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OPTIMUM WATER MANAGEMENT IN A COMMAND AREA

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PREFACE

The dynamics of water within the unsaturated zone of soil is a complex phenomenon dependent on properties of the atmosphere, soil and vegetation. For agriculture water management, it is necessary to have models that accurately predict the behaviour of soil moisture. In this study, a model is developed to simulate the dynamics of soil moisture within the root zone in an agriculture command. Focus is given to incorporate the spatial variation in crop type, soil type and rainfall in the command area and the dynamics of soil-water-plant interaction is simulated.

The soil water balance is simulated using a simple distributed conceptual model. It is applied to the field data of the Lakhaoti command area under the Madhya Ganga Canal system. The data inputs to the model include rainfall, potential evapo-transpiration, and various crop and soil characteristics. Three important inputs of the model, i.e. rainfall, soil type, and crop type have been considered to be spatially distributed. The command area is discretized into a finite number of rectangular grids and water balance computations are made for each grid. In the absence of the crop type data at the scale of individual fields, multi-temporal remote sensing data are used to find the actual cropping pattern in the command for the year 1998-99. Soil variation is introduced using a soil map of the command area and using the results of laboratory analysis of different soil type samples. A Thiessen polygon was used to account for the rainfall variation in the area.

The model is coupled with the spatial database to simplify data input and provide an efficient way to display and manipulate results. The model works either at daily or weekly time step. Effective soil depth is assumed to be the root zone depth in a grid which keeps on increasing with time till it attains a maximum value. The model estimates the actual evapo-transpiration and the soil moisture content at the end of each day/week using the available information on soil water availability, rainfall, potential evapo-transpiration and the plant water uptake. The output of the model is the actual evapo-transpiration during the day/week, the soil moisture content at the end of the week, supplementary water requirement, water stress condition in the crop, and the recharge. The developed procedure will allow us to estimate the spatial and temporal distribution of irrigation demands in the command area that can be usefully incorporated into larger computer-based irrigation management models.

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ABSTRACT

Success of an irrigation system depends on efficient water management. Irrigation scheduling, which anticipates the temporal water need of crops, i.e., when to irrigate and how much water to apply, is an important management activity affecting the performance of irrigation projects. Efficient operation of irrigation systems adopting sophisticated techniques leading to real-time water management is an urgent need of the hour. The dynamics of water within the unsaturated zone of the soil is a complex phenomenon dependent on the properties of atmosphere, soil and vegetation. Mathematical models are developed to simulate the physical processes of crop-soil-water systems for providing the knowledge of the amount and timing of water needed.

Large amount of information about various processes is involved in irrigation management of a command area. This information needs to be continuously updated for real-time management. With the advent of satellite remote sensing, it has now become possible to update the information at regular intervals. Using a Geographic Information System (GIS), the spatial information can be efficiently stored, analysed and retrieved.

The objective of this study is to simulate the dynamics of soil moisture within the root zone. An analytical model of soil-water balance, distributed in space and time, is developed and applied to field data of the Lakhaoti command under the Madhya Ganga Canal system. The data inputs to the model include rainfall, potential evapo-transpiration, and various crop and soil characteristics. Three important inputs of the model, i.e. rainfall, soil type, and crop type have been considered to be spatially distributed. The command area is discretized into a finite number of rectangular grids and water balance computations are made for each grid. Type of crop in each grid is determined using multi-temporal remote sensing data. Based on the soil survey maps and laboratory analysis, various soil parameters have been determined.

Effective soil depth is assumed to be the root zone depth in a grid which keeps on increasing with time till it attains a maximum value. The model estimates the actual evapo-transpiration and the soil moisture content at the end of each day/week using the available information on soil water availability, rainfall, potential evapo-transpiration and the plant water uptake. The output of the model is the actual evapo-transpiration during the day/week, the soil moisture content at the end of the week, supplementary water requirement, water stress condition in the crop, and the recharge. The model is effective in predicting spatial distribution of average soil moisture conditions in a command area. A computer program is developed to perform the water balance computations for each grid in the command area. The developed program will allow us to estimate the spatial and temporal distribution of crop water demand in the command area that can be usefully incorporated into larger computer-based irrigation management models. The system also permits display of information on maps for easy handling. This visualisation allows users to more readily participate in decision-making processes.

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CHAPTER – 1
INTRODUCTION

Water is essential for sustaining life on Earth. Fresh water resources are finite and vulnerable. There are competing demands for available fresh water resources from various uses – domestic, agricultural, industrial and environmental. Irrigated agriculture accounts for about 80% of water withdrawals in India. Management of land and water resources for enhancing the agricultural production is of growing concern world-wide and this is especially true for developing countries like India. At present, India needs to meet the growing demand of food, fodder and fuel for a population of more than 1000 million with diminishing per capita land availability from 0.50 ha in 1983 to 0.33 ha in 2000 AD. Current patterns of water use involve wasteful use of the scarce resource in all sectors. There is great scope for water savings through more efficient planning, conservation and management of the developed water resources. Water, though abundant in India, is still a scarce commodity as far as its use in irrigation is concerned. The development and management of irrigation facilities has been recognized as the key to national development in India since independence. It was given a prominent position in all the five-year plans. As a result, irrigated area increased from 22.6 million hectare (M ha) in 1950-51 to 84 M ha by 1994-95. The eighth five-year plan allocation for irrigation was Rs.33511.26 crores.

1.1 PROBLEMS OF IRRIGATION MANAGEMENT IN INDIA

Despite the high priority and massive investments in the irrigation sector in India and its phenomenal growth since independence, the performance of irrigation systems, both in economic terms of crop yields, farm incomes and cost recovery, as well as in water distribution terms of adequacy, equity, and timeliness of water supplies, has been disappointing. Not only is there unsatisfactory performance in terms of crop productivity but also poor utilisation of the potential created through major and medium irrigation projects. Because of the poor enforcement of equity in irrigation water distribution, excess water is used at the head end of the command area in the belief that more water will give more yield. The tail end of the command area is deprived of irrigation facilities leading to complaints and discontent. On account of excess irrigation, large areas in the command get waterlogged due to rise in the subsoil watertable, which is detrimental for normal crop production. Continued waterlogging results in salinity development that renders the land completely unproductive in extreme cases.

The large size and complexity of irrigation operations is one of the causes for low efficiency of major irrigation systems. It is also recognised that substantial increase in benefits can be derived by achieving even small improvements in operating efficiencies of existing systems. While the demands for water by all the sectors are rising, investments for development of additional water resources are limited. In recent years, water resources planning has, therefore, emphasised augmenting water resources by more efficient and cost effective management of existing water systems than by developing additional water resources. Keeping this in view, the National Water Policy adopted in 1987, advocated scientific, objective, integrated, and multidisciplinary development and management of water resources systems. The implementation of the policy is feasible in the irrigation sector only if a formal framework for water resources decision-making, that enables spatial assessment of water supplies and demands in real time and a balancing of the two to meet specified objectives, is available. Long term and current data, simulation models of system processes (hydrologic, chemical and biological), and optimization models are essential components of such framework. Large volumes of data, collected routinely at high cost, can be actually used in irrigation decision-making and integrated into information systems, using such a framework.

The knowledge of irrigation system processes is not confined to any single discipline. It has to be extracted from many disciplines and converted to a form usable for irrigation systems planning and operation. Finally, the linkages between the system's goals, data and processes need to be developed. Computer based mathematical simulation models of the relevant processes are the most suitable tools for such knowledge extraction, conversion and linkage. Recent advances in computer hardware and software including increased speed and storage, advanced software debugging tools, and GIS/spatial analysis software have allowed large area simulation to become feasible.

Success of an irrigation system depends on efficient water management. For this purpose, it is necessary to know the soil moisture status at different locations as well as at different growth stages in a command area in near real-time. Irrigation scheduling, which anticipates the temporal water need of crops, i.e., when to irrigate and how much water to apply, is an important management activity affecting the performance of irrigation projects. Efforts to improve agricultural practice by making more efficient use of the available water resources are common nowadays. Most such efforts require mathematical models to simulate the dynamics of water allocation in the root zone of a crop. Once the soil/crop models are developed and the field parameters are derived, one may carry out numerical experiments on the computer to visualise the effect of different irrigation management strategies upon crop yield and system performance.

Water balance of cropped area is a dynamic process. It is influenced by the soil properties, climatological parameters and growth stage of crops. Large amount of information about various processes is involved in irrigation management of a command area. This information needs to be continuously updated for real-time management. With the advent of satellite remote sensing, it has now become possible to update the information at regular intervals. Remote sensing is playing a useful role for providing information about the crop types, their stress conditions (due to water or pests, diseases etc.), water logged and saline areas in a command and reservoir water availability. The advances in remote sensing technology have led considerable saving of time spent in data collection and data input. A Geographic Information System (GIS) is a computer-based system designed to store, process and analyze geo-referenced spatial data and their attributes. Using a GIS, the spatial information can be efficiently stored, analysed and retrieved. GIS have 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 the hydrology and water resources in a command area and to integrate and analyse multidisciplinary data.

1.2 OBJECTIVES AND SCOPE OF THE STUDY

Irrigation is required to obtain high crop production through optimum scheduling of water application on farms. Water availability, particularly in critical periods of crop growth, is important in determining final crop yields. The objective is to deliver water to the farms in an equitable manner, to ensure maximum agriculture production using optimum quantity of water so that the soil moisture is kept in the optimum range and does not fall to the stress level.

Efficient operation of irrigation systems by adoption of sophisticated techniques leading to real-time water management is the urgent need of the hour. This requires computer-based simulation and optimisation models that can be inter-linked and operated using data that are collected in irrigation projects. Such a technology will enable appropriate decision leading to optimal utilisation of water resources.

The objective of this report is to develop a general framework for canal irrigation projects so that a scientific basis could be formed for rational water management. A spatially distributed water balance model is developed to simulate the dynamics of soil moisture within the root zone. Focus is given to incorporate the spatial variation of crop, soil and rainfall in the dynamics of soil-water-plant interaction for irrigation management. For incorporating spatial crop variation in a given command, model requires the information about actual crops grown in different fields in the area. The collection of such vast information is beyond the scope of the present report. Hence the remote sensing data have been used and the approximate crop type variation in the study area is derived. GIS tools are used for geo-referencing the various thematic input layers to the same co-ordinate system and for converting the inputs and outputs in the format required by the model. The model computes various components of water balance, such as supplementary water requirement, final water content, stress condition, recharge etc. by using the database produced by GIS. Model application is presented for Lakhaoti command under the Madhya Ganga system.

