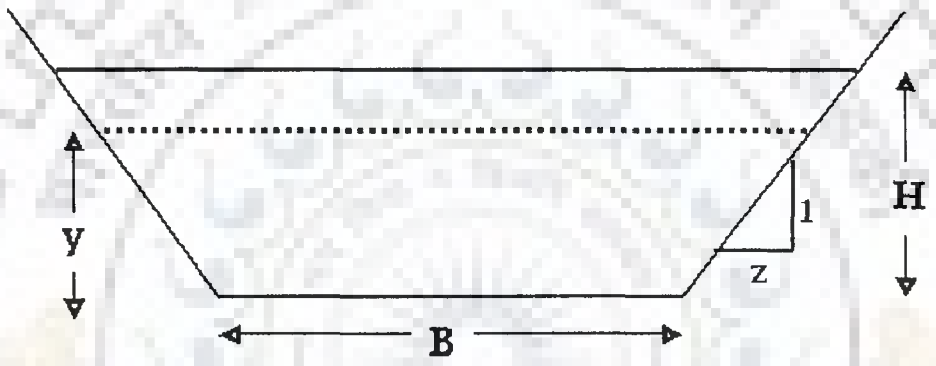


Figure – 4.3: Representation of variables in a canal section

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, $$CSEEP_{id} = REQDIS_{id} * (1 - CEFF_{id}) * RUNTIM_{id} \qquad ...(4.16)$$

If ISCOD = 2, $$CSEEP_{id} = \frac{(BEDW_{id} + y)^{0.667}}{200} * \frac{ALEN_{id}}{1000} * RUNTIM_{id} \qquad ...(4.17)$$

If ISCOD = 3, $$CSEEP_{id} = (BEDW_{id} + 2*y*\sqrt{1+z^2}) * ALEN_{id} * SEEPR_{id} * RUNTIM_{id} \qquad ...(4.18)$$

Eq. (4.17) 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:

$$TWSCN_{id} = REQDIS_{id} * RUNTIM_{id} \quad \ldots(4.19)$$

$$TWGCN_{id} = TWRCN_{id} + CSEEP_{id} + WRSN(IDS_{id}) - TWSCN_{id} \quad \ldots(4.20)$$

$WRSN(IDS_{id})$ 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:

$$TWSCN_{id} = TWSCN_{id} - AWAV_{id} \quad \ldots(4.21)$$

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 the high priority demands in the 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 the canal water demand exceeds the conveyance capacity of the segment. To settle the groundwater demands in intermediate segments, demands in the downstream network need to be curtailed. Calculations proceed in upstream direction from the tail end. Four methods have been provided in the present model for selecting the segments whose canal water demands are to be curtailed. 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 the 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 <u>nearest</u> 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

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

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 the supply.

Policy – 2: Based on least depth of pumping

Under this policy, the identification of segments for demand curtailment is governed by average groundwater depth under different segments. The 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 next. If deficit still persists at the head, then segments with higher priority are considered 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

Under 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 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 the ratio of water availability (WAV_M) to total canal water demand ($WRSN_M$) at the node:

$$RATIO = \frac{WAV_M}{WRSN_M} \qquad \ldots(4.23)$$

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

$$WAVS_{is} = TWSCN_{is} * RATIO + AWAV_{is} \qquad \ldots(4.24)$$

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:

$$TWRCNN_{is} = RATIO * TWRCN_{is} \qquad \ldots(4.25)$$

$$WAV(IDS_{is}) = WAVS_{is} - TWRCNN_{is} - CSEEP_{is} \qquad \ldots(4.26)$$

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:

$$WAVF_M = WAV_M - WRSNP_M \quad ...(4.27)$$

$$WRSNF_M = WRSN_M - WRSNP_M \quad ...(4.28)$$

$$RATIO = \frac{WAVF_M}{WRSNF_M} \quad ...(4.29)$$

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

$$TWSCNF_{is} = TWSCN_{is} - TWSCNP_{is} \quad ...(4.30)$$

$$WAVS_{is} = RATIO * TWSCNF_{is} + AWAV_{is} + TWSCNP_{is} \quad ...(4.31)$$

If $WAVS_{is} < TWSCN_{is}$ & $IPRIO_{is} = 1$, $\quad TWRCNN_{is} = TWRCN_{is}$ ...(4.32)

If $WAVS_{is} < TWSCN_{is}$ & $IPRIO_{is} = 2$, $\quad TWRCNN_{is} = RATIO * TWRCN_{is}$ ...(4.33)

If $WAVS_{is} > TWSCN_{is}$, $\quad TWRCNN_{is} = TWRCN_{is}$ ...(4.34)

$$WAV(IDS_{is}) = Min.of\,[WAVS_{is} - TWRCN_{is} * RATIO - CSEEP_{is},\ WRSNP(IDS_{is})] \quad ...(4.35)$$

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

$$WAV(IDS_{is}) = WRSNP(IDS_{is}) \quad ...(4.36)$$

$$TWRCNN_{is} = WAVS_{is} - CSEEP_{is} - WAV(IDS_{is}) \quad ...(4.37)$$

If priority of selected segment is normal, then the revised canal water demand in local irrigable command and available water at downstream is calculated using Eq. 4.24 through Eq. 4.26.

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

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. 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

Under this policy, canal-run configuration corresponding to minimum energy demand for pumping groundwater in the irrigation system is derived. First, the Policy-2 related to conjunctive use of water is applied and the canal-run configuration corresponding to minimum depth of pumping is derived. This policy results in larger 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.

4.3.6 Output of CNSM

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

a) Model results in map form

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

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

b) Tabular presentation of results

Detailed results of CNSM are prepared in tabular form also. Two tables are prepared by CNSM. First table presents the operation results for each canal segment. Various details of the canal network operation include: identity of segment, upstream segment identity, average groundwater depth, groundwater availability in segment, total irrigation demands in local command area, canal water demands in local command area, canal water demands in the downstream network, canal seepage loss in the segment, total canal water demands in the segment, required discharge, required water depth, fill-time of segment, run-time of segment, and required groundwater pumping. In case of priority of some segments, additional columns containing information about total priority demands in downstream network of each segment, canal seepage for meeting priority demands, total priority demands, and required discharge for meeting priority demands is provided.

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

c) Gross water use scenario over the whole command

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

4.4 PROPOSED USAGE OF CNSM

In the operation scheme proposed in this study, the CNSM is used to analyze the alternate policies of canal water allocation. The model makes detailed calculations of different operation variables using the real-time spatial irrigation demands (as determined by SWBM), probable canal water input, and prevailing groundwater conditions in the command. CNSM incorporates the spatial variability of canal network characteristics in the command area.

Using the simulation model, the manager can visualize the extent of demands that can be satisfied from 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 system performance can be evaluated. By running CNSM continuously (say, for the complete crop growth season) along with SWBM and 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 use of the available surface and groundwater resources and also keeps the groundwater conditions in balance, can be adopted for the command area.

4.5 CHAPTER CLOSURE

With the availability of remote sensing technology and GIS tools, it is now possible to gather instant observations over large areas. By using a simulation model, it is possible to integrate and manage different types of information to find optimum irrigation operation under given conditions.

A distributed CNSM is developed in this chapter to simulate the operation of a canal network. Rather than assuming demand pattern to be fixed, the model uses real-time spatial irrigation demands at weekly time step. Taking advantage of the GIS database, spatial variation of canal irrigable areas and groundwater conditions have been accounted for. Based on probable supply of canal water at the system head during the week, irrigation demands, and the water table position in the command, canal-run configuration is derived for various water allocation policies and the areas requiring groundwater pumping are identified. The results of the model are presented in the form of maps and tables for easy visualization by the decision maker or those who are affected by the canal operation.

The model results can help the irrigation manager to simulate various water allocation scenarios and analyze their performance. Using the model, it is possible to locate the system constraints for the supply of canal water. Long-term use of the model can be used to plan the water delivery in the command area and evaluate its performance. The model can also be used to design a canal network or to simulate the effect of revising an existing network (such as lining of canals, improving the field channel efficiency and water application efficiency, extending the canal layout, planning augmentation wells etc.)

* * *

CHAPTER - 5

INTEGRATED GEO-SIMULATION SCHEME

5.1 GENERAL

The geo-simulation scheme proposed in the present study consists of three interlinked models: demand model (using soil water balance approach), allocation model (using canal network simulation approach), and groundwater behavior model (using groundwater modeling approach). Distributed soil water balance model and canal network simulation models have been developed and described in Chapter-3 and Chapter-4 respectively. To analyze the spatially distributed behavior of groundwater, a groundwater simulation model with GIS interface is already available in the literature (Visual MODFLOW) and the same has been linked to the present scheme to generate groundwater surfaces corresponding to various policies of canal operation. In this chapter, a brief description of Visual MODFLOW is presented. In addition to the three main models as stated above, nine other modules have been developed for generation of database for the scheme and for linking the input and output of various component models with GIS. Description of these modules is given in this chapter. After the development of different modules, the sequencing of operation of different modules for database generation is presented. Finally, a flow chart of the integrated geo-simulation scheme is given.

5.2 ROLE OF GROUNDWATER MODEL IN THE DEVELOPED SCHEME

In the proposed scheme, knowledge of prevailing groundwater surface in the command area is an important input for deciding the canal water allocation plan. Groundwater consideration in this study is made in two contexts: first, to restrict the development of waterlogging conditions in some part and mining of groundwater in other part, and second, to allocate the available canal water in such a way as to minimize the requirement of energy for groundwater pumping.

The proposed scheme can be utilized in two modes: operational planning for full crop season at the beginning of the season, and real-time operation of the canal system. Operational planning requires modeling of aquifers in the command area so that revised groundwater surface corresponding to pumping and recharge stresses in the command (which depend on the adopted water allocation policy) at intermediate time steps during the planning season could be obtained and incorporated in the allocation model. For real-time operation, the need of groundwater modeling depends on the frequency of acquisition of groundwater level data at observation wells in command. If the groundwater observations are not available on real-time basis, which is mostly the case in Indian conditions, then it is required to model the groundwater aquifer.

With this need in view, a distributed groundwater model [Visual MODFLOW 3.0 (VMOD)], developed by the Waterloo Hydrogeologic Inc. (2002), is utilized in this study. A brief description of the model is given in the following.

5.3 DESCRIPTION OF VMOD

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

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

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

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)-W=S_s\frac{\partial h}{\partial t} \qquad \ldots(5.1)$$

where,

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

In general, S_s, K_{xx}, K_{yy} and K_{zz} are functions of space whereas W and h are functions of space and time. Equation (5.1) together with specification of flow conditions at the boundaries of an aquifer system and specification of initial head conditions constitutes a mathematical model of ground water flow. Possible inflow/outflow terms in a groundwater system include recharge from rainfall, artificial recharge through wells, pumping through wells, evapotranspiration, recharge through river/canal cells, outflow into a river/canal cell, inflow/outflow across a boundary cell, outflow through drains, spring flow etc. Input to the groundwater model include initial groundwater conditions; boundary conditions; characteristics of aquifer such as transmissibility, specific storage, effective porosity; recharge data, evapotranspiration data, pumping to/from the wells, artificial recharge etc. Major outputs from the model are in form of water levels, drawdowns, water balance of the model domain, and inflow/outflow across model boundaries.

MODFLOW discretizes the model domain with a mesh of blocks called 'cells' in which medium properties are assumed to be uniform. The varying thickness of vertical layers of aquifer systems are transformed into a set of parallel 'layers'. The location of each cell is described in terms of rows, columns, and layers. Within each cell there is a point called a 'node' at which groundwater head is calculated. The model distinguishes a cell into: i) variable-head cell (the head varies with time), ii) constant head cell (the head is constant), or iii) no flow or inactive cell (no flow takes place within the cell). The period of simulation is divided into a series of 'stress period' within which stress parameters are constant. Each stress period, in turn, is divided into a series of time steps. The user specifies the length of stress period, the number of time steps at each stress period, and the time step multiplier. Using these terms, the program calculates the length of each time step in the stress period. With these discretization in space and time, Equation (5.1) leads to a system of simultaneous linear algebraic equation which are solved iteratively.

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

5.4 DEVELOPMENT OF VARIOUS INTER-LINKING MODULES

Nine modules have been developed to design the database for geo-simulation scheme, link the input and output with GIS, and to evaluate the system performance. Four modules are developed for database generation (DIMENSION, CODE, IMAGE, and FDIR) and four modules are developed for linking various models of the scheme (SOURCE, GWRD, AGGREGATE, and WELL). PERFORM module is developed to derive various performance indices for the system operation. These modules are described in the following:

a) DIMENSION

The purpose of this module is to reduce the dimensions of model program. As specified earlier and shown in Figure-3.1, a command area is considered as being composed of a number of regular square grids. The modeling approach considers the command in the form of rows and columns and the calculations proceed for each grid of all rows and columns. Generally, the boundaries of a command form an irregularly shaped area such that a number of grids in rectangular image representation lie outside of the command. These grids do not contribute to the analysis for the command but unnecessarily increase the dimensions of the computer program.

The objective of *DIMENSION* module is to find the number of grids in each row that lie within the boundaries of the command area and their location in the row. Input to the module is the rectangular raster image of the command area in ASCII format, which is generated using a GIS. Output of the module specifies for each row, the location of the starting grid which lies within the boundary of the command area and the total number of grids within the command boundary in the row. The result file of this module is used by all other modules to find the position of grids within a rectangular image for which analysis is to be carried out.

b) CODE

The purpose of this module, is to reduce the dimensions of the model program. A number of spatially distributed data (crop, soil, rainfall, flow direction, surface elevation, groundwater depth etc.) are used by different models/modules. If all these data are input as separate thematic image layers, then the dimensions of the program may exceed the working limit of compilation. Therefore, data of four spatial variables (crop, soil, nearby rainfall station, and flow direction), which do not vary within a crop season, are merged in the form of a single code.

The objective of *CODE* module is to develop the code depending on the value of four variables at a grid. Inputs to the module include result file of *DIMENSION* module and image files of crop, soil, Thiessen polygons, and flow direction. Image files are generated in ASCII format by the GIS. Different crops, soils, Thiessen polygons, and flow directions are represented by different numeric numbers. The module can account for 99 different types of soils and Thiessen polygons in a command area. Any number of crops can be considered. Up to nine flow direction identities can be specified for a grid.

c) FDIR

The purpose of *FDIR* module is to find the flow direction at each grid on the basis of digital elevation model (DEM) of the area, canal network layout, and the general slope of the command area. Flow direction map is a representation of the direction in which water will flow on the land surface and is generally obtained by finding the steepest slope downhill at each grid using a DEM. In a GIS system, a neighbourhood function is used to find the grid of lowest elevation from the eight neighbouring grids surrounding each grid.

Flow directions may get modified if a canal obstructs the direction of steepest descent. Therefore, it is required to find the flow directions on the basis of DEM and the canal layout. Further, to account for the situations where a grid has two or more directions of steepest descent, the information about general slope of the area is utilised. Input to the *FDIR* module includes the result file of *DIMENSION* module and three images corresponding to the DEM, canal network layout, and the general slope of the command. All the images are generated in GIS and converted to the ASCII format for input to FDIR module. The module analyses the elevation in eight neighbouring grids of each grid and finds the grid with lowest elevation. Based on the position of lowest elevation grid with reference to the central grid, the flow direction at the central grid is decided and it is represented by a numeric identity. For example, a flow direction with '1' numeric identity (shown in Figure – 3.6) signifies North-West flow direction at the central grid. If the neighbouring grid of lowest elevation coincides with a canal segment, then that lowest elevation grid is not considered for flow direction estimation and comparison of elevations of the remaining neighbouring grids is made to finalise the flow direction. If there happen to be two or more neighbouring grids of lowest elevation, then the information about general slope in the command is utilised and precedence is given in a particular defined order for flow estimation. The output of *FDIR* module constitutes a flow direction map, which is used to find the direction of movement of overland flow, if it is generated at any grid in the command.

d) IMAGE

The purpose of *IMAGE* module is to convert a rectangular image file (generated in a GIS) into a data file for input to the simulation scheme or to convert the model output into the image form for display in a GIS.

The *IMAGE* module uses the result file of *DIMENSION* module to remove the redundant grids from the image and the data of command area grids are stored in a separate file. After the analysis is performed and spatial output is obtained from the model (such as irrigation demands at different grids in the command), the same is required to be converted to the image form for display in a GIS. To convert the model results, the redundant grids are attached to the command area grids so as to form a rectangular image, which is then imported in a GIS system and displayed.

e) SOURCE

The purpose of *SOURCE* module is to find the amount and source of irrigation supply (whether surface water or groundwater) at a grid in the command based on its location, irrigation demands, and canal water supply during a week. This information is used to find the spatial distribution of canal water application and groundwater withdrawal in the command area for input to SWBM. For the grids that lie outside of the irrigable command of canal network, there is no option but to use groundwater. For grids that lie within the irrigable command, the source and amount of water supply depends on the irrigation demands and actual canal operation during the week.

Grid-wise irrigation demands are first transferred to the canal network using the water application and field channel efficiencies. Then, based on the actual water supply (discharge and run-time) in different canal segments during a week, the canal seepage loss is determined and the water actually available in canal segments for irrigation use is found out. The comparison of water demand and supply for irrigation in each canal segment is made in terms of a delivery factor (= supply/demand). Canal water application in each grid within the irrigable command of canal segment is found by multiplying the irrigation demand at the grid by the delivery factor of the canal segment. Delivery factor greater than 1 signifies that more water is sent to the canal segment than required while a factor less than 1 signifies that canal supply is not sufficient to meet the full irrigation demands and groundwater needs to be extracted (total irrigation demand – canal water supply) to satisfy the full irrigation demands of various grids within the irrigable command of canal segment. Input to the *SOURCE* module includes: i) result file of the *DIMENSION* module, ii) spatially distributed irrigation demands as obtained from SWBM, iii) spatially distributed irrigable area, iv) canal system characteristics, and v) actual canal operation during a week. Output of the module gives spatial distribution of irrigation application, groundwater withdrawal, canal seepage, and recharge due to irrigation application.

f) GWRD

The purpose of *GWRD* module is to find the spatial distribution of net recharge or withdrawal of water at each grid in the command area and the total power requirement to extract groundwater. In the geo-simulation scheme, recharge from two different sources is considered: recharge from rainfall as obtained from SWBM and recharge due to seepage from canals, field channels and agricultural fields as obtained from SOURCE module. Spatial withdrawal of groundwater in the command is also obtained from the SOURCE module. The energy requirement (ENER in kilowatt-hour) for pumping groundwater in each grid is calculated by the following equation:

$$ENER = \frac{9.817 * GWW * GWD}{36 * P_{eff}} \quad \ldots(5.2)$$

where GWW is the groundwater withdrawal in cubic meter at the grid, GWD is the groundwater depth at the grid in meter, and P_{eff} is the pump efficiency. In field practice, energy requirement would also depend on the rated capacity of a pump. The input to the *GWRD* module includes the result file of the *DIMENSION* module and the spatial distribution of groundwater withdrawal, groundwater depth, and recharge due to rainfall, canal seepage, and irrigation application. Output of the module provides spatial distribution of net recharge or pumping at each grid in the command.

g) AGGREGATE

The aquifer characteristics and groundwater behaviour are not expected to change over short distances from grid to grid. Therefore, spatial results of pumping and recharge, which are calculated at finer grid-size, are aggregated to a coarser grid size for input to the groundwater simulation model.

For aggregation, grids containing the pumping/recharge information are first converted to the regular image form using the *IMAGE* module so that they occupy their true location in the map. Then, the pumping/recharge value of a group of grids is added to obtain the net pumping/recharge for the coarser grid. For example, if the original grid size is 24 m * 24 m and the coarser grid size is 480 m * 480 m, then the pumping/recharge values of the 20 pixels along the row and 20 pixels along the column are added to find the net pumping/recharge for the 480 m * 480 m grid. The input to the *AGGREGATE* module includes the result file of the *DIMENSION* module and the image file of net pumping/recharge. The output of the module provides the net pumping/recharge at coarser grid size.

h) WELL

The purpose of WELL module is to link the aggregated pumping and recharge data in each coarser grid to the groundwater simulation model (VMOD). Each coarser grid is represented by a well through which pumping/recharge interaction takes place with the groundwater aquifer. This module prepares the data in a form which can be directly imported in VMOD. The format for the data includes the identity of the well, its location coordinates, the identity of the screen, the elevation of the top and bottom surface of the screen, the stress period of recharge/pumping, and the value of recharge/pumping during the stress period. The module generates a unique identity for each well. The top elevation of the screen is taken to coincide with the elevation of land surface (obtained from DEM). A part of the output file prepared by the module is given in Table– 5.1. Weekly pumping/recharge information of four weeks is specified.

Table - 5.1: Pumping/recharge information for input to VMOD

Well Identity	Location (m)		Screen Identity	Screen Elevation (m)		Stress Period (days)	Pumping/ Recharge (m3)
	X – Coord.	Y – Coord.		Top	Bottom		
W0001	18360	108912	W0001	211.13	161.13	7	5083.11
W0001	18360	108912	W0001	211.13	161.13	14	-811
W0001	18360	108912	W0001	211.13	161.13	21	108.5
W0001	18360	108912	W0001	211.13	161.13	28	1637.5
W0002	18840	108912	W0002	210.49	160.49	7	4906.31
W0002	18840	108912	W0002	210.49	160.49	14	293.5
W0002	18840	108912	W0002	210.49	160.49	21	147.5
W0002	18840	108912	W0002	210.49	160.49	28	1551.6

i) PERFORM

The purpose of *PERFORM* module is to find the spatial distribution of various performance indices for the irrigation system. Four indices specifying the performance of a particular water allocation policy have been included in the module: adequacy, efficiency, equity, and dependability. These are briefly described below:

Adequacy

A fundamental concern of water-delivery systems is to deliver the amount of water required to adequately irrigate crops. The required amount is a function of the area of land irrigated, crop water demands, application losses, and cultural practices. Adequacy of delivery is dependent on water supply, specified delivery schedules, conveyance capacity of hydraulic structures to deliver water according to schedules, and operation and maintenance of hydraulic structures. The objective of adequacy states the desire to deliver required amount of water. It is stated by the expression:

$$P_A = \frac{1}{T}\Sigma p_a \qquad \text{...(5.3)}$$

$$\text{and } p_a = \frac{Q_D}{Q_R}, \text{ if } Q_D \leq Q_R \qquad \text{...(5.4)}$$

$$p_a = 1, \text{ otherwise}$$

where Q_D is the volume of water delivered, Q_R is the volume of water required in a canal segment in a week, T is the total number of weeks of operation. p_a is the adequacy during a time step while P_A represents the average adequacy during the entire duration of irrigation supply.

Efficiency

A water delivery system that delivers a greater-than-adequate supply does not conserve water resources and results in reduced efficiency of irrigation system. Excess water delivery to farms promotes conditions of water logging and salinity. Objective of water-delivery efficiency embodies the desire to conserve water by matching water deliveries with water demands. Efficiency is denoted by the following expression:

$$P_F = \frac{1}{T} \Sigma p_f \qquad ...(5.5)$$

$$\text{and } p_f = \frac{Q_R}{Q_D}, \text{ if } Q_R \leq Q_D \qquad ...(5.6)$$

$$p_f = 1, \text{ otherwise}$$

where P_F is the average efficiency over the entire season and p_f is the efficiency during a week. As the value of P_F approaches unity, the efficiency of the system indicates an increasing compatibility with the goal of efficient water delivery for the region.

Dependability

It is defined as the temporal uniformity of the ratio of the delivered amount of water to the required or scheduled amount. A system that performs in a consistent manner may be considered dependable. Dependability of water delivery is important to farmers because it allows for proper crop planning. Dependability is expressed as:

$$P_D = \frac{1}{R} \Sigma_R CV_T \left(\frac{Q_D}{Q_R} \right) \qquad ...(5.7)$$

where P_D is the average dependability over the entire region 'R', $CV_T \left(\frac{Q_D}{Q_R} \right)$ is the temporal coefficient of variation (ratio of standard deviation to mean) of the ratio $\left(\frac{Q_D}{Q_R} \right)$ over the time period T.

Equity

Equity can be defined as the delivery of a fair share of water to users throughout a system. A share of water represents a right to use a specified amount. The fair share of water may be based on a legal right for water, as in a prior appropriation system, or may be set as a fixed proportion of a water supply, as is done in many rotational delivery schemes. In this study, equity is defined as being spatial uniformity of the ratio of the delivered amount of water to the required or scheduled amount and is represented by following expression:

$$P_E = \frac{1}{T}\Sigma_T CV_R\left(\frac{Q_D}{Q_R}\right) \qquad \ldots(5.8)$$

where $CV_R\left(\frac{Q_D}{Q_R}\right)$ is the spatial coefficient of variation of the ratio $\left(\frac{Q_D}{Q_R}\right)$ over the region R.

Depending upon the cause of deviation from the demand, i.e. structural, or managerial, corresponding performance indices can be derived.

In the geo-simulation scheme, water demand in each segment of the canal network is estimated at weekly time step and stored in relevant files. Similarly the water allocation in each canal segment is proposed by the CNSM at the beginning of a week. At the end of week, spatial information about the actual operation of canal network is also obtained in the scheme and recorded in relevant files. By knowing the weekly water demands and allocation for each segment of the canal network, spatial variation of adequacy, efficiency and dependability can be represented in map form for each canal segment.

If the desired amount of water at some canal segment is not allocated by the CNSM, then it specifies the cause of deficiency, such as waterlogging conditions, canal capacity constraint (structural), or the water availability constraint (managerial). By knowing the cause of water delivery deficiency, spatial distribution of structural or managerial based performance indices can also be visualized.

5.5 USE OF MODULES FOR DATABASE GENERATION

Various thematic layers of database are first prepared in the GIS and then exported as ASCII file for use in the simulation model. Before their use in simulation models, different modules for database generation are applied to reduce the dimensions of study area.

The thematic layers digitised in GIS include boundary of the command, soil types, Thiessen polygons, contours and spot levels, groundwater levels in observation wells, general slope, canal network layout, canal irrigable area, villages, and water bodies. The layers in vector format are converted to raster format. The crop types, interpreted from the remote sensing data, are imported in GIS as a crop layer. The contour and spot levels are used to generate the DEM for the area using interpolation technique. Similarly, groundwater surface is generated using the point interpolation of groundwater level data. The subtraction of groundwater surface from the DEM gives the groundwater depth at each grid in the command. All the data layers are exported in ASCII and various modules are applied in the following sequence:

a) *DIMENSION* module is executed with boundary layer to find the location of grids within the command area.
b) *FDIR* module is executed with the DEM, canal layout, and general slope layer to find the flow direction at each grid.
c) *IMAGE* module is executed independently with various thematic layers (crop, soil, Thiessen polygon, flow direction, DEM, groundwater depth, canal irrigable area) to remove redundant grids and reduce image dimensions.
d) *CODE* module is executed with four thematic layers (crop, soil, Thiessen polygon, and flow direction) to merge them in form of a unique code.

5.6 INTEGRATED GEO-SIMULATION SCHEME

After the spatial database is generated using various modules, different models of the geo-simulation scheme are run sequentially to operate the canal system. Overall geo-simulation scheme, which is applied for each week of the cropping season, is presented in Figure – 5.1.

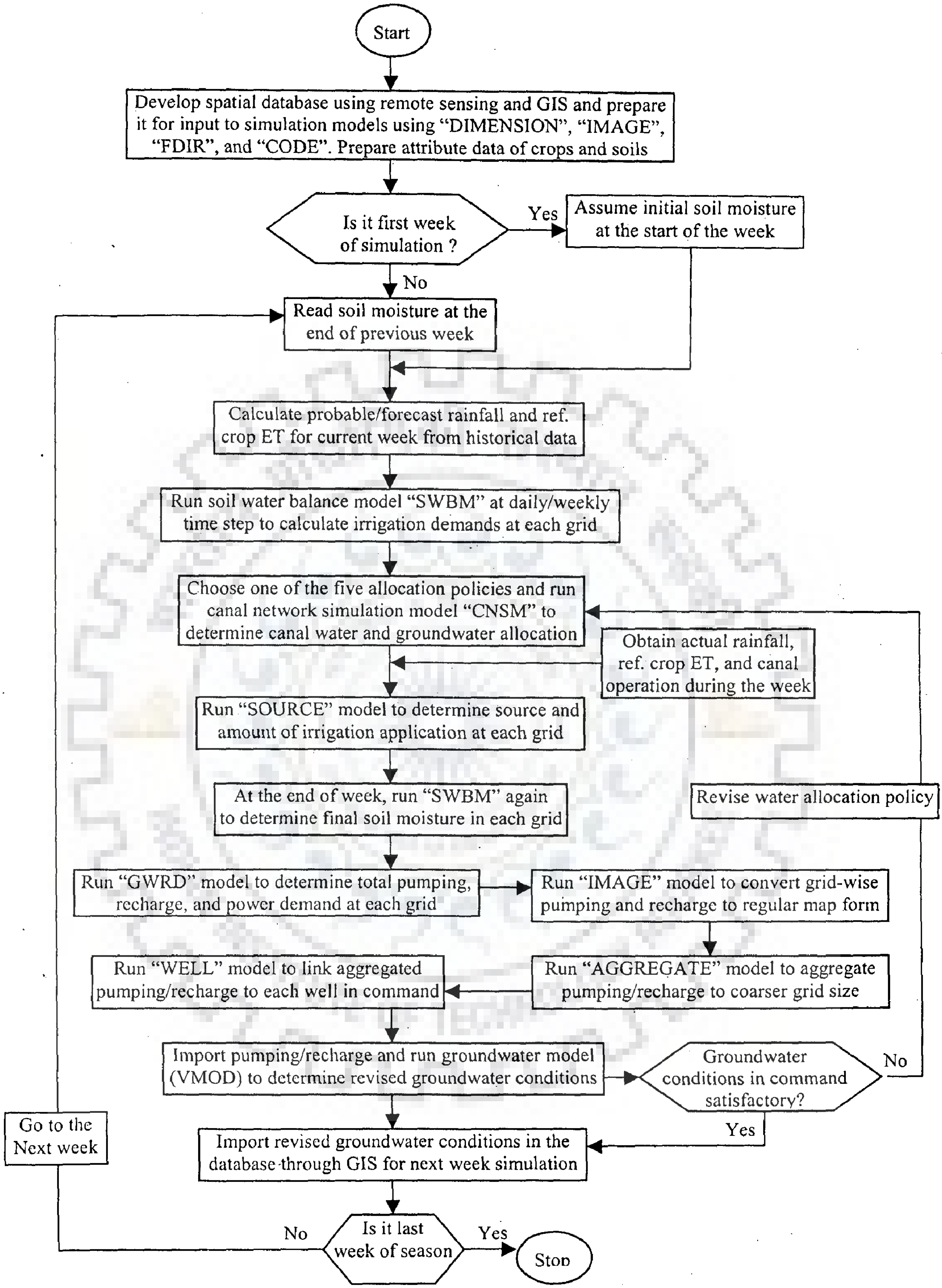


Figure – 5.1: Integrated geo-simulation scheme

CHAPTER - 6

DATABASE CHARACTERISATION IN GIS ENVIRONMENT

6.1 GENERAL

The geo-simulation scheme developed during the study 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 got waterlogged. This chapter covers the description of physical characteristics of the area and the methods adopted for generation of spatially distributed database for application of the proposed scheme. Basic data have been obtained from literature, from various Government agencies working in the study area, from field observations, and from satellite imageries.

In this chapter, first, general characteristics of the study area like topography, climate, soils, groundwater conditions, cropping pattern, crop characteristics, canal water availability etc. are described. Then, the development of database in GIS, like digitization of various layers, generation of DEM and groundwater depth maps etc. are presented. Subsequently, remote sensing analysis for deriving the cropping pattern and delineation of canal network is given. Finally, characterization of canal network, development of database for groundwater simulation model, and estimation of reference crop evapo-transpiration for the area are described.

6.2 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 – 6.1.

6.3 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.

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 the 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 (Govt. of U.P. 1990).

In the absence of the surface water supplies in the area 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.

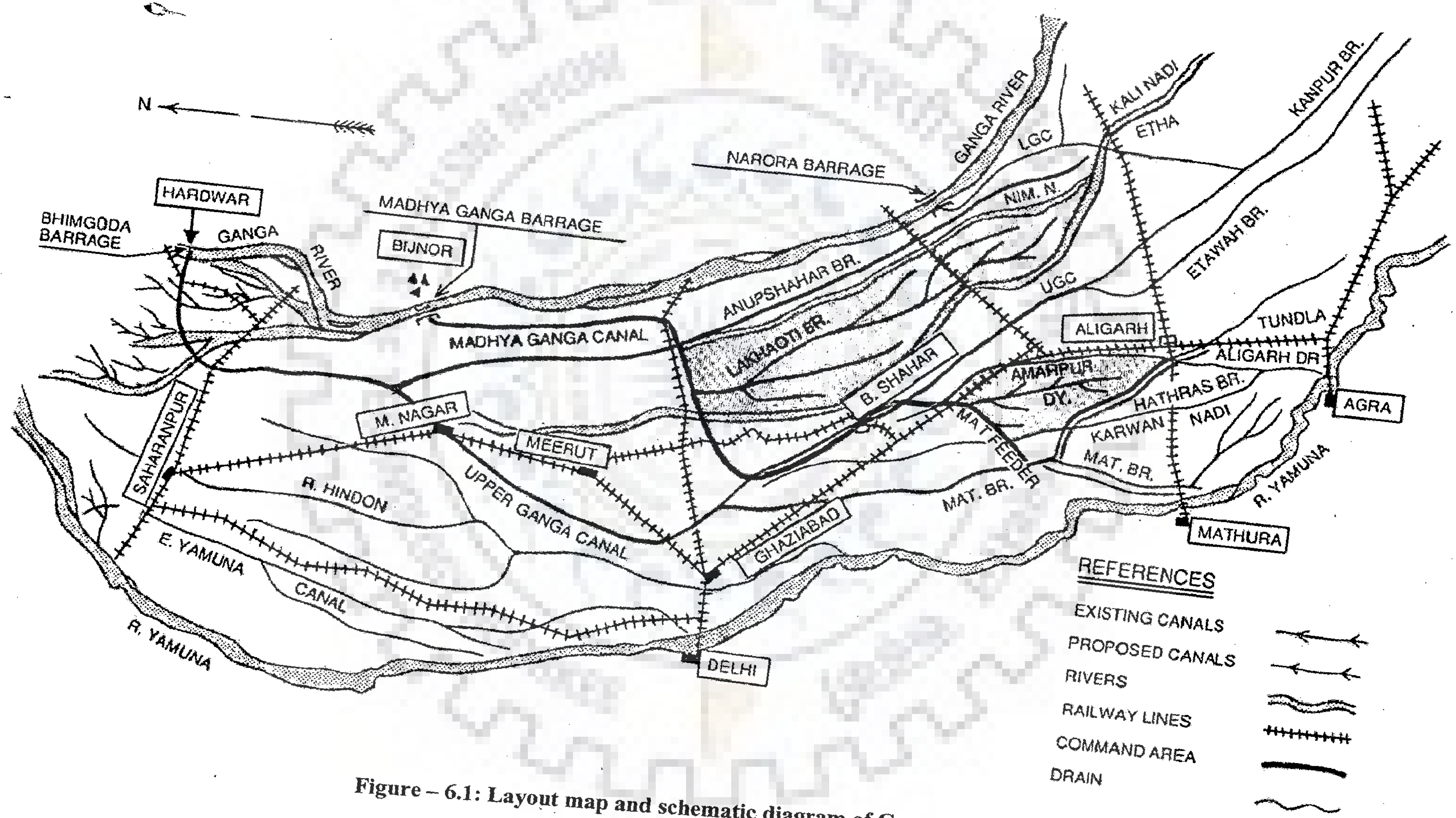


Figure – 6.1: Layout map and schematic diagram of Ganga Canal System

6.3.1 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 – 6.9. Thiessen polygon map is prepared and the weights of various stations are: Siyana (0.198), Bulandshahr (0.210), Anupshahr (0.168), Khurja (0.078), and Atrauli (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 – 6.1. Monthly rainfall in the command in various years is compared in Figure – 6.2.

Table – 6.1: 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

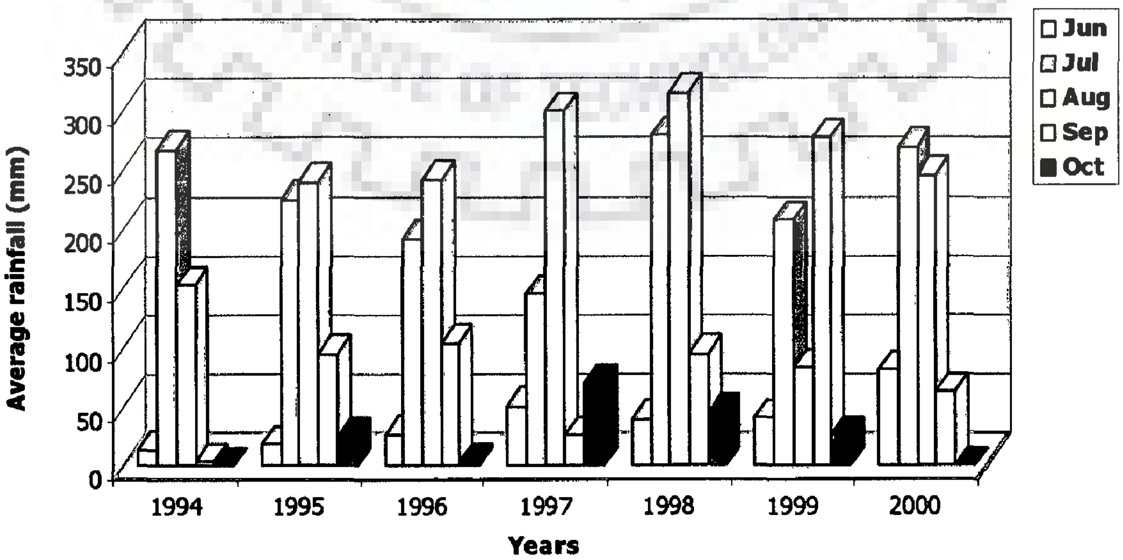


Figure – 6.2: Monthly rainfall in Lakhaoti command

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.

6.3.2 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 the 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, variation of soil type in the command area was an important input to the root zone soil water balance model. The soil map of U.P. State at a scale of 1:500,000 is obtained from the National Bureau of Soil Survey and Land Use Planning (NBSSLUP), New Delhi. The soil map of Lakhaoti command is derived from this map and is presented in Figure – 6.6. 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 6.4.2.

6.3.2.1 Identification of soil parameters

In this study, the soil properties of interest are: a) porosity, b) field capacity, c) permanent wilting point, and d) specific gravity. Field visits have been made and samples have been collected for all the nine varieties of soils. Three samples at different depths are collected for each soil type and analyzed in laboratory for finding parameters of interest. Identification of various parameters is briefly described below:

a) Particle size distribution

Particle size distribution determines the relative proportion of different grain sizes for assigning soil texture. Particle size distribution is evaluated for all soil types. Figure – 6.3 shows the distribution for the Soil 112. Based on the USDA soil texture classification, the soils in Lakhaoti command vary from "Sand Loam" to "Silt Loam" texture class.

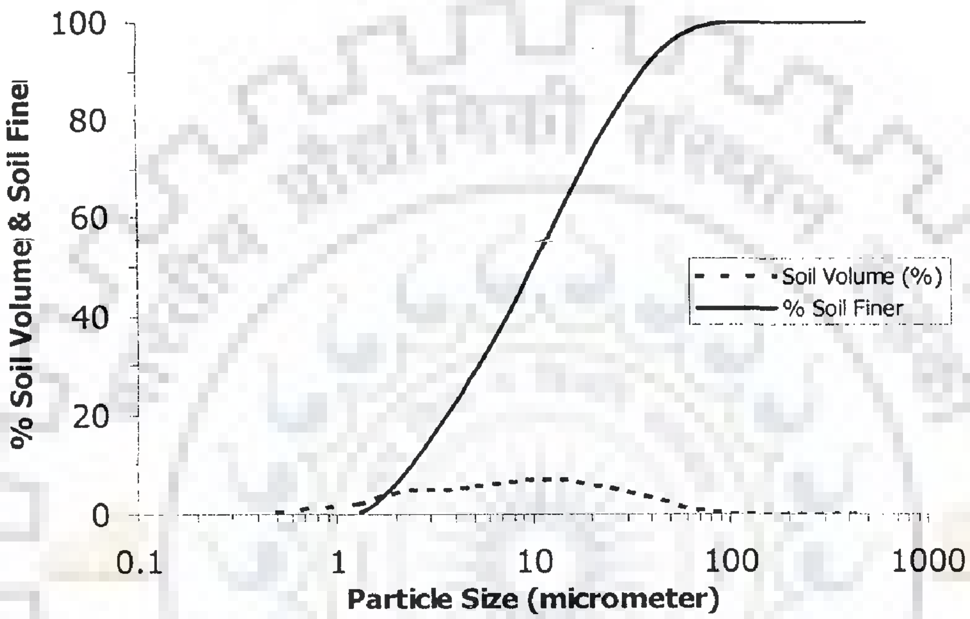


Figure – 6.3: Particle size distribution for Soil 112

b) Soil moisture characteristic curve

Soil moisture characteristic curve is the plot of moisture content versus suction head. It is determined by equilibrating a soil sample at a number of suctions of known tension and determining the corresponding moisture. A soil matrix potential of about -1/3 bars has been found to correspond to the field capacity, whereas a soil matrix potential of about -15 bars has been found to correspond to wilt point (Hillel, 1982). In this study, moisture contents are evaluated corresponding to soil suction pressures (bars) of -0.1, -0.33, -1, -3, -5, and –10. Soil moisture characteristic curves are prepared, and using best-fit relations, moisture content corresponding to –15 bar are obtained for all soils. Soil moisture characteristic curve for Soil 112 is shown in Figure – 6.4.