The output of the model gives spatial information about the amount of supplementary water requirement, stress etc. in the command at daily/weekly time step. This spatial information is immensely useful for field irrigation management, canal regulation and in reducing the risk of crop damage during sensitive growth stages. Further, such information can be usefully incorporated into larger computer-based irrigation management models. The system also permits display of information in the form of maps for easy handling. This visualisation allows the users to more readily participate in decision-making processes.

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CHAPTER - 2
WATER BALANCE MODEL

2.1 OBJECTIVE OF ROOT ZONE MODELLING

Irrigation is vital to the well being of the people in this world and plays a significant role in local and national economics. However, irrigation also has created problems, such as water logging and salinisation of land. Many of the problems in irrigated agriculture can be mitigated or avoided by improved technology and management. The problem of efficient operation and management of an irrigation system is complex. A prerequisite for such an operation is a formal framework that links project goals, operational decisions, and system responses with environmental and other real-time data.

Knowledge of moisture content of soils in the root zone is crucial for several applications related to agriculture and irrigation planning and management. Simple water balance models have been preferred for field applications and large area studies with example applications in prediction of irrigation demands, crop water stress effects, irrigation schedules and crop yields and prediction of groundwater recharge. However, the soil water balance of cultivated area is a dynamic process. Its components (such as rainfall, evapo-transpiration demand, moisture status in root zone, moisture holding capacity etc.) vary spatially as per the soil properties, climatological parameters and the type and growth stage of crops. As the root depth increases, the effective soil depth also increases with corresponding change in equivalent water depths. These have direct impact on the soil water balance situation. Recognising the importance of spatial variation of crop type, soil type and meteorological parameters, the problem discussed herein refers to the determination of spatially distributed real-time irrigation water requirements in a command area. Remote sensing data were used for identification of various crop types in the command area and the analytical capability of GIS was utilised for carrying out the spatial analysis. The model, used herein, is mainly designed for studying water supply- demand of agriculture area.

2.2 REVIEW OF LITERATURE

A number of studies have been reported in the literature that utilise soil moisture modelling of the root zone for various purposes such as preparing the irrigation schedules, recharge calculation etc. A brief review of relevant studies is presented in the following section.

Jain and Murty (1985) developed a mathematical model for simulating soil water content in the root zone by taking into consideration physical properties of soil, crop types and climatic parameters. The model predicted daily moisture profile for irrigation scheduling. Water uptake by plants was simulated using different sink functions given by Feddes et al. (1976) and Dejong and Cameron (1979). Water table influence on the root zone was neglected and the model was tested for a small sandy loam field under wheat crop. The model predictions were in good agreement with field data.

Hargreaves and Samani (1987) presented a procedure to relate the topographic elevation with the crop selection and for estimating crop water requirements. The elevation data were related to the maximum and minimum temperatures, which was used to select a suitable crop for an area (based on the FAO classification of agricultural crops with respect to optimum and operative temperature ranges). The potential evapo-transpiration was also related to the elevation using the maximum and minimum temperatures. The procedure was applicable in tropical (low altitude) regions within a narrow range of latitude where the maximum and minimum temperatures do not vary greatly throughout the year.

Koch et al. (1987) presented a simple physically based model and described the processes of redistribution of the soil moisture profile, drainage, and evapo-transpiration from the root zone. Using the sharp wetting front approximation, simple expressions were derived. Application of the model using soil parameters selected a priori (from soil survey results) indicated good results. However, crop characteristics, particularly root zone depth, was of significant importance in the successful application since it controlled the rate of depletion and the amount of application for irrigation scheduling.

Rao (1987) proposed a simple conceptual model of soil water balance and tested it with the field data from an irrigation area. The model estimated the actual evapo-transpiration and the soil moisture content at the end of each week using the available information on soil water availability and plant water uptake. The focus of the study was on utilising the information on the dynamics of soil water balance in the larger context of irrigation management. Instantaneous redistribution of the soil moisture over the effective root zone was assumed and the contribution of the groundwater to the root zone was neglected.

Feddes et al. (1988) reviewed the principles underlying water dynamics in unsaturated zone and presented the overview of simulation modelling of soil water flow. The basic relations describing the kinetics of flow and governing equations of flow were presented in general form considering unsteady multidimensional anisotropic and non-homogeneous flow. Numerical approximations to solve governing equations were emphasised. The status of collecting model parameters was discussed and several practical examples of flow simulation in unsaturated zone were presented. Feddes (1988) presented the state-of-the-art on modelling and simulation in hydrologic systems related to agricultural development. He presented the general principles of modelling the water balance of cropped soils and of modelling growth/ yield in relation to water use. The importance of time scale in determining the approach of modelling was also emphasised. Three methods of calculating root water uptake, as proposed by Feddes et al. (1978), Hoogland et al. (1981), and Prasad (1986), were described. Examples of water balance computation with SWATRE program were presented and computations were verified in the field.

Bronswijk (1988) outlined a general procedure to model the water balance of clay soils. The main feature of this procedure was the introduction of shrinkage characteristics into simulation models in addition to water retention and hydraulic conductivity curves. The effects of swelling and shrinkage on water transport were shown by comparing models for rigid soil, cracking soil and field measurements. Occurrence of shrinkage cracks resulted in considerable bypass flow.

In most of the evapo-transpiration and root water extraction models, a constant rate of extraction was assumed for the entire depth of the root zone, such as Feddes et al. (1978), Prasad (1984) etc. Rama Prasad (1988) proposed a model of root water extraction in which a linear variation of extraction rate with depth was assumed. Soil moisture depletion under optimal conditions from different layers was simulated for five crops and compared with the constant extraction rate model. Rooting depth was assumed to vary linearly with potential evapo-transpiration for each crop during the vegetative phase. The proposed linear extraction rate model gave better results as compared to the constant rate extraction model.

Jarvis (1989) defined root water uptake as a function of the potential transpiration rate and a weighted stress index that accounts for the effects of vertical distribution of roots and soil water content. The soil profile within the root depth was divided in different number of layers. Based on the proportion of root length and the stress index in each layer, weighted stress index was worked out. The actual transpiration rate was assumed to be directly proportional to the potential rate and a function of the weighted stress index. The model predictions compared well with the field measurements.

Piper et al. (1989) developed the irrigation demand model based on simple field water balance. The field water storage was divided into three levels: minimum level to which water can fall before irrigation is necessary, normal or desired storage, and the maximum field storage determined by height of bunds (if any). For dry crops, these parameters represented storage characteristics of soil. Water requirement for land preparation for paddy was assumed to vary from 250 to 300 mm/month and deep percolation losses were taken to be 2-3 mm/day.

Bhirud et al. (1990) made an analysis of water-delivery schedules based on a water-balance simulation approach using a crop growth simulation model. Five rotational schedules of two, three, four, five and six weeks were compared to an on-demand schedule in terms of evapo-transpiration, total water applied, and yield. Simulated yields for on-demand and a two-week rotation schedule were comparable. Longer rotation schedules resulted in yield decreases. Modifying the rotation schedule in critical growth periods saved water and resulted in minimum yield losses. The best-modified rotation schedule produced 94% of the on-demand yield.

Jarvis and Harrison (1990) presented a dynamic simulation model of the soil water balance in a clay soil. It is found that the soil structure influence not only the recharge, but also the root water uptake. It is concluded that water regime in clay soil can be accurately predicted by two processes: water uptake by the roots and the rapid flow of water in cracks.

Mohan Rao et al. (1990) presented a method of estimating ground water recharge based on the soil moisture accounting model. The assumption of the concept of field capacity, often quantified at 0.33 bar tension, was made a more realistic flow parameter by quantifying it from the capillary conductivity – moisture content relation. The proposed soil moisture accounting model for estimation of return flow was compared with a distributed model based on the finite difference solution of the Richard's equation. Use of an identical database showed reasonable agreement between the seasonal totals of return flow as predicted by both models. The method of quantifying field capacity as a flow parameter was found to be more suitable for coarse soils.

Turner (1990) described the development of water deficits in field crops and the methods used to measure the deficits, with particular emphasis on their use in irrigation management. It was concluded that extractable soil water content can be reduced by 50 % in many crops before there is any influence on the physiological activity leading to crop loss. Leaf rolling index was found to be a sensitive indicator of reduced soil water availability in rice and sorghum. It was shown that in few crops, mild water deficit can even increase yield.

Gini and Bras (1991) carried out water and salt balance of the root zone for water allocation and salt movement simulation. A lumped input and lumped parameter conceptual model was formulated with precipitation and irrigation water as the inputs. The soil column was considered as a two-layered system, including the unsaturated and saturated zone. The model was useful to answer questions relative to crop productivity in saline soils and possible irrigation with saline water. The results of the study indicated that for the shallow water table in sandy loam soils, water table elevation had an important effect on the soil moisture depletion dynamics of the unsaturated zone.

Various crop development stages possess varying sensitivity to moisture stress (Doorenboss and Kassam, 1979). With limited irrigation, it is essential to distribute the water according to the developmental stage. Singh et al. (1991) conducted field studies under wide variety of limited irrigation conditions of mustard crop and found that this crop was most sensitive to moisture stress from the vegetative to early-flowering stage. Hence, first preference for irrigation should be given to this stage. Panigrahi et al. (1992) undertook a case study of the Mahanadi-Kathjori-Devi delta and formulated irrigation water requirement model for 11 major crops of the region.

Shih and Jordan (1992) investigated the use of mid-infrared (MIR) satellite data as an alternative method of surface soil moisture assessment. Landsat satellite TM data were used to assess the regional soil moisture conditions. The MIR data of TM band 7 were overlain onto four principal land-use categories (agricultural/irrigated, urban/clearings, water, forest/ wetlands) using a GIS. MIR data were used to assess four qualitative surface soil-moisture conditions (water/very wet, wet, moist, and dry) within each land-use category. The MIR response was inversely related to the qualitative surface soil-moisture content. Integration of MIR data with land-use through GIS was seen as a useful technique for high-resolution regional soil moisture assessment.

Tripathi (1992) presented a user-oriented technique for timing irrigation of wheat. The technique was based on the actual crop evapo-transpiration, initial soil moisture in the top 0.6 m profile, available water holding capacity of the top 1m profile, allowable soil moisture depletion, water table contribution, and rainfall. Estimated evapo-transpiration was calculated from the daily maximum and minimum air temperature, solar radiation, and a crop coefficient. The technique showed the need for one or two irrigation for optimum yield of wheat in soils with a water table between 0.5 m and 1.5 m deep. Soil moisture accounting procedure was adopted and watertable contribution was accounted by using the lysimeter observations in the study area.