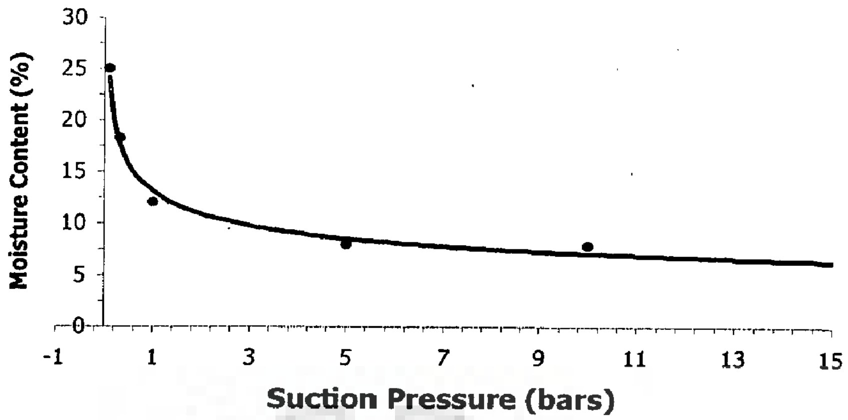


Figure – 6.4: Moisture characteristic curve for Soil 112

c) Apparent specific gravity

Specific gravity of soil (G) is the ratio of weight of a given volume of soil solids to the weight of an equal volume of water. Apparent specific gravity (G_a) refers to the soil mass instead of soil particles and takes into account the voids within the soil mass. Apparent specific gravity is related to the specific gravity by the expression:

$$G_a = (1 - n) * G \qquad \ldots(6.1)$$

where 'n' is the porosity of soil. The specific gravity for different soil types was evaluated in the laboratory. The values of field capacity, permanent wilting point, and specific gravity, as used in this study, are presented in Table – 6.2.

Table – 6.2: 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

6.3.3 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.

6.3.4 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 - 6.3.

The crop calendar that is broadly followed in the Lakhaoti command is presented in Table – 6.4. Sowing and harvesting dates for various crops have been collected from the Agriculture Department, Bulandshahr. In the simulation scheme proposed in this study, each crop is assumed to be sown and harvested at fixed times (calendar weeks) throughout the command.

Table – 6.3: 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 – 6.4: 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	—	→									←	—

6.3.4.1 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 and fortnightly crop factors, as used in this study, are presented in Table – 6.5.

Table – 6.5: 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

6.3.5 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 – 6.6 shows the supply discharge and volume of canal water available during different periods.

Table – 6.6: 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

6.3.6 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 calculation of canal seepage losses. These are presented in Table – 6.7.

Table – 6.7: 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	--	--	--	--	--	--

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 6.4.2.

6.4 GENERATION OF DATABASE FOR LAKHAOTI COMMAND IN GIS

An objective of this study is to integrate the irrigation system simulation model with spatially 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, storage, analysis, transformation and presentation of spatial data (ILWIS 3.0 Academic User's Guide, 2001). Although a number of GIS packages are available, the reason for selecting ILWIS GIS system for the present study is: a) easy availability, and b) experience in working with the system.

6.4.1 Digitisation of data layers from toposheets

Not all spatial data are available in the grid oriented digital format. Often, the data are available as analog maps that require digitization before entry into a digital database. In the present case, the Survey of India (SOI) toposheets at 1:25,000 scale are available for the Lakhaoti command. The total study area was covered in 37 toposheets. The toposheet numbers are: 53H14 (1-6), 53H15 (1-2, 4-6), 53L2 (2-3), 53L3 (1-6), 53L4 (1-2, 4-6), 53L8 (1-6), 54I1/4, 54I5 (1-2, 4-6), and 54I9/3.

The origin of command area map is taken at Latitude 27° 45′ N and Longitude 77° 45′ E. Since the toposheets and the remote sensing data are processed in Polyconic projection system, the same is adopted while creating the co-ordinate system. The datum is adopted as India (India, Nepal) and the ellipsoid is selected as Everest (India 1956). Cartesian co-ordinates of the origin are taken as X = 0 and Y = 0 and the maximum X and Y for the study area were taken as 82 km and 121 km respectively. Since the remote sensing data of IRS-1C satellite and LISS-III sensor with a processed grid size of 24 m are used in the study, the size of each grid is taken as 24 m x 24 m. Following eight features are digitized from toposheet and stored in separate files:

a) Boundary of the area containing the Kali river and Nim river.

b) Contours in the area at 5 m interval. The contour elevation in the area varies from 210 m in the north to 170 m in the south.

c) Spot levels at various points in-between the contours.

d) Forests, orchards, and plantations in the area.

e) Layout of railway lines to find suitable control points for geo-referencing.

f) Layout of road network to find suitable control points for geo-referencing.

g) Location of various towns and villages in the area.

h) Location of water bodies in the area.

Of the various themes digitized, boundary layer is used to separate the area of interest from the remote sensing image and other spatial data. Contour map and spot level data are used to generate the DEM for the area. Forest/plantation layer is used to separate the forests or plantations from the agricultural area. Village map is used to identify the location of groundwater observation wells. Boundary of the Lakhaoti command, digitized contours, and spot levels are shown in Figure – 6.5.

6.4.2 Soil map of Lakhaoti command

The available soil map, prepared by NBSSLUP, is geo-referenced in same co-ordinate and projection system as that for other digitized data. A segment map is created by digitizing the boundaries of various soil types such that each soil type forms a closed polygon. The segment map is polygonized and rasterized. Identifier values 1, 2, 3, 4, 5, 6, 7, 8, and 9 are assigned to nine soil types Soil 088, Soil 099, Soil 086, Soil 134, Soil 197, Soil 112, Soil 102, Soil 159, and Soil 203 respectively. Soil map of the study area is extracted from the whole map by using the boundary layer and is presented in Figure - 6.6. Using the soil map, various grids in the Lakhaoti command are associated with different water holding properties for soil water balance modeling.

6.4.3 Thiessen polygon map of Lakhaoti command

Five ordinary raingauge stations are located within or around the Lakhaoti command in major cities. These locations are Siyana, Bulandshahr, Anupshahr, Khurja, and Atrauli. The daily rainfall data at these stations are available for the year 1998-99. The data have been collected from the office of District Magistrate, Bulandshahr and Aligarh.

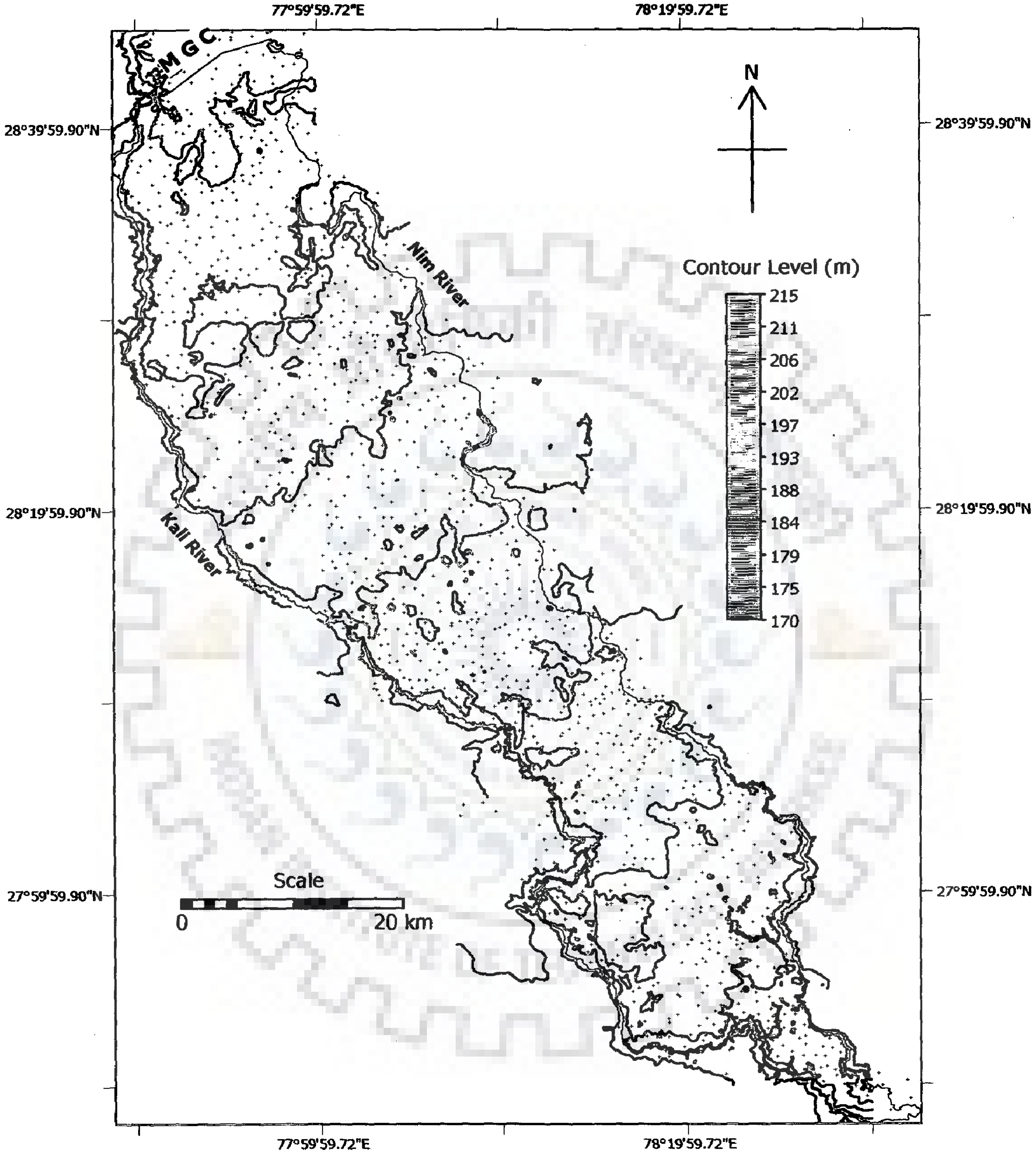


Figure – 6.5: Boundary, Contours, and Spot levels in Lakhaoti command area

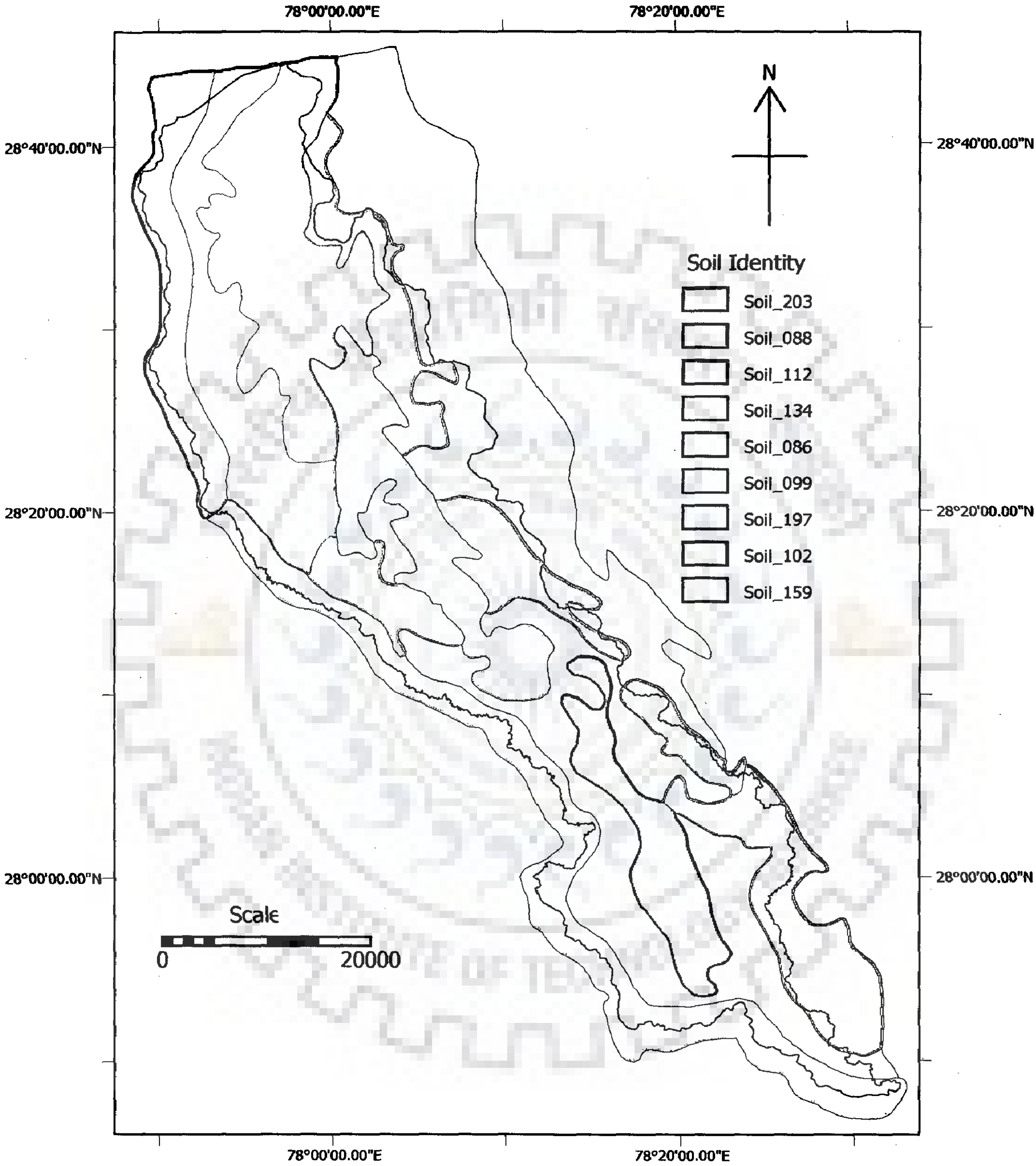


Figure – 6.6: Soil map of Lakhaoti command area

Thiessen polygon map of the area is digitized and geo-referenced to the same co-ordinate and projection system as that for other digitized data. The segment map is polygonized and rasterized. Thiessen polygons of Siyana, Bulandshahr, Anupshahr, Khurja, and Atrauli (Figure – 6.7) are given numeric identities of 1, 2, 3, 4, and 5 respectively. The study area portion is extracted out of the whole map using the boundary layer of Lakhaoti command. Using the map, different grids in the Lakhaoti command are associated with different rainfall stations.

6.4.4 Generation of digital elevation map for Lakhaoti command

Digital elevation model (DEM) is the digital representation of the continuously varying surface elevation of an area. In this study, in addition to the grid-wise elevation information, DEM is used to find the flow direction and the spatial depth of groundwater in the command area. Contours (vector data) and spot levels (point data) are used to generate the DEM.

Initially, linear interpolation method was used to find the elevation at each undefined grid from the grids of known elevation. Irregular humps and troughs in elevation were observed in the output. Therefore, kriging has been used to generate DEM for the area. The contour data are converted to point data and merged with the spot level data for point interpolation. Variance of the point elevation data is found to be 188. From the semi-variogram plot of point map, range is found to be 60 km corresponding to the variance of 188. Various models with different values of nugget, sill, and range have been tried to fit the observed semi-variogram as closely as possible. Gaussian model with nugget, sill, and range values of 0, 1500, and 170000 has been found to closely match with the semi-variogram within the estimated range. Using these variables, elevation values at intermediate grids have been found out. The plot of observed semi-variogram and the results of Gaussian model are presented in Figure – 6.8. Using the boundary file, DEM of the Lakhaoti command has been separated out which is presented in Figure – 6.9.

6.4.5 Development of flow direction map for Lakhaoti command

Flow direction map is a representation of the direction in which water will

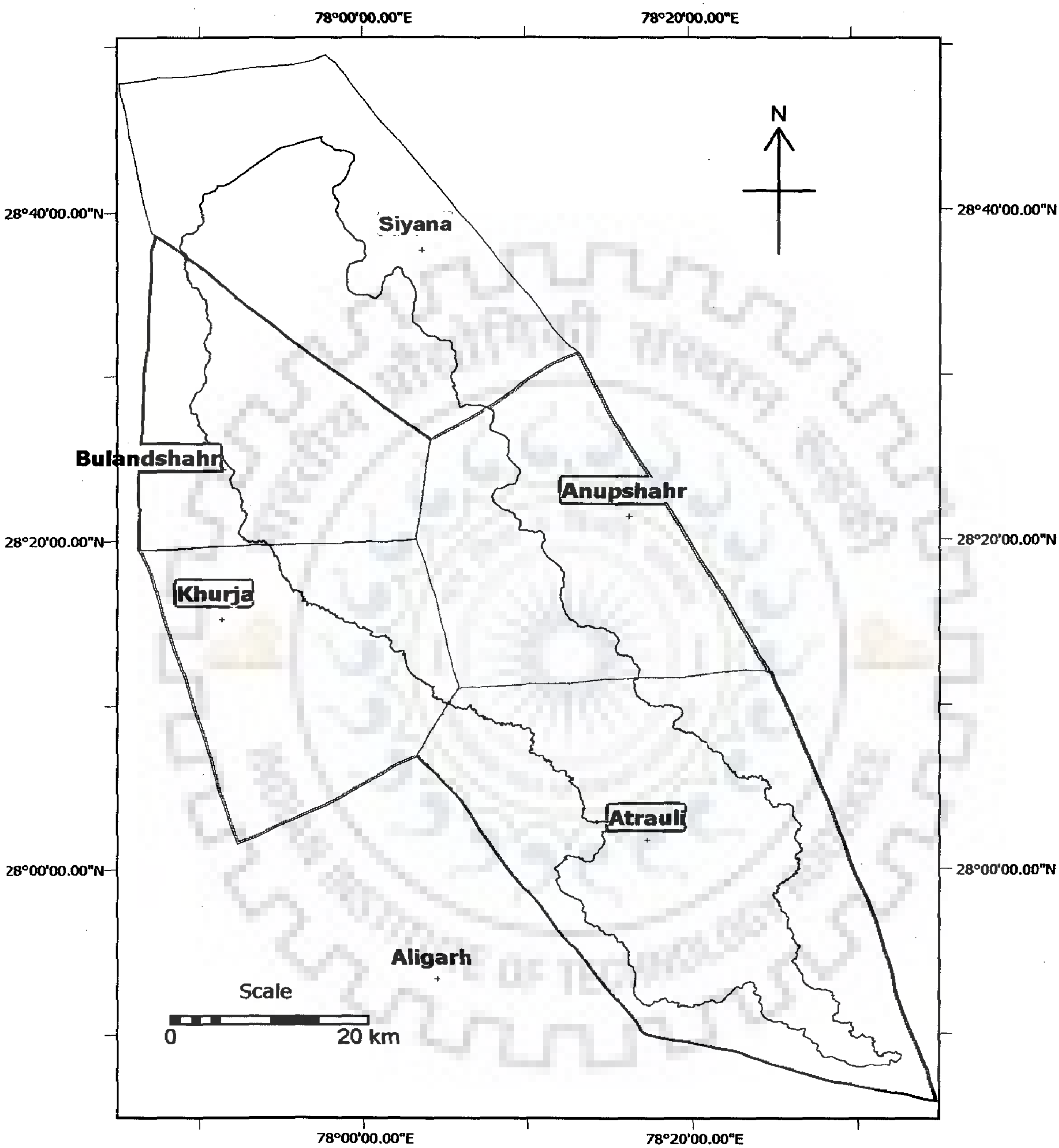


Figure – 6.7: Thiessen polygon map of Lakhaoti command area

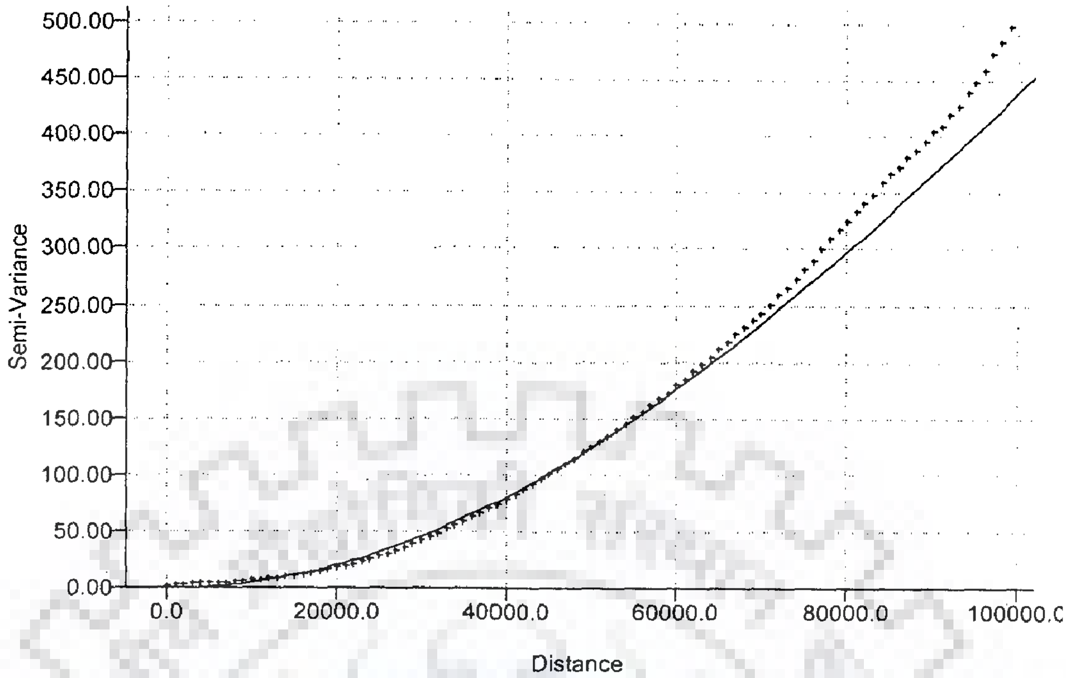


Figure – 6.8: Observed semi-variogram and Gaussian model fitted to data

flow on the land surface. It is calculated by finding the steepest downhill slope. In ILWIS, a neighborhood function is used to find the lowest elevation grid from the eight neighboring grids surrounding each grid. If more than one grid of lowest elevation is observed, precedence is given to the grids in ILWIS in a particular defined order. The Lakhaoti command has a flatter topography with higher chances of more than one lowest elevation neighbors. So, rather than using the ILWIS function directly, a flow direction module (FDIR), as explained earlier under Chapter-5, is developed to estimate flow direction at a grid. Total number of grids for Lakhaoti command comes out to be 3,610,053. Out of this, 86.7% grids are assigned flow direction on the basis of least elevation of neighboring grids, 13% are assigned flow direction on the basis of least elevation and general slope of Lakhaoti command. 0.3% pixels were classified as flat.

6.4.6 Development of groundwater depth map

In irrigated areas, groundwater conditions vary spatially and temporally. In the proposed simulation scheme, groundwater conditions in the command are incorporated through the use of spatially distributed groundwater depth in the command area.

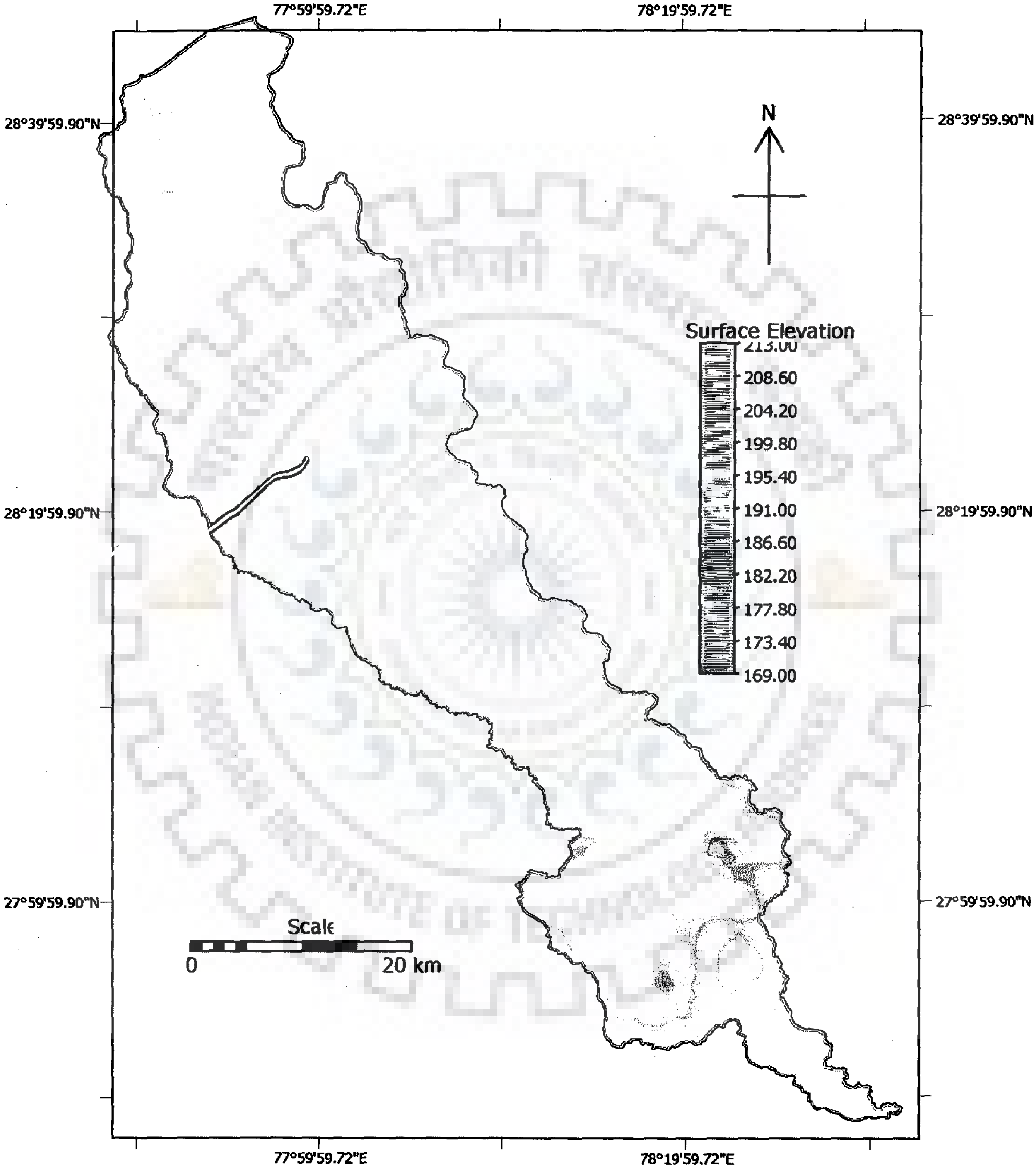


Figure – 6.9: Digital elevation map of Lakhaoti command area

Groundwater level data of 19 observation wells located within the Lakhaoti command are available for the year 1998-99 for the months of June (pre-monsoon), October and November (post-monsoon) as given in Table – 6.8 and the same have been used for generating the groundwater surface for different months. A number of point interpolation techniques have been tried to generate the groundwater surface. For kriging, Gaussian model fits best to observed semi-variogram but the interpolation did not yield satisfactory results because of irregular jumps and troughs in the generated surface. Then, the trend-surface method has been used which did not result in sudden jumps and troughs but large difference has been found between the observed and generated levels at the observation points. Finally, the moving-surface method of point interpolation (method in which a polynomial surface is calculated by a moving least square fit) is used which provides satisfactory results with respect to groundwater surface and the match between observed and generated levels at observation points. Details of the method are presented in (ILWIS 3.0 Academic User's Guide, 2001).

The groundwater surfaces for Lakhaoti command are generated for the month of June and October. The groundwater surface for June 1998 is shown in Figure – 6.10. 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 – 6.11.

Table – 6.8: Groundwater observation well data in Lakhaoti command for year 1998-99

Code	Station name	Surface elevation (m)	Depth in June (m)	Depth in October (m)	Depth in November (m)
W0677	Saidpur	209.06	7.51	4.84	3.9
W1345	Lakhaoti	204.99	9.41	5.48	5.22
W1497	Pali Partapur	203.94	11.81	9.45	9.07
W1471	Pabsara	204.7	9.55	7.56	7.21
W1728	Aurangabad	204.99	12.69	10.53	9.98
W1993	Jadol	202.72	11.13	8.93	8.45
W3745	Jakhauta	198.06	9.42	8.07	7.88
W2842	Jatauna	199.69	12.24	10.85	10.55
W3354	Rasidpur	199.95	13.29	11.38	10.96
W3992	Salempur	200.12	11.49	9.75	9.82
W3551	Jatpura	200.54	12.12	9.61	9.14
W6625	Atrauli	186.17	13.9	12	11.92
W8028	Hidramai	174.54	9.8	5.75	6.27
W6830	Pali	184.98	13.6	12.45	12.37
W5228	Dibai Crossing	189.84	11.55	8.95	8.65
W4813	Aurangabad	194.77	13.66	11.5	10.95
W0756	Sherpur	207.7	9.81	6.81	6.71
W0102	Hingwada	210.21	8.05	5.49	5.36
W5096	Bhimpur	191.63	9.03	6.88	6.96

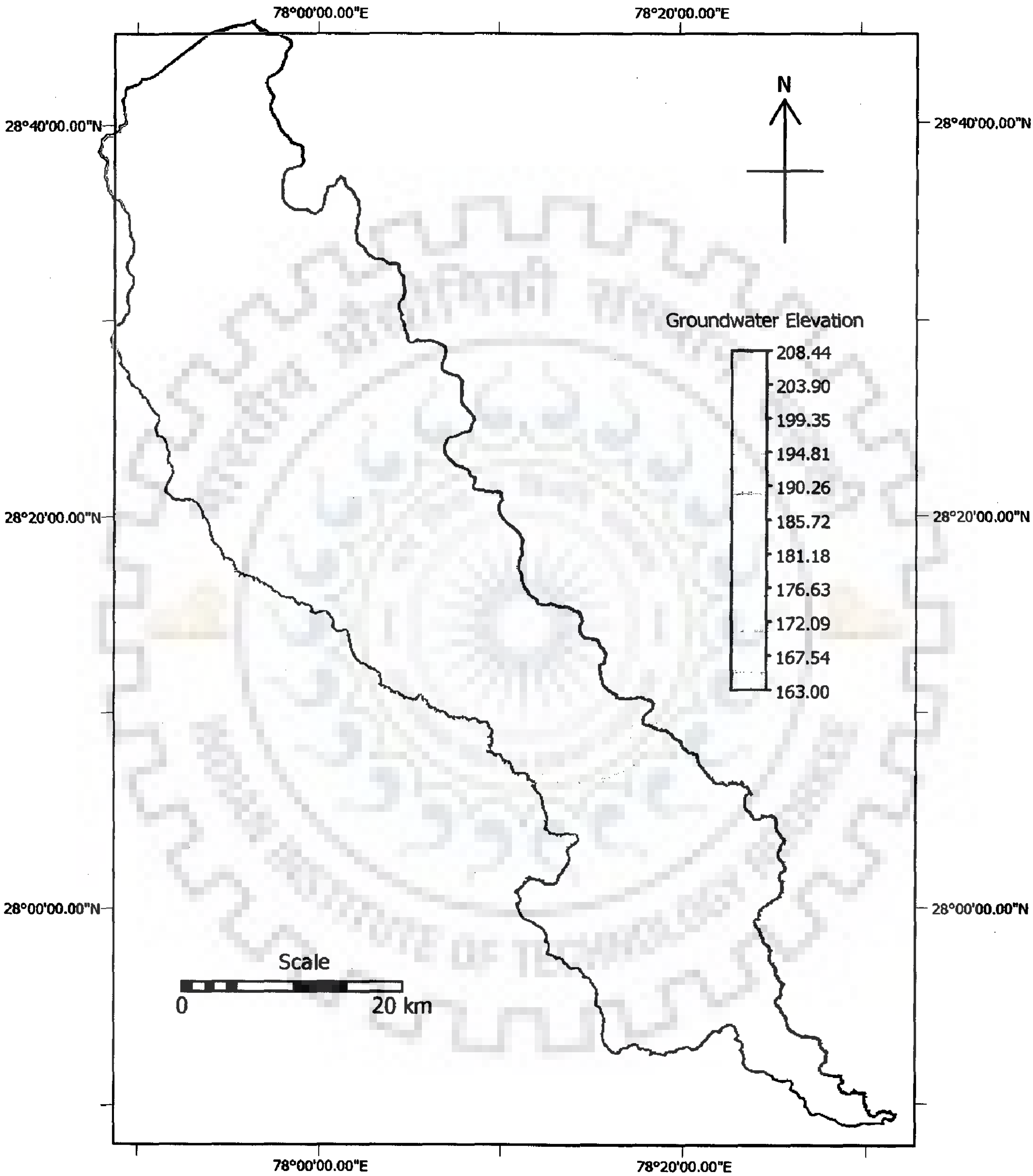


Figure – 6.10: Groundwater surface map for Lakhaoti command for June 1998

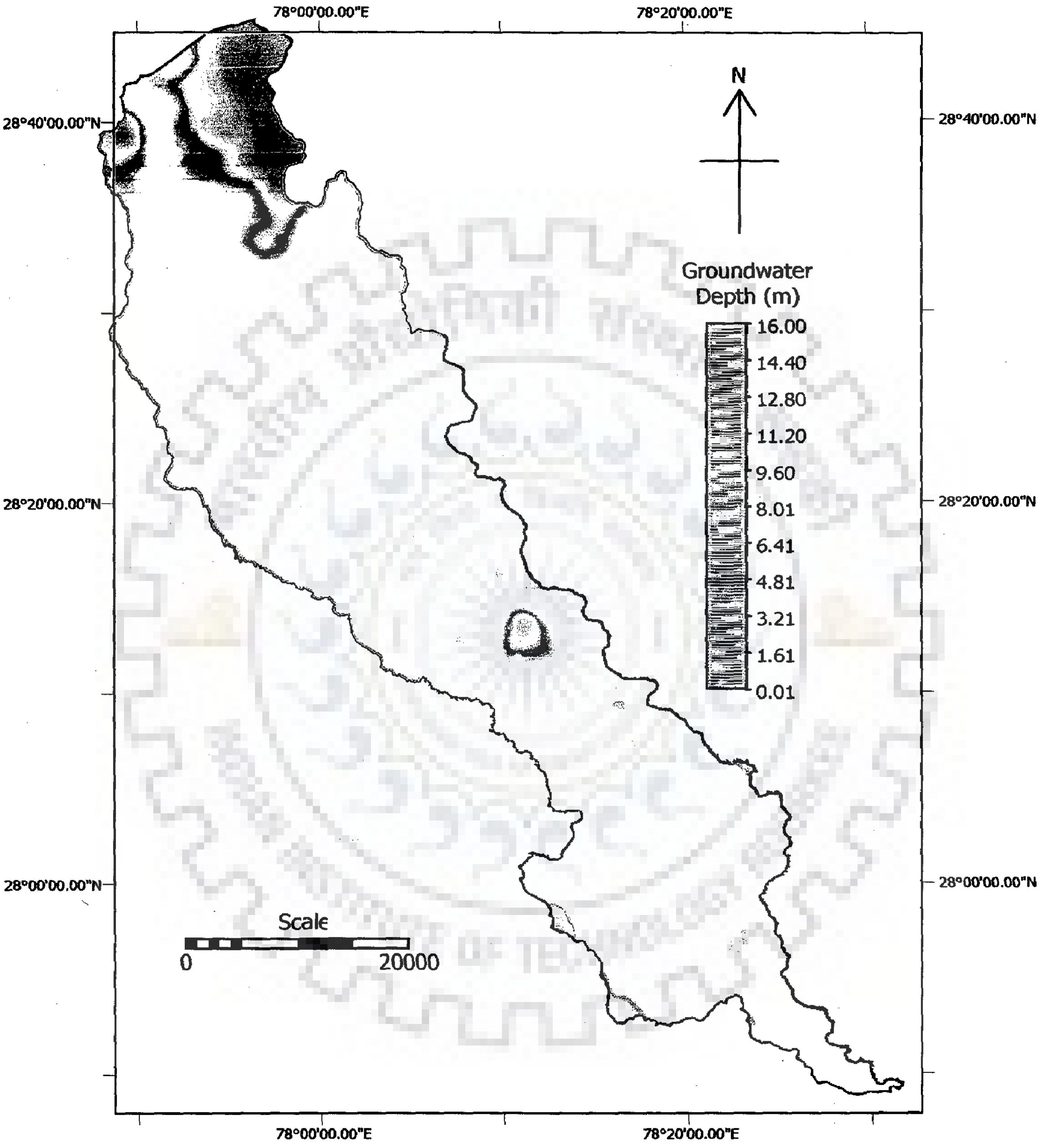


Figure – 6.11: Groundwater depth map of Lakhaoti command for October 1998

6.5 REMOTE SENSING ANALYSIS FOR LAKHAOTI COMMAND

For efficient water management in a command, there is a need to collect field information about the crops grown/to be grown so that geographically referenced water demands can be worked out and water distribution planned as per the prevailing conditions of water demand and availability. Application of the proposed scheme requires spatially distributed information about actual cropping pattern in the command. Manually, it becomes difficult and time consuming to gather such information for a large agricultural area. In this study, remote sensing data are used to identify the actual cropping pattern in the study area. The cropping pattern, so derived, is used in the simulation scheme for estimating irrigation demands at weekly time step. The image processing of remote sensing data is carried out on the ERDAS IMAGINE 8.3.1 system developed by ESRI, USA (ERDAS Field Guide, 1997).

6.5.1 Data used and preliminary processing

The application of proposed scheme is illustrated for the year 1998. Hence, the data of LISS-III sensor of IRS-1C/1D satellite for this year are used. This multi-spectral data has spatial resolution of 24 m. The study area is covered in Path 097 and Row 051 of IRS-1C satellite with 40% Shift Along Track (SAT). The entire study area is covered in one scene of the satellite. Based on the availability of cloud-free remote sensing data for the year 1998-99 and the crop calendar in command, digital data of five dates were acquired: June 3, 1998; July 23, 1998; October 9, 1998; October 31, 1998; and November 26, 1998. Various steps of analysis are described below.

6.5.1.1 Import & geo-referencing

Data of LISS-III sensor of IRS-1C satellite for five dates have been imported in the ERDAS system. Each scene has 6480 columns, approx. 6000 rows and data of four bands. The study area is covered in approx. 3700 columns and 4400 rows. A false color composite (FCC) of near-infrared (NIR), Red and Green bands shows distinct Kali river in all the images while Nim river is not distinguishable in its initial course. The main canal and the Lakhaoti branch are clearly visualized. The agricultural area (with red tone) is distinguishable from the built-up and residential areas.

In the digital spatial data handling systems, it is necessary to relate all entries in the dataset to a common co-ordinate and projection system and to mutually register and reference the data. While using the multi-temporal satellite data of the same area, it is required to geo-reference various images for overlaying and detecting land use changes. First, image-to-image registration has been done for all the satellite images. Geo-referencing is done by identifying similar control points (such as river crossings, road crossings, other pertinent points) in different images. Next, resulting images are geo-referenced with other thematic layers digitised in GIS, such as boundary, contour, plantation etc. using identifiable control points along the Kali and Nim rivers and road crossings. Results of geo-referencing are checked by overlaying the boundary image over remote sensing images of different dates and have been found to be satisfactory in all the cases. Overlay of the study area boundary on the remote sensing image of October 31 is presented in Figure – 6.12.

6.5.1.2 Identification of MGC in satellite image & separation of study area

The topographic survey of the study area was carried out in the year 1976-77 (marked on toposheets of SOI) while the canal system is introduced in the area in year 1988. Hence the layout of canal network was not available in the toposheets. To mark the location of Madhya Ganga Canal (MGC) in the boundary layer so as to form a closed polygon of the study area, the remote sensing data have been used. MGC was digitized on-screen from the geo-referenced remote sensing image and then merged with the boundary layer containing Kali and Nim rivers, thus forming an enclosed boundary of the study area.

For the purpose integrating remote sensing analysis with the simulation scheme, it is required to separate out the study area from its surrounding area. The boundary layer, digitized in ILWIS, was converted to raster form and imported in ERDAS. Using the MODELER option of ERDAS (used for manipulating geo-referenced multiple images), the study area was separated from the full scene of different images.

6.5.1.3 Separation of forests/plantations

The study area contains plantations of Babul and Oak and gardens of fruit trees.

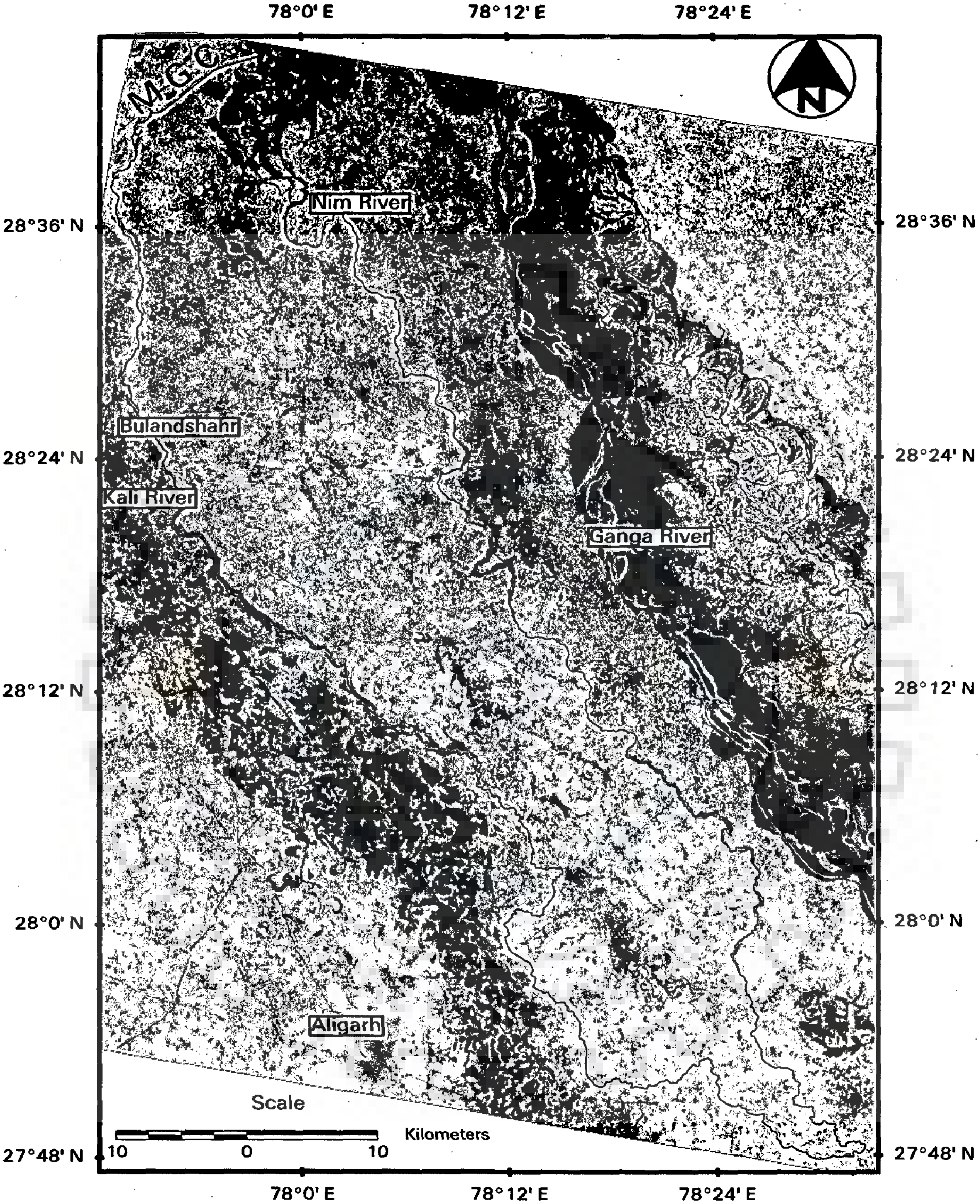


Figure – 6.12: Boundary of Lakhaoti command overlaid on satellite image of October 31, 1998

There are some deciduous forests also in the area. These plantations have reflectance properties quite similar to crops and, if not separated, can falsely get classified as agricultural crops. So, the plantations and forests are separated from remote sensing images. Forest/plantation layer, digitised from toposheets, is imported in the ERDAS system and overlaid on the remote sensing images of different dates. Using distinct appearance in comparison to agricultural area and the information from toposheet, forest/plantations have been separated out using supervised classification. The forest/ plantations identified using remote sensing analysis could be spotted in the command during various field visits. The forest/plantation area has been removed from the study area images of all dates using the MODELER option of ERDAS.

6.5.1.4 Identification of crops in Lakhaoti command

Various studies and methods of crop discrimination have been reported in literature (Bastiaanssen, 1998). Since the crop reflectance depends on a number of factors (anatomical structure of leaves, leaf age, leaf water content, mineral deficiencies, pest and disease attacks, reflectance of underlying soil etc.), crop identification on the basis of reflectance alone poses problems. Crop identification can be greatly enhanced by carefully selecting the timing and sequencing of images in accordance with the crop calendar. In the present study, multi-temporal remote sensing data are used to identify and locate major crops in the Lakhaoti command. Various steps followed in identification of crops are discussed below.

a) Conversion of digital numbers to radiance

For comparing or analysing multi-spectral data, digital numbers (DN) of the image are first converted to radiances. For each band represented by wavelength λ, the digital numbers, Q_{cal} on the satellite image are converted to radiance, L(λ) by the expression (derived from satellite data information file):

$$L(\lambda) = L_{min}(\lambda) + [L_{max}(\lambda) - L_{min}(\lambda)] * (Q_{cal}/Q_{cal,max}) \quad \ldots (6.2)$$

where L_{min} and L_{max} are the minimum and maximum radiance values of the sensor, obtained from its radiometric characteristics (supplied with satellite data information file). A model is developed using MODELER option in ERDAS system to convert the DN values to radiance. The radiance images have been used in subsequent analysis.

b) Separation of agricultural area

Since the aim of analysis is to discriminate among various crop types, first the agricultural area is separated from the full scene using the Vegetation Index approach. Vegetation Index (VI = NIR/Red) for an agricultural grid is very high as compared to other land uses (bare soil, built-up area). Using a threshold value of VI, each remote sensing image is classified as agricultural/non-agricultural area. Dwivedi and Sreenivas (2002) have used threshold value of Normalized Difference Vegetation Index (NDVI) to separate vegetated/non-vegetated area. Based on the visual inspection of FCC of an image, threshold VI value for an image is finalized. For the images of June 3, July 23, October 9, October 31, and November 26, the threshold VI values have been found to be 1.21, 1.43, 1.21, 1.21, and 1.20 respectively.

c) Crop Classification

In this study, different methods have been tried to discriminate among various crop types in the command area. After separating out the agricultural area (after step b), image contrast has been enhanced using histogram equalization, but identifiable difference among various crop types is not obtained. Next, various vegetation indices (presented by Bastiaanssen, 1998), such as normalized difference vegetation index (NDVI), Soil adjusted vegetation index (SAVI) etc. have been used to discriminate among various crop types (Ray and Dadhawal, 2001). In present case, significant contrast between different crop types could not be obtained. Tasselled-Cap transformation (Mather, 1990) is applied on the radiance image of four bands and FCC corresponding to brightness, greenness, and wetness layers is prepared. However, prominent variation within crop types could not be obtained. Based on these observations, multi-temporal attribute of remote sensing has been used in conjunction with the crop calendar to identify various crops in the study area. Procedure used to identify different crops is described below:

i) Sugarcane

Sugarcane is a perennial crop sown in the February/March. For identification of sugarcane, images of June 3, July 23, and October 9 have been utilized. From the crop calendar, it is seen that on June 3, major crops in the command are Urad (pulse crop), Moong (pulse crop) and Sugarcane. Since Urad and Moong crops in June are in their senescence stage with low VI, therefore, sugarcane is the only major crop in the command with appreciable VI. Thus, the image of June 3 is utilized to identify sugarcane grids. Using unsupervised classification, the image of agricultural area of June 3 is classified into two broad categories and the class with pronounced signature of vegetation (higher VI) is classified as Sugarcane. The sugarcane grids, so classified, have been checked for their presence in the images of July and October. The sugarcane area in the command came out to be 17878 ha.

ii) Rice

The rice crop in Lakhaoti command has been identified using the images of July 23 and October 9. It is well known that rice needs standing water in the field. In the early stages of its development, the growth of rice plant is quite small and remote sensing signatures of rice fields resemble water signatures. After development of rice plant, the canopy reflectance takes over and the reflectance characteristics represent vegetation signatures. This fact is utilized to identify rice grids in the Lakhaoti command. A comparison of the agriculture images of July 23 and October 9 reveals that a lot of grids, which are not classified as agriculture (rather, these represent water signatures with VI less than 1) in the July scene, are classified as agriculture in the October scene. Such grids were classified as rice grids. As a confirmation, most of the rice grids in the command area have been found to lie near the canal system as this crop consumes large amount of water. The radiance FCC of July 23 overlaid with the agriculture image of July 23 is presented in Figure – 6.13. The rice grown area identified in Lakhaoti command is presented in Figure – 6.14. The area of rice crop has come out to be 43887 ha.

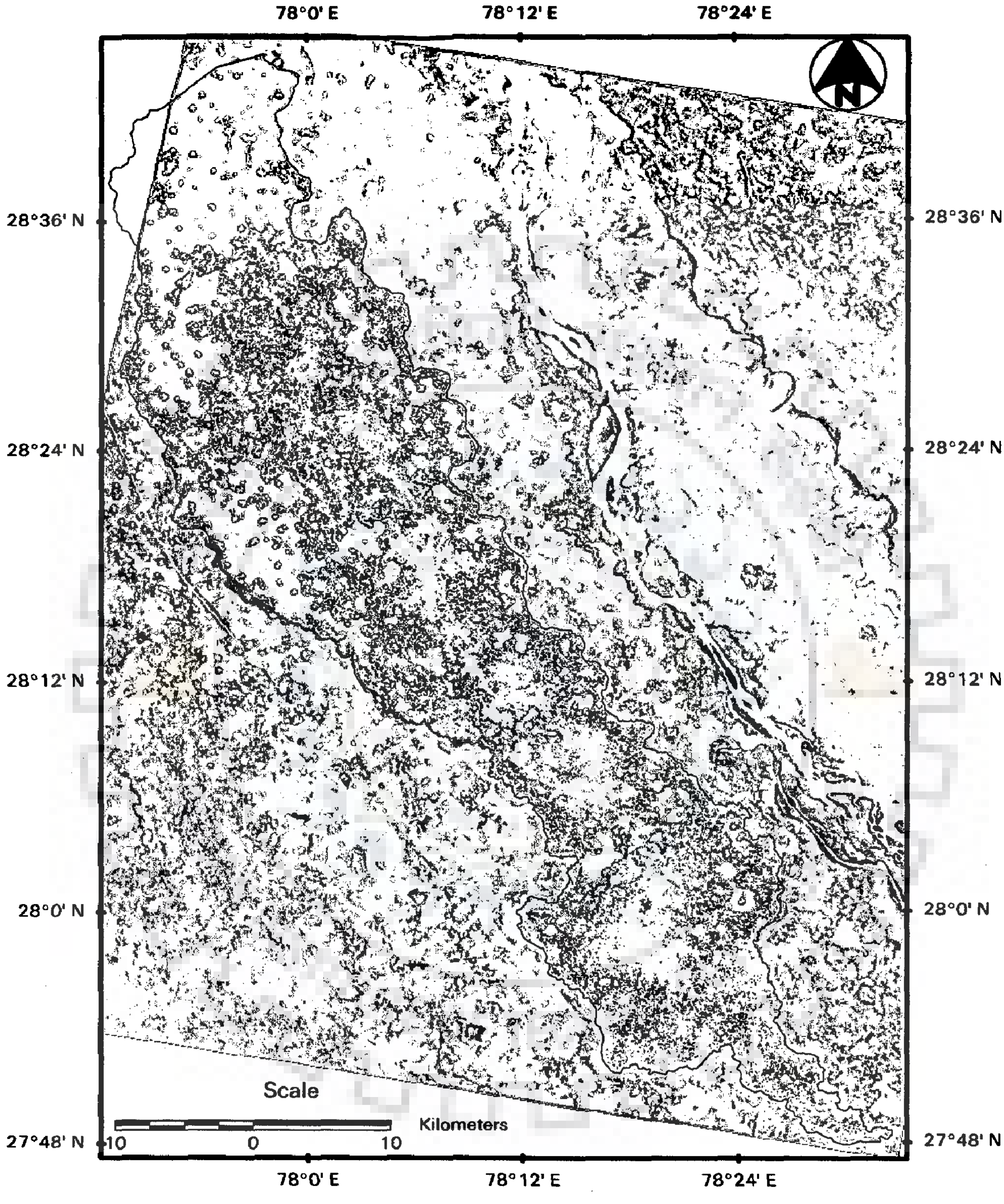


Figure – 6.13: Radiance FCC of July 23 overlaid with agriculture image of July 23

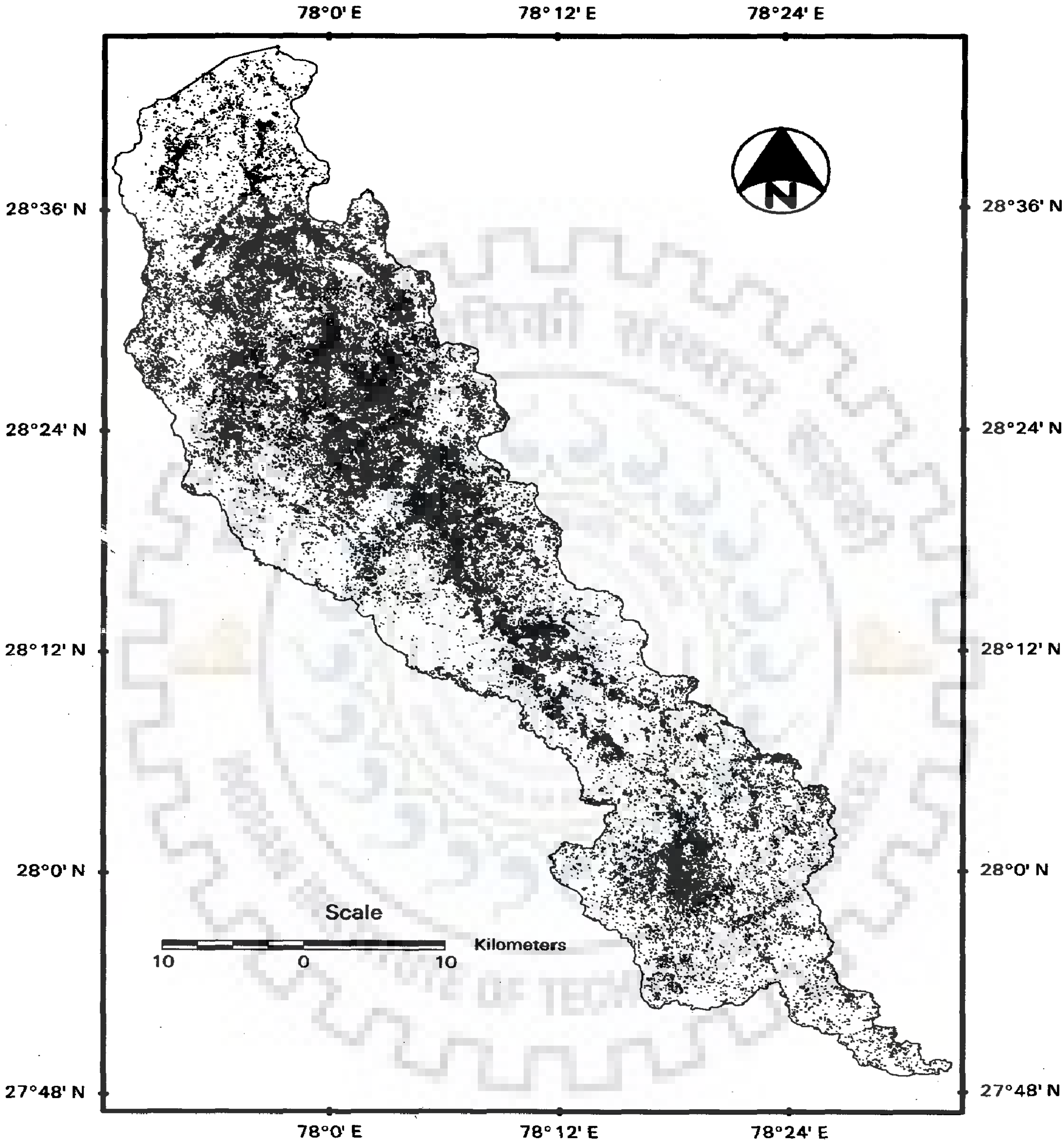


Figure – 6.14: Identified rice area in Lakhaoti command *iii) Arhar*

Arhar is a pulse crop. Of the various Kharif crops grown in Lakhaoti command, arhar is the only crop that remains in field up to middle of November. To identify this crop, the image of October 31, and classified images of sugarcane and rice are used.

On October 31, major Kharif crops present in the command are sugarcane, non-harvested rice, arhar and newly sown Rabi season crops. For identifying arhar grids, the images of sugarcane and rice crops are subtracted from the agriculture image of October 31 so that the remaining agriculture area represent mainly the arhar crop and other miscellaneous vegetation. Using unsupervised classification for the remaining agricultural area, two major classes have been identified and the class with pronounced vegetation signature (higher VI) is classified as arhar. The cropped area of arhar has come out to be 9148 ha.

iv) Maize/Guar

As per the crop calendar, maize crop is planted in June and the guar crop (fodder crop) is planted in July. Both these crops are harvested by the end of September. For identification of maize and guar, the image of July 23 and the classified images of sugarcane, rice, and arhar have been utilized. From the agriculture image of July, the classified images of sugarcane, rice, and arhar have been subtracted. The remaining agricultural area in image of July represents maize and guar crop in the command area. The two crops were classified using unsupervised classification. The area under maize came out to be 38330 ha and that under guar 2360 ha.

Areas under various crops obtained from remote sensing analysis match quite closely to the corresponding areas proposed in the command.

6.5.1.5 Composition of Kharif crop map

Thematic maps of various crops in the Lakhaoti command have been saved in separate files. A composite image, showing various Kharif crops in the command, has been formed. The individual layers of sugarcane, maize, rice, arhar and guar crops have been merged in one image and different numeric identity has been assigned to different crops (sugarcane – 1, maize – 2, rice – 3, arhar – 4, and guar – 5). The Kharif crop image of the command area is shown in Figure – 6.15. This image is used as one layer of information (crop variation within the command) for spatial root zone soil water balance modeling for finding real-time irrigation demands.

6.5.2 Cropping pattern analysis in Lakhaoti command

From the close view of Kharif crop image, it is observed that sugarcane crop is densely located in the head-reach of the command and it decreases steadily towards the middle where rice and maize are extensively cultivated. The percentage of sugarcane rises in the tail-end of the command also which has a well-built and well-maintained canal system. Maize crop is grown uniformly through the head and middle-reaches but diminishes towards the tail-end of canal system. Since water table rises close to the ground surface in parts of head-reaches of the command, more water-tolerant sugarcane crop is found in head-reaches. Rice crop is grown marginally in the head-reaches as compared to the middle and tail-reach. Arhar crop is grown extensively in tail-reaches of command as compared to any other reach of the system. These facts have also been corroborated during various field visits made in the command for verification of remote sensing analysis.

6.5.3 Accuracy assessment of crop classification

The accuracy of classification is reported in two ways: non site-specific and site-specific. In former, usually high classification accuracy is reported as compared to later method. An error matrix is generated representing the errors incurred in the identification of a crop with respect to other crops. An error matrix is a two-dimensional table with columns representing the reference classes and the rows representing the classification results. The diagonal represents the correctly classified pixels. The reference information is collected at the time of acquisition of remote sensing data. A number of random samples points are generated for the classes by the image processing system. The reference information is obtained based on signature in the multi-temporal images and crop calendar information used in the image classification.

For the Lakhaoti command, field visits have been made during the month of October and information about prominent reference points with existing crops have been recorded for various locations from head-reach to tail-end of the command. These reference points are transferred to the classified Kharif crop image taking help of the PAN sensor scene (road network was quite apparent in the PAN sensor image). using, mainly, the road network in the command, and compared with the results of remote sensing analysis. Since sequential technique is used in crop classification, reference information is also derived from the multi temporal data for sugarcane, rice, Arhar and Maize/Guar. Maize and Guar classes have been merged since their cropping periods were similar and the two are segregated using unsupervised classification. The confusion matrix, user's and producer's accuracy and Kappa estimates for the classification is given in Table – 6.9. Value of Kappa above 0.6 indicates satisfactory classification.

Table – 6.9: Confusion matrix for Kharif crop map

Reference → / Classification ↓	Sugarcane	Rice	Arhar	Maize/Guar	Total	User's accuracy
Sugarcane	25	1	3	6	35	71.4
Rice	1	30	3	1	35	85.7
Arhar	2	1	29	3	35	82.9
Maize/ Guar	3	1	2	29	35	82.9
Total	31	33	37	39	140	
Producer's accuracy	80.6	90.9	78.4	74.4	80.7	
% Kappa	0.743					
Overall % accuracy	80.7					

6.5.4 Delineation of canal network in Lakhaoti command

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

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

The PAN sensor image is imported in ILWIS GIS system for on-screen digitization of the canal network. Line diagram of the canal system has been used to identify different distributaries and minors in the PAN sensor image. A view of the zoomed PAN data showing a minor part of the canal system is shown in Figure – 6.16. The digitized information is saved in a segment file with each segment identity being represented by the name of canal. Layout of the canal system as obtained from the remote sensing data is presented in Figure – 6.17.

6.5.4.1 Digitization of command areas of canal segments

In the proposed scheme, each canal segment is linked to its irrigable command area for calculating irrigation demands. For this reason, it is necessary to digitize the irrigable command area of each individual segment in the canal network. The entire canal network has been bifurcated into individual segments (defined in Chapter-4) and different numeric identities are assigned to each. A total of 218 individual segments have been identified in the network. The identities of various canal segments are also shown in Figure - 6.17.

Digitization of irrigable command areas of different segments required the availability of field layout maps of all individual canal segments showing the boundary of the area under the command of each canal segment. Collection of such maps for all canal segments was not possible under this study. An approximate layout of the irrigable command areas of different segments has been obtained from the Irrigation Department. The proposed profitable area (PPA), which specifies the profitable area from a canal segment, of each distributary/minor is also collected from field records. Some guidelines provided by the Irrigation Department, like a) at diversions of distributaries and minors, water is generally not withdrawn up to a distance of about 200 m from the diversion point so as to generate the required head in distributary/ minor, and b) in the head reaches of network, canal water hardly goes beyond 0.5 km from the canal segment, helped in digitizing irrigable area.

With these criteria in mind, an approximate layout of the command of each individual canal segment is digitized such that it lies in the proximity of the canal segment. Each irrigable area is a closed polygon. After digitization, the agriculture area under the area has been evaluated and matched with the field records (given as PPA). By trial and error, the irrigable area boundary for each segment has been adjusted till the irrigable area under canal segment matches close to the specified PPA of the segment. Layout of the command area of each individual canal segment is presented in Figure – 6.18.

To differentiate irrigable commands of each segment, all individual commands have been polygonized giving different numeric identity to each polygon (same as that of the corresponding canal segment). The polygons have been rasterized so as to obtain the irrigable areas of each segment. Grids located outside of the irrigable command of any canal segment have been assigned a numeric identity of zero.

6.5.4.2 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. Characteristics required for each segment are detailed in Chapter-4.

For the Lakhaoti command, field visits have been made during the month of October and information about prominent reference points with existing crops have been recorded for various locations from head-reach to tail-end of the command. These reference points are transferred to the classified Kharif crop image taking help of the PAN sensor scene (road network was quite apparent in the PAN sensor image). using, mainly, the road network in the command, and compared with the results of remote sensing analysis. Since sequential technique is used in crop classification, reference information is also derived from the multi temporal data for sugarcane, rice, Arhar and Maize/Guar. Maize and Guar classes have been merged since their cropping periods were similar and the two are segregated using unsupervised classification. The confusion matrix, user's and producer's accuracy and Kappa estimates for the classification is given in Table – 6.9. Value of Kappa above 0.6 indicates satisfactory classification.

Table – 6.9: Confusion matrix for Kharif crop map

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Arhar	2	1	29	3	35	82.9
Maize/ Guar	3	1	2	29	35	82.9
Total	31	33	37	39	140	
Producer's accuracy	80.6	90.9	78.4	74.4	80.7	
% Kappa	0.743					
Overall % accuracy	80.7					

6.5.4 Delineation of canal network in Lakhaoti command

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

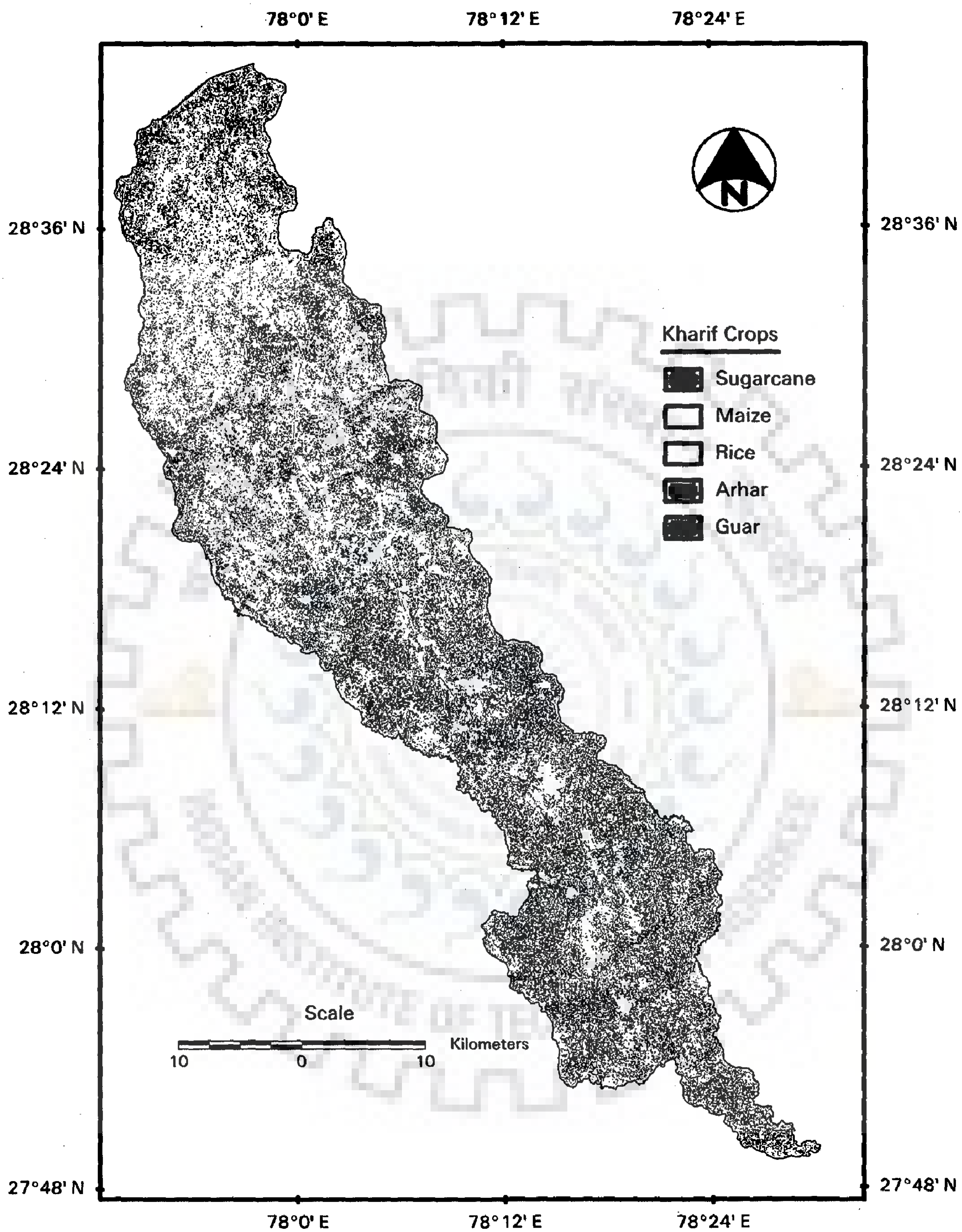

Figure – 6.15 Kharif crops in Lakhaoti command in the year 1998-99

delineating the canal system. Line diagram of the canal system showing the names and lengths of various canal segments, as obtained from Irrigation Department, is utilized for this purpose.

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

The PAN sensor image is imported in ILWIS GIS system for on-screen digitization of the canal network. Line diagram of the canal system has been used to identify different distributaries and minors in the PAN sensor image. A view of the zoomed PAN data showing a minor part of the canal system is shown in Figure – 6.16. The digitized information is saved in a segment file with each segment identity being represented by the name of canal. Layout of the canal system as obtained from the remote sensing data is presented in Figure – 6.17.

6.5.4.1 Digitization of command areas of canal segments

In the proposed scheme, each canal segment is linked to its irrigable command area for calculating irrigation demands. For this reason, it is necessary to digitize the irrigable command area of each individual segment in the canal network. The entire canal network has been bifurcated into individual segments (defined in Chapter-4) and different numeric identities are assigned to each. A total of 218 individual segments have been identified in the network. The identities of various canal segments are also shown in Figure - 6.17.

Digitization of irrigable command areas of different segments required the availability of field layout maps of all individual canal segments showing the boundary of the area under the command of each canal segment. Collection of such maps for all canal segments was not possible under this study. An approximate layout of the irrigable command areas of different segments has been obtained from the Irrigation Department. The proposed profitable area (PPA), which specifies the profitable area from a canal segment, of each distributary/minor is also collected from field records. Some guidelines provided by the Irrigation Department, like a) at diversions of distributaries and minors, water is generally not withdrawn up to a distance of about 200 m from the diversion point so as to generate the required head in distributary/ minor, and b) in the head reaches of network, canal water hardly goes beyond 0.5 km from the canal segment, helped in digitizing irrigable area.

With these criteria in mind, an approximate layout of the command of each individual canal segment is digitized such that it lies in the proximity of the canal segment. Each irrigable area is a closed polygon. After digitization, the agriculture area under the area has been evaluated and matched with the field records (given as PPA). By trial and error, the irrigable area boundary for each segment has been adjusted till the irrigable area under canal segment matches close to the specified PPA of the segment. Layout of the command area of each individual canal segment is presented in Figure – 6.18.

To differentiate irrigable commands of each segment, all individual commands have been polygonized giving different numeric identity to each polygon (same as that of the corresponding canal segment). The polygons have been rasterized so as to obtain the irrigable areas of each segment. Grids located outside of the irrigable command of any canal segment have been assigned a numeric identity of zero.

6.5.4.2 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. Characteristics required for each segment are detailed in Chapter-4.

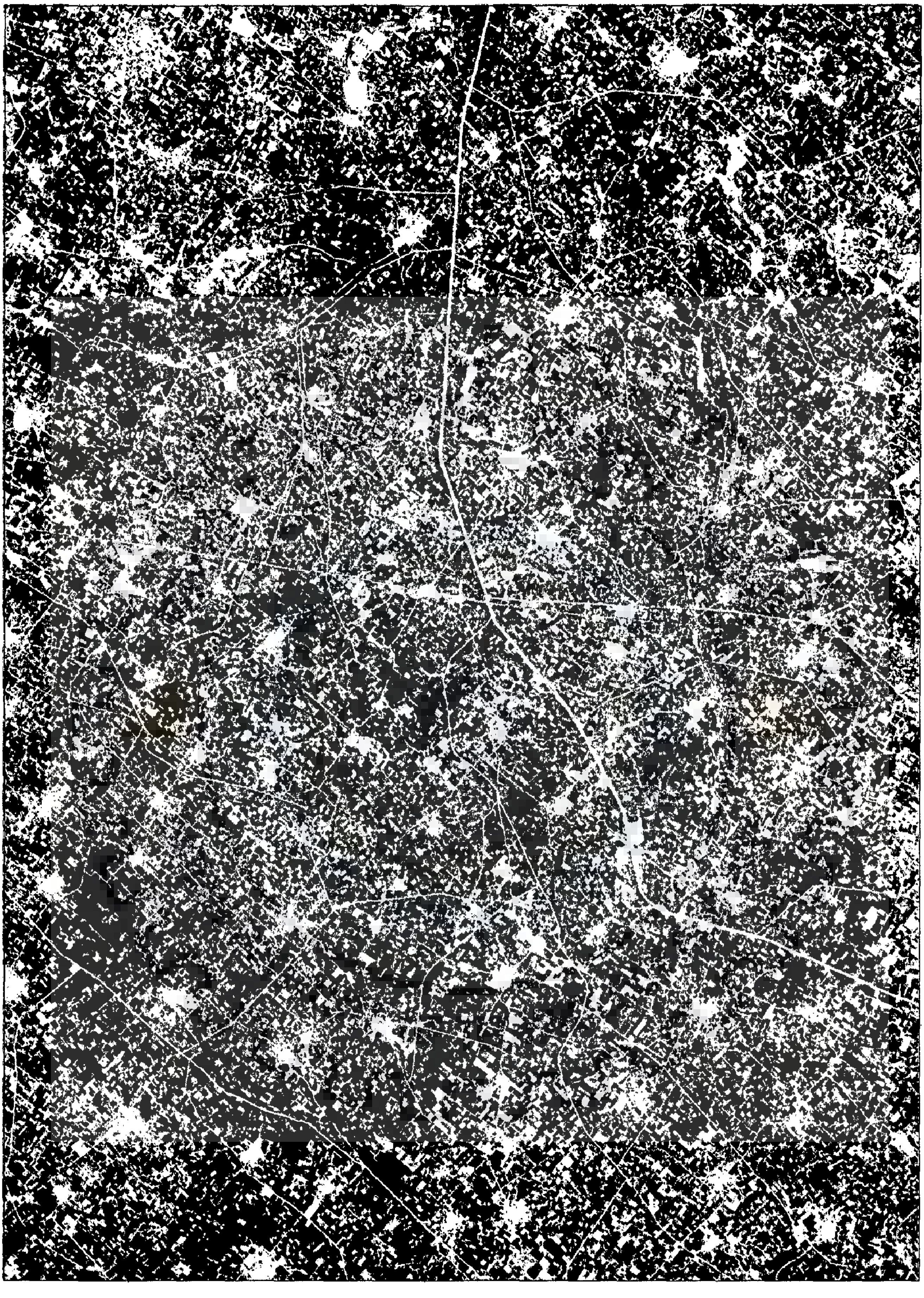

Figure – 6.16: A view of PAN data showing the layout of a part of canal system

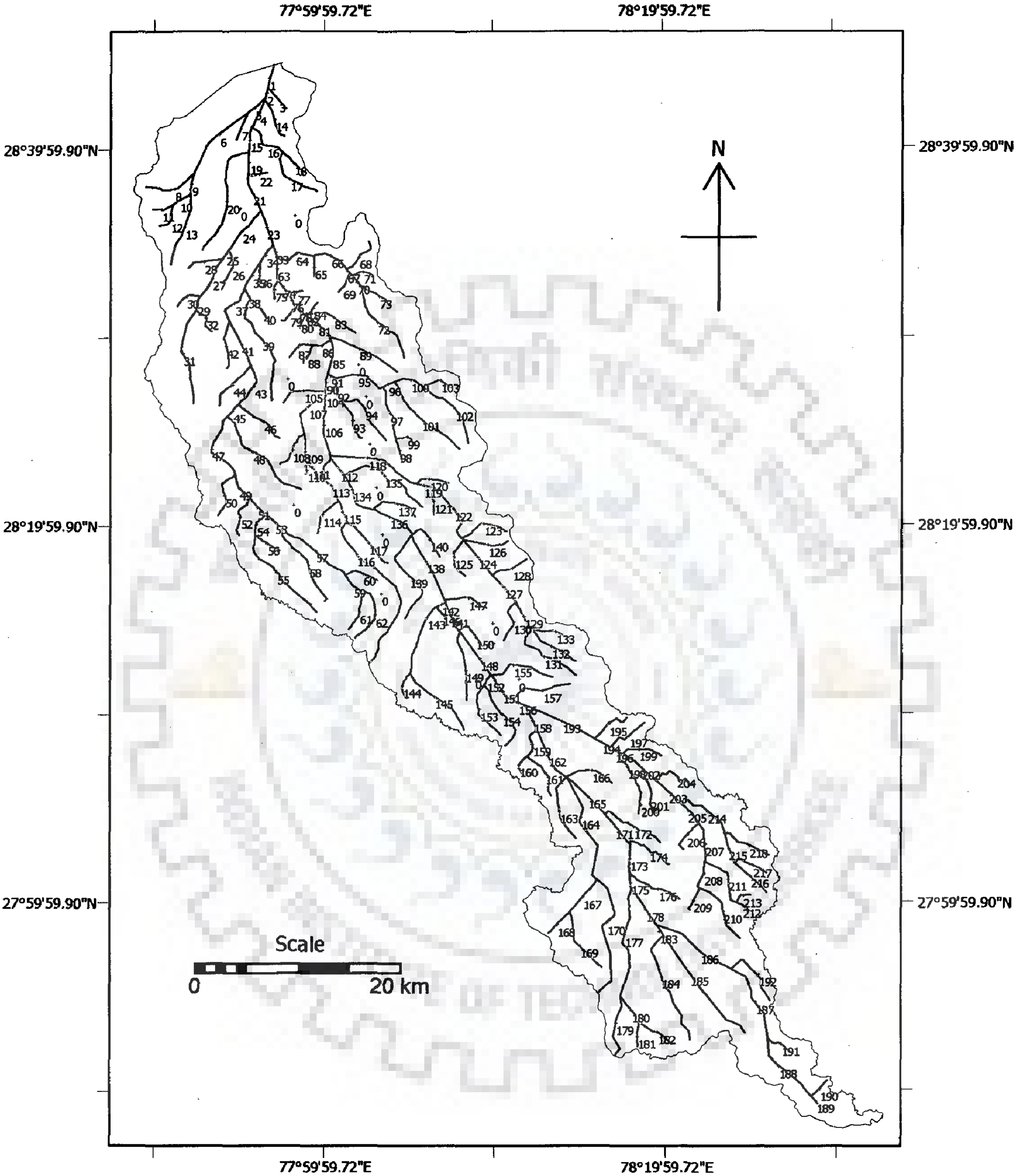

Figure – 6.17: Canal layout map for Lakhaoti command

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:

$$\text{Canal Seepage} = [(\text{Bed width} + \text{Water depth})^{2/3}/200] * \text{Length of segment} * \text{Run-time} \qquad \ldots(6.3)$$

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, the irrigation in command was fully dependent on the groundwater. Further, during the non-monsoon season, the canal water supply is not planned and therefore, the groundwater continues to be the only source of irrigation water supply during Rabi season. The characteristics of various canal segments are presented in Table – 6.10.

From Table – 6.10, 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 Table – 6.10, 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.