Water Resources Development Training Centre in association with U.P. Water and Land Management Institute (1993) carried out a study related to conjunctive use management of surface and groundwater in Madhya Ganga command area. A linear programming formulation was used to find the optimum cropping pattern for the area based on the available water and prevailing conditions in the area. Elnur (1991) evaluated the water resources in the Lakhaoti branch command under the Madhya Ganga system.

Zelt and Dugan (1993) simulated the soil water balance in the Great Plains of the central US during the period 1951 – 1980 for obtaining mean annual estimates of infiltration, runoff, actual evapo-transpiration, potential recharge, and consumptive water and irrigation requirements. GIS was used to integrate and map the simulation results on the basis of spatially variable climatic, soil, and vegetational characteristics. The interpretation of regional soil-water conditions was limited by the coarse spatial and temporal resolution of the climatic, soil, and vegetational information.

Bardsley and Campbell (1994) reported the results of a groundwater experiment. It was found that confined aquifers can act as giant weighing lysimeter, with pore water pressures giving real-time measures of changes in amounts of surface and near-surface water. It was concluded that if suitable confined aquifers are available, then the technique has diverse applications such as quantification of evapo-transpiration loss, areal precipitation measurement, monitoring the water content of an accumulating snowpack, and net lateral groundwater transfer in unconfined aquifers.

Lamacq and Wallender (1994) used a soil water storage simulation model to calculate the daily soil water storage and corresponding evapo-transpiration and deep percolation. Based on the simulated evapo-transpiration and deep percolation for different operation schedules, a water allocation policy was suggested which provide incentives to the growers for optimising scheduling.

Crop coefficient represents the crop specific water use and facilitates accurate estimation of irrigation water requirements. In the case of tropical climatic conditions, especially in India, only a few studies were reported on the crop coefficients and water requirements of crops. Suryavanshi et al. (1990) summarised the available literature on this subject under tropical Indian climatic conditions and report crop coefficients for maize, cowpea, groundnut, and safflower. Mohan and Arumugam (1994) estimated crop coefficients for some major crops for tropical south India based on the lysimetric measurements. The estimated values differ markedly from the FAO specified values. The difference was attributed to the local climatic characteristics.

Griffiths and Wooding (1996) evaluated the multi-temporal SAR (active microwave data) imagery of ERS-1 satellite for monitoring soil moisture. A comparison of daily and hourly rainfall and soil moisture measurements with backscatter for different cover types showed that the observed trends in backscatter are dominated by moisture effects. A high positive correlation between volumetric soil moisture in the range 10-40% was observed for bare soil fields while a much weaker positive relationship was observed for grassland fields. It was found that the attenuating effect of a vegetation canopy under different moisture conditions on backscatter partly masks the variations in soil moisture.

Prajamwong et al. (1997) developed a software package called Command Area Decision Support Model (CADSM) to estimate aggregate crop-water requirements and to study management options for irrigated areas. Daily water and salt balances were simulated for individual fields within the command area based on crop type and stage of development, field characteristics, soil properties, possible groundwater contribution, salinity level, and several queuing factors that take cultural practices into account. The simulation model CADSM allowed the user to freely experiment with a number of planning and operational variables, and to consequently examine the results of each run on a comparative basis. The model could be applied on a daily time step to analyse short-term water management issues when daily weather data are available.

Antonopoulos (1997) carried out a simulation study of soil moisture under cotton. The soil moisture dynamics was evaluated using a one-dimensional Richard's model based on the Galerkin finite element method. The model was applied to simulate the state of a cotton crop-soil system under dynamic environment conditions and irrigation schedules. The simulated results compared well with the available measurements.

Arnold et al. (1998) developed a conceptual, continuous time model called SWAT, to assist water resources managers in assessing the impact of management on water supplies and non-point source pollution in watersheds and large river basins. The model operated on a daily time step and allowed a basin to be subdivided into grid cells or natural sub-watersheds. Major components of the hydrologic balance and their interactions were simulated including surface runoff, lateral flow, groundwater flow, evapo-transpiration, channel routing and reservoir storage.

Finch (1998) used a simple water balance model to estimate direct groundwater recharge and carried out the sensitivity analysis to determine the parameters having the greatest influence on the estimates of recharge. The results of varying the vegetation canopy parameters for forests and permanent and annual short vegetation were analysed. Recharge estimates were found to be relatively insensitive to the vegetation canopy parameters for short vegetation but sensitive to forest canopy parameters. The study showed that the most crucial land surface parameters were those required by the soil water component and the sensitivity of parameters like rooting depth, fractional available water content and fractional field drainable water was very high.

Data of water storage limits of soil profiles, i.e. field capacity (FC) and permanent wilting point (PWP) are essential for running soil water balance models. Rao et al. (1998) presented a procedure for estimating these parameters for Indian soils. The values of FC and PWP for different textural classes were estimated independently for alluvial, black and red soils. The estimated parameters were tested by running a soil water balance model for a case study area. The estimated parameters were compared with corresponding values of US soils. Difference in PWP between US soils and Indian soils was found to increase at finer soil textures. The approach is useful when it is not possible to sample large number of individual fields and for large area studies in irrigation and drainage planning and management.

Singh et al. (1999) used the physically based distributed modelling system, MIKE SHE, to simulate the hydrological water balance of a small watershed with the objective of developing the irrigation plan. Simulation results showed that in spite of the frequent rainfall during the Kharif season, there were phases when the water content in the root zone went below the allowable deficit. Based on the water balance analysis, irrigation schedule for paddy and a protective irrigation plan for Rabi season was suggested. The results illustrated the applicability of a comprehensive hydrological modelling system for the management of water resources for agricultural purposes, based on the water balance analysis.

Frankenberger et al. (1999) developed a daily soil moisture routing (SMR) model for simulating the hydrology of watersheds for making management decisions to reduce non-point source pollution from manure spread fields. The model combined the elevation, soil, and land use data within the GIS system GRASS, and predicted the spatial distribution of soil moisture, evapo-transpiration, saturation access overland flow, and interflow through a watershed. Uncertainty in input data and measurement of distributed hydrology was found to be a large source of error that hamper meaningful comparisons between predicted and measured values. The paper concluded that though further refinements in the existing SMR model are possible, yet it can be used as a tool to assist in management decisions.

Belmonte et al. (1999) developed a GIS based procedure to better manage an aquifer system. The system was designed to integrate information from different sources, such as remote sensing, fieldwork data and administrative files. The method was used to estimate the spatial and temporal distribution of water extractions needed for crops and their irrigation systems. These estimates were useful in aquifer modelling. The developed system displayed the output results on maps for easy handling which allowed the users to more readily participate in decision-making processes.

The brief review of the literature, presented above, shows that considerable efforts have been made in modelling the soil moisture in the root zone for various purposes. It has been recognised that models of irrigation water requirements play a very important role in the irrigation management and help to predict the amount of irrigation water required for different crops in any area. Once the irrigation water requirements are worked out, it remains a management decision to finalise the source of water and to see how it is arranged. In the past decade, the tendency has been to develop models that describe different hydrological components in great detail. However, they become very complicated, needing experts to handle them and requiring much data and extensive computational time. To overcome these problems, a simpler approach has been considered in the present study to estimate the soil moisture variation in a command area in near real-time.

The trend shows that advanced systems, which take advantage of the computational ability of computers, remote sensing information and the GIS based analytical tools, are being developed recently. However, such studies are either carried out for experimental purposes either at micro-scale or at macro-scale with a coarse resolution. Root depth of short vegetation has been reported to be a sensitive parameter for soil moisture accounting. With the advent and advancement of remote sensing technology, it is now possible to predict the actual cropping pattern in a command area even at a scale of few meters. Using the remote sensing input and the GIS platform for analysis, it is possible to account for the soil moisture variations in a command area for irrigation management. The objective of this study is to develop a general framework for determining the spatially distributed real-time water demands in a command area so that allocation of available water resources can be made with reference to the prevailing demands and water distribution criteria. Some researchers have also projected the need for such a framework for real-time management.

2.3 PROPOSED WATER BALANCE MODEL

The hydrologic water balance equation is a statement of the 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, be exported therefrom, or flow out either on the surface or underground. The water balance method allows the planner to compute a continuous (daily/weekly/fortnightly) record of soil moisture, actual evapo-transpiration, ground water recharge, and surface runoff from meteorological, soil and crop records.

The dynamics of water within the unsaturated zone of soil is a complex phenomenon dependent on the atmosphere, soil and vegetation. It is an important component in the study and modelling of agricultural and hydrologic systems, since the processes of infiltration, redistribution, drainage and evapo-transpiration (ET) affect both, the amount and timing of irrigation applications, as well as the contribution of precipitation to surface runoff and subsurface flow. As a result, for agriculture water management or continuous hydrologic simulation, it is necessary to have models that predict the behaviour of soil moisture. In the present study, an approach has been considered to determine the spatially distributed soil moisture status in the unsaturated zone in real-time. When developing the model, the aims are as follows:

1) to integrate and process spatial and temporal information coming from different sources, e.g., meteorological data, soil variation, and crop inventory.
2) to allow considerable spatial details.
3) to be computationally efficient.
4) to display data in form of maps for easy visualisation, thereby allowing the greatest number of users to participate in decision-making process.

The model used is mainly designed to study the water supply-demand relationship of rainfed agriculture and the basic concepts are the same as used by Phien (1988). The schematic sketch of soil reservoir is presented in Fig. – 1 and different water contents useful in irrigation are shown in Fig. – 2. Definition sketch of various limits of water depths used in the current model for paddy and other crops is presented in Fig. – 3. Important components of water balance are briefly described in the following:

a) Water Depth at Saturation (WDS)

In saturated soil, all the pore space is filled with water. Water depth at saturation (WDS) represents the water depth equivalent to moisture content at saturation in mm and is given by:

$$\mathrm{WDS} = 10 * \eta * \mathrm{H} \qquad \ldots(1)$$

where η is the porosity of the soil in % and H is the depth of effective soil reservoir in meter.

b) Water Depth at Field Capacity (WDFC)

It is defined as the moisture content of soil which remains held up against the force of gravity. This water depth depends on the soil characteristics. Moisture content at field capacity in terms of equivalent depth of water in mm is given by:

$$\mathrm{WDFC} = 10 * \mathrm{FC} * G_A * \mathrm{H} \qquad \ldots(2)$$

where FC is the field capacity of soil expressed as percent on dry weight basis and G_A is the apparent specific gravity (a dimensionless parameter equal to bulk density in gm/cc) of soil.

c) Water Depth at Permanent Wilting Point (WDO)

It is the moisture 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:

$$\mathrm{WDO} = 10 * \mathrm{PWP} * G_A * \mathrm{H} \qquad \ldots(3)$$

where PWP is the permanent wilting point expressed in percent of dry weight basis.