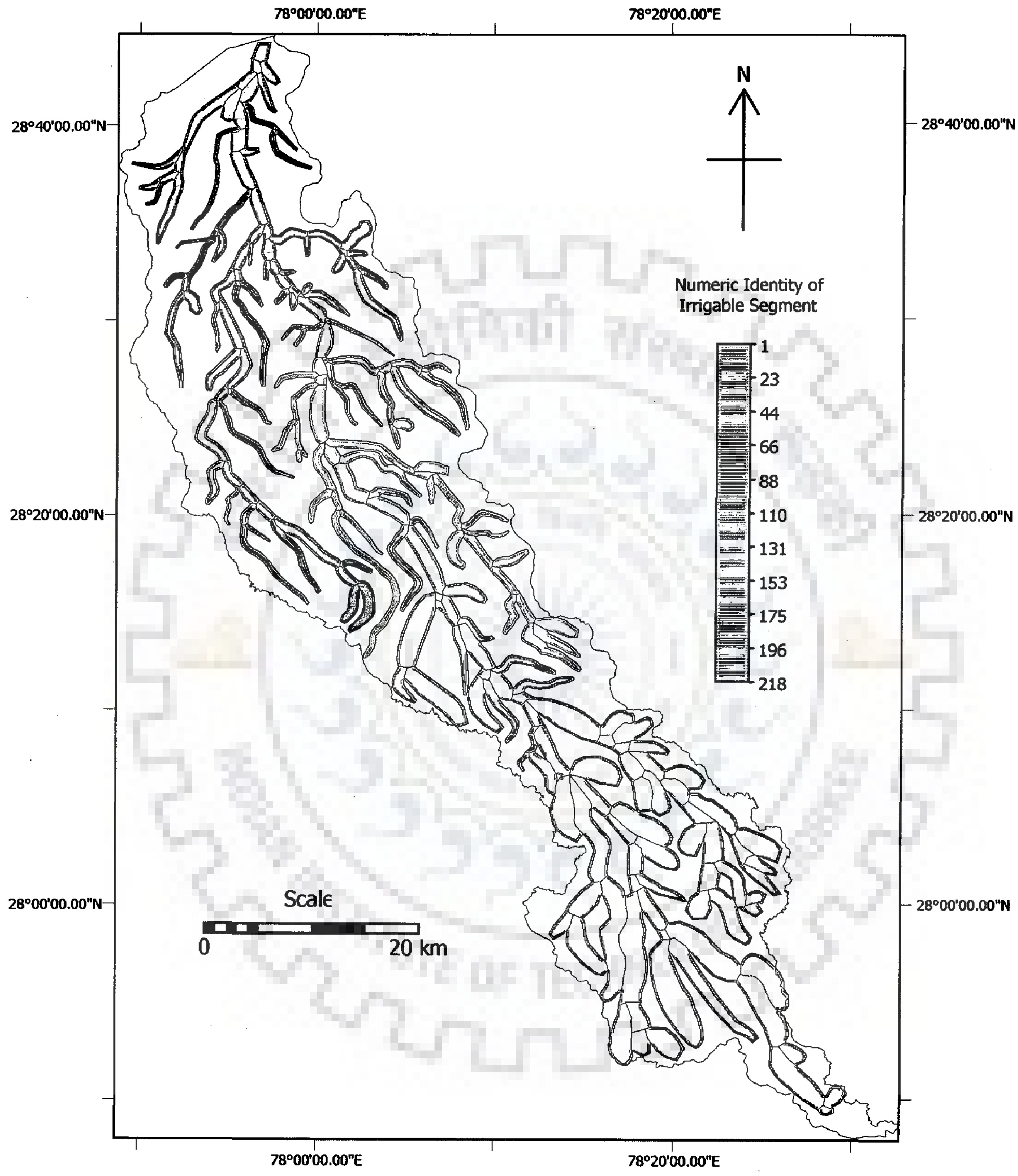

Figure – 6.18: Irrigable command area of different canal segments

Table – 6.10: 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	-	-	-	-
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	-

Segment Name	Numeric Identity	Discharge Capacity (cumec)	Length (m)	Bed Width (m)	Water Depth (m)	Design PPA (ha)	Calculated PPA (ha) at Head of Dist./Minor	Conveyance Efficiency	Head Node Number	Number of d/s Nodes	Tail Node Number	Number of Immediately d/s Segments	Numeric Identity of Immediately d/s Segments			
Col. 1	Col. 2	Col. 3	Col. 4	Col. 5	Col. 6	Col. 7	Col. 8	Col. 9	Col. 10	Col. 11	Col. 12	Col. 13	C.14	C.15	C.16	C.17
M_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	-	-	-	-
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_Biblyana	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	-	-	-	-

Segment Name	Numeric Identity	Discharge Capacity (cumec)	Length (m)	Bed Width (m)	Water Depth (m)	Design PPA (ha)	Calculated PPA (ha) at Head of Dist./Minor	Conveyance Efficiency	Head Node Number	Number of d/s Nodes	Tail Node Number	Number of Immediately d/s Segments	Numeric Identity of Immediately d/s Segments			
Col. 1	Col. 2	Col. 3	Col. 4	Col. 5	Col. 6	Col. 7	Col. 8	Col. 9	Col. 10	Col. 11	Col. 12	Col. 13	C.14	C.15	C.16	C.17
M_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	-	-
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	-	-	-	-

6.6 DATABASE GENERATION FOR GROUNDWATER FLOW MODEL

In this study, a groundwater behavior model (Visual MODFLOW) is used 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.

6.6.1 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).

6.6.2 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.

6.6.3 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.

6.6.4 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:

$$C = K.L.W/M \qquad \ldots(6.4)$$

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 river and Nim river 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:

$$q = k\ (B + A\,H) \qquad \ldots(6.5)$$

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.

6.6.5 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 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 was 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 – 6.19 and representation of data for a well in VMOD are presented in Figure – 6.20.

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, as mentioned in Table – 6.8, are imported in VMOD. The layout of head observation wells in Lakhaoti command is shown in Figure – 6.21.

6.6.6 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 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. The conductivity and storage characteristics maps of the Lakhaoti aquifer system are shown in Figure - 6.22 and Figure - 6.23 respectively.

6.7 ESTIMATION OF EVAPO-TRANSPIRATION

The meteorological factors that are useful in the root zone soil water balance computation include rainfall and reference crop evapo-transpiration RET. Daily RET depends on several factors such as maximum and minimum temperature during the day, maximum and minimum relative humidity, solar radiation, average wind speed, time of the year, the latitude and altitude of place. The water consumption by the plants is computed on the basis of daily/weekly RET in the area. A number of 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} in an area. 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:

$$RET = \frac{0.408.\Delta.(R_n - G) + \gamma \frac{900}{T + 273}.u_2.(e_s - e_a)}{\Delta + \gamma(1 + 0.34.u_2)} \qquad ...(6.5)$$

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 to find the reference evapo-transpiration in Lakhaoti command. The meteorological data (maximum and minimum temperature and dry and wet bulb temperature) 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.

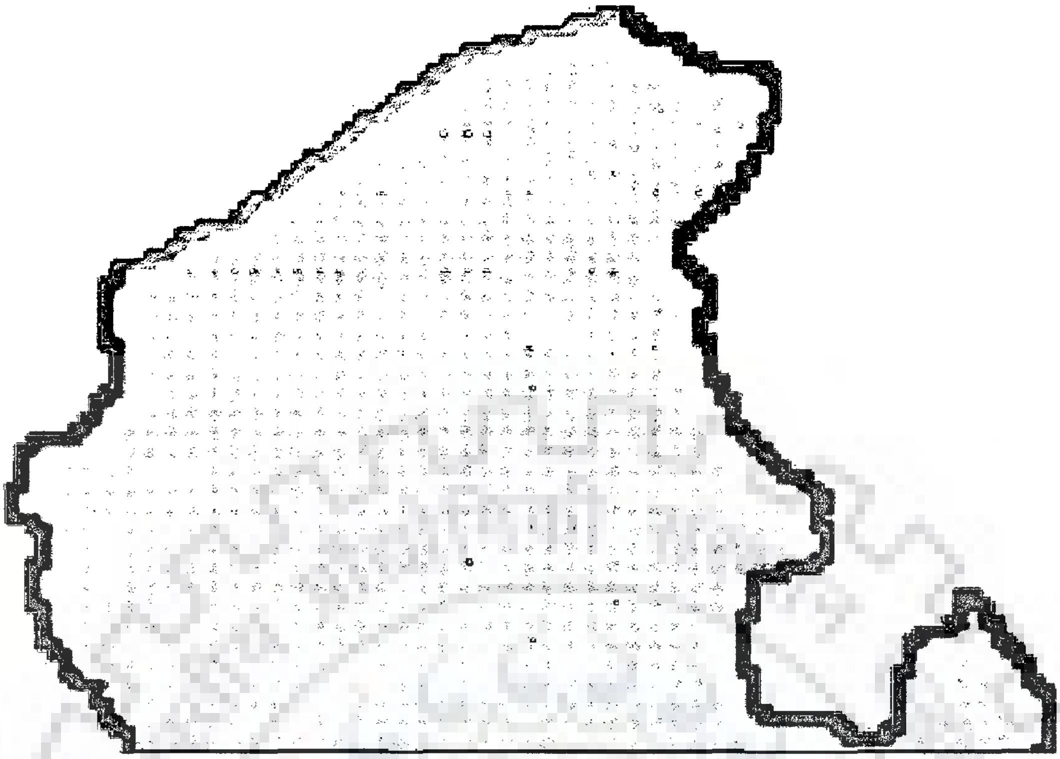

Figure – 6.19: Layout of pumping wells in a part of Lakhaoti command

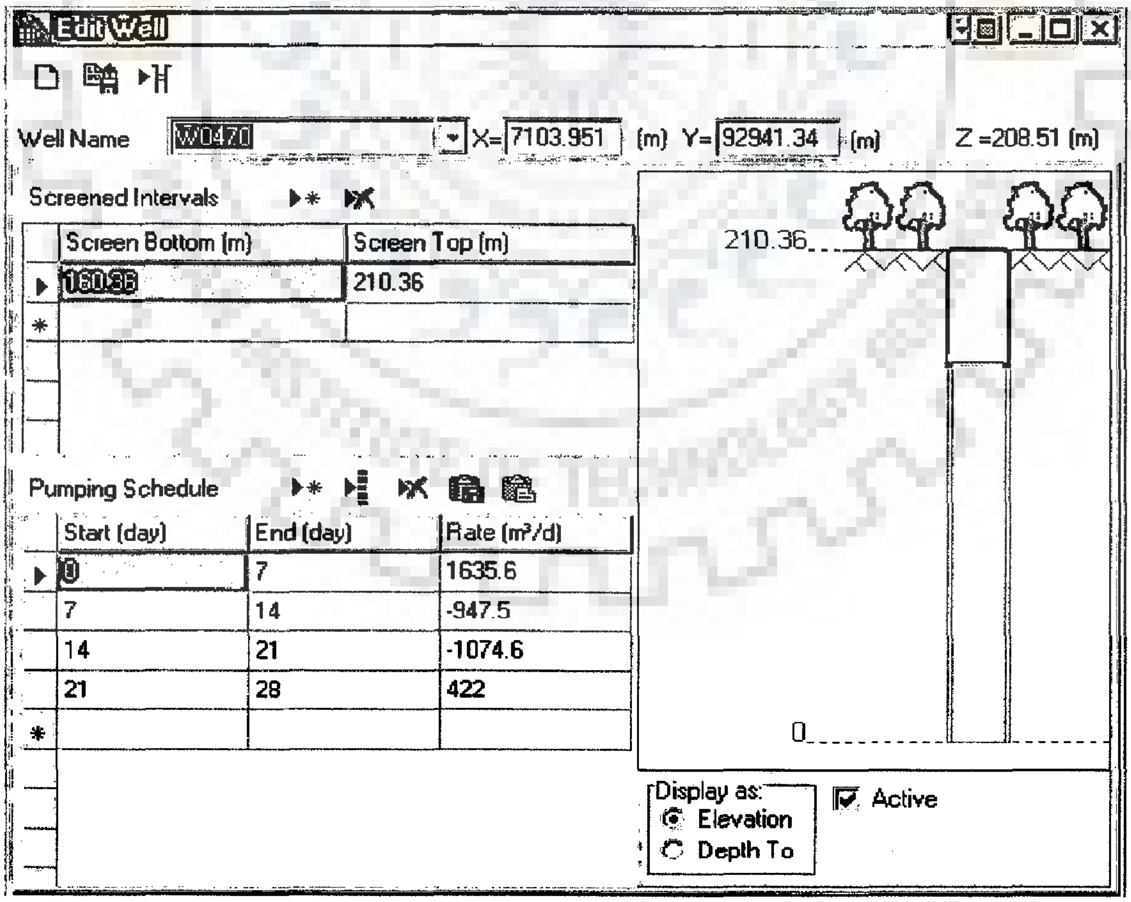

Figure – 6.20: Representation of pumping well data in VMOD

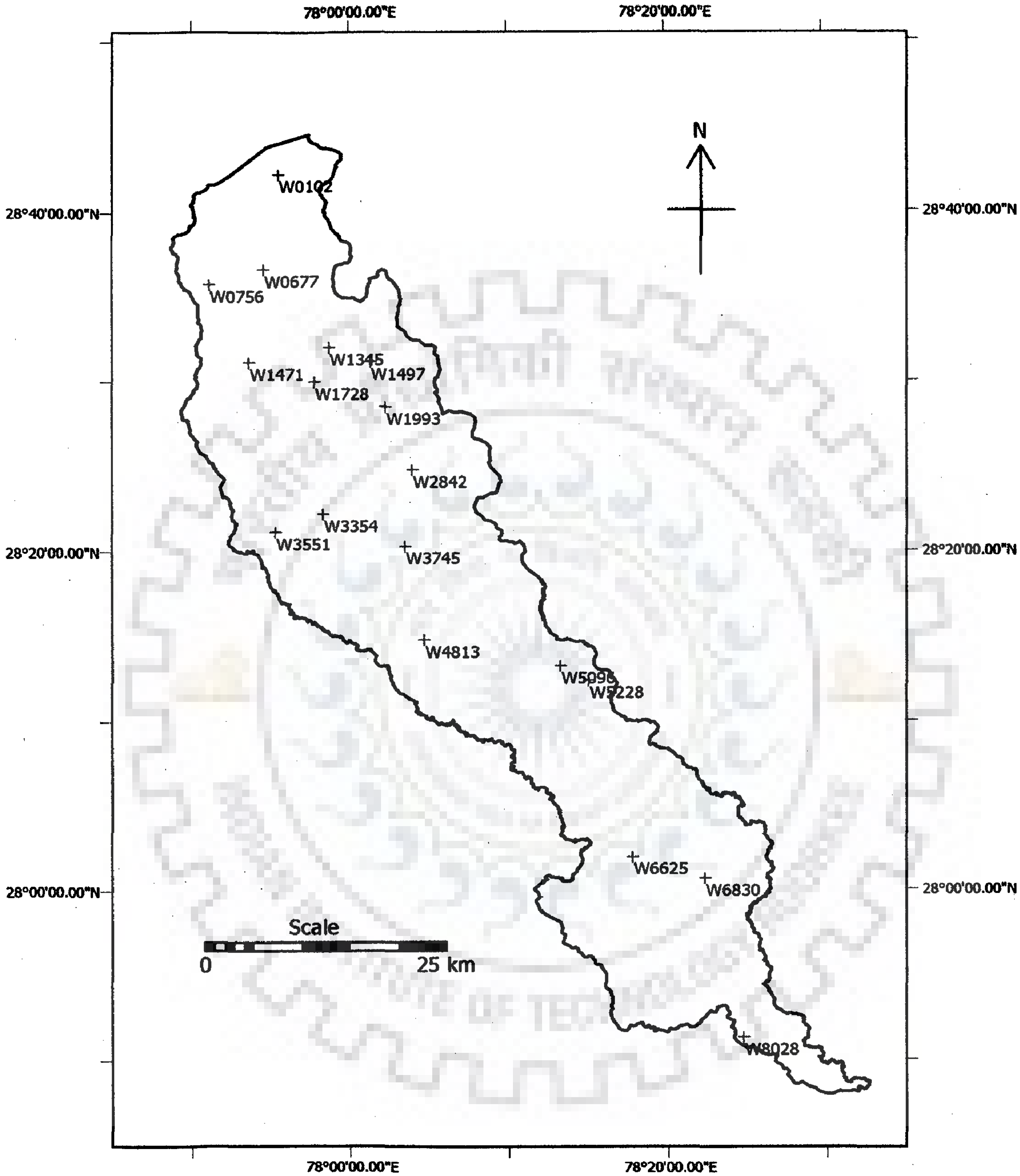

Figure – 6.21: Layout of head observation wells in Lakhaoti command

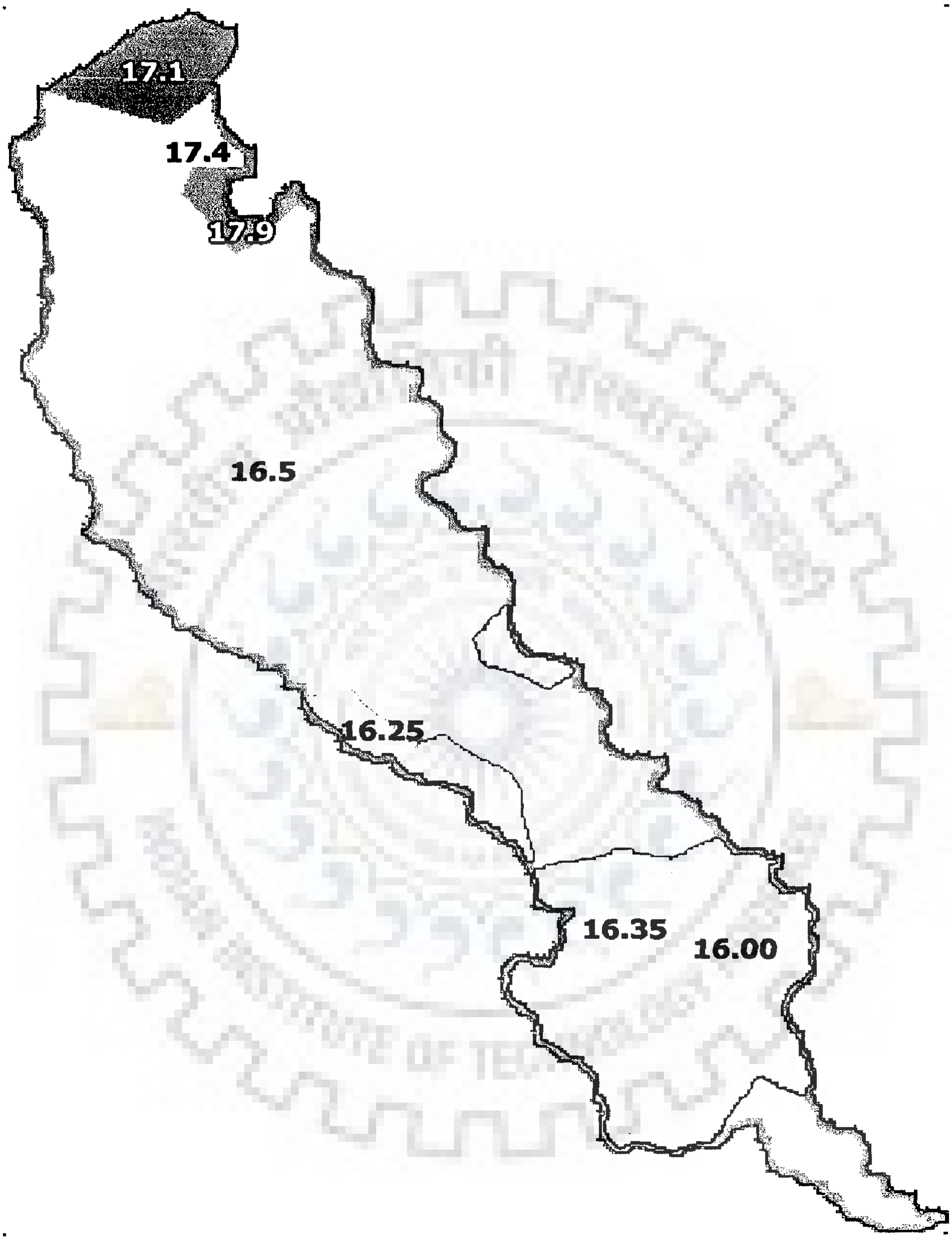

Figure – 6.22: Conductivity (m/d) map of aquifer system in Lakhaoti command

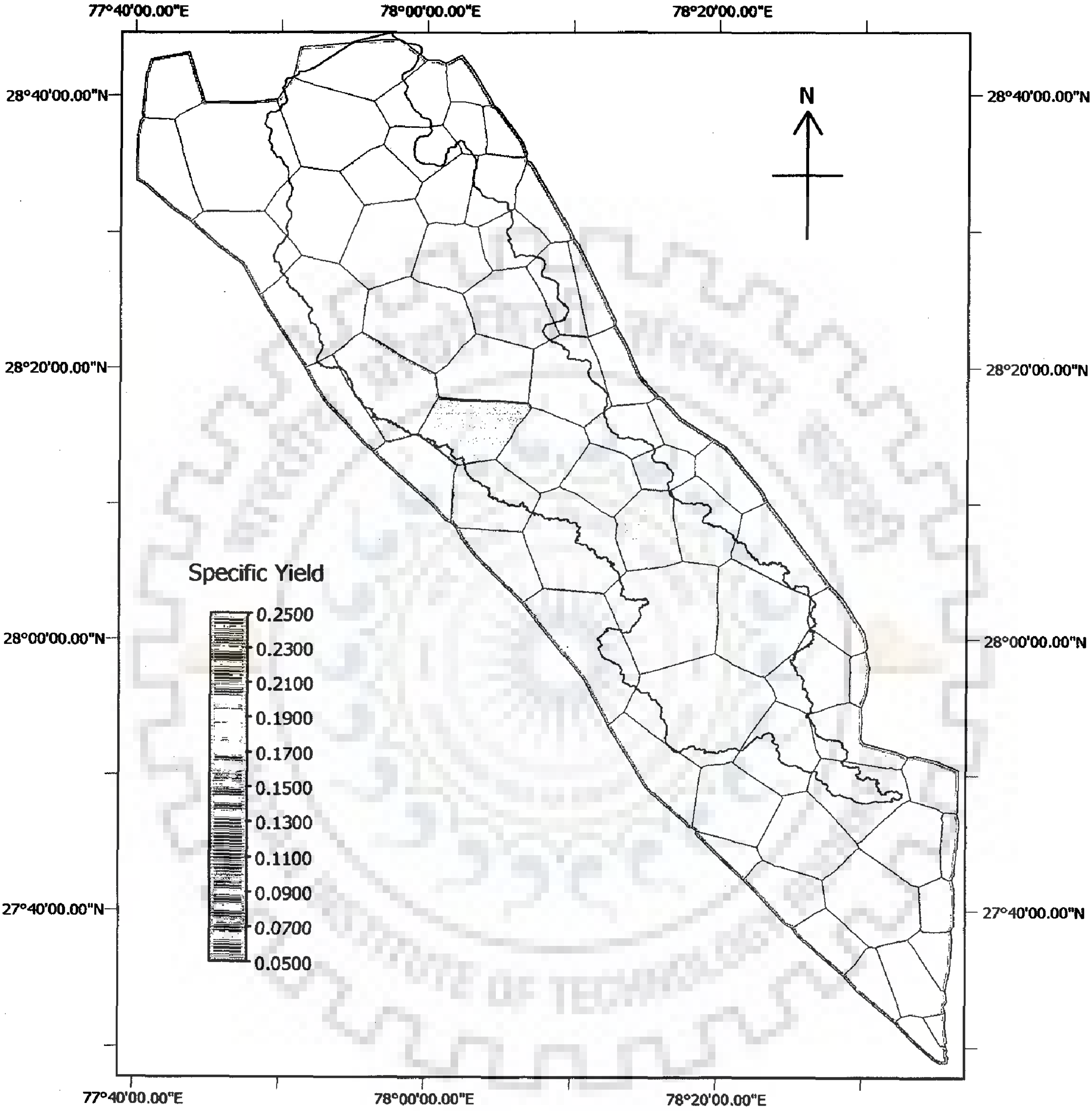

Figure – 6.23: Specific yield map for aquifer system in Lakhaoti command

However, the FAO-56 manual recommends the following equation for estimation of approximate value of radiation from the temperature data:

$$R_s = k_{rs} \cdot \sqrt{(T_{max} - T_{min})} . R_a \qquad \ldots(6.6)$$

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 – 6.24. The rainfall values of the year 1998 are also plotted in Figure – 6.24 to show the effect of weather change on the daily RET values.

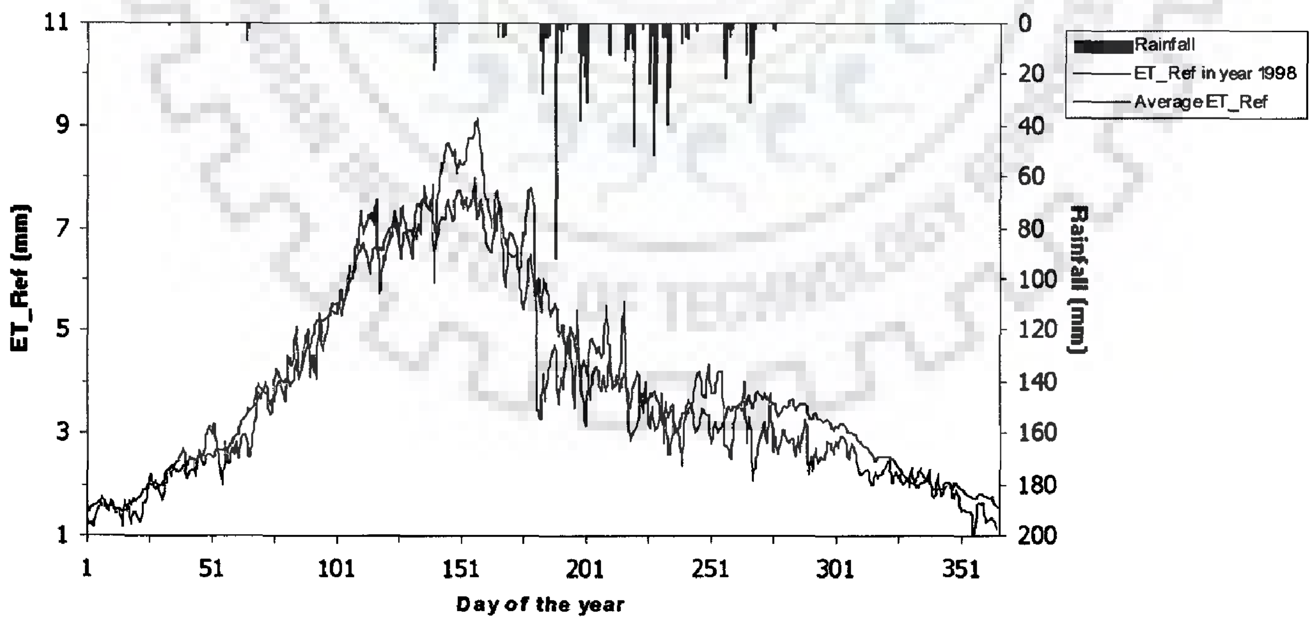

Figure – 6.24: Reference crop evapo-transpiration in Lakhaoti command

6.8 CHAPTER CLOSURE

This chapter demonstrates the characterization of database in GIS environment for use in a geo-simulation scheme. Through a case study, a number of thematic layers corresponding to cropping pattern, soil type, Thiessen polygon, canal network layout, irrigable command areas, groundwater depth, and aquifer characteristics etc. have been digitized/generated and stored in a GIS database. A number of attribute information related to crops, soils, and canal system characteristics has been generated.

By developing a geo-simulation model that can link with the GIS-based database, effective utilization of vast amount of information can be made to arrive at some meaningful decisions regarding the operation of canal network in an irrigation system without making gross assumptions and loosing the accurate representation of the system.

* * *

CHAPTER – 7

ANALYSIS AND DISCUSSION OF RESULTS

7.1 GENERAL

The geo-simulation scheme as proposed in Chapter-5 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 – 6. 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. The results of this analysis are discussed in this chapter.

7.2 APPLICATION OF SOIL WATER BALANCE MODEL

Development of SWBM has been discussed in Chapter-3. 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. A command area may contain a very large number of grids (depending upon its size). Presentation of output for each variable could make it difficult to draw useful inferences and conclusions. Therefore, the output of SWBM is presented in the map form for easy visualisation and comprehension, and thus make decision-making user-friendly. This spatial information is integrated with canal operation model for computer-based rational management of irrigation water.

The SWBM is applied first at the beginning of week for weekly planning and then at the end of the week for updating. For weekly planning, spatially distributed irrigation water demand is estimated based on the moisture content at the end of the previous week, forecast rainfall and crop evapo-transpiration demand during the week. For updating, spatially distributed moisture content at the end of a week based on the moisture content at the end of previous week, actual rainfall, actual crop evapo-transpiration demand, and actual irrigation water application in the command during the week. Results are illustrated here for the calendar week number 30 (July 23 – 29, 1998) assuming the initial moisture content at the beginning of the week to lie midway between the field capacity and wilting point at each grid. Reasons for assuming lower value of initial moisture are: a) for the sake of illustration of different water stress conditions in the command, it is essential to take reduced initial moisture in the command, and b) for illustration of the effect of reduced root zone moisture content on the actual crop evapo-transpiration, it is essential to take reduced initial moisture content. Computations are made at weekly time step, thereby assuming lumped rainfall and lumped reference crop evapo-transpiration demand over the week. The output of model shows that water balance of the area is maintained (Final moisture content = Initial moisture content + Rainfall + Irrigation – Actual crop evapo-transpiration – Recharge – Overland flow going out of command). Total volume of initial water in the root zone of command is estimated to be 129.64 Mm^3 (million cubic meter). Figure – 7.1 shows the spatial variation of final moisture content in the command considering actual rainfall and reference crop evapo-transpiration but no irrigation input. The rainfall volume input to the command area comes out to be 9.69 Mm^3. Actual crop evapo-transpiration in the area is calculated to be 35.15 Mm^3. Due to low rainfall, no overland flow is generated in the command. Total volume of final moisture content in the root zone of command comes out to be 104.17 Mm^3. If crop evapo-transpiration occurs at potential rate, then the total crop evapo-transpiration in the command comes out to be 46.35 Mm^3. Without irrigation, water stress occurs causing the actual crop evapo-transpiration. Figure – 7.2 shows the spatial distribution of stress conditions in command based on the soil water balance. Visualization of stress map can be used to to prioritise canal supply in affected canal segments to avoid crop failure.

Desirable limit of week end moisture content is used to find weekly irrigation demands. Irrigation demand can be estimated for two different scenarios: a) to maintain week-end moisture content in each grid at upper limit (field capacity + standing water depth in case of rice crop and field capacity in case of other crops), or b) to maintain the week-end moisture content in each grid at some specified percentage of readily available moisture [moisture content in-between field capacity and minimum moisture content without causing stress (D_{min})]. Assuming that week-end moisture content is regulated to be at upper desirable limit, the total volume of irrigation demands in the command comes out to be 105.17 Mm^3. For the case when the week-end moisture content in each agricultural grid is brought to 80% of the readily available moisture, the irrigation demand comes out to be 86.99 Mm^3. Figure – 7.3 shows the spatial variation of irrigation requirements.

As described in Chapter – 6, canal segments may have limited canal-irrigable area as compared to the cultivable acoomand area, only the irrigable area under canals can be irrigated by canal water and the rest of the culturable area is irrigated through groundwater withdrawal. Based on the location of grids, layout of canal-irrigable area, and actual canal supply in a command, the source of water supply (whether canal water or groundwater) is decided. Recharge at a grid is calculated in three separate components as discussed in Chapter-5 under section (e). Total recharge in the command during the week 30 comes out to be 79.86 Mm^3 while required groundwater withdrawal comes out to be 165.24 Mm^3. Estimation of recharge and groundwater pumping in the command is used to generate the groundwater surface for the subsequent week. For input to the groundwater model, net recharge/pumping are

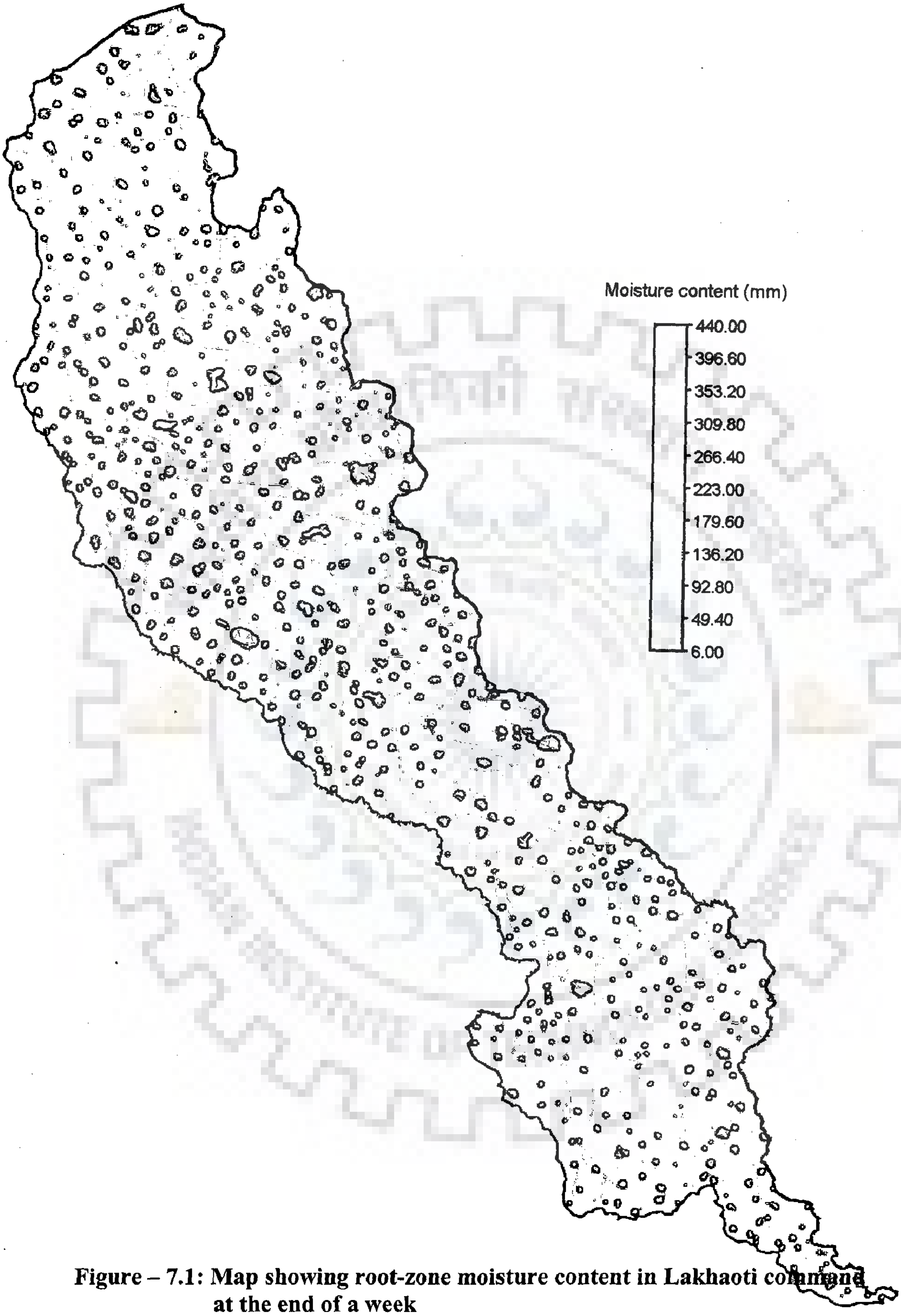

Figure – 7.1: Map showing root-zone moisture content in Lakhaoti command at the end of a week

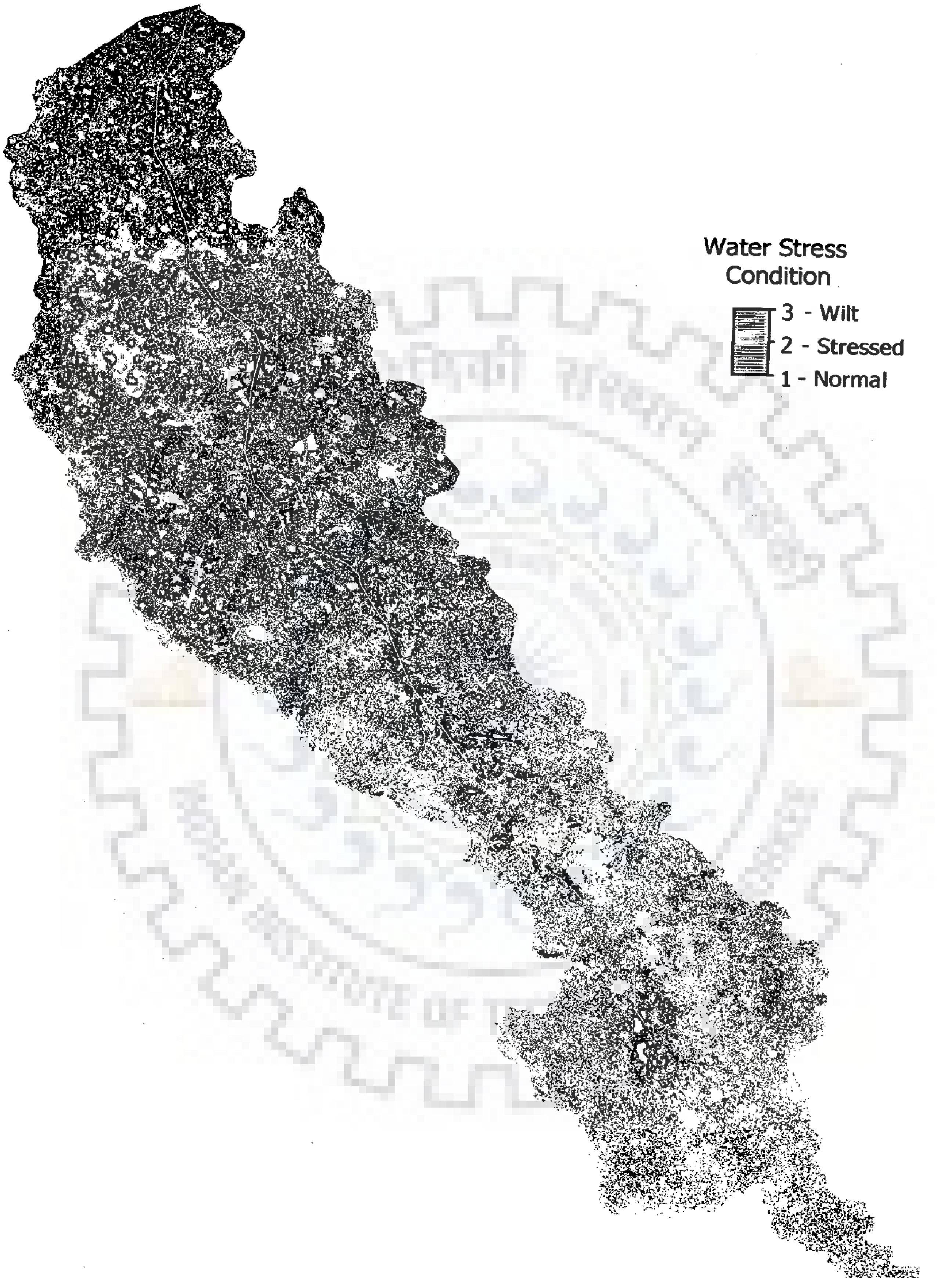

Figure – 7.2: Map showing water stress conditions in Lakhaoti command in a week with overlay of canal network