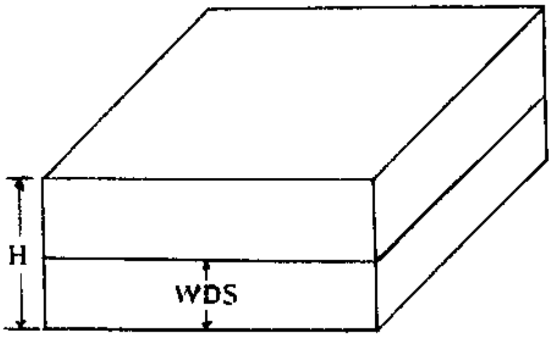


Fig. – 1 Undisturbed Soil Reservoir

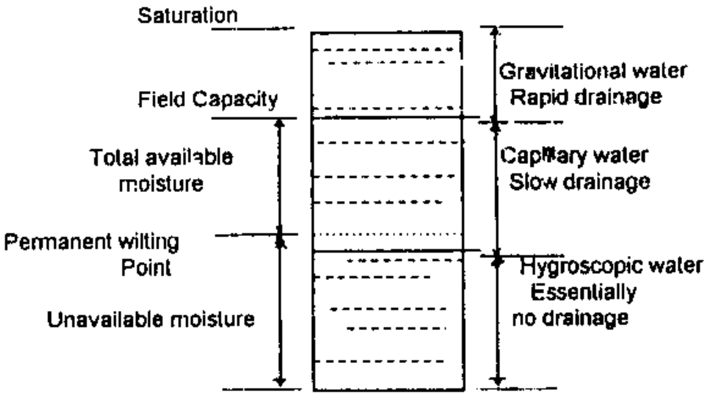
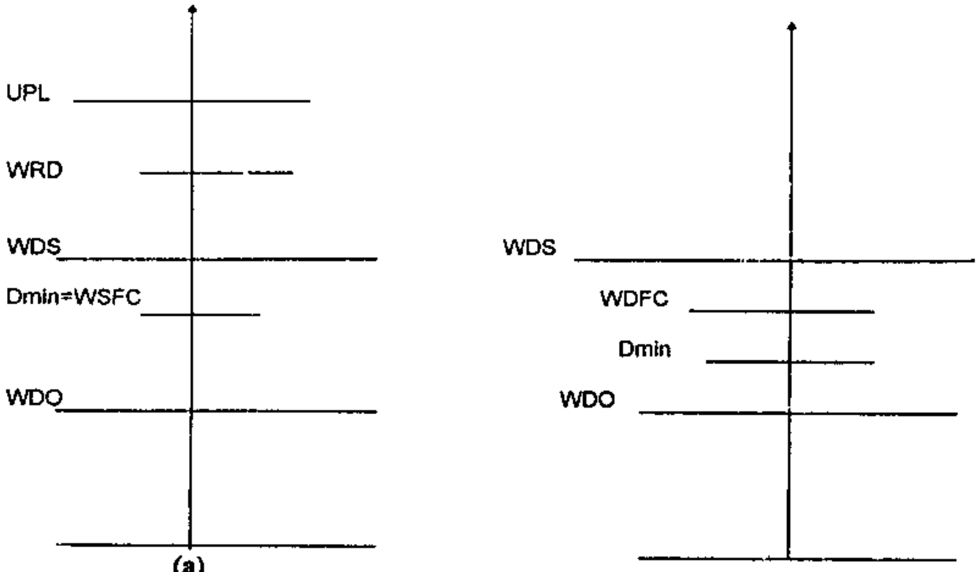


Fig. – 2 Definition Sketch of Different Soil Water Contents



(a)

(b)

Fig. – 3 Definition Sketch of Different Water Depth Limits
(a) for Paddy (b) for Other Crops

d) Upper Limit of Water Depth (UPL)

This limit is used for setting a maximum soil water depth. It represents the sum of the water depth at saturation and the standing water requirement, if any. For paddy crop, there is need of standing water in the field. UPL represents the equivalent water depth in mm and is used in calculating the irrigation requirement. It is given by:

$$UPL = WDS + D_{max} \qquad ...(4)$$

where D_{max} is maximum standing water, equals 150 mm for paddy and 0 for other crops.

e) Lower Limit of Water Depth (D_{min})

This limit represents the minimum soil moisture required for plant growth without any stress. It indicates the level at which a crop just starts to react to the shortage of the soil moisture. D_{min} in equivalent water depth in mm is given by:

For Paddy: $D_{min} = WDFC * 100$ ...(5)
For other crops: $D_{min} = 10 * [FC - p * (FC-PWP)] * G_A * H$ ...(6)
Or $D_{min} = WDFC (1- p) + WDO * p$

where p is the fraction of available water which can be extracted by plants without any stress, and D_{min} is the minimum water depth that should be available in the soil for plant without causing stress.

f) Water Balance Computation

The water balance computation is carried out by computing the water depth on day j, WD(j). The water balance calculation is performed as follows:

$$WD(j) = WD(j-1) + RF(j) - ET_c(j) \qquad ...(7)$$

where WD(j) is the water depth equivalent to soil moisture in the root zone on j^{th} day/week, in mm, RF(j) is the rainfall on j^{th} day or week in mm, and $ET_c(j)$ is the crop evapo-transpiration on the j^{th} day or week in mm. Initially, it is assumed that the evapo-transpiration is occurring at potential rate. The maximum WD(j) is restricted to the sum of water depth at saturation (WDS) and bund height (BH). Bund height is explained under (m).

g) Stress Conditions

Stress is assumed to occur on a plant when the water depth in root zone on jth day or week is less than the minimum required water depth, i.e. when $WD(j) < D_{min}(j)$. Three states of stress have been assumed. First, the NORMAL condition, when the final water depth on any day is more than or equal to D_{min}. Second is the STRESS condition, when the final water depth is between D_{min} and permanent wilting point. Third is the WILT condition, when the final water depth is less than the permanent wilting point.

h) Recharge (RCHG)

Recharge or deep percolation is assumed to occur at a grid when the final water depth is more than the equivalent water depth at field capacity. Since, in case of paddy, water is kept above the equivalent depth at saturation, a recharge value of 3 mm per day has been assumed, as per CWC (1995), provided the final water depth is above the field capacity limit. The value of deep percolation is computed as:

If $WD(j) < WDFC$, $RCHG(j) = 0$
If $WD(j) > WDFC$, $RCHG(j) = f$ (infiltration capacity, water availability)

i) Crop Evapo-transpiration (ET_c)

Reference crop evapo-transpiration E_{rc} is the basic parameter for demand simulation. Average daily E_{rc} can be computed based on the daily data on temperature, humidity, sunshine hours, and wind speed. After computing E_{rc}, the crop evapo-transpiration ET_c is calculated on the basis of known crop coefficient, K_c, as follows:

$$ET_c(j) = K_c(j) * E_{rc}(j) \qquad \ldots(8)$$

where ET_c is the crop evapo-transpiration and E_{rc} is the reference crop evapo-transpiration.

j) Actual Crop Evapo-transpiration (AET)

Crop evapo-transpiration at the potential rate occurs when sufficient water is available to the crop and it is under NORMAL conditions. However, if the crop, at any time, happens to fall in the STRESS stage, the evapo-transpiration takes at a rate lower than the potential rate. At or below the WILT stage, the crop can no longer transpire and ET_c becomes zero. So, based on the actual moisture content in the root zone and the stress condition of the crop, the actual crop evapo-transpiration is worked out. In between the water content from D_{min} to WDO, the coefficient of stress has been assumed to vary linearly from 1 to 0. Actual crop evapo-transpiration is given by:

$$AET(j) = K_s(j) * ET_c(j) \qquad \ldots(9)$$

where $K_s(j)$ is the stress coefficient indicating the severity of stress condition for the jth day/week. According to Boonyatharokul and Walker (1979),

If $WD(j) \geq D_{min}(j)$, then $K_s(j) = 1$ ...(10)
If $WDO(j) < WD(j) < D_{min}(j)$, then

$$K_s(j) = 1 - [\{D_{min}(j) - WD(j)\}/\{D_{min}(j) - WDO(j)\}] \qquad \ldots(11)$$

K_s equal to 1 indicates no stress condition and K_s equal to 0 indicates that water depth has reached at PWP.

k) Actual Water Depth (AWD)

Initially, the water depth computations mentioned under section (f) are carried out assuming that potential crop evapo-transpiration occurs at the location. Since the actual crop

ET depends on the stress condition of the plant, the stress coefficient is worked out based on the water depth computation and the corresponding actual crop ET is estimated. After the estimation of actual crop ET, actual water depth is calculated in the following way:

$$AWD(j) = WD(j-1) + RF(j) - AET(j) \qquad ...(12)$$

Using this actual water depth for day (j), the revised stress coefficient and crop evapotranspiration is estimated again. This way, the computations are repeated till the difference in assumed and computed actual crop ET comes within a specified close limit.

l) Final Water Depth (FWD)

Final water depth at the end of a particular day/week is worked out by considering the actual water depth at the end of the day/week and the recharge or percolation to groundwater, if any. For a crop location, if the water depth, calculated under section (k), is more than the water depth at field capacity, then, the final water depth is computed by subtracting the recharge from the actual water depth. The final water depth at the end of the day/week becomes the initial available water depth at the start of the next day/week.

$$\begin{array}{lll} \text{if } AWD(j) > WDFC(j) & FWD(j) & = \text{Minimum of }(AWD(j) - RCHG(j), WDFC(j)) \qquad ...(13) \\ \text{if } AWD(j) < WDFC(j) & & = AWD(j) \end{array}$$

m) Overland Flow

In the water balance computations, the overland flow is assumed to occur at a grid when the water depth exceeds the sum of the water depth at saturation and the bund height of the field. Small bunds are generally prepared by the farmers around their fields to constrict the flow of water within the fields. This practice restricts the movement of water from one plot to the next. However, when the rainfall depth or the canal water application on a particular day or week exceeds the specified limit, the balance flow will occur in the form of overland flow from one grid to its subsequent lower elevation grid.

Though bund height (BH) may vary from field to field, the variation is generally not very significant. In the present study, it is assumed to be a property related to the type of crop in the field and is read by the program from the data file related to crops. For each crop type, the bund height is specified. After calculating the final water depth at a grid, the calculations are revised for consideration of overland flow. If the final water depth at a grid exceeds the sum of water depth at saturation and bund height (WDS+BH), then the overland flow depth from the grid to its subsequent lower elevation grid is computed as:

$$OLF(j) = WD(j-1) + RF(j) - AET(j) - (WDS + BH) - RCHG(j) \qquad ...(14)$$

To find the grid to which the overland flow is contributed, the digital elevation model (DEM) of the area is utilised. Using the DEM, the flow direction map (the lowest elevation grid around the periphery of each grid) is computed. The overland flow depth as generated from eq. (14) is added to the final water depth of the peripheral lower elevation grid and this process is continued till the calculations are made for all the grids in the command area.

n) Supplementary Water Requirement (SWR)

Supplementary water requirement represents the depth of water required to be supplied at a location so that the total water available depth reaches the upper desirable limit of water depth at that location (UPL in case of paddy and WDFC in case of other crops). The amount of supplementary water requirement is computed by the equation:

$$SWR(j) = WDR(j) - FWD(j) \qquad \ldots(15)$$

where WDR(j) is the water depth requirement on j^{th} day or week (equivalent to UPL for paddy and WDFC for other crops).

2.3.1 Consideration of Root Depth

The effective soil depth in a grid in each day/week was assumed to be the average root depth of the crop during that period. The root depth of a crop changes with time in the initial stages of development till it attains a maximum value. After reaching the maximum, the root depth remains constant for the rest of the period of the crop. Different crops have different growth patterns and different values of maximum depths.

In this study, the initial root depth of 75 mm was assumed. Data related to maximum root depth and time to reach maximum root depth were obtained from the FAO-24 (1977). The crop depth in-between the period from sowing of crop to the time of maximum root development was interpolated linearly. After the time of maximum root development, root depth was assumed constant equal to the maximum depth.

2.3.2 Assumptions in the Model

The general objective of the investigation described herein is to simulate the dynamics of soil moisture within the root zone. It will allow us to estimate the spatial and temporal distribution of water demand for crops. The following assumptions about the properties of the physical system are incorporated in the simulation:

1) Soil medium is homogeneous in the vertical direction.
2) For the weekly/daily time step, the total depths of rainfall from discrete rainfall events occurring in the week/ay are lumped and assumed as input to the soil zone at the beginning of the week/day itself.
3) Water is distributed uniformly over the root zone and is withdrawn uniformly by evapo-transpiration.
4) The effective depth of the root zone is constant for the week.
5) Any water above field capacity in the root zone is treated as deep percolation. There is no moisture movement at moisture contents less than or equal to field capacity. Further, there is complete drainage of excess moisture at moisture contents greater than field capacity.

6) The part of the unsaturated zone below the root zone is always at field capacity and acts as a passive pathway for drainage of excess moisture.
7) The moisture content at the start of the simulation is assumed to be mid-way between the field capacity and the permanent wilting point at any location. However, simulation can be performed by assuming any state of initial moisture content.
8) The water table is deep and its contribution to the soil moisture storage in the root zone is neglected.

With regard to assumption (1), it may be noted that spatial variability of soil in the command has been considered but for each individual grid, the soil is assumed to have the same properties downwards. Since we are mainly concerned with the moisture content in the root zone having small depth (less than 2 m), this assumption seems to hold true in most of the instances. Under the assumption (2), all of the rainfall during the week is assumed to occur instantaneously. The overland flow is assumed to occur when the total depth of water at any grid exceeds the sum of water depth at saturation and the bund height. The bund height is specified in the data file and different bund heights can be specified for grids of different crops. For more rigorous analysis, daily time period can be selected and daily data can be input to the model. The assumption of instantaneous redistribution of soil moisture is justified in view of the slow rate of evapo-transpiration and large intervals of irrigation operations.

Under assumption (3), water is assumed to be distributed uniformly in the root zone. In the model, the soil reservoir is divided in two zones: one up to the root depth, and second, below the root depth. The entire root zone is taken as a single unit with the aim of finding the average moisture content in this zone rather than modelling the variation of moisture within it. Under assumption (5), though the field capacity has been taken as a flow parameter in some studies, it has been considered to be constant in this model. However, provision can be made for defining FC as a flow parameter in the model. This relationship needs to be established for different soil types in the command area. Under assumption (7), some initial moisture has to be assumed to start the simulation process. Under assumption (8), the presence of water table and its contribution to soil moisture storage in the root zone has not been specifically considered in this study. However, as long as the water table remains at least 2 m below the effective root zone at any time, its contribution to the soil moisture storage is not significant.

The focus of this study is on utilising the information on the dynamics of soil water balance in the larger context of irrigation management. The scale of the problem in this case, both in terms of the large size of cropped areas (space) and the convenient time intervals for operating irrigation systems, as well as the operational constraints in irrigation system, provide a justification for the use of the simplified model.

* * *

CHAPTER – 3

THE STUDY AREA

3.1 GANGA CANAL SYSTEM

The agricultural land in western part of Uttar Pradesh state, India is served by major river diversion schemes on the Ganga and Yamuna rivers. The selected area for investigation is under the Madhya Ganga Canal Project (MGCP). The location map and a schematic diagram showing the development in and near the Upper Ganga Canal (UGC) Command and the linkage of Madhya Ganga Canal (MGC) with UGC and other canal systems is shown in Fig. - 4. The MGCP envisages the utilisation of surplus water of River Ganga during the monsoon period for providing irrigation to 178000 hectares of command area for rice cultivation. Out of this, 114000 hectares is proposed in the command area of Upper Ganga Canal System through existing channels and 64000 hectares through new canal system in new command area in districts Bulandshahr and Aligarh.

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

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

3.2 LAKHAOTI BRANCH SYSTEM

The Lakhaoti branch command area that forms a part of the Madhya Ganga Canal Project has been selected for the present study. The command area lies in the districts of Bulandshahr, Aligarh and Ghaziabad in the Ganga-Yamuna doab between latitude 27°45′ N to 28°45′ N and longitude 77°45′ E to 78°35′ E. The study area is fertile one, irrigated by state tube wells, private tube wells and other minor irrigation works. Development of minor irrigation works is taking place at fast rate. Lakhaoti branch is supplying water during the monsoon period for Kharif irrigation. An index map of the area is given in Fig. - 5.

The command area is bounded by the Kali River in the west and the Nim River in the east. These are two main drainage of the area. During non-monsoon, these run mostly dry.

In the absence of the surface water supplies till about 1988, irrigation water requirements were being met by pumpage from groundwater reservoir. Excessive pumpage led to gradual depletion of water table in the area thereby increasing the cost of pumpage and causing loss of natural vegetation. Recent introduction of canal irrigation has led to greater recharge to ground water. Water table build-up in the command area needs to be monitored systematically to control waterlogging and soil salinity.

3.2.1 Climate and Rainfall

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

3.2.2 Topography

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

3.2.3 Physiography & Soil Characteristics

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

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

3.2.4 Groundwater Conditions in the Area

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

3.2.5 Existing Cropping Pattern

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

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

3.2.6 Surface Water Availability

The Lakhaoti branch is the only source of surface water to the cultivable command of 193000 hectares. Water is released in this canal only during the months of June to September at varying rates. Table - 1 shows the supply discharge and the corresponding volume of canal water available during June, July, August and September.