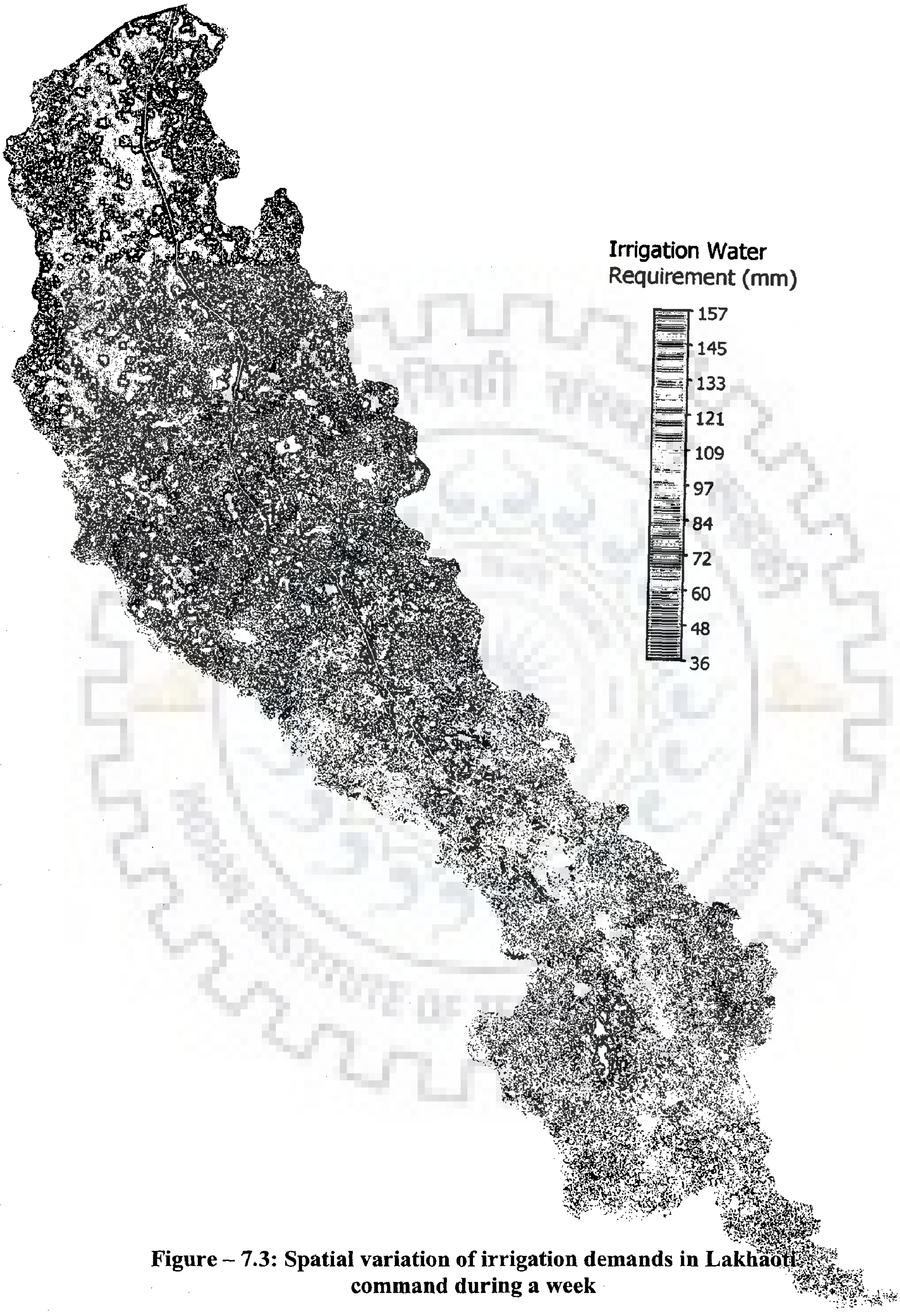

Figure – 7.3: Spatial variation of irrigation demands in Lakhaoti command during a week

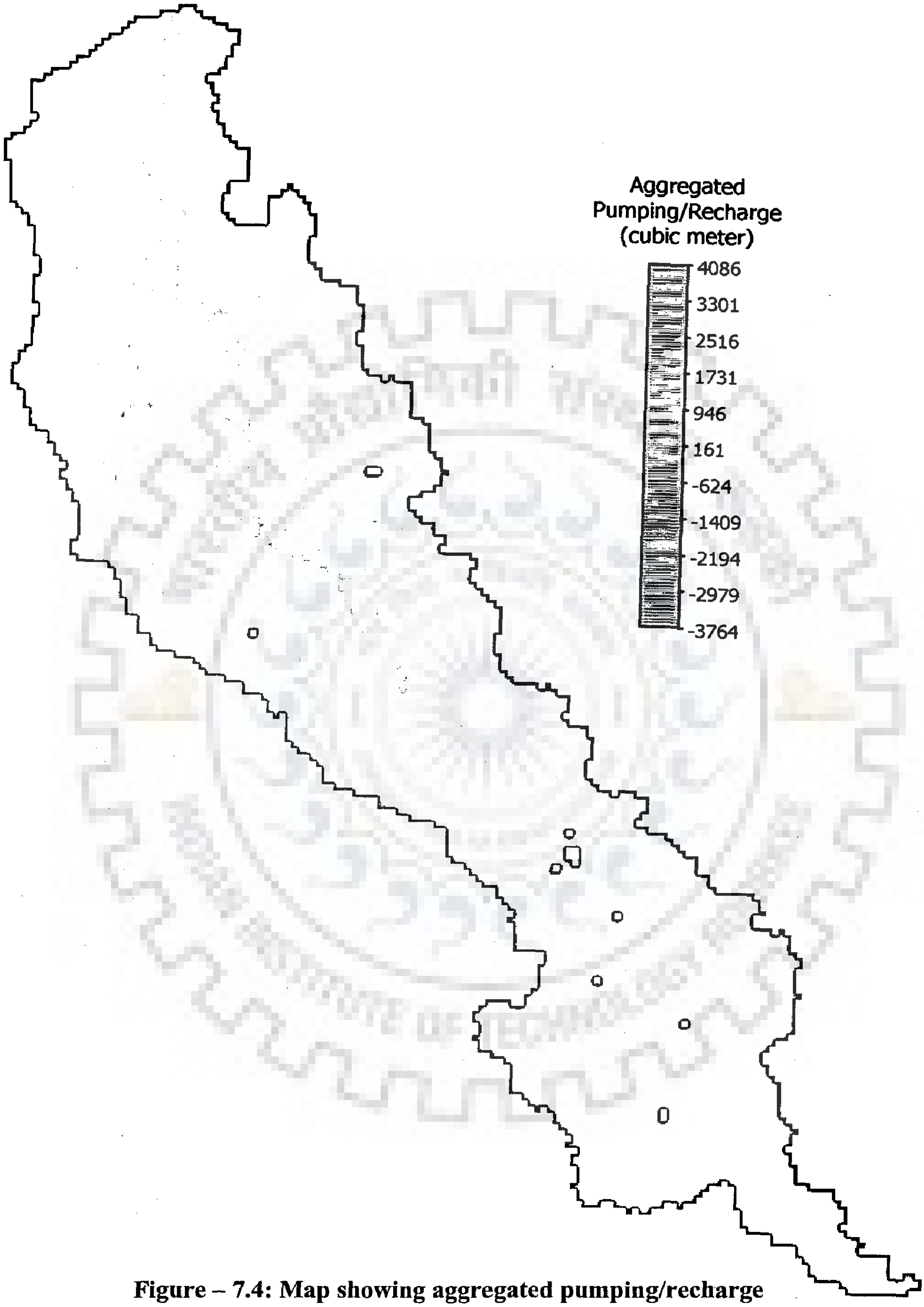

Figure – 7.4: Map showing aggregated pumping/recharge in Lakhaoti command during a week

aggregated to a grid size of 480 m. Recharge is represented with a positive sign while pumping is represented with a negative sign. Figure – 7.4 shows the aggregated pumping and recharge in the command for calendar week 30.

7.2.1 Effect of using daily time step

Selection of time step is an important factor in the accuracy of estimation of various components of soil water balance model. While making water balance computations, it is assumed that various inputs and outputs in the soil reservoir, e.g. rainfall, crop evapo-transpiration, recharge etc. occur at uniform rate during the time step. However, this may not happen in reality. For example, if we use weekly time step, then it is assumed that all of the rainfall at uniform rate during the week. In reality, it may happen that all of the rainfall occurs on the last day of the week. When using daily time step, water balance computations in the root zone are carried out for each day of the week considering daily rainfall, crop evapo-transpiration, recharge, and overland flow (if any). The final moisture content at the end of each day in each grid is taken as the initial moisture content at the beginning of next day of the week. Though shorter time step increases the computational time, water balance computations become more reliable. The results of water balance by adopting different time steps can vary with regard to: a) actual crop evapo-transpiration (if the initial moisture content lies close to the D_{min} such that moisture content within the week goes below this limit), and b) recharge computation and generation of overland flow (if very high rainfall occurs within a short time). For Week 30 (July 23 to July 29), daily rainfall record for five rain gauge stations in Lakhaoti command shows that there is no rainfall on all stations in the command for first six days and then some rainfall (0.0, 12.6, 7.6, 12.0, 0.0 mm at Siyana, Bulandshahr, Anupshahr, Khurja, and Atrauli respectively) is recorded on the seventh day. Using daily time step, total crop evapo-transpiration in the command during the week comes out to be 24.15 Mm^3 while it was 35.15 Mm^3 when weekly time step was adopted. No irrigation input is assumed while computing these results. Smaller crop evapo-transpiration under daily time-step indicates that the crops in the command were under stress during the week such that the actual crop evapo-transpiration was less than the potential evapo-transpiration. The recharge values are same as for weekly time-step because the rainfall on the last day is not very heavy so as to induce any recharge in the command.

Crop evapo-transpiration is affected by the root zone moisture content at any stage reduces below D_{min}. If the initial moisture content in the root zone is high or there is intermittent supply of water (either through rainfall or irrigation) such that root zone moisture content never falls below D_{min} during the week, crop evapo-transpiration will not be affected. Further, recharge computation will not be affected unless storm of a very high magnitude (that has intensity higher than the saturated hydraulic conductivity of the soil) occurs in the command. Thus, based on the desired accuracy of computation of various components of soil water balance and the computational time available, one can choose between daily and weekly time steps.

7.3 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 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.

In this section, the potential use of CNSM is investigated through application study of Lakhaoti command for the sample week 32. Canal system characteristics have been detailed in Table – 6.10 and the canal network layout showing the identity of different segments is presented in Figure – 6.17. For illustration, conventional assumption of water application efficiency of 70% and field channel efficiency of 80% has been made for all canal segments. The Lakhaoti command is dependent on groundwater for irrigation in Rabi season. Therefore, sufficient number of pumping wells with average pump capacity of 3 horse power (HP) and power supply availability of 84 hours per week have been assumed. Taking the initial moisture content at field capacity, the aggregated volume of initial moisture in the effective soil zone in the Lakhaoti command comes out to be 226.41 Mm^3 and rainfall input in the command during the week is 58.89 Mm^3.

Using the layout of canal-irrigable command areas and canal system details, grid-wise irrigation demands (as worked out by SWBM) are transferred to canal segments using various field channel efficiency and field application efficiency and the total water demand (in terms of discharge and runtime) in all canal segments are worked out. Total canal water demands at the network head comes out to be 58.44 Mm^3. Table – 7.1 shows the initial calculations of irrigation demands, seepage losses, groundwater potential, required discharge, run-time, fill-time, and groundwater requirement for various canal segments. These are initial calculations in the sense that canal capacity constraint (of intermediate canal segments) and canal water availability constraint are not considered. Column-1 of the table shows the identity of canal segments while Column-2 shows the identity of segment located upstream of the current segment, thus illustrating the connectivity of canal network. In Column-1, the symbol 'F' along with the segment identity represents that the canal segment is free, i.e. it does not have any downstream connecting segment. Column–4 shows the groundwater availability in a canal segment, which depends on average groundwater depth (Column-3), number of pumping wells, average capacity of pumps, and duration of power supply. Column-5 shows the irrigation demands from the irrigable area of canal segment while Column-6 presents the irrigation demands that can be met from the existing canal capacity. It is seen that a number of segments (segment 3, 8, 17 ... etc.) have capacity constraint in meeting full irrigation demands. Column-7 presents the water demands in a canal segment because of the downstream canal network while Column-8 shows the seepage loss in a canal segment which depends on the conveyance efficiency, wetted perimeter, discharge, and run-time of the segment. Total canal water demand (Column-9) is the sum of Column-6 to Column-8 and represents the total canal water demands in the segment including its seepage losses.

Table – 7.1: Initial calculations of canal operation for a week

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

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

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

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

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

7.3.1 Results with different methods of satisfying capacity constraint

Three methods, as explained in Chapter-4, have been provided in CNSM for selecting segments for demand curtailment. Table - 7.2 shows the intermediate segments with capacity constraint and the affected downstream segments whose demands are curtailed (depending on the selected method) to satisfy the capacity constraints. Column-3 represents the distance of a segment head from the canal system head while Column-4 represents the distance of a segment tail from the head of canal network. As can be seen from Table - 7.2, when the heads of two segments have the same distance from the canal network head (say, for intermediate segment 33), then the segment length is also accounted for and the segment having greater length is selected for demand curtailment under method of head-reach priority. Since method of tail-reach priority also selects the segments for demand curtailment on the basis of distance, segment length information is also utilised in this case and the canal segment of least distance from canal head is selected for demand curtailment. Under the method based on groundwater depth, the segments with least depth of water table are selected iteratively till the capacity constraints of intermediate segments are satisfied.

Table – 7.2: Selection of canal segments for demand curtailment (for satisfying capacity constraint) using various methods

Intermediate Segment with Capacity Constraint	Method of Head-Priority			Method Based on Groundwater Depth		Method of Tail-Priority		
	Affected Segment	Distance of Segment Head From System Head (m)	Column-3 + Length of Affected Segment (m)	Affected Segment	Average GW Depth (m)	Affected Segment	Distance of Segment Head From System Head (m)	Column-3 + Length of Affected Segment (m)
Col. 1	Col. 2	Col. 3	Col. 4	Col. 5	Col. 6	Col. 7	Col. 8	Col. 9
16	17	10772	16726	18	4.77	18	10772	13618
23	167	94405	98506	135	11.56	33	18515	19871
33	170	94405	107363	82	10.88	63	19871	21952
	167	94405	98506	115	11.53	64	19871	23884
	-	-	-	135	11.56	-	-	-
34	57	53305	60995	36	9.18	36	20674	22933
	54	51114	53531	44	13.26	35	20674	23601
	-	-	-	61	13.30	-	-	-
	-	-	-	50	13.59	-	-	-
35	58	53305	61902	39	12.00	38	23601	24857
	57	53305	60995	38	9.47	37	23601	27623
	-	-	-	44	13.26	39	24857	35903
37	59	60995	63462	42	11.24	42	27623	32564
	55	53531	63764	56	11.25	41	27623	32578
	56	53531	56336	54	11.40	-	-	-
	58	53305	61902	52	11.59	-	-	-
	-	-	-	44	13.26	-	-	-
38	39	24857	35903	40	10.18	40	24857	28063
	-	-	-	39	12.00	39	24857	35903
41	61	63462	67422	55	10.13	43	32578	37064
	60	60995	64342	58	10.79	-	-	-
	59	60995	63462	56	11.25	-	-	-
43	62	63462	69386	55	10.13	45	37064	38641
	61	63462	67422	-	-	-	-	-
57	62	63462	69386	60	12.14	59	60995	63462
	-	-	-	61	13.30	-	-	-
59	62	63462	69386	61	13.30	61	63462	67422
63	170	94405	107363	75	8.75	74	21952	23474
	-	-	-	83	11.34	75	21952	23943
	-	-	-	82	10.88	-	-	-
64	72	29939	38433	65	8.25	65	23884	25846
	73	29939	33405	68	11.10	66	23884	27569
	69	28470	30672	69	11.41	68	27569	31528
	-	-	-	71	12.74	70	28470	29939
	-	-	-	72	13.05	-	-	-
66	72	29939	38433	68	11.10	67	27569	28470
	-					68	27569	31528
70	72	29939	38433	72	13.05	73	29939	33405
74	175	94653	96196	77	8.61	77	23474	25045
	170	94405	107363	84	10.61	76	23474	25773
	-	-	-	79	10.74	86	30910	32862
	-	-	-	89	11.11	85	30910	34376
	-	-	-	80	11.25	-	-	-
	-	-	-	83	11.34	-	-	-
76	176	94653	100238	119	10.57	78	25773	26829
	175	94653	96196	-	-	79	25773	27760
	-	-	-	-	-	83	27301	32338
	-	-	-	-	-	86	30910	32862
78	206	95217	98657	122	10.13	82	26829	27301
	176	94653	100238	207	10.41	80	26829	28553
	-	-	-	-	-	81	26829	30910
	-	-	-	-	-	84	27301	28674
	-	-	-	-	-	83	27301	32338
81	-	-	-	-	-	86	30910	32862
82	83	27301	32338	84	10.61	84	27301	28674
85	207	95217	99221	122	10.13	91	34376	35051
	206	95217	98657	-	-	90	34376	36047
86	87	32862	35634	88	13.79	88	32862	34833
	88	32862	34833	87	13.90	87	32862	35634
90	178	96196	100692	124	9.76	104	36047	36916
	207	95217	99221	122	10.13	105	36047	40671
	-	-	-	-	-	107	36916	41767
91	100	41533	44575	97	11.97	92	35051	37265
92	94	37265	43897	94	12.23	93	37265	41843

Intermediate Segment with Capacity Constraint	Method of Head-Priority			Method Based on Groundwater Depth		Method of Tail-Priority		
	Affected Segment	Distance of Segment Head From System Head (m)	Column-3 + Length of Affected Segment (m)	Affected Segment	Average GW Depth (m)	Affected Segment	Distance of Segment Head From System Head (m)	Column-3 + Length of Affected Segment (m)
Col. 1	Col. 2	Col. 3	Col. 4	Col. 5	Col. 6	Col. 7	Col. 8	Col. 9
95	102	44575	52018	102	11.92	96	40296	41533
	103	44575	47718	100	10.87	97	40296	45770
	101	41533	50804	97	11.97	-	-	-
	100	41533	44575	-	-	-	-	-
96	102	44575	52018	102	11.92	100	41533	44575
97	98	45770	48087	98	11.53	99	45770	47817
	99	45770	47817	99	12.05	98	45770	48087
100	102	44575	52018	103	11.26	103	44575	47718
104	178	96196	100692	124	9.76	107	36916	41767
106	178	96196	100692	124	9.76	112	42484	44892
107	108	41767	45777	109	13.80	109	41767	44707
	109	41767	44707	108	13.97	108	41767	45777
109	110	44707	46002	111	13.42	111	44707	45534
	111	44707	45534	110	13.56	110	44707	46002
112	178	96196	100692	207	10.41	134	44892	49685
113	116	49584	66940	114	11.93	115	47452	49584
	117	49584	55450	116	11.96	114	47452	51419
	114	47452	51419	-	-	116	49584	66940
115	116	49584	66940	117	9.73	117	49584	55450
118	123	59626	64627	120	11.07	119	51666	53316
	126	59626	64347	133	14.33	120	51666	55020
	124	59626	64334	129	12.79	122	53316	59626
	-	-	-	127	8.92	-	-	-
119	127	64334	67818	121	10.24	121	53316	56092
	123	59626	64627	132	11.48	122	53316	59626
	-	-	-	133	14.33	-	-	-
122	130	67818	72288	125	9.65	125	59626	63982
	129	67818	70900	126	10.13	124	59626	64334
	128	64334	68090	123	10.22	-	-	-
	127	64334	67818	132	11.48	-	-	-
124	131	70900	78551	130	8.41	127	64334	67818
	132	70900	76334	131	8.78	128	64334	68090
	133	70900	75027	128	10.79	-	-	-
	130	67818	72288	132	11.48	-	-	-
127	131	70900	78551	130	8.41	129	67818	70900
134	177	96196	107295	137	10.61	136	49685	54323
	178	96196	100692	209	13.75	-	-	-
	-	-	-	208	10.85	-	-	-
136	177	96196	107295	140	8.16	140	54323	58634
	-	-	-	139	10.35	138	54323	61783
	-	-	-	153	13.46	-	-	-
	-	-	-	209	13.75	-	-	-
138	183	100692	101739	147	9.31	142	61783	62611
	169	98506	105121	210	12.62	141	61783	65022
	168	98506	101451	195	12.64	-	-	-
	177	96196	107295	146	12.82	-	-	-
	-	-	-	201	13.37	-	-	-
	-	-	-	153	13.46	-	-	-
141	186	100692	109045	150	11.47	150	65022	69466
	183	100692	101739	172	11.74	148	65022	70152
	-	-	-	174	12.30	-	-	-
	-	-	-	199	12.32	-	-	-
	-	-	-	210	12.62	-	-	-
148	186	100692	109045	155	6.78	152	70152	71341
	-	-	-	154	11.26	151	70152	73386
	-	-	-	172	11.74	-	-	-
151	184	101739	113427	157	6.92	156	73386	74777
	186	100692	109045	159	10.15	157	73386	79504
	-	-	-	166	10.79	193	74777	82213
	-	-	-	204	11.73	-	-	-
152	154	71341	78763	154	11.26	153	71341	77331
156	184	101739	113427	159	10.15	158	74777	77419
	-	-	-	-	-	193	74777	82213
158	184	101739	113427	159	10.15	159	77419	80512
159	161	80512	85422	160	12.39	160	80512	82711
	160	80512	82711	161	13.42	161	80512	85422

Intermediate Segment with Capacity Constraint	Method of Head-Priority			Method Based on Groundwater Depth		Method of Tail-Priority		
	Affected Segment	Distance of Segment Head From System Head (m)	Column-3 + Length of Affected Segment (m)	Affected Segment	Average GW Depth (m)	Affected Segment	Distance of Segment Head From System Head (m)	Column-3 + Length of Affected Segment (m)
Col. 1	Col. 2	Col. 3	Col. 4	Col. 5	Col. 6	Col. 7	Col. 8	Col. 9
162	185	101739	114243	166	10.79	166	82998	87991
	184	101739	113427	-	-	-	-	-
164	169	98506	105121	170	15.72	167	94405	98506
165	192	109045	115416	172	11.74	171	87995	91639
	185	101739	114243	-	-	172	87995	94488
167	169	98506	105121	168	14.92	168	98506	101451
	-	-	-	169	15.93	169	98506	105121
171	192	109045	115416	174	12.30	173	91639	94653
173	187	109045	117216	176	12.48	175	94653	96196
	192	109045	115416	187	13.88	176	94653	100238
175	187	109045	117216	187	13.88	178	96196	100692
177	182	110392	114271	179	15.24	180	107295	110392
	181	110392	112798	182	15.72	179	107295	113606
	179	107295	113606	180	17.97	182	110392	114271
	180	107295	110392	-	-	-	-	-
178	188	117216	124574	185	12.26	183	100692	101739
	191	117216	119982	191	12.56	186	100692	109045
	187	109045	117216	188	13.70	-	-	-
180	~~182~~	~~110392~~	~~114271~~	181	15.10	181	110392	112798
	-	-	-	182	15.72	182	110392	114271
183	185	101739	114243	185	12.26	184	101739	113427
186	190	124574	126775	190	9.97	192	109045	115416
	189	124574	125583	189	11.71	187	109045	117216
	188	117216	124574	192	12.48	-	-	-
193	208	99221	102049	218	11.66	194	82213	83824
	215	98600	101623	214	11.52	195	82213	86410
	207	95217	99221	-	-	197	83824	88250
	-	-	-	-	-	198	85212	88174
	-	-	-	-	-	199	85212	89367
	-	-	-	-	-	202	85212	89400
194	208	99221	102049	218	11.66	196	83824	85212
	-	-	-	-	-	197	83824	88250
196	211	99221	104893	218	11.66	198	85212	88174
	208	99221	102049	-	-	-	-	-
198	201	88174	93231	201	13.37	200	88174	91669
202	211	99221	104893	206	11.47	203	89400	92550
	-	-	-	218	11.66	-	-	-
203	211	99221	104893	215	11.37	205	92550	95217
	-	-	-	206	11.47	-	-	-
205	209	102049	104473	206	11.47	206	95217	98657
	211	99221	104893	-	-	-	-	-
207	212	104893	106437	212	11.16	208	99221	102049
	210	102049	108670	211	9.88	211	99221	104893
	209	102049	104473	210	12.62	-	-	-
208	210	102049	108670	210	12.62	209	102049	104473
211	213	104893	106634	213	9.98	212	104893	106437
	212	104893	106437	212	11.16	213	104893	106634
214	216	101623	105817	216	10.09	215	98600	101623
	217	101623	105182	217	11.60	218	98600	103485
	218	98600	103485	215	11.37	-	-	-
215	216	101623	105817	216	10.09	217	101623	105182

It needs to be mentioned here that only free segments are selected for demand curtailment. However, if the demands of all the free segments below an intermediate segment are curtailed, then the intermediate segment is also treated as a free segment. In Table- 7.2 for intermediate segment 35 under the method based on groundwater depth, it is found that first the demands of segment 39 with groundwater depth of 12 m are curtailed and then the demands of segment 38 with groundwater depth of 9.47 m are curtailed. The reason is that below segment 38, there lie two segments 39 and 40. Demands of segment 40 are curtailed to satisfy capacity constraint of segment 38. Now for satisfying capacity constraint of segment 35, segment 38 cannot be selected as long as it acts as intermediate segment (segment 39 is the downstream segment with canal water demands). So, first segment 39 is selected for demand curtailment and if its demands are fully curtailed and still capacity constraint exists at segment 35, then segment 38 (which becomes a free segment after the curtailment of demands of segment 39) is considered for curtailment. Further, it is noted from the table that one segment is selected again and again for demand curtailment (say segment 44 in Column-5). The reason is that corresponding to intermediate segments 34 and 35, only partial demands of segment 44 are curtailed. So this segment is still available until its demands are completely curtailed for satisfying capacity constraint of segment 37.

The revised canal operation scenario after satisfying the capacity constraint is presented in Table – 7.3. Table shows that groundwater demand of most of the intermediate segments has reduced to zero and for this reason, demands of a number of free segments are met through groundwater pumping. However, there are a few intermediate segments (such as segment 54, 97, 100, 109 etc.) that still require groundwater. The reason is that all downstream demands of these intermediate segments have been curtailed and these have now become free segments. For geographic depiction of the extent of canal system that can be supplied with canal water, output of CNSM is linked to GIS. Tabular output of model is imported in GIS and linked to the canal network layout through the identifiers of different canal segments. The geographic depiction of operation results of Table – 7.3 in map form is shown in Figure – 7.5. In addition to running/non-running canals, maps corresponding to various attributes such as required discharge, run-time, groundwater demand, canal seepage loss etc. can be visualized. The map corresponding to required discharge is presented in Figure – 7.6. By selecting a particular segment, details such as its identifier, name, and attribute value (say, required discharge) are displayed on the screen as shown in Figure – 7.6. The discharge requirement at the head of canal system comes out to be 62.54 cumec. The canal system can be run according to the derived plan (discharge and run-rime for various canal segments as obtained in

Table – 7.3: Revised operation scenario after canal capacity constraint

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

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

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

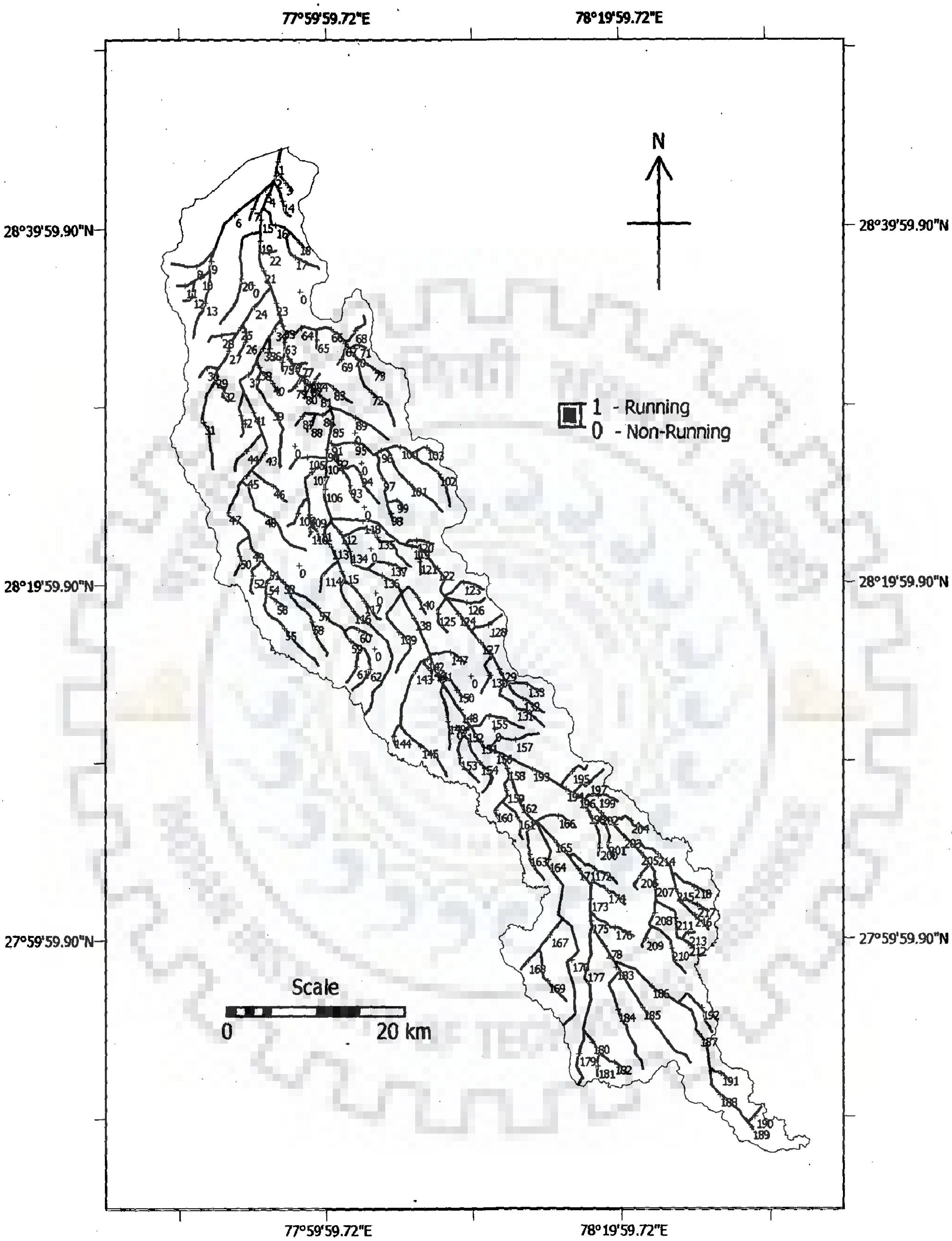

Figure – 7.5: Operation plan of Lakhaoti canal network with adequate canal water supply

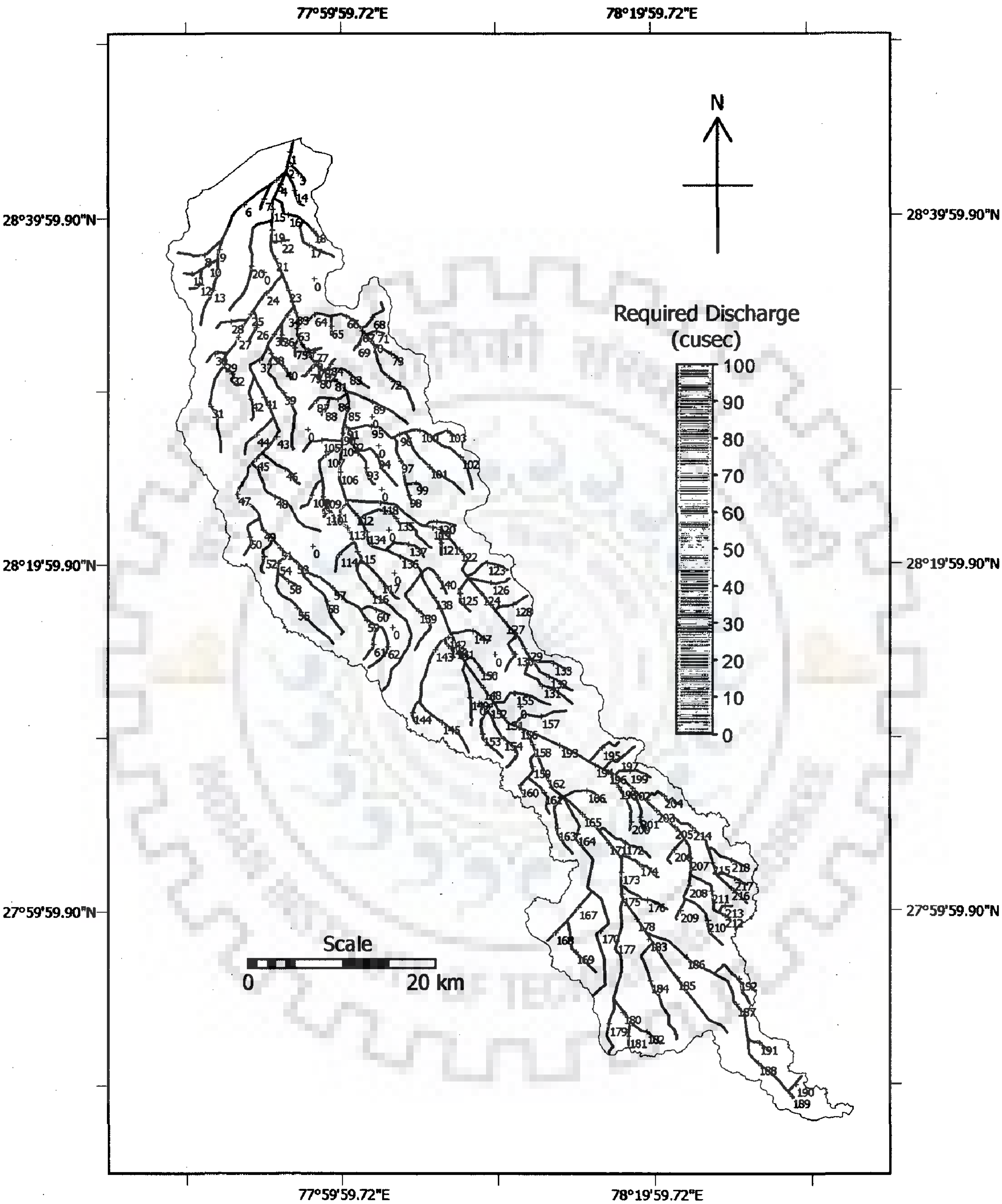

Figure – 7.6: Map showing discharge requirement in Lakhaoti canal network

Table - 7.3 if required discharge is available at canal head. However, if the discharge availability at head is less than the demand, then some allocation policy needs to be adopted for deriving the spatial distribution plan of available canal water.

7.3.2 Analysis of allocation policies

Under deficit condition, when the canal water supply at network head is less than the required demand, it is not possible to meet the complete demands of full network from existing surface water resources and some subjective criteria needs to be adopted for the allocation of available surface and groundwater. For deficit conditions, five distribution/allocation policies, as described in Chapter-4, have been included in CNSM. To compare the results of different allocation policies, it is assumed that 40 cumec of water is available at canal head (against the demand of 62.54 cumec).

Table - 7.4 shows the operation scenario generated while adopting the policy of **head-reach priority (Policy-1)**. Under this policy, canal water is allocated starting from the network head and the demands of various canal segments (which are planned to be run as per Table - 7.3) are met in full as far as canal water could reach in the network. Operation results with Policy-1 are depicted in map form in Figure – 7.7.

Table - 7.5 shows the operation scenario generated while adopting the **policy of conjunctive use (Policy-2)**. Under this policy, water deficit at the network head is compensated by curtailing the demands of those segments which have least depth of water table. The segment demands are curtailed iteratively till the water demand at canal head matches with the supply. The results in map form for Policy-2 are presented in Figure – 7.8. Generally, groundwater occurs at shallow depth in the head-reach of a command area due to greater availability and application of canal water in the absence of control mechanism and more seepage because of continuous running of head-reach canal.