Table - 1
Availability of Water from Lakhaoti Branch

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

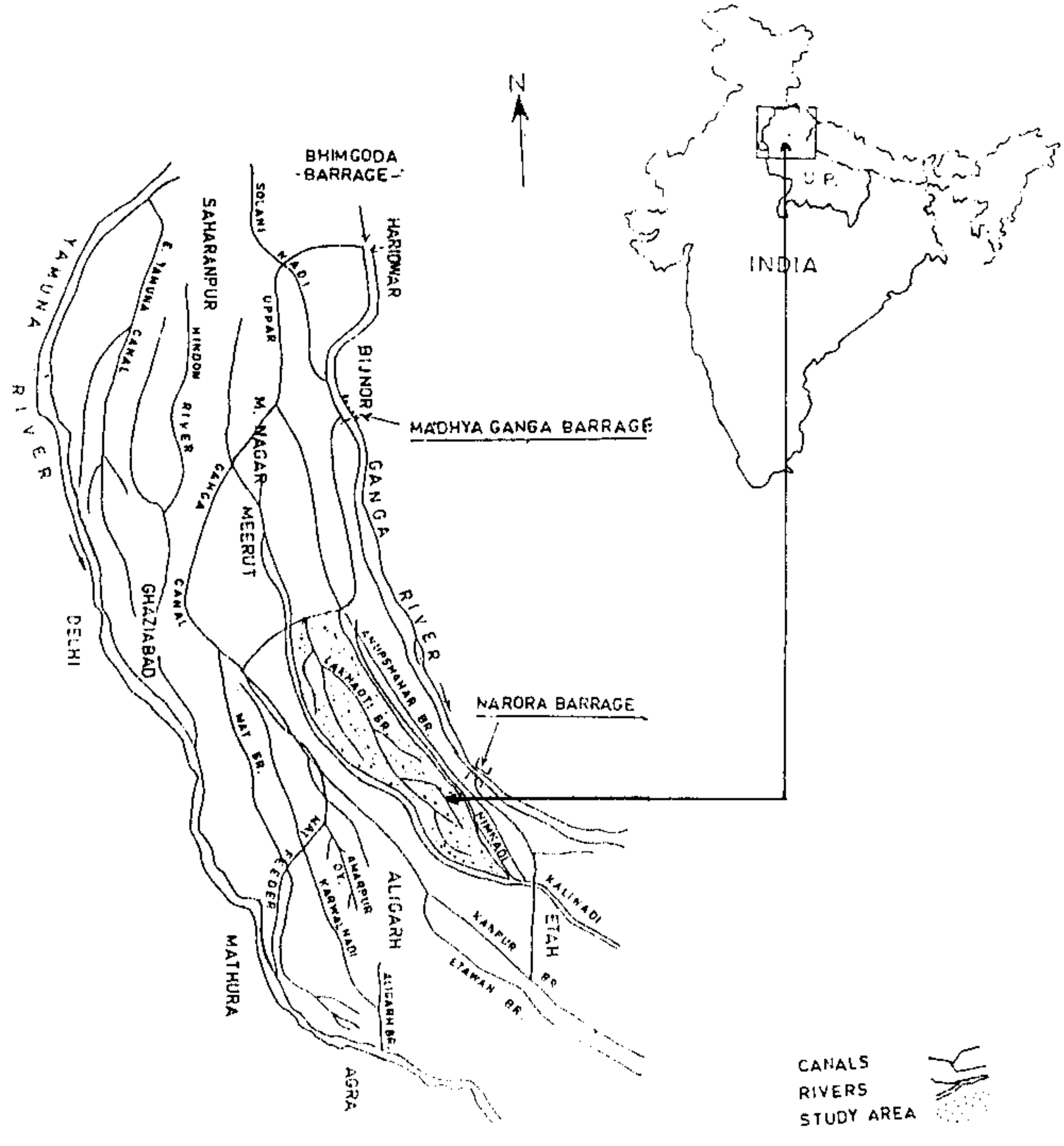


Fig. – 4 Index Map of Madhya Ganga Canal Project

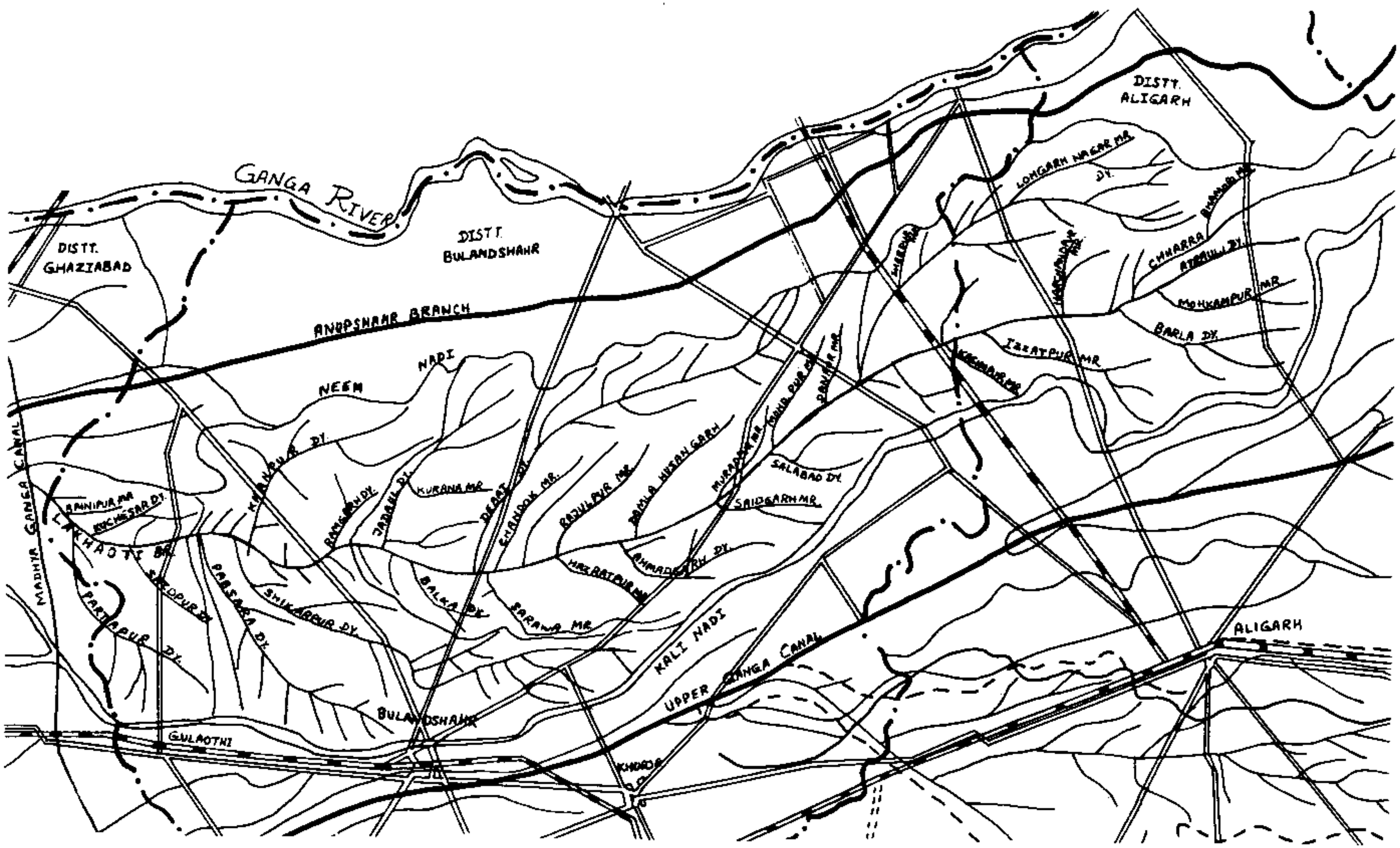


Fig. – 5 Index Map of Lakhaoti Branch Canal System

CHAPTER – 4

DATABASE GENERATION USING REMOTE SENSING & GIS

4.1 NEED OF DATABASE

Information is vital in reducing uncertainty, evaluating alternative courses of action and revealing new avenues. Availability of the right information at the right time to the right person and at the right cost is a crucial factor in decision-making. For the formulation of a distributed model, information on existing land use/cover, cropping pattern, soil characteristics and their spatial distribution is a prerequisite. These data and information need to be efficiently analysed, stored and retrieved in an user-friendly environment.

Large amount of information about various processes is necessary for irrigation management in a command area. Conjunctive management of water requires huge volume of data pertaining to hydrological, hydrogeological, hydrometeorological, soil, agronomic, and cropping pattern parameters in command areas. It is also required to continuously update this information for real-time management. For this purpose a database is operated to provide instantaneous information about the various activities under conjunction operation. The database can be of hierarchical, network or relational type. The hierarchical type is utilized when there is a large degree of dependency among the variables involved while the network and relational types are utilised when parameters involved are independent. However, in all these cases, the entire data that is simulated in the computer provides an integrated picture of the total system.

Simulation studies of irrigation systems are mostly computational in nature and contain complex equations involved in the process. Computers now make it possible to use larger data sets, more sophisticated analytical techniques and a variety of graphic means of presenting analysis results. The objective of the data analysis process is to provide decision-makers with the kind of information that cannot be efficiently provided by conventional methods. The information systems require powerful software that is normally referred to as Data Base Management System (DBMS). The effective functioning of information systems envisages high speed and large processing capacity computers, data storage capacity, disc drives and DMBS software.

The conventional procedure of storing, handling and updating irrigation data is slow, un-systematic, occupies large space and requires huge manpower. Further, such data/ information are conventionally updated at an interval of 4 to 5 years. With the advent of remote sensing and GIS tools, it has become possible to rapidly prepare dynamic resource maps at various levels of confidence. Remote sensing provides multi-spectral and multi-temporal synoptic coverage for the area of interest, while the GIS provide the facilities to integrate and analyse multi-disciplinary data. For natural resource management to be socially acceptable, decision-making must be a public and participatory process. The capability of GIS to express the information in maps and pictures, can make the general public more informed and can involve them in decision making activities. Similarly, decision makers are able to get comprehensive information in real-time mode for managing water distribution plan in a command area.

4.2 REMOTE SENSING INPUT TO DATABASE FOR A COMMAND

Remote sensing implies sensing from a distance. These systems are used to observe the earth's surface and analyse the information about resources over large areas. Satellite remote sensing can play a vital role in implementing and monitoring water management plan in a command area. The land use changes with time need a continuous monitoring and satellite data have been extensively used for mapping and monitoring of surface water bodies/reservoirs, identification of water logged areas in the command areas, and inventory of crop lands and cropping patterns. By using multi-spectral satellite data suitably, different ground features can be differentiated from each other and thematic maps depicting land use can be prepared.

Each satellite data 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. Other sources of spatially distributed data are also often available for regions of interest. These include simple maps that show topography, soil type, cities, towns and villages, roads, water bodies, forests etc. Frequently, these other spatial data sources are used for drawing inferences from the remotely sensed information about the regions on the earth's surface.

4.2.1 Remote Sensing Applications in Command Areas

Management of water supplies for irrigation in command areas with limited quantities is a critical problem to tackle. This requires information on total demand and the distribution of demand for irrigation in command areas. Moreover, the vastness of areas involved, time constraints and yearly changes demand fast inventory of the situations. With more area being brought under irrigation, crop monitoring also becomes essential for estimating agricultural production and efficient planning of water management. In all these circumstances, remote sensing can be looked upon as an aid in planning and decision making. The usefulness of remote sensing techniques in inventory of irrigated lands, identification of crop types, their extent and condition and production estimation has been demonstrated in various investigations. Some of the potential applications of remote sensing in command area studies are briefly described below:

a) Landuse/Land cover Mapping

Remote sensing technology has made most significant contribution in the area of land use mapping. Data collected by different sensors over various regions of electromagnetic spectrum help in differentiating one feature from the other. Landuse features can be identified, mapped, and studied on the basis of their spectral characteristics. Healthy green vegetation has considerably different characteristics in visible and near infrared regions of the spectrum, whereas dry bare soil has a relatively stable reflectance in both the region of the spectrum. Water shows very low reflectance in visible part and almost no reflectance in infrared part of the spectrum. Thus, by using multispectral data suitably, different ground features can be differentiated from each other and thematic map depicting land use can be prepared.

b) Identification of Crops

Crop classification involves mapping of the area of a given crop. This requires identification of the specific crop species in the area. Various crops can be identified using multispectral and multidate imagery. Simultaneous images of the same area, acquired in various wavelength regions, provide complementary information that greatly facilitates recognition of various crop types. The crop identification and acreage estimation procedure broadly consists of identifying representative sites of various crops/land cover classes on the image based on the ground truth, generation of signature for different training sites and classifying the image using training statistics. Change in the field condition becomes the major clue of identification when utilising multidate imagery in conjunction with a crop calendar of the area/region. Multidate imagery helps in confirming earlier identification and often crops that could not be identified in the first instance, can be identified in later imagery.

c) Identification of Crop Stress

Natural calamities (flood and drought) and stresses due to nutrient and water deficiency, salinity and alkalinity, insect damage, diseases etc. affect crop growth and consequently the yield. The crop yield loss due to pests alone can be up to 20 percent of the potential production. Significant portion of these losses can be prevented with early warning on the intensity of impending agricultural hazard based on the reliable, objective and up-to-date information. Remote sensing data analysis and interpretation is connected with the surface reflectance of the crops, particularly leaves that are the primary indicator for insects and pest damage. This technology can be utilised for detecting changes caused to healthy plants by insects and disease. Different projects such as Crop Production Forecasting (CPF), Crop Stress Detection (CSD), and Crop Yield Monitoring (CYM) have been taken up under IRS-UP (Utilisation Program) to develop appropriate techniques.

d) Assessment of Waterlogged/Saline Area

Salinity and alkalinity are some of the major land degradation processes that restrict the economic and efficient utilisation of soil and land resources in command areas. The soil salinisation is often linked with waterlogging. Reliable mapping of areas affected by these processes with their location and extent can be extremely useful in chalking out suitable water management strategies and also to undertake remedial measures to prevent their advancement. Remote sensing techniques have shown great scope for providing a quick inventory of waterlogged, saline and alkaline soils and their monitoring.

e) Soil Moisture Assessment

Quantitative assessment of soil moisture regime is essential for water balance models, irrigation scheduling, crop management, surface and subsurface flow predictions. Remotely sensed data have great potential for providing aerial estimates of soil moisture rather than point measurements. Remote sensing of soil moisture can be accomplished to some degree by all regions of the electromagnetic spectrum. The application of remotely sensed data for soil moisture depends upon the measurement of electromagnetic energy that is reflected or emitted from the surface. Microwave remote sensing can directly measure the dielectric properties of the earth surface, which in turn is strongly dependent on the moisture content. The physical relationship between moisture, dielectric properties and microwave response together with the ability of microwave sensors to penetrate clouds make them a useful all weather sensor. Estimation of soil moisture using remote sensors is still in research phase and is yet to be implemented for practical applications.

4.3 GEOGRAPHIC INFORMATION SYSTEMS FOR DATABASE MANAGEMENT

The amount of data to be handled in a database, that contains spatial sources such as satellite imagery along with maps and other different types of information, is enormous, particularly if the data cover a large geographical region. Clearly, there is a need of efficient means by which data types can be stored, retrieved, manipulated, analysed and displayed. This is the purpose of Geographic Information System (GIS).

GIS is a computer based system designed to store, process and analyse spatial data and their corresponding attribute information. This database can provide an efficient and cost-effective means of analysing and manipulating spatial data. GISs have diverse applications in water resources such as hydrologic modelling, watershed and command management, groundwater investigations etc. Satellite images can be used to monitor current situations, compare the changes over time and predict future conditions. The use of satellite images with GIS adds the much needed element of timeliness in the analysis.

4.3.1 Potential GIS Applications in a Command

The conventional procedures of storing, handling and updating records are slow, not systematic, occupy large space and require huge manpower. Further, such records are rarely updated. With the advent of GIS tools, it has become possible to prepare the dynamic resource maps. GIS have provided the planners with an inexpensive, rapid and flexible tool for combining earth related facts for creating decision alternatives. GIS can highly assist in water resources management by efficiently handling spatial and temporal information of the hydrology and water demands in a basin. Some of the potential applications of GIS in command area studies are described below:

a) Topographical Studies

Topographical studies for a command area can be easily carried out with the help of digitized contour maps. Digital elevation model (DEM), which is the digital representation of the spatial altitudes, can be generated in a GIS by interpolating the contour lines of different elevations. DEM is one of the most frequently used input maps in a GIS and serve for a wide range of applications, such as slope, aspect, hill shading, generation of 3-dimensional view, calculation of cut and fill, and automatic delineation of catchment and drainage pattern.

b) Water Resources Management Studies

A large number of soil, climatological and crop parameters are needed for water management of an irrigation command. A GIS can easily handle these different layers of information. Using the water balance approach, spatially distributed irrigation demands can be determined in the command area in real-time. Knowing the demands, availability of water, stress condition and type of crop, and extent of waterlogged and saline areas, management plan can be formulated. Since irrigation management decisions affect large areas, alternate scenarios can be simulated and their impact can be evaluated. The results can be presented through GIS in the form of maps for easy interpretation by the public.

c) Waterlogging Assessment

The ground water level at different observation wells during time periods can be interpolated and the temporal fluctuation of water table can be assessed. Same as for surface levels, DEM of ground water levels also can be created. Knowing the grid-wise ground water levels and the surface levels, the depth of water table at different locations can be determined. Thus the area affected/likely to be affected by waterlogging can be delineated.

d) Soil/Land Suitability Classification

Soil suitability classification is based on various soil parameters like effective depth, textural classification, permeability, available water holding capacity, salinity/alkalinity, presence of coarse fragments and stones and erosion status. Land irrigability classification depends on the physical factors also in addition to the soil irrigability classification. Different layers of information can be overlaid to come out with the final classification.

e) Participatory Decision-Making

For sustainable natural resource management, the management practices must be ecologically sound, economically feasible, and socially acceptable. For natural resource management to be socially acceptable, decision-making must be a public and participatory process. The capability of GIS to present the information in the form of maps and pictures, makes the general public more informed and involves them in decision-making activities. Different scenarios of water management in a command area can be simulated and their results can be visualised. The common man may not understand the mathematical equations governing a process but may understand the final outcome in the form of information pertaining to his interest. For example, if the simulation results illustrate the area likely to become waterlogged after a few years if the present allocation policy is continued, then the affected farmers may like to change the present pattern to avoid such situation.

4.4 DATA FORMATS

Three types of spatial information are in the form of point, line and area. Irrespective of the type, for a spatial data set to be manipulated using the techniques of digital image processing, it must share two characteristics with multispectral data. First, it must be available in discrete form with some specified value. In other words, it must consist of or be able to be converted to grids, with each grid describing the properties of a given (small) area on the ground; and the value ascribed to each grid must be expressible in digital form. Secondly, it must be in correct geographic relation to a multispectral image. In digital spatial data handling systems, it is necessary to relate all entries in the data set to a common co-ordinate and projection system and to mutually register and reference the data sets.

Not all sources of spatial data are originally available in the grid oriented digital format. Indeed, often the data is available as analog maps that require digitisation before entry into a digital database. That is particularly the case with line and area data types, in which case, consideration has to be given to the "value" that will be ascribed to a particular grid. Consider the case of creating a digital topographic map from its analog contour map. First, it is necessary to convert the contours on the paper map to records contained in a computer. This is done by using an input device such as a stylus or cross-hair cursor to mark a series of points on each contour between which the contour is regarded by-the computer to be a straight line. Information on a contour at this stage is stored in the computer's memory as a file of points. This format is referred to as vector format owing to the vectors that can be drawn from point to point (in principle) to reconstruct a contour on a display or plotter. Some spatial data handling computer systems operate in a vector format entirely. However, to be able to exploit the techniques of digital image processing, the vector-formatted data has to be converted into a set of grids arranged on rectangular grid centres. This is referred to as raster format (or some times grid format). The process of interpolation obtains the elevation values for each grid in the raster form over the points recorded on the contours.

Raster format is a natural one for the representation of multispectral image data since the data of that type is generated by digitising scanners, is transmitted digitally and is recorded digitally. Raster format, however, is also appealing from a processing point of view since the logical records for the data are the grid values (irrespective of whether the data is of the point, line or area type) and neighbourhood relationships are easy to establish by means of grid addresses. In contrast, vector format does not offer this feature. However, an advantage of vector format, often exploited in high quality graphics display devices, is that resolution is not limited by grid size.

4.5 GENERATION OF DATABASE FOR LAKHAOTI COMMAND

Information is vital in reducing uncertainty, evaluating alternative courses of action and revealing new alternatives. For any conjunctive use development program, information on existing land use/cover, cropping pattern, soil characteristics and their spatial distribution is a prerequisite. These data and information need to be carefully, effectively and efficiently analysed, stored and retrieved whenever required. With the advent of remote sensing and GIS tools, it has become possible to prepare the dynamic resource maps. Remote sensing provides multi-spectral and multi-temporal synoptic coverage for the area, while the GIS provide the facilities to integrate and analyse multi-disciplinary data. The objective of this study was to develop a procedure that can utilise the data in the image or map form and can produce the output in similar form for easy interpretation.

4.5.1 Digitisation of Data Layers from Toposheets

Not all sources of spatial data are originally available in the grid oriented digital format. Particularly in India, the data are available as analog maps in the form of toposheets that require digitisation before their use as a digital database.

In the present case, SOI toposheets at 1:25,000 scale were available for the area. The total study area was covered in 37 toposheets. The toposheets 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 the command area map was taken at Latitude 27°45′ N and Longitude 77°45′ E. Since the toposheets and the remote sensing data were processed in the Polyconic projection system, the same was adopted while creating the co-ordinate system in the present case also. The datum was adopted as Indian (India, Nepal) and the ellipsoid was selected as Everest (India 1956). Cartesian co-ordinates of the origin were taken as X = 0 and Y = 0 and the maximum X and Y for the study area were 82000.00 m and 121000.00 m respectively. Since the remote sensing data of IRS-1C satellite and LISS-III sensor have a processed grid size of 24.0 m, the size of each grid was taken as 24 m x 24 m. The data from the toposheets were digitised in the ILWIS 2.2 (Integrated Land and Water Information System) system.

The data of following nine features were digitised from each toposheet and kept in separate files:

a) Boundary file containing the courses of Kali River and Nim River.

b) Contour file containing the contours in the area at 5 m interval. Elevation values were specified to the contours. The contour elevation in the area varied from 210 m in the north to 170 m in the south.

c) A file containing the spot levels at various places in-between the contours. These were digitised to increase the accuracy of the digital elevation map of the area.

d) Drainage file containing the location of major drains in the area. Since the majority of area has flat topography, very few drains were found near the Kali and Nim River.

e) Plantation file containing the forests and plantations in the area.

f) A file containing the layout of railway lines in the area.

g) A file containing the layout of road network in the area. Since the area is agriculture dominated, it contains dense network of single roads connecting one village to other.

h) A file containing the names and boundary of villages in the area.

i) A file containing the extent and location of water bodies in the area. Two types of water bodies were digitised – temporary and permanent. Temporary water bodies were found near almost all the villages. These get filled up in the monsoon season and dry up subsequently. Some water bodies were permanent.

First, each toposheet was fixed on the digitising tablet. The digitizer was set with reference to the map using five control points (geographic latitude and longitude). The error of referencing in all the cases was less than 7.5 m, which is well below the permissible limits.

After referencing the digitiser, a map layer corresponding to a particular theme (such as boundary, or contour etc.) was opened and the theme information was digitised using the cross-hair cursor. In this way, various thematic layers were created and the information from analog maps was converted to digital form for computer processing.