Similar tables can be generated for **proportionate supply policy (Policy-3)** and the **tail-reach priority policy (Policy-4).** Here, the results with these policies are presented in map form in Figure – 7.9 and Figure – 7.10 respectively. 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

Table – 7.4:Operation scenario with water availability constraint using Policy-1

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

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

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

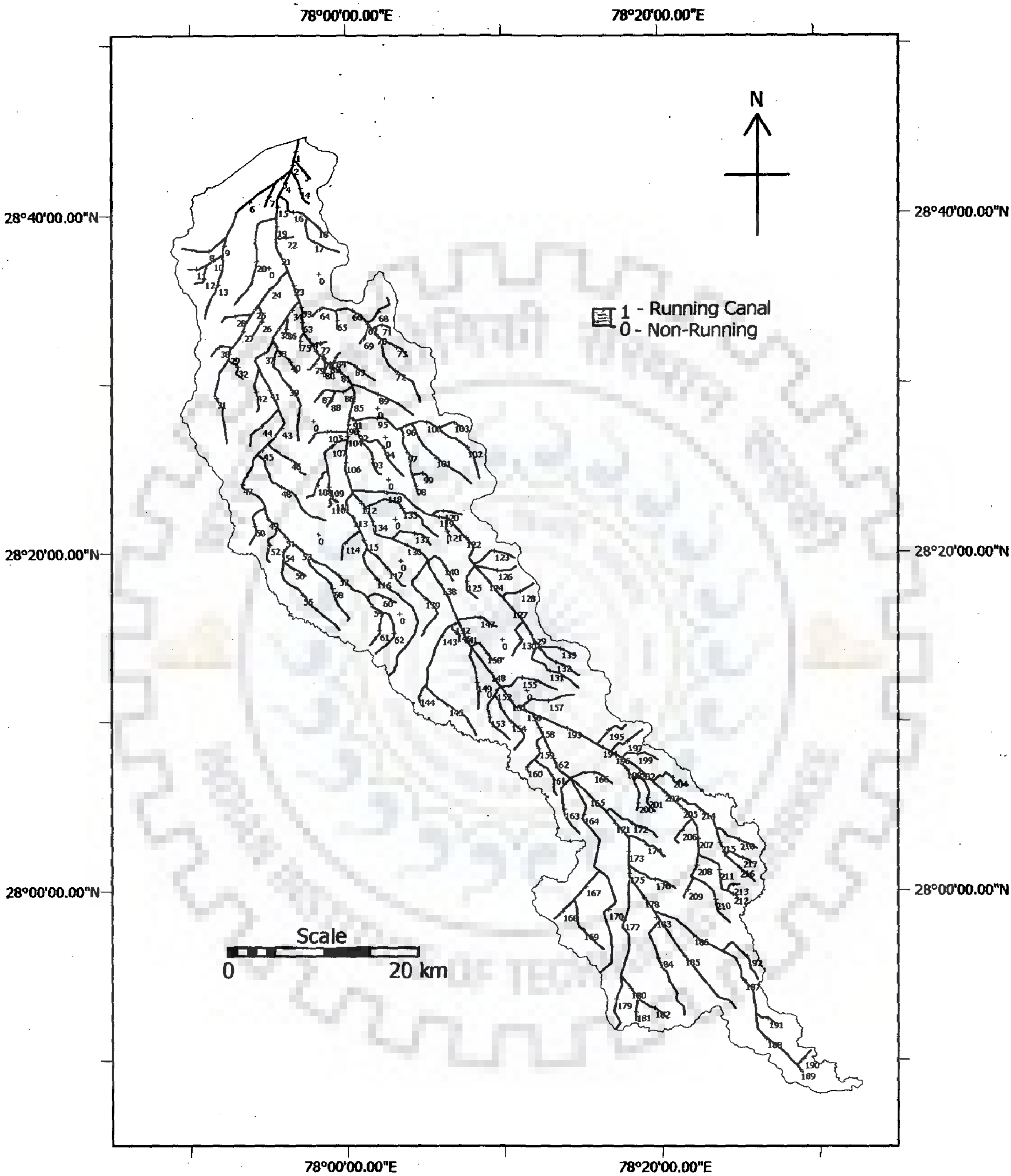

Figure – 7.7: Operation plan of Lakhaoti canal network under deficit conditions with policy of head-reach priority

Table – 7.5: Operation scenario with water availability constraint using Policy-2

Seg. Iden.	U/s Seg. Iden.	Local Irrigation Demand (Ham)	Canal Water Demand (Ham)	Total D/s Demand (Ham)	Canal Seepage Loss (Ham)	Total Canal Water Demand (Ham)	Required Discharge (Cumec)	Water Depth (m)	Fill Time (Hour)	Run Time (Hour)	Total GW Demand (Ham)
1	0	4.75	4.75	2402.10	11.85	2418.70	39.99	2.25	0.00	168.00	0.00
2	1	4.30	4.30	2386.03	11.77	2402.10	39.91	2.24	0.83	167.17	0.00
3F	1	8.42	0.00	0.00	0.00	0.00	0.00	0.00	0.83	0.00	8.42
4	2	2.10	2.10	2364.85	19.09	2386.03	39.75	2.22	1.24	166.76	0.00
5	2	3.80	0.00	0.00	0.00	0.00	0.00	0.00	1.24	0.00	3.80
6	5	34.44	0.00	0.00	0.00	0.00	0.00	0.00	2.93	0.00	34.44
7F	5	11.79	0.00	0.00	0.00	0.00	0.00	0.00	2.93	0.00	11.79
8F	6	11.58	0.00	0.00	0.00	0.00	0.00	0.00	9.06	0.00	11.58
9	6	7.42	0.00	0.00	0.00	0.00	0.00	0.00	9.06	0.00	7.42
10	9	11.31	0.00	0.00	0.00	0.00	0.00	0.00	10.63	0.00	11.31
11F	10	0.62	0.00	0.00	0.00	0.00	0.00	0.00	12.56	0.00	0.62
12F	10	2.18	0.00	0.00	0.00	0.00	0.00	0.00	12.56	0.00	2.18
13F	9	15.27	0.00	0.00	0.00	0.00	0.00	0.00	10.63	0.00	15.27
14F	2	7.43	0.00	0.00	0.00	0.00	0.00	0.00	1.24	0.00	7.43
15	4	14.15	14.15	2324.69	26.01	2364.85	39.64	2.19	2.29	165.71	0.00
16	4	12.69	0.00	0.00	0.00	0.00	0.00	0.00	2.29	0.00	12.69
17F	16	11.47	0.00	0.00	0.00	0.00	0.00	0.00	5.30	0.00	11.47
18F	16	1.12	0.00	0.00	0.00	0.00	0.00	0.00	5.30	0.00	1.12
19	15	8.04	8.04	2291.07	25.57	2324.69	39.18	2.16	3.17	164.83	0.00
20F	15	9.96	0.00	0.00	0.00	0.00	0.00	0.00	3.17	0.00	9.96
21	19	29.53	29.53	2236.34	25.20	2291.07	38.78	2.15	3.90	164.10	0.00
22F	19	5.30	0.00	0.00	0.00	0.00	0.00	0.00	3.90	0.00	5.30
23	21	36.87	36.87	2178.68	20.80	2236.34	38.18	2.11	5.29	162.71	0.00
24	21	26.45	0.00	0.00	0.00	0.00	0.00	0.00	5.29	0.00	26.45
25	24	7.96	0.00	0.00	0.00	0.00	0.00	0.00	7.90	0.00	7.96
26F	24	26.29	0.00	0.00	0.00	0.00	0.00	0.00	7.90	0.00	26.29
27	25	28.56	0.00	0.00	0.00	0.00	0.00	0.00	8.45	0.00	28.56
28F	25	7.53	0.00	0.00	0.00	0.00	0.00	0.00	8.45	0.00	7.53
29	27	7.25	0.00	0.00	0.00	0.00	0.00	0.00	10.63	0.00	7.25
30F	27	5.65	0.00	0.00	0.00	0.00	0.00	0.00	10.63	0.00	5.65
31F	29	23.93	0.00	0.00	0.00	0.00	0.00	0.00	11.38	0.00	23.93
32F	29	14.47	0.00	0.00	0.00	0.00	0.00	0.00	11.38	0.00	14.47
33	23	9.59	9.59	1852.96	28.56	1891.11	32.54	2.07	6.56	161.44	0.00
34	23	23.78	23.78	248.15	15.64	287.57	5.29	1.55	6.56	150.91	0.00
35	34	37.17	37.17	197.47	13.50	248.15	4.59	1.50	7.38	150.10	0.00
36F	34	10.98	0.00	0.00	0.00	0.00	0.00	0.00	7.38	0.00	10.98
37	35	29.05	29.05	157.69	10.74	197.47	3.68	1.42	8.48	148.99	0.00
38	35	11.38	0.00	0.00	0.00	0.00	0.00	0.00	8.48	0.00	11.38
39F	38	46.72	0.00	0.00	0.00	0.00	0.00	0.00	9.37	0.00	46.72
40F	38	20.68	0.00	0.00	0.00	0.00	0.00	0.00	9.37	0.00	20.68
41	37	44.51	44.51	104.59	8.58	157.69	2.97	1.32	10.00	147.47	0.00
42F	37	14.55	0.00	0.00	0.00	0.00	0.00	0.00	10.00	0.00	14.55
43	41	42.31	42.31	56.59	5.69	104.59	2.00	1.19	11.86	145.61	0.00
44F	41	32.53	0.00	0.00	0.00	0.00	0.00	0.00	11.86	0.00	32.53
45	43	10.07	10.07	46.40	0.12	56.59	1.09	1.08	13.54	143.94	0.00
46F	43	23.70	0.00	0.00	0.00	0.00	0.00	0.00	13.54	0.00	23.70
47	45	32.88	0.00	0.00	0.00	0.00	0.00	0.00	14.12	0.00	32.88
48F	45	38.32	38.32	0.00	8.08	46.40	0.90	0.66	14.12	143.36	0.00
49	47	8.95	0.00	0.00	0.00	0.00	0.00	0.00	16.89	0.00	8.95
50F	47	11.54	0.00	0.00	0.00	0.00	0.00	0.00	16.89	0.00	11.54
51	49	7.61	0.00	0.00	0.00	0.00	0.00	0.00	17.94	0.00	7.61
52F	49	2.80	0.00	0.00	0.00	0.00	0.00	0.00	17.94	0.00	2.80
53	51	7.69	0.00	0.00	0.00	0.00	0.00	0.00	18.77	0.00	7.69
54	51	3.69	0.00	0.00	0.00	0.00	0.00	0.00	18.77	0.00	3.69
55F	54	14.00	0.00	0.00	0.00	0.00	0.00	0.00	22.00	0.00	14.00
56F	54	2.85	0.00	0.00	0.00	0.00	0.00	0.00	22.00	0.00	2.85
57	53	43.65	0.00	0.00	0.00	0.00	0.00	0.00	19.58	0.00	43.65
58F	53	18.11	0.00	0.00	0.00	0.00	0.00	0.00	19.58	0.00	18.11
59	57	15.01	0.00	0.00	0.00	0.00	0.00	0.00	22.48	0.00	15.01
60F	57	11.31	0.00	0.00	0.00	0.00	0.00	0.00	22.48	0.00	11.31
61F	59	34.22	0.00	0.00	0.00	0.00	0.00	0.00	23.41	0.00	34.22
62F	59	34.10	0.00	0.00	0.00	0.00	0.00	0.00	23.41	0.00	34.10
63	33	20.24	20.24	1759.80	27.29	1807.33	31.19	2.06	7.05	160.95	0.00
64	33	48.94	44.41	0.00	1.22	45.63	1.91	1.05	7.05	66.39	4.53
65F	64	11.28	0.00	0.00	0.00	0.00	0.00	0.00	9.21	0.00	11.28
66	64	23.84	0.00	0.00	0.00	0.00	0.00	0.00	9.21	0.00	23.84
67	66	1.57	0.00	0.00	0.00	0.00	0.00	0.00	11.14	0.00	1.57
68F	66	20.04	0.00	0.00	0.00	0.00	0.00	0.00	11.14	0.00	20.04
69F	67	10.33	0.00	0.00	0.00	0.00	0.00	0.00	11.60	0.00	10.33
70	67	8.00	0.00	0.00	0.00	0.00	0.00	0.00	11.60	0.00	8.00
71F	67	4.03	0.00	0.00	0.00	0.00	0.00	0.00	11.60	0.00	4.03
72F	70	69.13	0.00	0.00	0.00	0.00	0.00	0.00	12.35	0.00	69.13

Seg. Iden.	U/s Seg. Iden.	Local Irrigation Demand (Ham)	Canal Water Demand (Ham)	Total D/s Demand (Ham)	Canal Seepage Loss (Ham)	Total Canal Water Demand (Ham)	Required Discharge (Cumec)	Water Depth (m)	Fill Time (Hour)	Run Time (Hour)	Total GW Demand (Ham)
73F	70	17.41	0.00	0.00	0.00	0.00	0.00	0.00	12.35	0.00	17.41
74	63	17.29	17.29	1715.93	26.57	1759.80	30.51	2.04	7.79	160.21	0.00
75F	63	11.43	0.00	0.00	0.00	0.00	0.00	0.00	7.79	0.00	11.43
76	74	23.52	23.52	1666.50	25.91	1715.93	29.85	2.03	8.33	159.67	0.00
77F	74	10.92	0.00	0.00	0.00	0.00	0.00	0.00	8.33	0.00	10.92
78	76	9.83	9.83	1631.51	25.16	1666.50	29.14	2.01	9.15	158.85	0.00
79F	76	8.73	0.00	0.00	0.00	0.00	0.00	0.00	9.15	0.00	8.73
80F	78	12.10	0.00	0.00	0.00	0.00	0.00	0.00	9.53	0.00	12.10
81	78	24.22	24.22	1582.65	24.64	1631.51	28.60	2.00	9.53	158.47	0.00
82	78	1.99	0.00	0.00	0.00	0.00	0.00	0.00	9.53	0.00	1.99
83F	82	22.38	0.00	0.00	0.00	0.00	0.00	0.00	9.93	0.00	22.38
84F	82	6.75	0.00	0.00	0.00	0.00	0.00	0.00	9.93	0.00	6.75
85	81	56.02	56.02	1509.86	16.78	1582.65	28.00	1.97	10.98	157.02	0.00
86	81	8.53	0.00	0.00	0.00	0.00	0.00	0.00	10.98	0.00	8.53
87F	86	3.74	0.00	0.00	0.00	0.00	0.00	0.00	12.89	0.00	3.77
88F	86	5.80	0.00	0.00	0.00	0.00	0.00	0.00	12.89	0.00	5.80
89F	81	20.97	0.00	0.00	0.00	0.00	0.00	0.00	10.98	0.00	20.97
90	85	26.37	26.37	1467.49	16.00	1509.86	26.92	1.94	12.22	155.78	0.00
91	85	4.12	0.00	0.00	0.00	0.00	0.00	0.00	12.22	0.00	4.12
92	91	13.16	0.00	0.00	0.00	0.00	0.00	0.00	12.58	0.00	13.16
93F	92	19.69	0.00	0.00	0.00	0.00	0.00	0.00	14.17	0.00	19.69
94F	92	43.82	0.00	0.00	0.00	0.00	0.00	0.00	14.17	0.00	43.82
95	91	49.01	0.00	0.00	0.00	0.00	0.00	0.00	12.58	0.00	49.01
96	95	11.42	0.00	0.00	0.00	0.00	0.00	0.00	15.50	0.00	11.42
97	95	39.35	0.00	0.00	0.00	0.00	0.00	0.00	15.50	0.00	39.35
98F	97	14.32	0.00	0.00	0.00	0.00	0.00	0.00	19.35	0.00	14.32
99F	97	16.03	0.00	0.00	0.00	0.00	0.00	0.00	19.35	0.00	16.03
100	96	14.09	0.00	0.00	0.00	0.00	0.00	0.00	16.35	0.00	14.09
101F	96	42.10	0.00	0.00	0.00	0.00	0.00	0.00	16.35	0.00	42.10
102F	100	15.90	0.00	0.00	0.00	0.00	0.00	0.00	18.60	0.00	15.90
103F	100	5.11	0.00	0.00	0.00	0.00	0.00	0.00	18.60	0.00	5.47
104	90	7.74	7.74	1432.60	15.43	1455.78	26.06	1.92	12.82	155.18	0.00
105F	90	22.85	9.69	0.00	2.02	11.71	0.21	0.43	12.82	155.18	13.16
106	104	73.96	73.96	1305.75	25.58	1405.29	25.21	1.91	13.13	154.87	0.00
107	104	29.37	24.59	0.00	2.72	27.31	0.49	0.58	13.13	154.87	4.78
108F	107	10.81	0.00	0.00	0.00	0.00	0.00	0.00	17.21	0.00	10.81
109	107	13.30	0.00	0.00	0.00	0.00	0.00	0.00	17.21	0.00	13.30
110F	109	4.43	0.00	0.00	0.00	0.00	0.00	0.00	19.83	0.00	4.43
111F	109	2.06	0.00	0.00	0.00	0.00	0.00	0.00	19.83	0.00	2.06
112	106	27.61	27.61	1254.38	23.76	1305.75	23.72	1.86	15.12	152.88	0.00
113	106	56.60	0.00	0.00	0.00	0.00	0.00	0.00	15.12	0.00	56.60
114F	113	15.03	0.00	0.00	0.00	0.00	0.00	0.00	17.87	0.00	15.03
115	113	14.53	0.00	0.00	0.00	0.00	0.00	0.00	17.87	0.00	14.53
116F	115	59.46	0.00	0.00	0.00	0.00	0.00	0.00	19.06	0.00	62.63
117F	115	14.85	0.00	0.00	0.00	0.00	0.00	0.00	19.06	0.00	16.21
118	106	76.28	0.00	0.00	0.00	0.00	0.00	0.00	15.12	0.00	76.28
119	118	14.16	0.00	0.00	0.00	0.00	0.00	0.00	19.74	0.00	15.00
120F	118	24.71	0.00	0.00	0.00	0.00	0.00	0.00	19.74	0.00	24.71
121F	119	12.08	0.00	0.00	0.00	0.00	0.00	0.00	20.56	0.00	12.08
122	119	43.08	0.00	0.00	0.00	0.00	0.00	0.00	20.56	0.00	43.08
123F	122	9.06	0.00	0.00	0.00	0.00	0.00	0.00	23.67	0.00	9.06
124	122	36.48	0.00	0.00	0.00	0.00	0.00	0.00	23.67	0.00	36.48
125F	122	42.06	0.00	0.00	0.00	0.00	0.00	0.00	23.67	0.00	42.06
126F	122	10.53	0.00	0.00	0.00	0.00	0.00	0.00	23.67	0.00	10.53
127	124	22.57	0.00	0.00	0.00	0.00	0.00	0.00	26.01	0.00	22.57
128F	124	8.91	0.00	0.00	0.00	0.00	0.00	0.00	26.01	0.00	8.91
129	127	6.04	0.00	0.00	0.00	0.00	0.00	0.00	27.74	0.00	6.04
130F	127	9.31	0.00	0.00	0.00	0.00	0.00	0.00	27.74	0.00	9.31
131F	129	8.28	0.00	0.00	0.00	0.00	0.00	0.00	29.27	0.00	8.28
132F	129	8.41	0.00	0.00	0.00	0.00	0.00	0.00	29.27	0.00	8.41
133F	129	4.95	0.00	0.00	0.00	0.00	0.00	0.00	29.27	0.00	4.95
134	112	74.99	74.99	1156.56	22.83	1254.38	22.92	1.84	15.98	152.02	0.00
135F	112	56.50	0.00	0.00	0.00	0.00	0.00	0.00	15.98	0.00	56.50
136	134	54.26	54.26	1058.47	43.83	1156.56	21.38	1.79	17.70	150.30	0.00
137F	134	23.76	0.00	0.00	0.00	0.00	0.00	0.00	17.70	0.00	23.76
138	136	110.92	110.92	907.43	40.12	1058.47	19.78	1.75	19.37	148.63	0.00
139F	136	44.48	0.00	0.00	0.00	0.00	0.00	0.00	19.37	0.00	44.48
140F	136	23.81	0.00	0.00	0.00	0.00	0.00	0.00	19.37	0.00	23.81
141	138	34.62	34.62	793.58	32.63	860.82	16.38	1.68	22.05	145.95	0.00
142	138	7.10	7.10	39.17	0.34	46.61	1.70	0.71	22.05	75.97	0.00
143	142	31.62	31.62	4.67	2.88	39.17	1.44	0.64	22.49	75.52	0.00
144F	143	4.12	4.12	0.00	0.56	4.67	0.18	0.40	26.41	71.60	0.00
145F	143	18.02	0.00	0.00	0.00	0.00	0.00	0.00	26.41	0.00	18.02
146F	142	9.23	0.00	0.00	0.00	0.00	0.00	0.00	22.49	0.00	9.23
147F	138	29.76	0.00	0.00	0.00	0.00	0.00	0.00	22.05	0.00	29.76

Seg. Iden.	U/s Seg. Iden.	Local Irrigation Demand (Ham)	Canal Water Demand (Ham)	Total D/s Demand (Ham)	Canal Seepage Loss (Ham)	Total Canal Water Demand (Ham)	Required Discharge (Cumec)	Water Depth (m)	Fill Time (Hour)	Run Time (Hour)	Total GW Demand (Ham)
148	141	52.70	52.70	710.80	30.08	793.58	15.23	1.64	23.21	144.79	0.00
149F	141	24.25	0.00	0.00	0.00	0.00	0.00	0.00	23.21	0.00	24.25
150F	141	24.29	0.00	0.00	0.00	0.00	0.00	0.00	23.21	0.00	24.29
151	148	34.69	34.69	645.83	26.81	707.33	13.75	1.60	25.06	142.94	0.00
152	148	3.40	3.40	0.00	0.07	3.47	0.65	0.60	25.06	14.80	0.00
153F	152	18.62	0.00	0.00	0.00	0.00	0.00	0.00	25.94	0.00	18.62
154F	152	48.90	0.00	0.00	0.00	0.00	0.00	0.00	25.94	0.00	48.90
155F	148	45.48	0.00	0.00	0.00	0.00	0.00	0.00	25.06	0.00	45.48
156	151	6.90	6.90	614.45	24.48	645.83	12.65	1.56	26.23	141.77	0.00
157F	151	43.53	0.00	0.00	0.00	0.00	0.00	0.00	26.23	0.00	43.53
158	156	8.80	8.80	479.32	7.63	495.76	9.75	1.54	26.73	141.27	0.00
159	158	22.80	0.00	0.00	0.00	0.00	0.00	0.00	27.85	0.00	22.80
160F	159	1.92	0.00	0.00	0.00	0.00	0.00	0.00	30.46	0.00	1.92
161F	159	14.70	0.00	0.00	0.00	0.00	0.00	0.00	30.46	0.00	14.70
162	158	34.21	34.21	437.73	7.38	479.32	9.50	1.38	27.85	140.15	0.00
163F	162	25.72	15.48	0.00	3.52	19.00	0.38	0.76	29.93	138.07	10.24
164	162	42.03	42.03	72.45	11.40	125.88	2.56	0.90	29.93	136.50	0.00
165	162	35.37	35.37	257.39	0.09	292.85	5.89	1.30	29.93	138.07	0.00
166F	162	25.13	0.00	0.00	0.00	0.00	0.00	0.00	29.93	0.00	25.13
167	164	23.49	23.49	18.71	2.14	44.35	0.96	0.76	38.48	127.95	0.00
168F	167	6.34	0.00	0.00	0.00	0.00	0.00	0.00	41.20	0.00	6.34
169F	167	28.10	16.52	0.00	2.20	18.71	0.51	0.58	41.20	102.55	11.58
170F	164	114.63	22.62	0.00	5.48	28.10	0.87	0.62	38.48	89.91	92.00
171	165	8.97	8.97	243.09	5.33	257.39	5.26	1.28	32.13	135.87	0.00
172F	165	43.04	0.00	0.00	0.00	0.00	0.00	0.00	32.13	0.00	43.04
173	171	21.59	21.59	216.47	5.03	243.09	5.03	1.24	33.66	134.34	0.00
174F	171	28.22	0.00	0.00	0.00	0.00	0.00	0.00	33.66	0.00	28.22
175	173	9.11	9.11	207.13	0.24	216.47	4.51	1.26	34.82	133.18	0.00
176F	173	44.45	0.00	0.00	0.00	0.00	0.00	0.00	34.82	0.00	44.45
177	175	157.04	68.78	0.00	9.61	78.39	1.64	0.90	35.42	132.58	88.26
178	175	72.53	72.53	53.11	3.10	128.74	2.70	1.15	35.42	132.58	0.00
179F	177	41.30	0.00	0.00	0.00	0.00	0.00	0.00	46.32	0.00	41.30
180	177	18.06	0.00	0.00	0.00	0.00	0.00	0.00	46.32	0.00	18.06
181F	180	22.72	0.00	0.00	0.00	0.00	0.00	0.00	49.31	0.00	22.72
182F	180	18.40	0.00	0.00	0.00	0.00	0.00	0.00	49.31	0.00	18.40
183	178	9.77	9.77	39.05	4.29	53.11	1.13	0.80	37.32	130.68	0.00
184F	183	85.81	33.00	0.00	6.04	39.05	0.84	0.70	38.16	129.84	52.81
185F	183	58.01	0.00	0.00	0.00	0.00	0.00	0.00	38.16	0.00	58.01
186	178	80.92	0.00	0.00	0.00	0.00	0.00	0.00	37.32	0.00	80.92
187	186	41.05	0.00	0.00	0.00	0.00	0.00	0.00	41.91	0.00	41.05
188	187	32.79	0.00	0.00	0.00	0.00	0.00	0.00	44.93	0.00	34.52
189F	188	2.92	0.00	0.00	0.00	0.00	0.00	0.00	46.27	0.00	2.92
190F	188	10.69	0.00	0.00	0.00	0.00	0.00	0.00	46.27	0.00	10.69
191F	187	13.85	0.00	0.00	0.00	0.00	0.00	0.00	44.93	0.00	13.85
192F	186	25.69	0.00	0.00	0.00	0.00	0.00	0.00	41.91	0.00	26.73
193	156	74.30	74.30	42.32	2.07	118.69	2.33	1.28	26.73	141.27	0.00
194	193	6.87	6.87	34.54	0.91	42.32	0.85	1.23	30.10	137.90	0.00
195F	193	13.63	0.00	0.00	0.00	0.00	0.00	0.00	30.10	0.00	13.63
196	194	4.14	4.14	18.58	0.64	23.35	0.81	1.10	30.79	79.76	0.00
197F	194	27.61	9.32	0.00	1.87	11.19	0.23	0.40	30.79	137.21	18.29
198	196	17.79	17.79	0.00	0.78	18.58	0.65	0.70	31.33	79.23	0.00
199F	196	14.54	0.00	0.00	0.00	0.00	0.00	0.00	31.33	0.00	14.54
200F	198	12.76	0.00	0.00	0.00	0.00	0.00	0.00	33.26	0.00	12.76
201F	198	14.24	0.00	0.00	0.00	0.00	0.00	0.00	33.26	0.00	14.24
202	196	16.46	0.00	0.00	0.00	0.00	0.00	0.00	31.33	0.00	16.46
203	202	9.28	0.00	0.00	0.00	0.00	0.00	0.00	32.74	0.00	9.28
204F	202	21.93	0.00	0.00	0.00	0.00	0.00	0.00	32.74	0.00	22.32
205	203	15.60	0.00	0.00	0.00	0.00	0.00	0.00	33.59	0.00	15.60
206F	205	21.86	0.00	0.00	0.00	0.00	0.00	0.00	34.57	0.00	21.86
207	205	34.73	0.00	0.00	0.00	0.00	0.00	0.00	34.57	0.00	34.73
208	207	15.81	0.00	0.00	0.00	0.00	0.00	0.00	35.94	0.00	15.81
209F	208	9.41	0.00	0.00	0.00	0.00	0.00	0.00	36.91	0.00	9.41
210F	208	17.78	0.00	0.00	0.00	0.00	0.00	0.00	36.91	0.00	17.78
211	207	19.33	0.00	0.00	0.00	0.00	0.00	0.00	35.94	0.00	19.33
212F	211	3.51	0.00	0.00	0.00	0.00	0.00	0.00	40.82	0.00	3.51
213F	211	5.76	0.00	0.00	0.00	0.00	0.00	0.00	40.82	0.00	5.76
214	203	41.17	0.00	0.00	0.00	0.00	0.00	0.00	33.59	0.00	43.84
215	214	12.97	0.00	0.00	0.00	0.00	0.00	0.00	37.15	0.00	12.97
216F	215	18.84	0.00	0.00	0.00	0.00	0.00	0.00	38.24	0.00	18.84
217F	215	12.98	0.00	0.00	0.00	0.00	0.00	0.00	38.24	0.00	12.98
218F	214	26.17	0.00	0.00	0.00	0.00	0.00	0.00	37.15	0.00	26.17

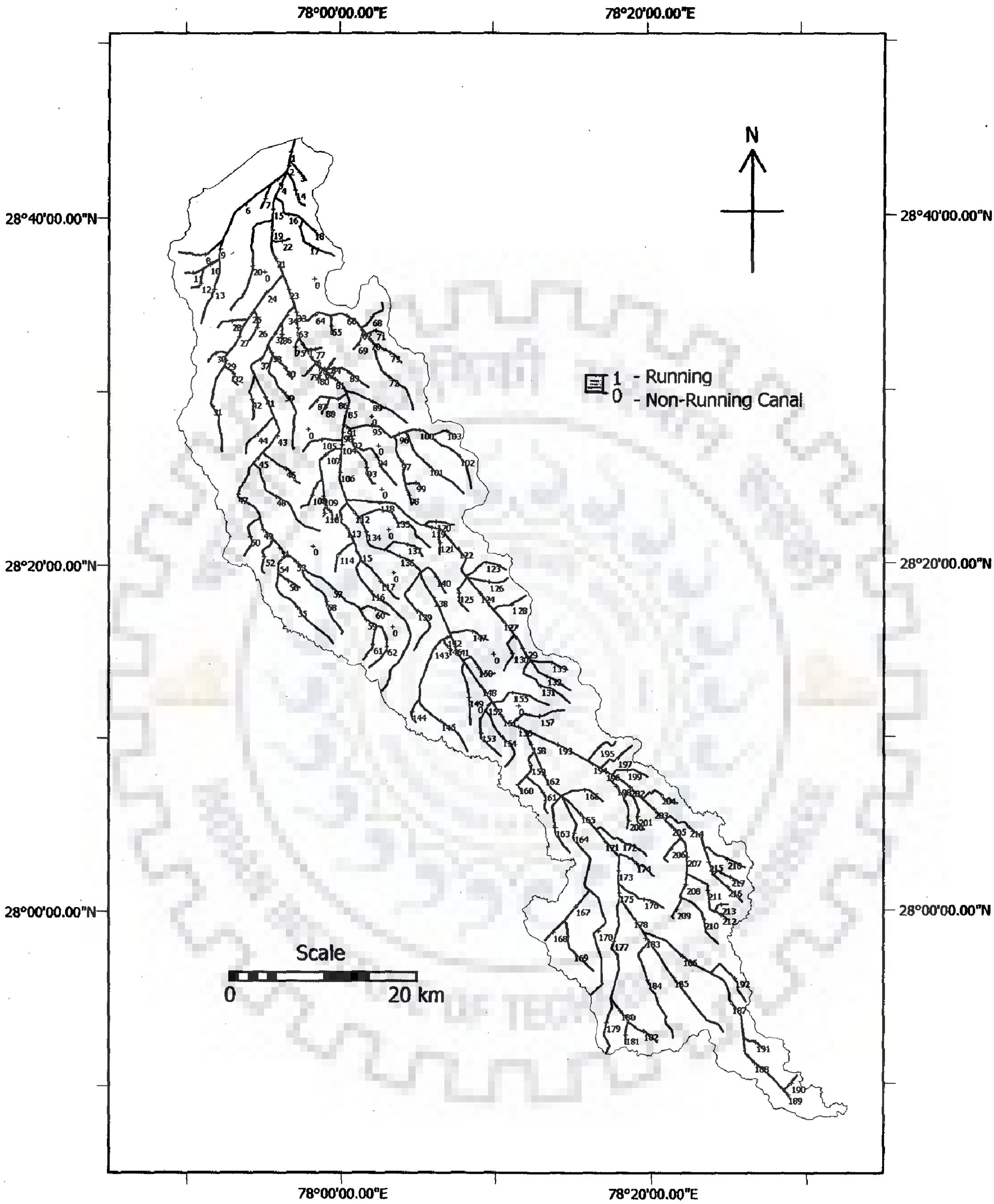

Figure – 7.8: Operation plan of Lakhaoti canal network under deficit conditions with policy of conjunctive use

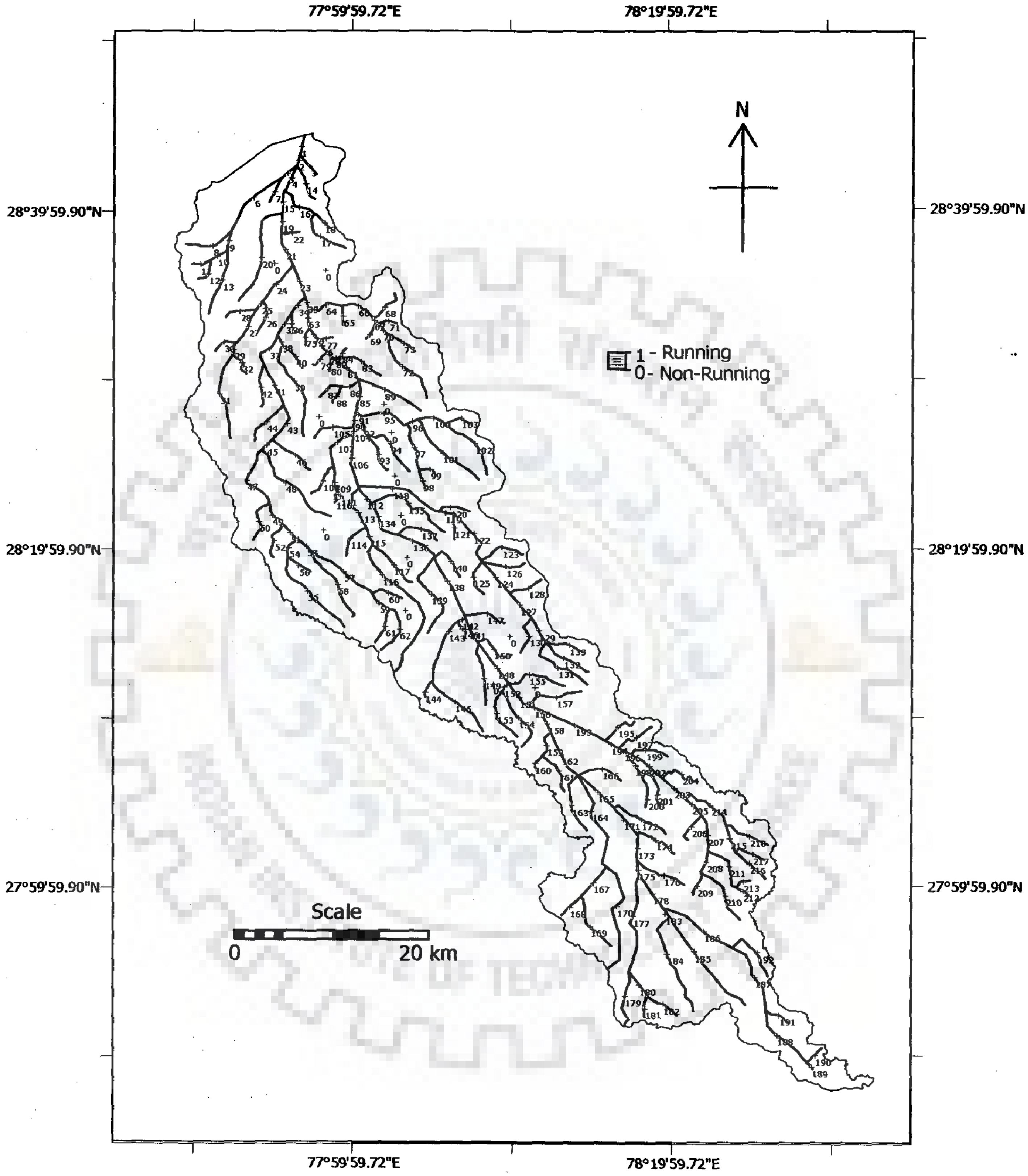

Figure – 7.9: Operation plan of Lakhaoti canal network under deficit conditions with policy of proportionate supply

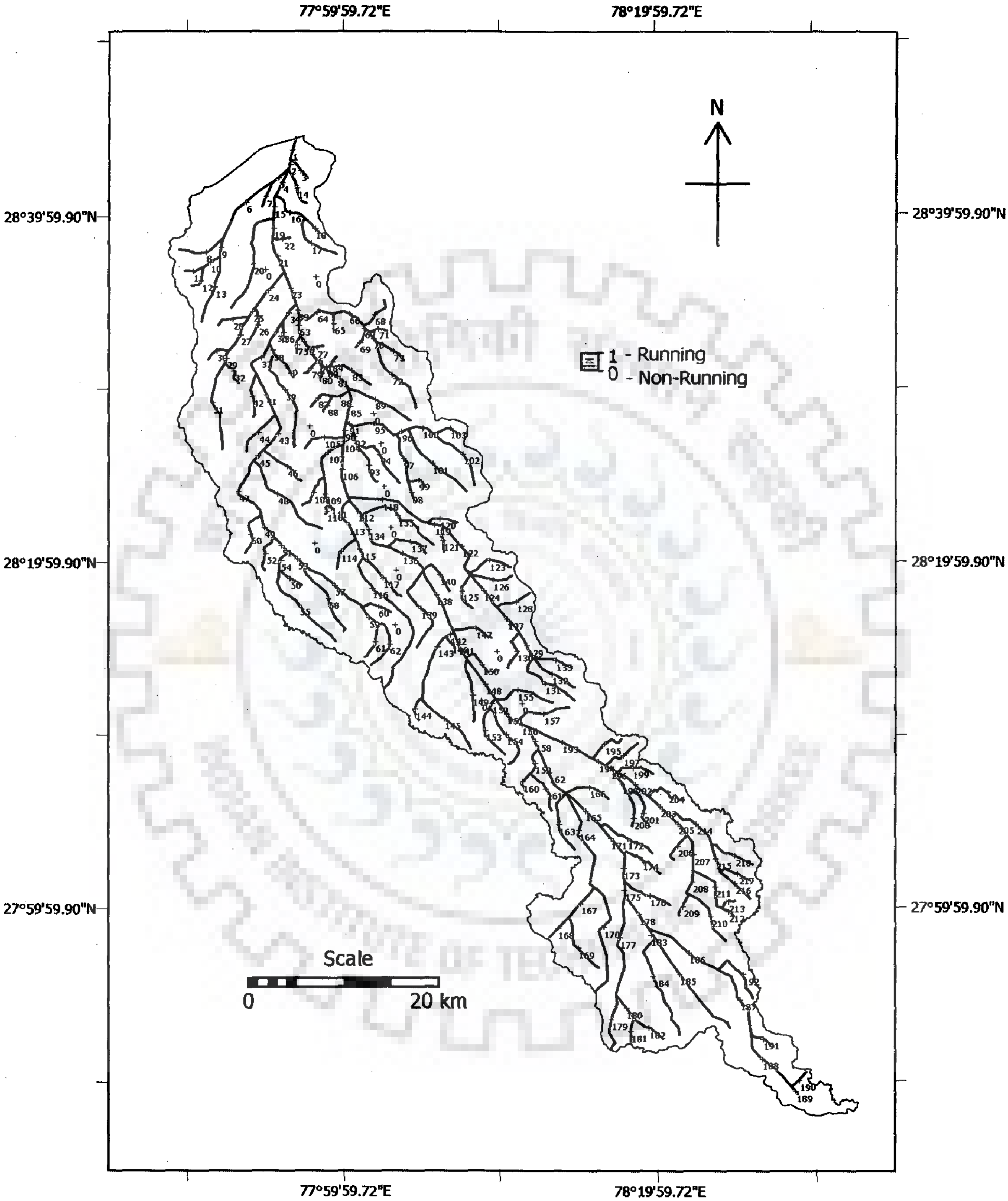

Figure – 7.10: Operation plan of Lakhaoti canal network under deficit conditions with policy of tail-reach priority

of segments can be met with canal water using this policy. Under the tail-reach priority policy, 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 – 7.10.

Summary results of four policies are compiled in Table – 7.6. 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 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

Table – 7.6: Summary results of four allocation policies

Performance Measure	Policy-1	Policy-2	Policy-3	Policy-4
Surface Water Available at Canal Head (Mm3)	24.19	24.19	24.20	24.19
Irrigation Demand at Head (Mm3)	50.75	50.75	50.75	50.75
Surface Water Utilized for Irrigation (Mm3)	18.84	16.50	17.37	14.40
Canal Seepage Loss (Mm3)	5.35	7.69	6.84	9.79
Groundwater Use in Command (Mm3)	31.91	34.37	33.38	36.25
Energy Demand in Canal-irrigable Area (MKwh)	1.2942	1.3269	1.3329	1.3706

allocating canal water and groundwater. However, since deeper water table generally occurs in the tail-reaches of command, Policy-2 tries to allocate canal water in the tail reaches of command with the result that canal seepage losses increase and the effective water utilized for irrigation application decreases. This results in increased withdrawal of groundwater, though from a shallower water table area. The overall energy requirement for groundwater pumping under Policy-2 may be less or more than that under Policy-1 depending on the extent and location of additional groundwater pumping as compared to Policy-1.

Based on these observations, it has been concluded that though the Policy-2 allocates canal water in areas of deeper water table, thus saving energy demand, still a lot of canal water is lost through seepage in transporting it to areas of deep water table. Therfore, there may lie a canal-run configuration in-between canal-run configuration of Policy-1 and Policy-2 that may result in lesser requirement of energy. With this background, Policy-5 has been formulated in which operation simulation is carried out iteratively for various canal-run configurations and corresponding energy demand in the system is worked out. The configuration that requires minimum energy is finally adopted under Policy-5. Simulation analysis is started from the canal-run configuration of Policy-2 (shown in Figure – 7.8). The canal-run configuration is iteratively moved in the upstream direction towards the head by curtailing the canal water demands of most distant canal segment (from the network head) and using the saved water to meet the demands of upstream segments. Energy requirement for pumping groundwater in the command is computed for all canal-run configurations. Finally, the configuration which requires least energy for groundwater pumping is recommended under Policy-5. The variation of energy requirement in the command area as the canal-run configuration moves from Policy-2 in upstream direction for a week is presented in Figure – 7.11. The results of canal operation with Policy-5 are shown in Figure – 7.12.

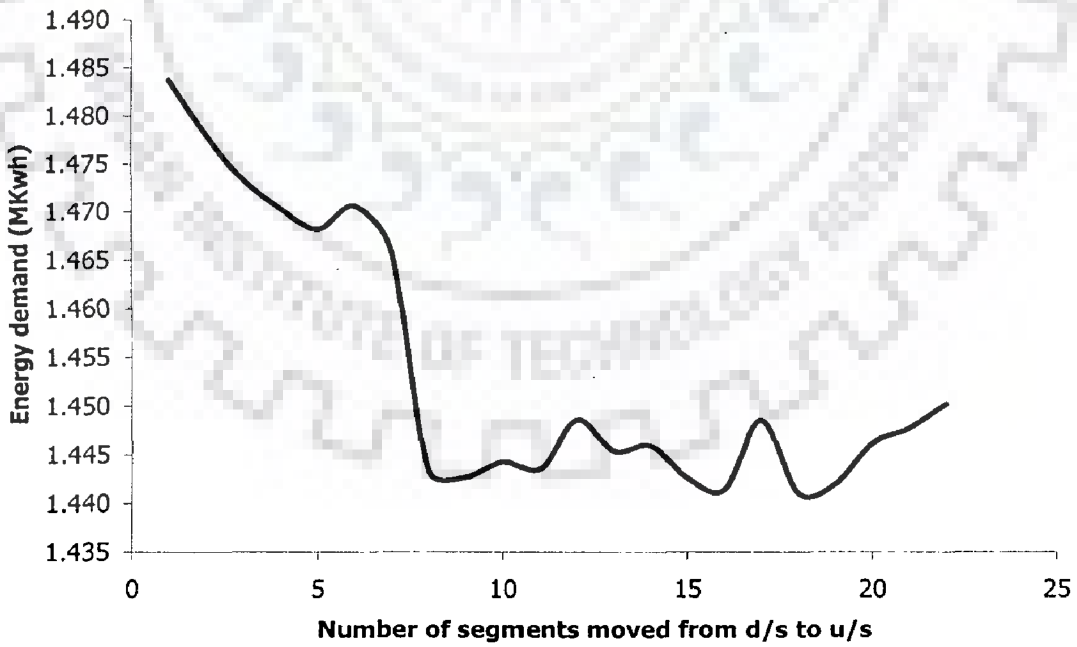

Figure – 7.11: Variation of energy demand for different canal-run configuration

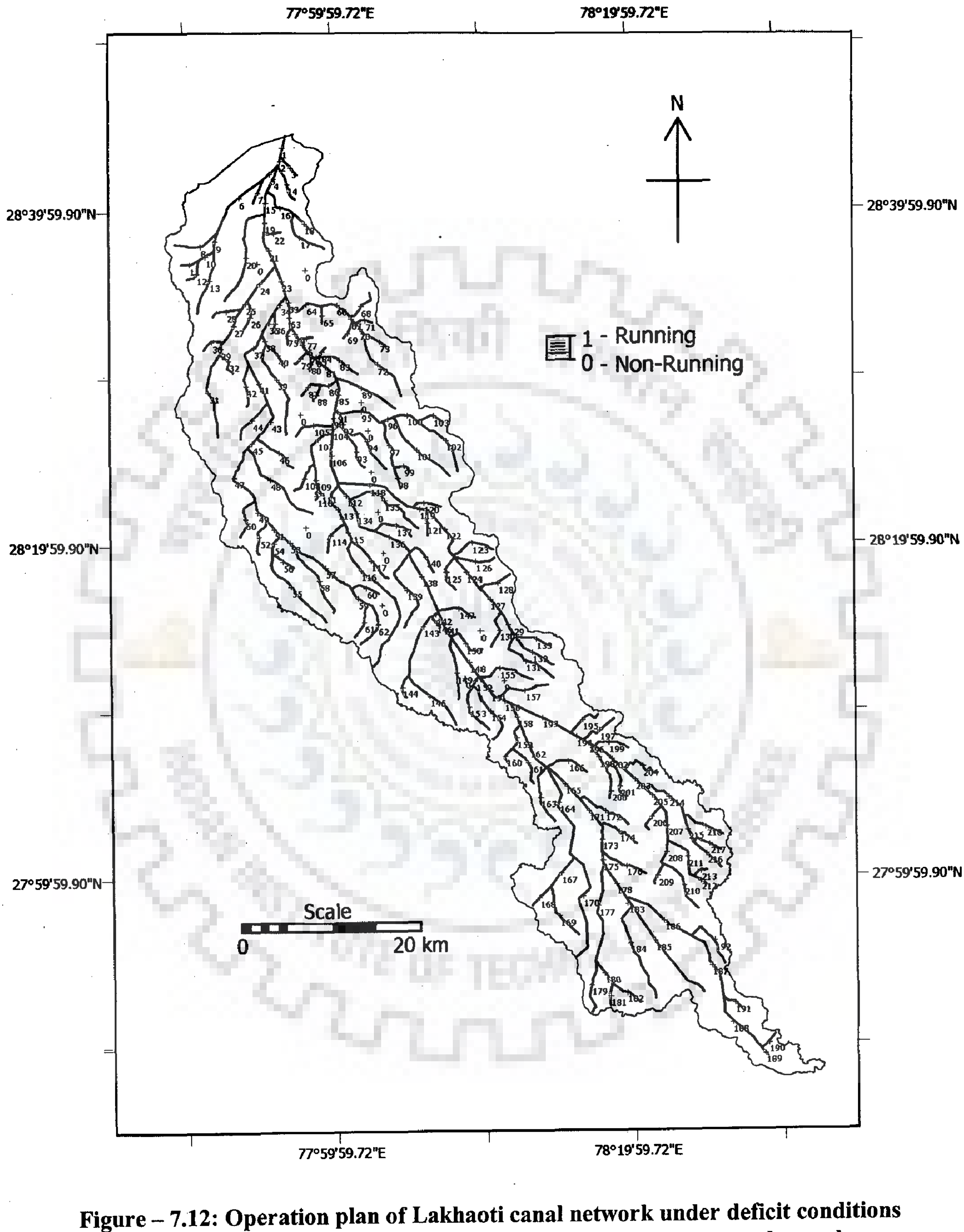

Figure – 7.12: Operation plan of Lakhaoti canal network under deficit conditions with policy of conjunctive use with minimum energy demand

Summary results of Policy-5 for the command show an irrigation utilization of 18.56 Mm3, canal seepage of 5.62 Mm3, groundwater withdrawal of 32.31 Mm3, and energy requirement of 1.286 million units for meeting irrigation demands in the irrigable command area. Comparison of results of Policy-5 with four other policies (Table – 7.6) 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 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 Policy-2, 3, and 4.

7.3.3 Analysis of priority assignment to some canals

In section 7.3.2, the results of different allocation policies are presented considering that all segments in the canal network have normal priority. However, in CNSM, it is possible 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 demand 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 – 7.7. The results in map form are presented in Figure – 7.13. 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 as observed from Table – 7.2 (for example, demands of segment 209 are curtailed for satisfying capacity constraint of segments 205 and 207). It is also observed from Figure – 7.13 and Figure – 7.7 that because of priority demands, a few segments of normal priority could not be allocated canal water in the head reaches.

7.3.4 Analysis of augmentation supply in the canal network

The canal network simulation model takes into account the augmentation supply in canal network at some intermediate location. From Table – 7.4, it is observed that with the water availability of 40 cumec at canal head and with the

Table – 7.7: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
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	155.85	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

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)
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
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

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)
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
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

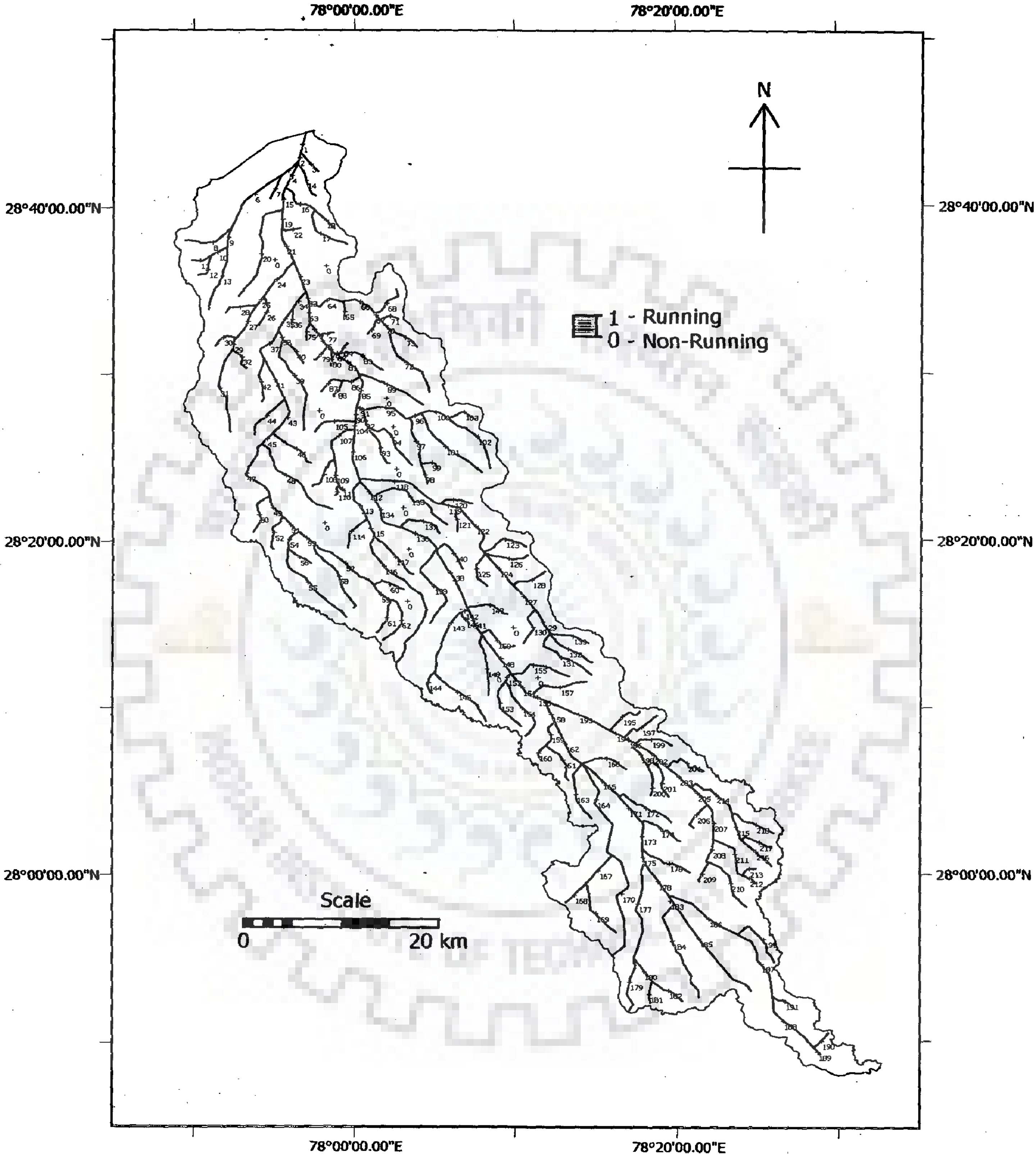

Figure – 7.13: Operation plan of Lakhaoti canal network with priority demands under deficit conditions with policy of head-reach priority adoption of Policy-1, discharge of 32.57 cumec is required at segment 23 while its discharge capacity is 54.79 cumec. Let augmentation supply of 10 cumec is made in segment 23. The resulting operation scenario is tabulated in Table – 7.8 and depicted in map form in Figure - 7.14.

It is seen from Figure – 7.14 that with intermediate augmentation supply, it is possible to meet the demands of a larger downstream network. In Table - 7.8, 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.

7.4 VALIDATION OF PROPOSED SCHEME FOR LAKHAOTI COMMAND

To check the validity of the proposed geo-simulation scheme, 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 (as discussed in Chapter-6) 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.

Table – 7.8: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
66	64	23.84	23.84	26.72	2.45	53.01	0.93	0.58	9.21	158.79	0.00
67	66	1.57	1.57	12.53	0.55	14.65	0.26	0.19	11.14	156.85	0.00
68F	66	20.04	10.54	0.00	1.53	12.07	0.21	0.60	11.14	156.86	9.50
69F	67	10.33	0.40	0.00	0.04	0.44	0.17	0.45	11.60	7.27	9.93
70	67	8.00	8.00	0.00	0.15	8.15	0.82	0.57	11.60	27.70	0.00
71F	67	4.03	3.37	0.00	0.56	3.94	0.07	0.40	11.60	156.40	0.66
72F	70	69.13	0.00	0.00	0.00	0.00	0.00	0.00	12.35	0.00	69.13

Seg. Iden.	U/s Seg. Iden.	Local Irrigation Demand (Ham)	Canal Water. Demand (Ham)	Total D/s Demand (Ham)	Canal Seepage Loss (Ham)	Total Canal Water Demand (Ham)	Required Discharge (Cumec)	Water Depth (m)	Fill Time (Hour)	Run Time (Hour)	Total GW Demand (Ham)
73F	70	17.41	0.00	0.00	0.00	0.00	0.00	0.00	12.35	0.00	17.41
74	63	17.29	17.29	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
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

Seg. Iden.	U/s Seg. Iden.	Local Irrigation Demand (Ham)	Canal Water Demand (Ham)	Total D/s Demand (Ham)	Canal Seepage Loss (Ham)	Total Canal Water Demand (Ham)	Required Discharge (Cumec)	Water Depth (m)	Fill Time (Hour)	Run Time (Hour)	Total GW Demand (Ham)
148	141	52.70	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
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

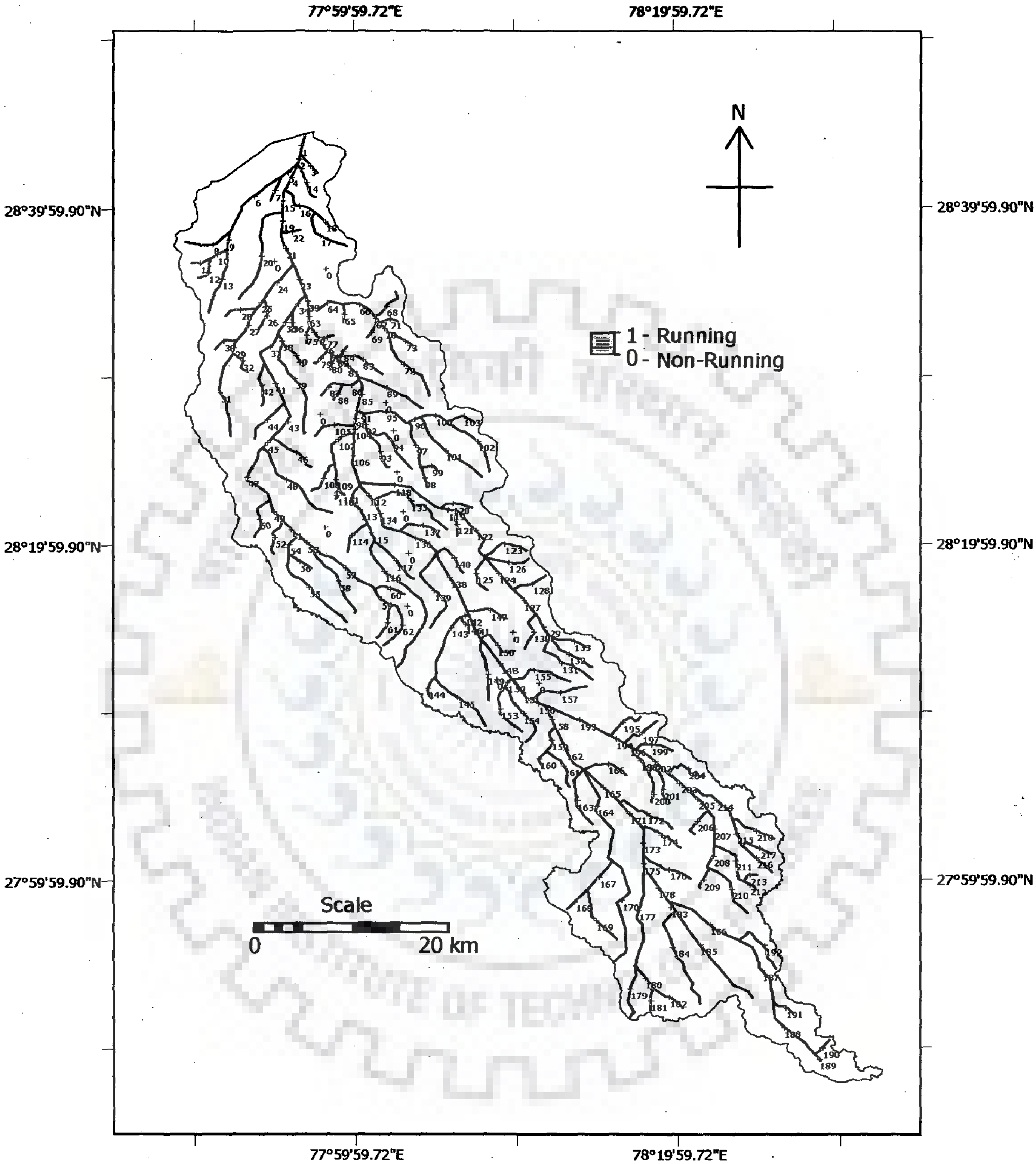

Figure – 7.14: Operation plan of Lakhaoti canal network with augmentation supply and under deficit conditions with policy of head-reach priority

7.4.1 Application of proposed geo-simulation scheme

The flow chart showing computational steps of the geo-simulation scheme is described in Figure – 5.1. The scheme 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 26^{th} calendar week (June 25) but due to the breach in the canal system, the canal was actually run from July 16, 1998. Weekly discharges available at the head of the canal network are specified in Table-7.9 (Column-6), which gives the summary of results of network operation for the year 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-5.1). 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 the groundwater behaviour model is imported in the scheme for use in 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 – 7.15. 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

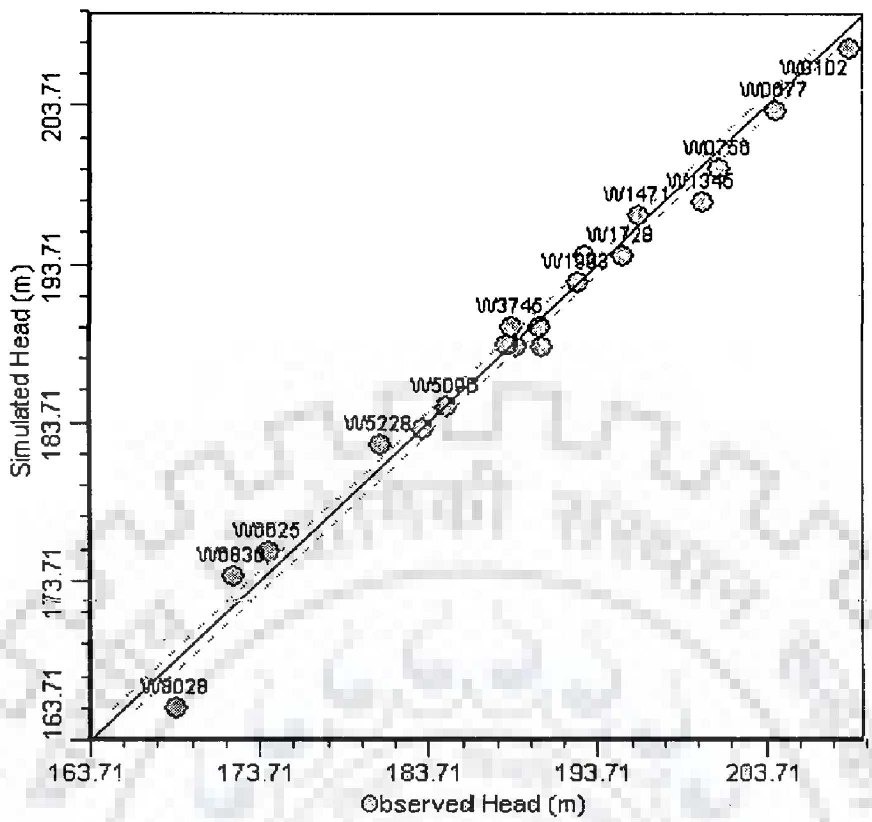

Figure – 7.15: Observed & simulated water levels in observation wells in October

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. Aggregated results of various components of the scheme for the command are presented in Table – 7.9.

7.5 EVALUATION OF ALLOCATION POLICIES

For validation, the Lakhaoti command has been simulated with the actual meteorological, hydrological, and hydro-geological data for the year 1998. The simulation results indicate that the year 1998 was a wet year with monsoon rainfall exceeding the normal rainfall by about 20%. Higher rainfall results in reduced irrigation demands in the command such that in 10 out of 13 weeks of canal operation, the water demand at canal system head has been less than the availability. In case of

Table – 7.9: Aggregated results of geo-simulation scheme for Lakhaoti command in Kharif season in 1998

Calendar Week	Initial Water Content (Mm3)	Total Rainfall in Command (Mm3)	Total Evapo-transpiration Demand (Mm3)	Field-level Irrigation Demand in Total Command (Mm3)	Required Discharge at Canal Head (Cumec)	Available Discharge at Canal Head (Cumec)	Demand not considered because of waterlogging (Mm3)	Canal seepage loss (Mm3)	Total groundwater pumping (Mm3)	Total groundwater recharge (Mm3)	Power demand for pumping groundwater (MKwh)
24	80.710	61.292	78.449	9.189	18.850	0.000	0.000	0.000	16.448	5.750	54.989
25	78.360	4.853	30.578	26.291	39.585	0.000	0.000	0.000	47.054	17.143	168.516
26	82.767	74.020	55.204	3.864	8.601	0.000	0.000	0.000	6.907	15.197	27.140
27	93.274	146.205	47.896	55.748	58.449	0.000	0.000	0.000	99.473	148.714	372.283
28	144.260	22.587	36.946	56.057	59.820	0.000	0.000	0.000	100.193	65.744	376.194
29	174.902	312.188	51.461	2.053	4.848	10.460	0.000	0.986	2.087	211.692	7.504
30	231.203	9.755	45.932	22.542	38.683	47.426	0.000	8.941	25.585	30.914	89.271
31	237.583	60.980	57.350	16.754	33.682	49.120	0.000	7.563	17.006	29.684	64.284
32	267.861	97.504	44.207	6.221	18.517	55.463	0.000	5.477	5.414	52.076	21.434
33	296.891	214.289	48.717	0.336	1.493	63.713	0.000	0.122	0.414	124.208	1.535
34	333.764	220.801	42.094	0.385	1.609	49.696	0.000	0.194	0.404	140.534	1.547
35	344.464	36.111	47.852	6.425	10.272	33.867	0.000	2.012	7.934	16.032	24.742
36	330.125	0.000	35.165	35.267	54.741	37.033	0.000	8.276	48.202	37.932	167.409
37	321.764	66.277	46.588	6.905	18.541	48.840	0.000	3.490	6.531	26.234	19.686
38	326.015	80.165	45.220	3.249	8.343	49.250	0.008	0.858	3.254	30.715	9.358
39	328.127	38.154	36.954	10.302	24.440	48.005	0.003	6.002	9.592	24.917	31.647
40	326.742	18.094	36.187	21.004	41.689	12.198	0.020	3.464	33.838	25.077	107.848
41	237.193	0.000	18.190	22.762	46.385	5.768	0.026	1.490	38.436	24.714	122.134

surplus water conditions, the canal water is allocated as per the demand in various segments subject to system capacity constraints. No allocation policy is required in such cases. However, under canal water deficit conditions, some policy is required to allocate the available canal water and groundwater in the irrigation system. In CNSM, different allocation policies are invoked only when there is water deficit condition in the command and the irrigation demand at head exceeds the water availability. For this reason, a test case of water deficit condition has been assumed so that different policies of canal operation could be evaluated and their impact on the irrigation system performance could be analysed.

For creating deficit conditions, the weekly rainfall in the year 1998 has been taken to be 60% of the actual weekly rainfall and the water availability at canal head is reduced to 75% of the planned supply in the canal system (given in Table - 6.6) from week 24 to 41. With the selection of 60% limit for rainfall occurrence and 75% limit for canal supply availability, water scarcity in the command occurred in 12 out of 18 weeks. With these two limitations of water supply, the proposed scheme is run for the Lakhaoti system for 18 weeks (the period for which the canal system is planned to be run) starting from week 24. The Lakhaoti system simulation was run for five times (for each of the five operation policies) adopting a specific operation policy for each run. All the canal segments are assigned normal priority and no augmentation supply is assumed. Under each run with a particular policy, the groundwater surface is generated for each month in a similar way as has been done under validation of the scheme. The results of five policies are presented in the form of tables and figures.

7.5.1 Discussion of results of allocation policies

Table – 7.10 shows the general hydrological details in Lakhaoti command under assumed deficit conditions. Column-2 shows the aggregated volume of initial moisture content in the effective soil depth in the command (root zone of crops in agricultural grids and minimum soil depth of 150 mm in non-agricultural grids). At the start of simulation, the soil moisture in each grid is assumed to lie mid-way between the field capacity and wilting point limits at the grid. It is seen in Column-2 that initial water in week 24 is high, it reduces in week 25, and then increases steadily till week

Table – 7.10: Hydrological information for Lakhaoti command under deficit conditions

Calendar Week	Initial Water Content (Mm3)	Total Rainfall in Command (Mm3)	Total Evapo-transpiration Demand (Mm3)	Field-level Irrigation Demand in Total Command (Mm3)	Field-level Irrigation Demand in Canal-irrigable Command (Mm3)	Required Discharge at Canal Head (Cumec)	Available Discharge at Canal Head (Cumec)
Col. 1	Col. 2	Col. 3	Col. 4	Col. 5	Col. 6	Col. 7	Col. 8
24	82.68	37.56	58.45	11.41	6.68	19.13	9.63
25	73.20	2.92	27.41	30.48	17.73	44.91	9.63
26	79.10	45.74	43.11	8.87	5.61	27.52	9.63
27	89.16	89.82	43.54	57.37	49.69	62.27	47.86
28	116.39	13.83	33.40	72.91	58.58	62.71	47.86
29	142.28	186.12	51.89	24.99	20.44	45.82	47.86
30	198.01	5.81	44.79	55.61	39.06	62.93	47.86
31	205.72	36.75	48.72	55.76	40.56	62.04	47.86
32	240.47	58.89	40.91	33.48	27.86	58.68	47.86
33	275.18	131.98	48.87	7.69	6.65	18.51	47.86
34	307.07	134.02	42.22	6.02	4.99	15.09	47.86
35	327.60	22.31	45.18	26.43	20.29	47.70	47.86
36	322.20	0.00	32.63	42.65	31.92	62.46	47.86
37	323.31	40.38	42.52	14.65	11.98	31.64	47.86
38	323.26	48.08	43.34	11.30	9.13	25.93	47.86
39	327.26	23.37	33.53	15.96	13.43	36.25	23.93
40	323.31	10.76	26.63	24.63	18.71	48.13	23.93
41	238.51	0.00	18.06	22.74	18.42	46.70	11.89

35. Initial moisture in week 25 decreases because moisture content in non-agricultural grids reduces [because potential evapo-transpiration demand in week 24 (50.73 mm) is higher than the rainfall in the command] below the initial values and irrigation supply (either canal water or groundwater) is made only for the agricultural grids. Since rice and guar crops are planted in first week of July, a major part of command remains under fallow land in week 25. After week 25, the cropped areas build up and the root zone of different crops also increase steadily which increases the aggregated initial moisture content in the effective soil depth in the command. In week 36, 38, and 40, there is marginal decrease in aggregated initial moisture in the command which could be attributed to the low rainfall in previous week as compared to potential evapo-

transpiration which decreases the moisture content in non-agricultural grids. There is a major decrease in aggregated initial moisture in the command in week 41 which could be because of the harvesting of two crops (maize and guar) in the command in week 40 such that the effective soil depth at such grids reduces to 150 mm, thus affecting the aggregated moisture value.

Column-3 shows the total rainfall volume over the command and Column-4 shows the aggregated actual evapo-transpiration volume in command which seems to be very high for week 24 though there is appreciable rainfall in the command. The reason is that major part of the rainfall in week 24 has occurred on the last day of the week and because of the six initial hot dry days, the aggregated potential evapo-transpiration in the week is very high (50.73 mm). Actual evapo-transpiration depends on the effective soil depth, crop type and its growth stage, soil type, and available moisture. Column-4 shows the integrated effect of all factors on actual evapo-transpiration in the command. Column-5 shows the aggregated irrigation demands at field-level in the overall command while Column-6 presents the field-level aggregated irrigation demands in the canal-irrigable area. From the two columns, it is observed that after the week 27 (introduction of rice crop), major demands in the command are coming from the canal-irrigable area. Column-7 shows the discharge requirement at canal head to meet the demands of canal-irrigable area while Column-8 shows the available discharge at canal head. In 12 weeks, demand is more than supply and some decision-making criteria are required in these weeks to allocate the canal water and groundwater.

The results of system operation with different allocation policies are presented in Table – 7.11. In this table, Columns 3 to 7 show the canal water use for meeting demands in the canal-irrigable area. Figure – 7.16 presents the canal seepage losses under different operation policies. It can be seen that head priority policy (Policy-1) results in maximum utilization of water for meeting irrigation demands as the canal seepage losses are minimum. However, since this policy does not consider the groundwater scenario in the command and allocates water in the head reaches, the total energy requirement (for groundwater withdrawal) for meeting full irrigation demands in the canal-irrigable and total command comes out to be 6.998 and 2596.10 Mkwh

Table – 7.11: Operation results of Lakhaoti command for five different allocation policies under deficit conditions

Calendar Week	Field-level Irrigation Demand in Canal Irrigable Area (Mm3)	Canal Water Used for Irrigation (Mm3)					Energy Demand in Irrigable Command (MKwh)					Groundwater Withdrawal in Total Command (Mm3)					Recharge in Total Command (Mm3)					Energy Demand in Total Command (MKwh)				
		Pol - 1	Pol - 2	Pol - 3	Pol - 4	Pol - 5	Pol - 1	Pol - 2	Pol - 3	Pol - 4	Pol - 5	Pol - 1	Pol - 2	Pol - 3	Pol - 4	Pol - 5	Pol - 1	Pol - 2	Pol - 3	Pol - 4	Pol - 5	Pol - 1	Pol - 2	Pol - 3	Pol - 4	Pol - 5
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
24	6.679	4.372	3.623	3.908	3.042	4.015	0.0984	0.0969	0.1033	0.1123	0.0913	16.00	16.75	16.47	17.33	16.36	8.38	9.11	8.87	9.57	8.74	54.19	54.02	54.72	55.54	53.46
25	17.732	4.609	3.598	4.161	2.579	4.345	0.5346	0.5275	0.5203	0.5490	0.5010	49.82	50.83	50.26	51.85	50.08	20.11	21.09	20.81	22.02	20.47	179.44	178.66	178.01	180.92	176.12
26	5.614	3.645	3.342	3.375	2.910	3.542	0.0855	0.0833	0.0917	0.1045	0.0799	12.19	12.49	12.46	12.92	12.29	8.92	9.32	9.34	9.59	9.20	47.79	47.59	48.44	49.82	47.26
27	49.692	21.762	19.295	20.776	17.350	19.935	1.1366	1.1569	1.1630	1.1949	1.1353	80.70	83.16	81.68	85.86	82.52	115.07	117.28	116.07	119.66	116.79	306.69	308.70	309.11	316.89	306.50
28	58.581	22.210	19.624	21.008	17.137	21.147	1.4602	1.4941	1.4952	1.5039	1.4671	108.00	110.56	109.18	113.82	109.04	81.48	83.59	82.51	86.40	82.35	404.54	407.47	407.85	416.29	404.57
29	20.437	17.829	18.580	17.687	17.642	18.601	0.0988	0.0650	0.1043	0.0950	0.0641	26.80	26.05	26.95	26.99	26.03	119.47	120.14	119.36	120.08	120.15	99.89	96.88	100.59	100.03	96.57
30	39.064	20.406	18.451	19.476	16.353	19.080	0.7822	0.7674	0.7751	0.8206	0.7501	78.88	80.83	79.81	82.95	80.20	51.02	53.08	52.22	54.87	52.54	295.20	294.66	294.88	300.43	292.39
31	40.562	20.548	18.517	19.528	16.059	19.285	0.8451	0.8360	0.8381	0.9006	0.8159	79.03	81.06	80.05	83.52	80.29	51.17	53.21	52.38	55.33	52.58	300.54	300.30	300.21	307.67	297.81
32	27.864	18.388	17.215	18.039	16.248	18.116	0.4233	0.4037	0.4193	0.4377	0.3888	41.38	42.56	41.73	43.53	41.66	42.75	43.91	43.33	44.87	43.27	162.54	160.76	162.28	164.10	159.30
33	6.652	6.635	6.642	6.635	6.642	6.642	0.0005	0.0004	0.0005	0.0004	0.0004	7.09	7.08	7.09	7.08	7.08	59.37	59.36	59.37	59.36	59.36	25.71	25.68	25.74	25.74	25.62
34	4.993	4.969	4.984	4.969	4.976	4.984	0.0009	0.0004	0.0009	0.0007	0.0004	5.76	5.74	5.76	5.75	5.74	75.44	75.47	75.45	75.46	75.46	22.63	22.56	22.66	22.62	22.47
35	20.289	17.509	17.730	17.386	17.913	17.763	0.1175	0.0875	0.1225	0.0921	0.0874	29.67	29.45	29.80	29.27	29.42	34.72	35.35	34.59	35.21	35.33	107.34	104.74	108.14	105.72	104.45
36	31.921	20.143	18.363	19.080	16.249	19.007	0.4805	0.4727	0.4876	0.5294	0.4526	56.02	57.80	57.09	59.92	57.16	43.44	44.96	44.41	46.81	44.43	202.82	202.54	204.05	210.09	200.48
37	11.980	11.927	11.981	11.833	11.680	11.981	0.0013	0.0000	0.0055	0.0095	0.0000	14.23	14.18	14.33	14.48	14.18	26.44	26.47	26.36	26.37	26.47	46.89	47.00	47.44	48.25	46.95
38	9.128	9.113	9.113	9.113	9.129	9.113	0.0001	0.0001	0.0001	0.0000	0.0001	11.07	11.07	11.07	11.06	11.07	23.54	23.54	23.54	23.55	23.54	35.74	35.99	35.89	36.32	35.87
39	13.435	9.583	8.815	8.903	7.640	9.153	0.1577	0.1498	0.1628	0.1985	0.1432	18.93	19.70	19.62	20.88	19.36	24.03	24.77	24.70	25.77	24.46	68.41	67.64	69.01	72.77	66.96
40	18.713	10.495	8.921	9.466	7.321	10.369	0.3097	0.3193	0.3255	0.3638	0.2932	33.50	35.07	34.52	36.67	33.62	27.79	29.25	28.82	30.64	28.01	115.60	117.04	117.47	122.65	114.12
41	18.423	5.665	4.842	5.024	3.304	5.473	0.4657	0.4702	0.4672	0.4778	0.4432	34.92	35.75	35.57	37.28	35.12	24.55	25.30	25.16	26.44	24.74	120.14	120.82	120.53	123.82	117.94

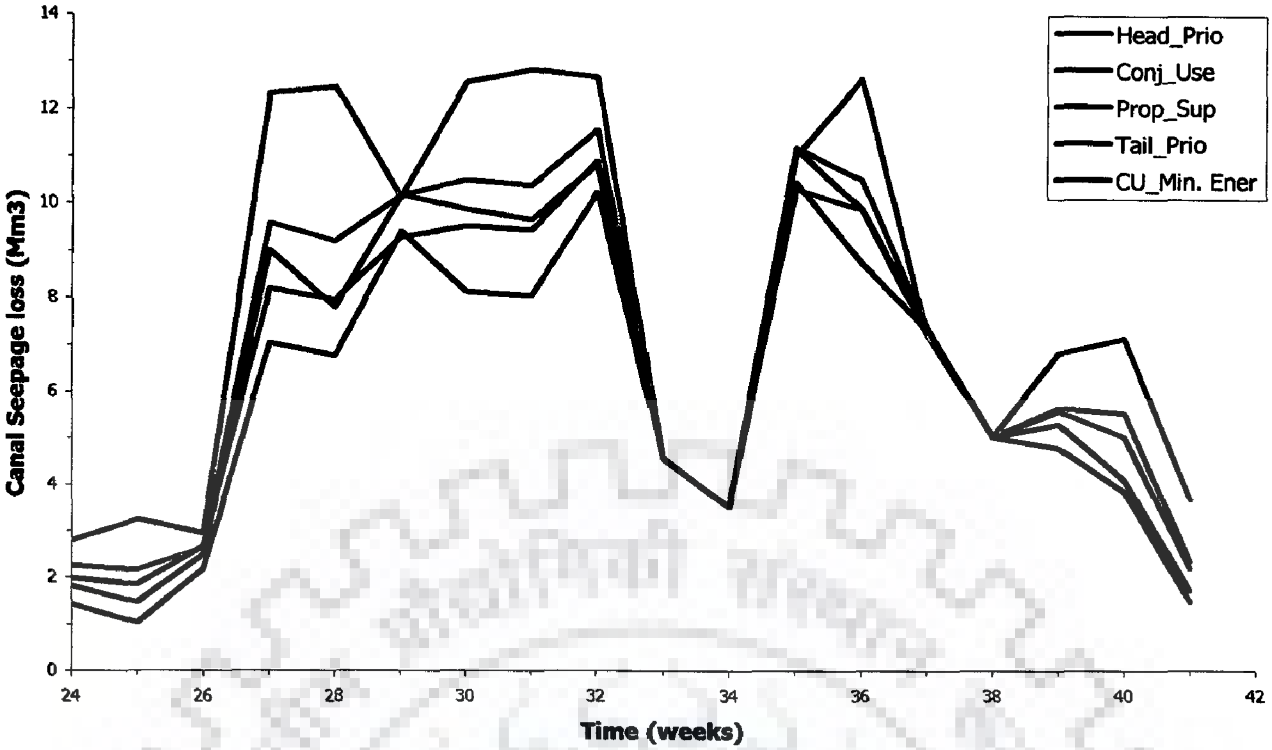

Figure – 7.16: Canal seepage losses under different allocation policies

respectively. On the other hand, policy of tail-priority (Policy-4) results in least use of canal water. Total energy requirement (for groundwater withdrawal) for meeting full irrigation demands in the canal-irrigable and total command under Policy-4 comes out to be 7.390 and 2659.67 MKwh respectively. Policy of conjunctive use (Policy-2) allocates the water in areas of deeper water depth and thus results in energy conservation, though seepage losses under this policy remain high. Under Policy-2, energy demand in canal-irrigable and total command comes out to be 6.931 and 2593.07 MKwh respectively. Policy of proportionate supply (Policy-3) results in relatively higher amount of canal water utilization for meeting irrigation demands (as compared to Policy-2 and Policy-4) and lesser canal seepage. However, since no consideration is given to the groundwater scenario in the command, this policy requires higher energy for withdrawing groundwater (7.082 in canal-irrigable area and 2607.02 MKwh in total command) for meeting full irrigation demands.

In comparison to the results with four conventional policies as mentioned above, the results with policy of minimum energy demand (Policy-5) indicate that by judiciously selecting the canal network for operation during a week, it is possible to achieve a relatively higher utilization of canal water for irrigation with higher canal seepage and with least energy demand for withdrawing groundwater for meeting full irrigation demands. From Figure – 7.16, it is seen that with Policy-5, the canal seepage is higher than Policy-1 thus recharging higher amount of water in aquifer system. The energy demand in canal-irrigable area and total command area under Policy-5 comes out to be 6.714 and 2568.82 Mkwh. For irrigable command, it is 0.282 Mkwh less than that required by Policy-1 while for total command, it is 27.28 Mkwh less than that for Policy-1. The reason for this large saving in energy in the total command could be that since Policy-5 supplies canal water in areas of deeper groundwater table, the canal seepage in those areas recharges the aquifer system such that water table builds up and the areas adjacent to the canal-irrigable areas withdraw water from a comparatively shallow depth resulting in saving of large amount of energy. It needs to be mentioned here that the amount of energy saving for total command area under policy-5 is case specific and depends on a number of factors such as irrigation demands, water deficit at head, cropping pattern, aquifer characteristics etc.

Figure – 7.17 shows the temporal distribution of groundwater withdrawal in the command. In week 25, water is required for field preparation for maize crop. The rainfall and irrigation input in the command are very low during week 25, therefore, groundwater withdrawal shows a rise during this week. After field preparation and crop plantation, crop water demand depends on potential evapo-transpiration, crop factor, and moisture condition in root zone. So, week 26 does not show any major water demand. In week 27, water is required for field preparation of rice (which has a large area) and guar crops requiring higher withdrawal of groundwater in spite of heavy rainfall in the command. Because of low rainfall in week 28 and heavy water demand by rice fields, groundwater withdrawal in week 28 is also high. Subsequently in week 29, heavy rainfall causes low pumping of groundwater. Figure – 7.18 shows the temporal distribution of recharge in the command which is highly influenced by rainfall in a week.

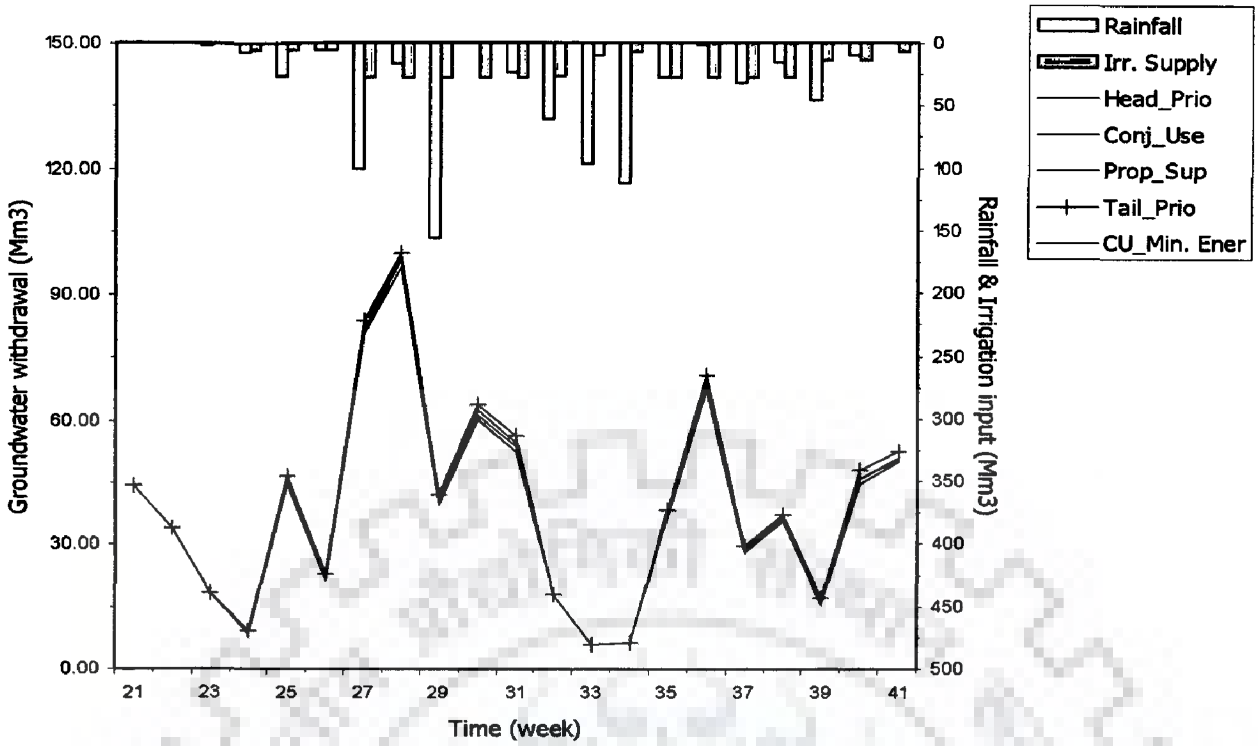

Figure – 7.17: Temporal variation of groundwater withdrawal in Lakhaoti command under five allocation policies

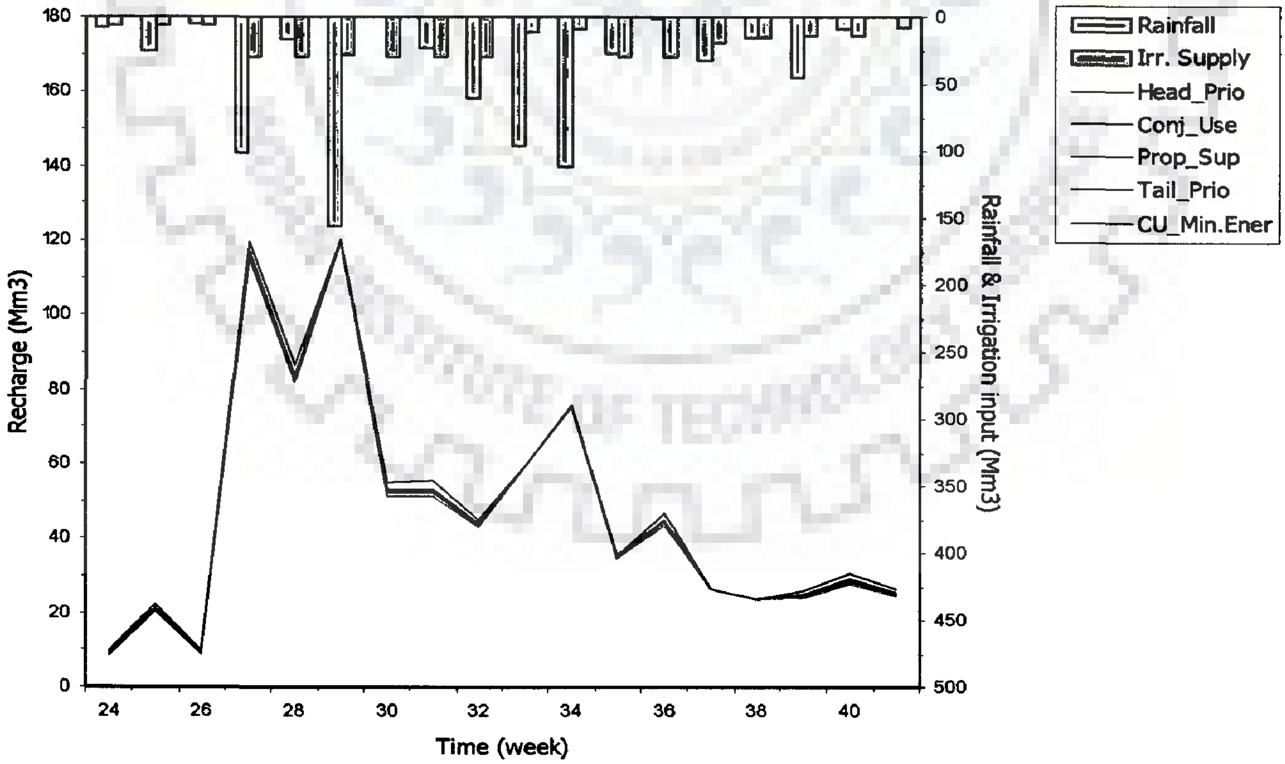

Figure – 7.18: Temporal variation of groundwater recharge in Lakhaoti command under five allocation policies

The effect of operation of Lakhaoti system with five allocation policies on the groundwater table is also analysed. Monthly groundwater surface is generated by the groundwater model for each of the five policies. The groundwater surface at the end of week 41 generated under five policies is presented from Figure – 7.19 to Figure 7.23. The contour patterns indicate that canal operation policy have a significant effect on the groundwater surface development in a command. Figure – 7.19 shows that with the policy of head-reach priority, water table is building up in the head reaches such that a contour of 208 m groundwater surface elevation has also appeared with this policy. Figure – 7.20 and Figure – 7.22, corresponding to Policy-2 and Policy-4 respectively, show the build-up of groundwater surface along the main canal system and its movement towards the tail-end of command.

7.5.2 Development of performance indicator maps

Various indicators of system performance, such as adequacy, efficiency, dependability, and equity have been defined in Chapter-5. Here, two maps showing the adequacy of water delivery in the canal system when operated with the policy of head-reach priority and policy of conjunctive use are presented in Figure – 7.24 and Figure – 7.25 respectively. The results of network operation corresponding to different weeks are saved in the database and the geo-simulation scheme picks up the relevant details, such as irrigation demands in various segments, actual canal water supply, cause of not meeting the demand etc. to calculate different performance indicators for all the canal segment. Similar maps can be generated for other performance indices corresponding to different allocation policies. This output is linked to the GIS to produce the information in map form.

7.6 CHAPTER CLOSURE

In this chapter, the application of the proposed geo-simulation model is presented for the case study of Lakhaoti command. The results are independently discussed for the two main models, SWBM and CNSM, which are a part of the scheme. Then, the validity of the proposed scheme is tested with the data of Lakhaoti command for the Kharif season of year 1998. The close match between the observed

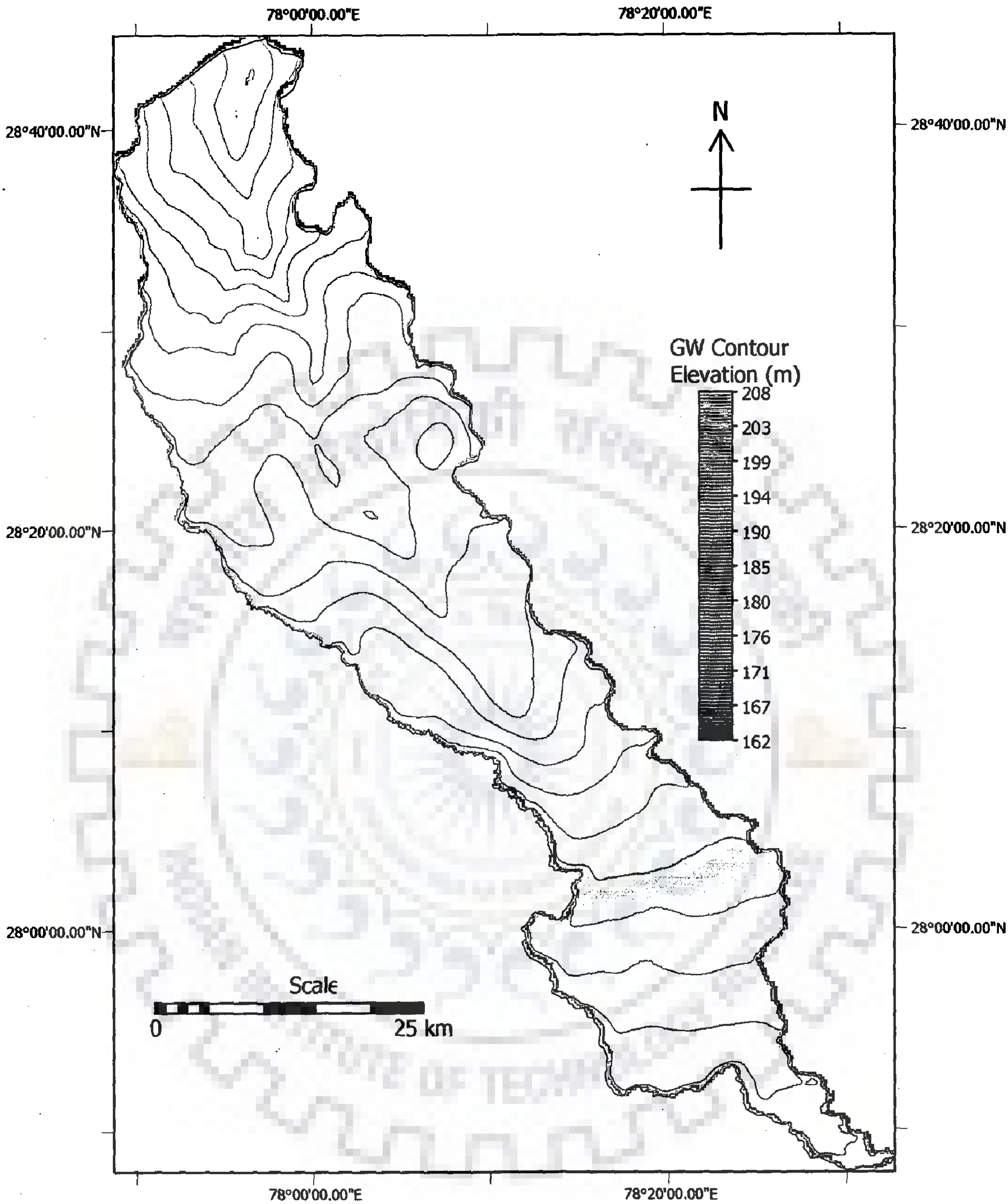

Figure – 7.19: Generated groundwater surface for Lakhaoti command for the month of October using the policy of head-reach priority

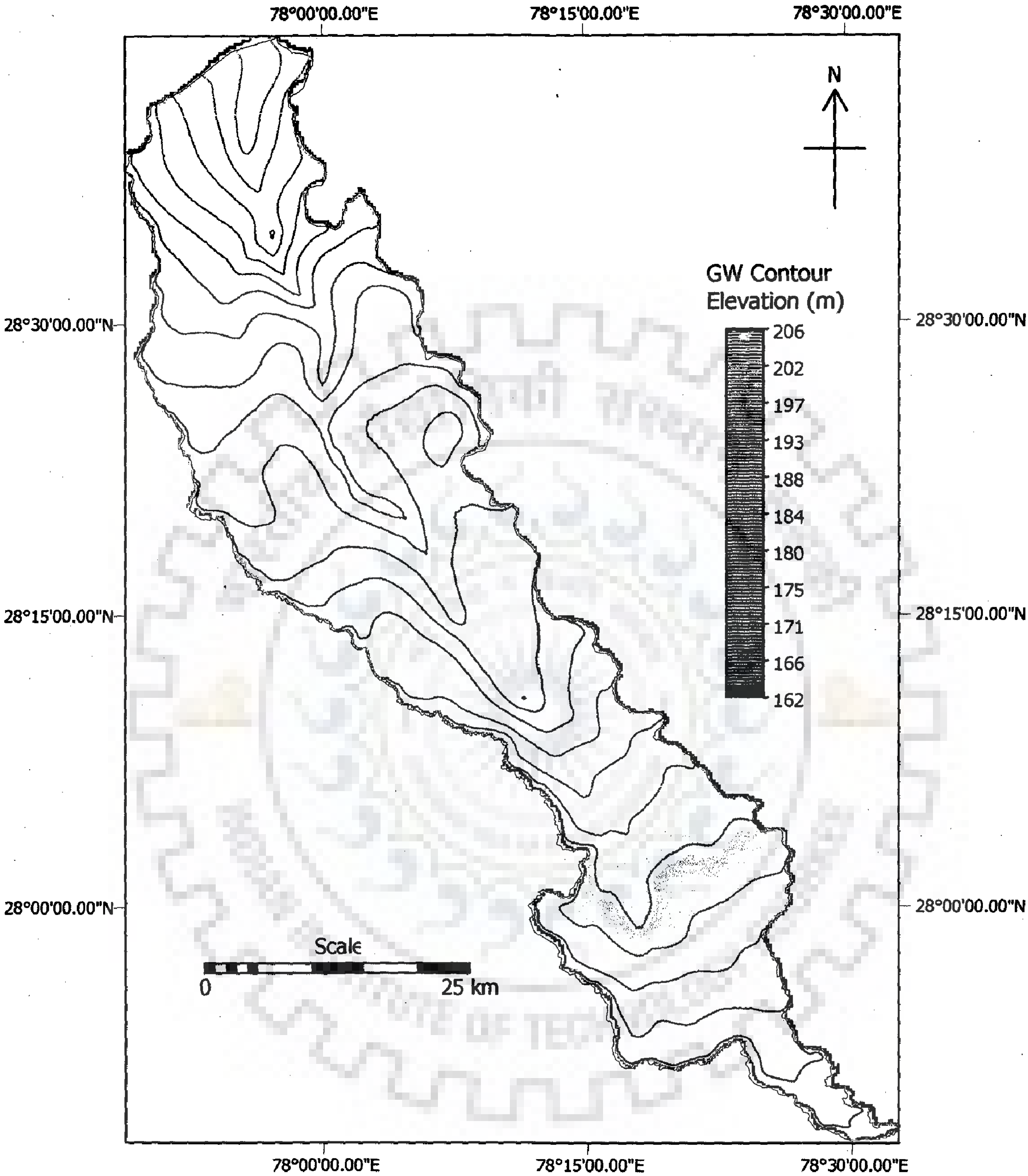

Figure – 7.20: Generated groundwater surface for Lakhaoti command for the month of October using the policy of conjunctive use

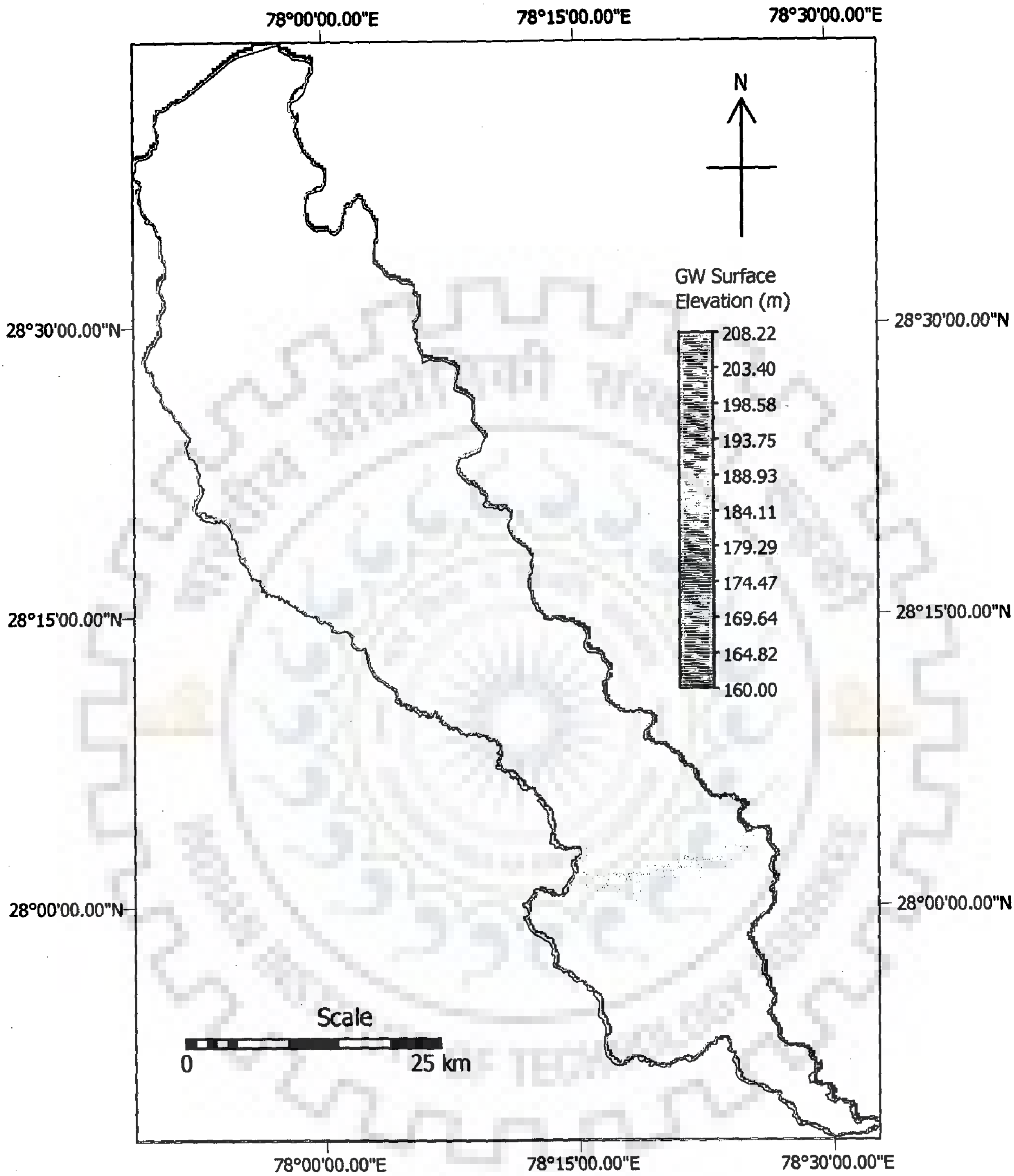

Figure – 7.21: Generated groundwater surface for Lakhaoti command for the month of October using the policy of proportionate supply

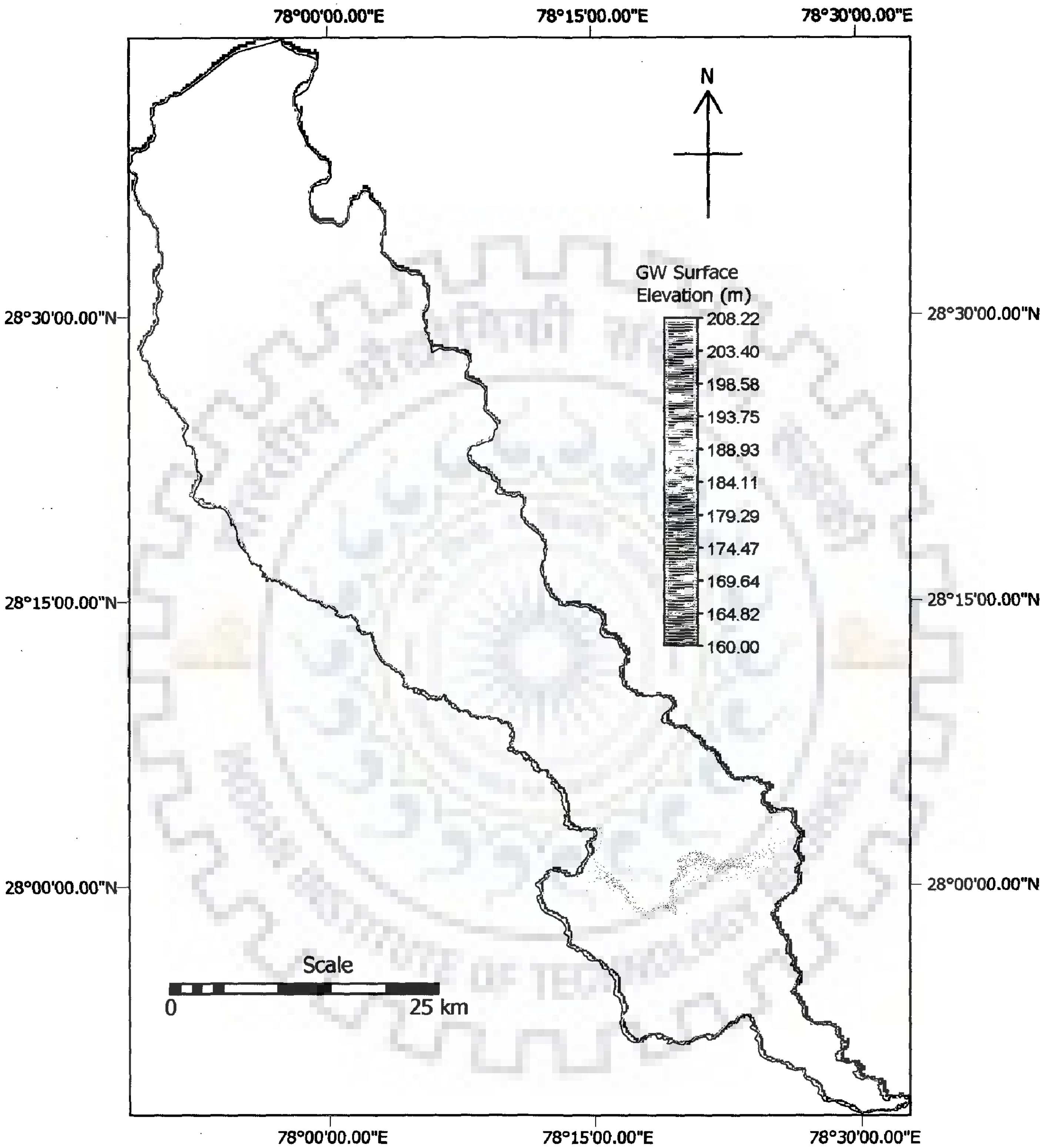

Figure – 7.22: Generated groundwater surface for Lakhaoti command for the month of October using the policy of tail-reach priority

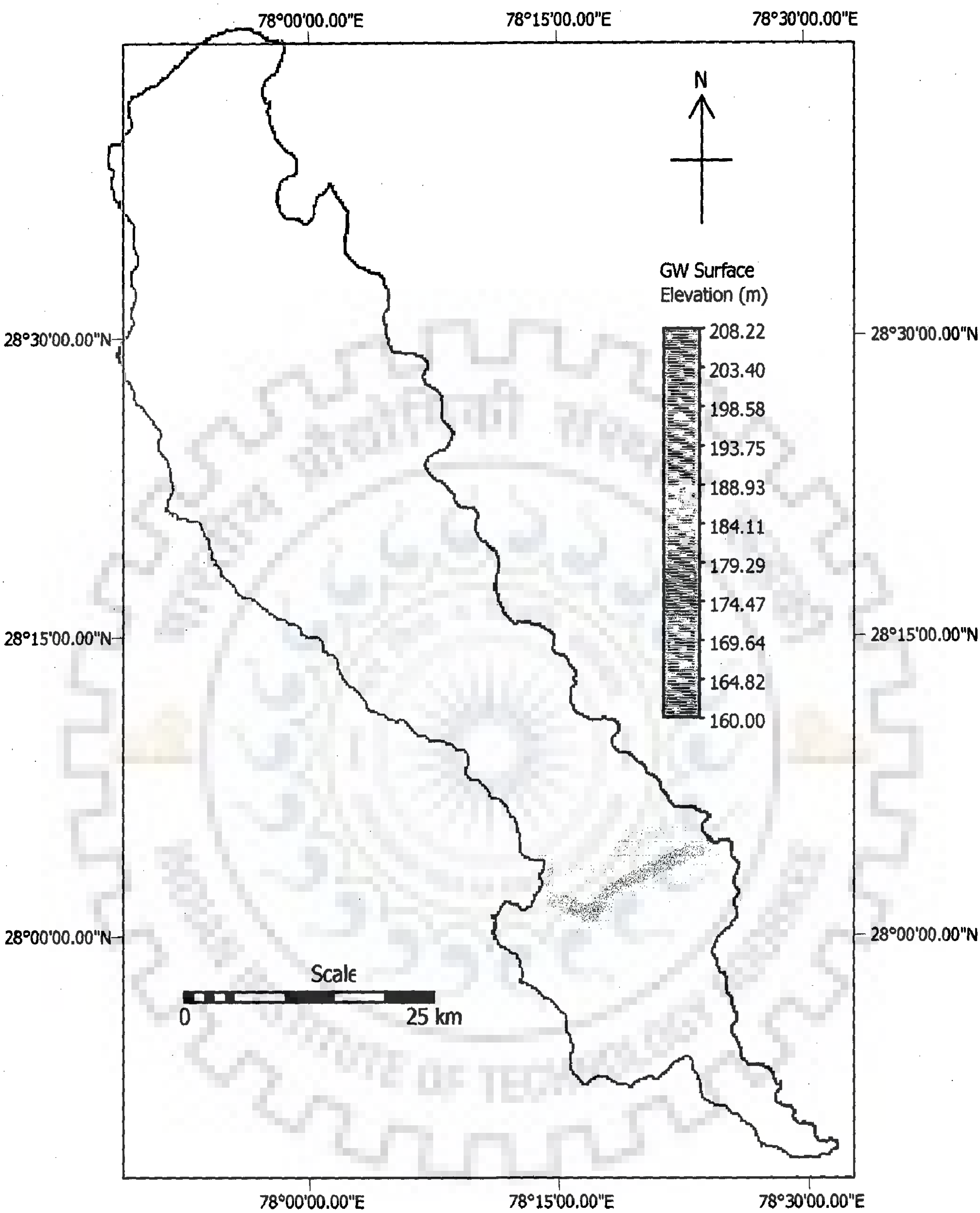

Figure – 7.23: Generated groundwater surface for Lakhaoti command for the month of October using policy of conjunctive use with minimum energy demand

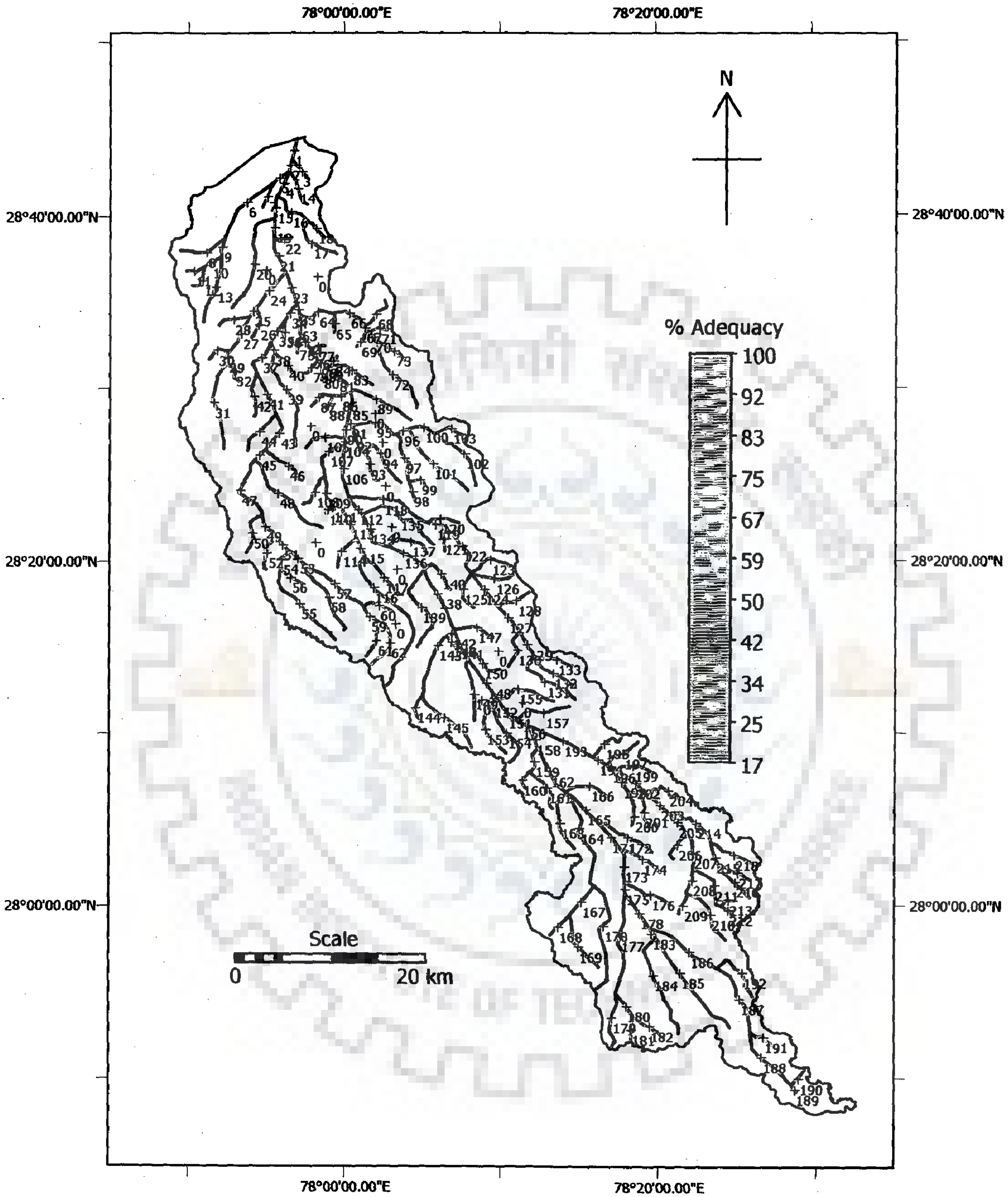

Figure – 7.24: Map showing the adequacy (in percent) of canal water delivery using the policy of head-reach priority

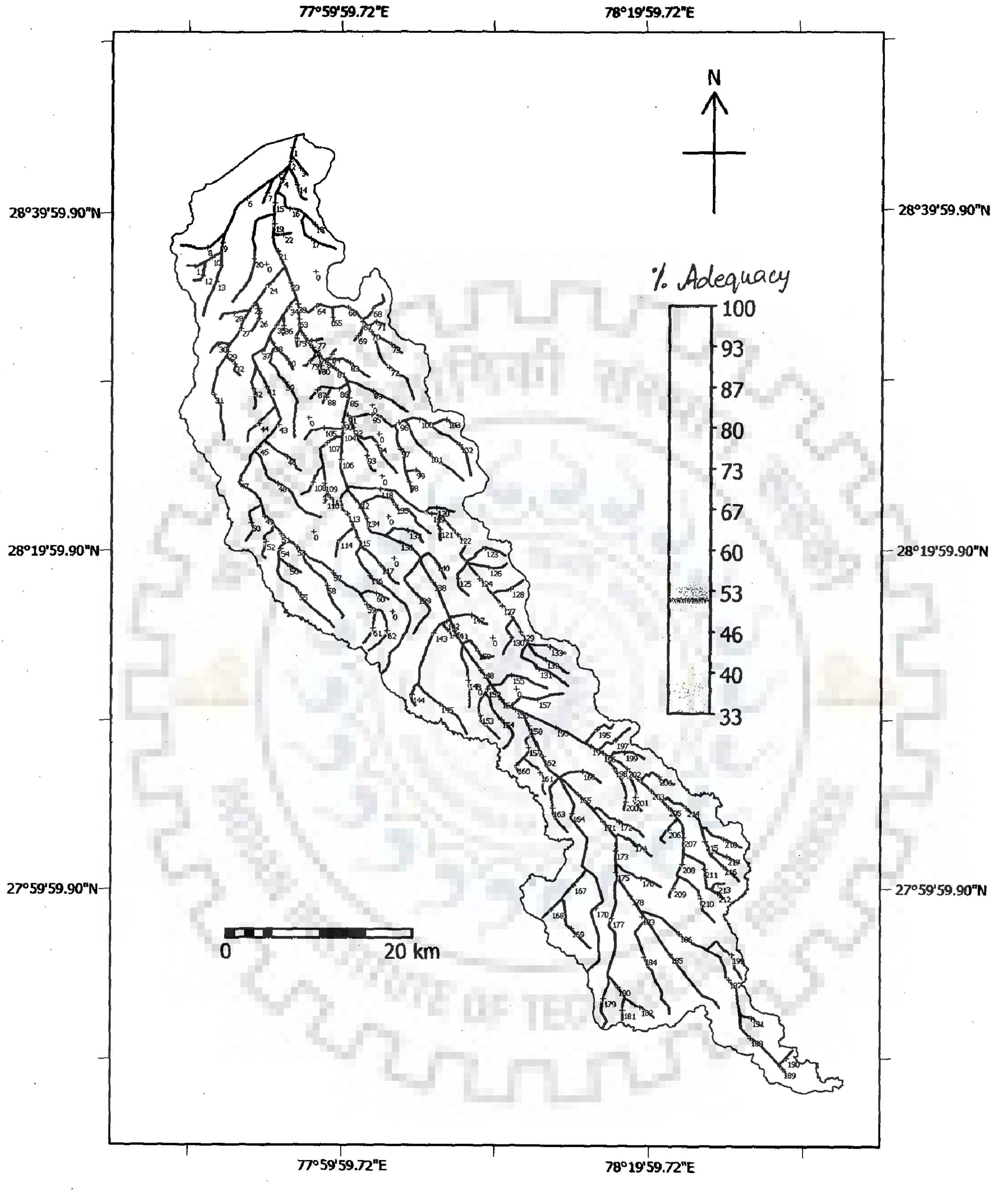

Figure – 7.25: Map showing the adequacy (in percent) of canal water delivery using the policy of conjunctive use

and simulated water levels at various observation wells in the command establishes the validity of the schme. To evaluate the performance of various allocation policies, test scarcity conditions have been assumed in the command and the simulation analysis has been carried out with all the five allocation policies. The results of five policies are analyzed and discussed. It is concluded that the policy of conjunctive use with minimum energy demand can result in large amount of energy saving as compared to other policies.

The proposed geo-simulation scheme can help the irrigation manager in optimally utilizing the vast database for judiciously operating a canal network. Consideration of groundwater conditions in the command in the operation of a canal network along with the irrigation demand and supply situation can help a long way for sustainable use of water resources in a command. A tool has now been developed (geo-simulation model) to integrate the multi-disciplinary information in a scientific way to converge at some meaningful decision-making. The presentation of results in map form can help a great deal in comprehending and understanding the system in great detail.

* * *

CHAPTER - 8

SUMMARY AND CONCLUSIONS

8.1 SUMMARY

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 scheme that can integrate the spatial and temporal information on relevant variables and processes for analyzing the weekly operation of a canal network.

The proposed geo-simulation scheme 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 scheme 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 in this study. For groundwater simulation, the scheme is linked to Visual MODFLOW. In addition, four modules (DIMENSION, FDIR, IMAGE, CODE) have been developed for preparing the spatial database and increasing the computational efficiency of the scheme while another four modules (SOURCE, GWRD, AGGREGATE, and WELL) have been developed for linking various component models of the scheme. For the developed models and modules, 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. To compare the performance of various allocation policies developed under CNSM, scarcity conditions with regard to rainfall and canal water supply have been artificially assumed. It is observed that considerable savings can be made by judiciously operating the canal system using the policy of conjunctive use with minimum energy demand. Groundwater surfaces corresponding to different policies of water allocation have been generated.

8.2 CONCLUSIONS

The problem of integrated operation of canal water and groundwater in an irrigation system is analyzed in the present study considering real-time spatial and temporal conditions in the command area. A distributed simulation scheme is developed to analyze various operation policies for the canal system.

The demand model of the scheme (SWBM) can be used to simulate spatially distributed irrigation demands in command area. The analysis can be performed at daily/weekly time step depending on the operational requirement. Irrigation demands can be estimated for various levels of depletion of readily available moisture in the root zone of crops. This model also finds out the areal distribution of a) crops under stress in the command area, b) deep percolation, and c) available water content in the root zone. Depiction of spatial results in map form makes it user-friendly to the irrigation manager in finding the priority areas for irrigation so as to avoid crop failure.

The allocation model (CNSM) can be used to generate spatially distributed allocation plan of canal water and groundwater for each week depending on a specified policy of irrigation water distribution. Various options have been added in the model to satisfy the canal capacity constraints. Five policies for canal water allocation have been considered: a) head-reach priority, b) proportionate supply, c) tail-reach priority, d) conjunctive use, and e) conjunctive use with minimum energy demand. Flexibility in operation is provided in the model to assign higher priority to a part of canal network with regard to a particular operation policy. Options to augment water supply at intermediate locations in canal system are also provided. The model output is linked to a GIS to visualize the operation results in form of maps.

CNSM maintains the water table conditions within permissible limits to avoid waterlogging and groundwater mining. With the application of this model in canal operation, use of irrigation water in an agricultural system can be made sustainable. Groundwater surface is generated in command corresponding to the applied stresses of pumping and recharge. Because of the spatial evaluation of pumping and recharge in the proposed scheme, it has been possible to make effective use of the groundwater simulation software, Visual MODFLOW.

The case study carried out for the Lakhaoti command demonstrates the generation and management of large database for an irrigation system. The case study also demonstrates the capability of the proposed scheme in integrating micro-level details to arrive at macro-level irrigation decisions without compromising the accuracy and without making gross assumptions, as has been done in the past. The results of study indicate that by judiciously allocating the canal water and groundwater in the command area with due consideration to the groundwater conditions, more than 27 million kilowatt-hour of energy requirement for groundwater pumping can be saved during the Kharif season while adopting the policy of conjunctive use with minimum energy demand as compared to the policy of head-reach priority under similar conditions of water supply to the existing crops.

8.3 POTENTIAL USE OF THE DEVELOPED SCHEME

The 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.

Performance indices, especially their spatial and temporal distribution, can be used to visualize the deficiencies of an irrigation system, such as structural constraints, growth of water intensive crops etc. By continuous analyses of spatial indices of system performance, location and cause of various discrepancies can be identified and measures can be taken to correct them.

8.4 FURTHER SCOPE

Some aspects, which can be further explored in geo-simulation scheme, are as follows:

a) In the present scheme, information about crop types and layout of canal system has been extracted from the satellite data. With the advancement in remote sensing and processing techniques, it is possible to deduce other important information about the command area (like actual crop evapo-transpiration, irrigated area etc.) and link the same to the modeling scheme.

b) In the soil water balance approach, the irrigation water demand is worked out on the basis of available and desired water content in the root zone. It is possible to link irrigation demands with the crop yield function to study the effect of water allocation on crop yield in command area.

c) CNSM is a demand-supply management model. It is possible to link the CNSM with a hydraulics model for analysis of time varying flow conditions.

d) It is possible to integrate an economic analysis model with the present scheme to study financial and economic aspects of canal water use and groundwater use for irrigation.

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APPENDIX - 1

Organisation of Computer Programs/Data files in CD

Various computer programs developed in this study and the database generated for the case study of Lakhaoti command area are given in enclosed CD. The study uses the ILWIS GIS system for maintenance of geographic database and visualization of results. The organisation of computer programs and database is described in the following:

1. Computer Programs

Various computer programs are provided in ***Directory "Computer_Programs"*** as Executable Files along with their Source Code. Because of the dimensional problem, the Soil Water Balance Model (SWBM) could not be compiled as a single program and has been bifurcated in to two Programs: SWBM1 and SWBM2. Following computer programs are provided:

a) DIMENSION – To find the dimensions of study area.

b) IMAGE – To remove redundant area from GIS ASCII file for use by different programs or convert a distributed output file as an ASCII image (attach redundant area) for import in GIS.

c) FDIR - To calculate flow direction map.

d) CODE - To merge crop, soil, Thiessen polygon, and flow direction as one code.

e) SOURCE – To find irrigation application from surface/groundwater.

f) GWRD – To find net pumping/recharge at each grid in the command.

g) AGGREGATE – To aggregate net pumping/recharge from smaller grid to a larger grid size.

h) WELL -- To attach the aggregated pumping/recharge information to different wells in the command for subsequent import in Visual MODFLOW software.

i) SWBM1 – To calculate grid-wise moisture content at the end of a week and recharge due to rainfall and irrigation application.

j) SWBM2 – To calculate grid-wise supplementary water requirements and water stress conditions in the command area.

k) CANOPER – To simulate the operation of canal network and analyse various allocation policies.

2. Database

Various data files are provided in ***Directory "Database"***. All the distributed data files, as obtained from ILWIS in ASCII format, have been zipped. Various distributed files are: BOUNDARY.DAT (for finding dimensions of study area with the image), CROP.DAT (cropping pattern), SOIL (Soil map), RSTN.DAT (Thiessen Polygon map), DEM.DAT (Digital elevation model), CANAL.DAT (Canal layout map for FDIR program), GENSLOP.DAT (General slope map for FDIR program), GWD.DAT (Groundwater depth map), and CRVW.DAT (Map showing canals, roads, village, water bodies, and surface drainage). In each file, after the first line, that specifies the title, second line gives information about the number of columns and rows in the image. BOUNDARY.DAT file, in addition also contains information about the maximum and minimum elevation in the command in the second line. Distributed data values start from third line in all the distributed data files.

In addition, various files related to soil characteristics (SLST.DAT), crop characteristics (CRST.DAT), Rainfall (DRAIN.DAT), Reference Evapo-transpiration (RET.DAT), Canal network characteristics (CCHA.DAT) are provided. Various attributes of crop and soil have been detailed in Chapter-3.

3. Sequential use of programs

The sequential use of various modules is shown in Integrated Geo-simulation Scheme (Figure – 5.1 in Chapter-5). All distributed data files are obtained from GIS in ASCII format. First, DIMENSION Program with BOUNDARY.DAT file is run to find dimensions of the area. Then, the FDIR Program is run to find the flow directions in each grid. Then IMAGE Program is run on all distributed data files (except BOUNDARY file) to reduce the dimensions of the data file for use in various programs. Subsequently SWBM1, SWBM2, CANOPER, SOURCE, SWBM1, GWRD, IMAGE, AGGREGATE, WELL in the order. The output of WELL becomes input for Visual MODFLOW.

* * *