Out of the various themes as mentioned above, only the boundary layer and the plantation layer were useful in the present study. The boundary layer was used to separate the area of interest from the remote sensing image and other spatial data such as soil map and the Thiessen polygon map. Plantation layer was used to identify the forests or plantations in the area so that they can be separated out from the agricultural crop area.

4.5.2 Identification of MGC Using Remote Sensing Data

The study area is bounded by the Kali river in the west, the Nim river in the east and the Madhya Ganga Canal in the north. The topographic survey of the area was carried out in the years 1976-77 while the canal system was introduced in the area after 1985. Hence the location of the canal system was not available in the toposheets.

To mark the location of the Madhya Ganga Canal in the boundary layer so as to get a closed polygon of the study area, the remote sensing data were used. The image processing in this study was carried out on the ERDAS IMAGINE 8.3.1 system. The boundary layer file (a segment file) in the ILWIS system was first converted into raster format and then exported in a format compatible in ERDAS IMAGINE 8.3.1. The boundary file was imported in the ERDAS system and visualised. The image of October 31, 1998 (in which the visual appearance of Kali river and Nim river was clear) was also imported in the system. Then the remote sensing image was geo-referenced with respect to the boundary file using various control points on the Kali river and Nim river in the boundary file and the corresponding points in the image file. The geo-referenced image file was overlaid with the boundary file. The visual match between the two was acceptable.

Using geo-referenced image in the background in the ILWIS system, the boundary file was edited by onscreen digitisation of the MGC. The segments of the Kali river, Nim river and the MGC that were extending beyond the intersections were removed by editing. This way, the complete boundary of the study area was digitised. Fig. – 6 shows the locations of the Kali and Nim river and MGC. The Lakhaoti branch of the MGC could also be digitised from the remote sensing data and the same is also shown in this figure. The locations of various plantations in the study area, as available in the toposheets are also shown in Fig. – 6.

4.5.3 Remote Sensing Analysis for Lakhaoti Command

A remote sensing system consists of radiation from an energy source, its reflection at the object and reception of the reflected energy by a sensor carried on a data collection platform. According to energy-matter relationships, different objects reflect energy differently with regard to frequency, direction and intensity. It provides information with unique and valuable characteristics in an unbiased form.

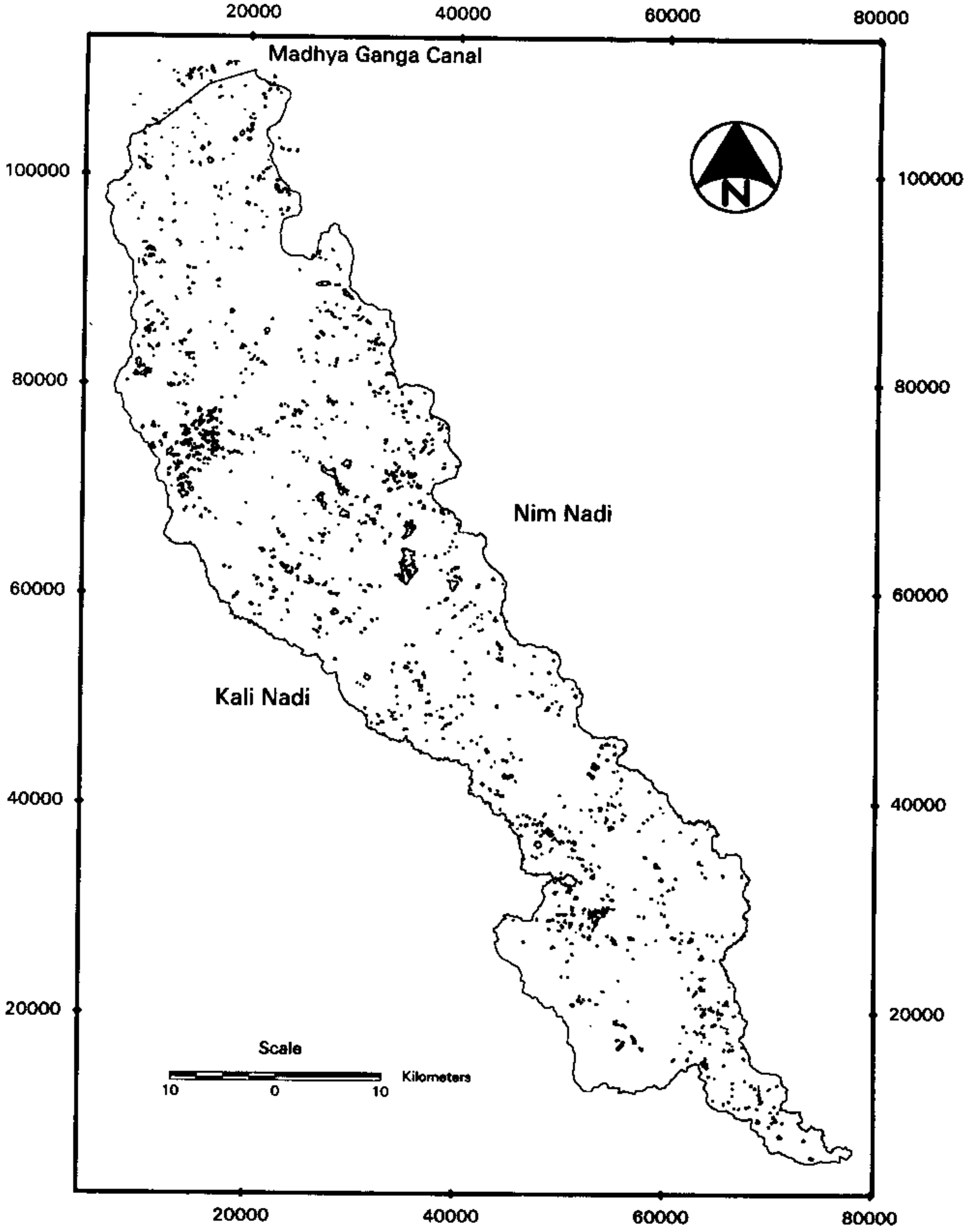


Fig. - 6 Boundary of the Study Area with Plantations/Forest Area as Digitised from Toposheets in time, displayed accurately, geographically referenced, prepared in real time (or very nearly so); prepared in useful storable format and produced in volumes never attainable before, yet use of even the available information to the fullest extent has not been developed fully. The use of remote sensing techniques in resource management is a relatively new development.

The application of the water balance model needed the information about actual crops grown in the command at the scale of individual fields. Such data are generally not available in the field records and it is very difficult to gather this information for a vast area. For efficient water management in a command area, there is a need to collect such information before the start of the cropping season so that geographically referenced actual demands can be worked out and water supply can be planned as per the prevailing conditions of demand and availability. There is a need to develop a system for collecting information related to the crops to be grown and the time of sowing at the field scale. The collection of such vast information was beyond the scope of the present study. Hence the remote sensing data were resorted to and the approximate crop type variation in the study area was derived. Using the derived cropping pattern, real-time irrigation demands in the area were worked out.

In this study, the analysis was carried out for the year 1998 – 99. The data of LISS-III sensor of IRS-1C/1D satellite were used. This data have higher resolution of 23.5 m and is considered suitable for crop discrimination and identification. The study area is covered in Path 097 and Row 051 of IRS-1C satellite with 40% Shift Along Track (SAT). Almost whole of the study area is covered in one scene of the satellite. Based on the availability of data for the year 1998-99 and the crop calendar in the command area, digital data of six dates were acquired. These dates were: 03.06.98, 23.07.98, 09.10.98, 31.10.98, 26.11.98, and 02.03.99. It can be seen that for the Kharif (monsoon) season, data of four dates were available while for the Rabi (winter) season, only two date's data were available. In the June scene, the major crop in the command was sugarcane. In the July scene, other kharif crops were also present but the rice fields could be recognised as water ponds. In the scene of October 9, some of the kharif crops were harvested but rice fields presented vegetation signatures. In the scene of October 31, rice crop was also harvested. In the scene of November, some of the rabi crops (except wheat and new sugarcane) appeared in the image some of which were harvested before the next scene of March. Various steps of remote sensing analysis are described below.

4.5.3.1 Import & Visualisation

The data of IRS-1C satellite and LISS-III sensor for six different dates were received from NRSA on CD-ROM media. The data were loaded on the computer from the CD-ROM and were imported in the ERDAS system. Each scene had 6480 columns, different number of rows (approx. 6000) and the information of four bands. The header bytes for IRS-1C LISS-III data were 540. The grid size of the processed data was 24 m. The study area was located in the upper left part of the full scene and was covered in approx. 3700 columns and 4400 rows.

A false colour composite (FCC) of near-infrared (NIR), Red and Green bands was prepared which correspond to the standard FCC. All the scenes were free from noise and cloud effects. The Kali river was quite distinct and clear in all the imageries while the Nim river (being a very small drainage) was not distinguishable in most of the imageries, at least in its upper reaches. The MGC and the Lakhaoti branch could also be clearly visualised in the monsoon season. The agricultural area was also distinguishable from the built-up and residential areas, such as villages and cities. The change in agricultural area with time (such as in June and July images) was quite significant and identifiable.

4.5.3.2 Geo-referencing

In the digital spatial data handling systems, it is necessary to relate all entries in the data set to a common co-ordinate and projection system and to mutually register and reference the data sets. While using the multi-temporal satellite data of the same area, it is required to geo-reference the imageries of different dates. Using the geo-referenced images, overlaying of scenes, detection of land use change, and identification of crop can be made.

First, image–to–image registration was done for all the images. The image of October 31 was considered as the master and the images of other dates were geo-referenced with respect to the master image. Geo-referencing was done by identifying similar control points (features such as river crossings, road crossings, permanent features, other pertinent points etc.) in the different images and then re-sampling the original image. This way, all the images were geo-referenced with respect to each other. The results were checked for all the images by displaying the two images one over the other and comparing the two using the SWIPE facility. The match between the images was satisfactory.

For a spatial data set from analog map to be manipulated with the multispectral data, the two must be in correct geographic relation to each other. After image–to-image registration, the resulting images were required to be in geographical conformity with other thematic layers such as boundary, contour, plantation etc. For this reason, the boundary image, finalised as mentioned under section 4.5.2, was considered as the master and the image of October 31 was geo-referenced with respect to this image. Control points were taken along the Kali river, Nim river and the MGC. The grid size of the two images was also kept same (24 m) and the projection system was specified as Polyconic. This way, the image of October 31 was registered to the co-ordinate and projection system of boundary file. Fig. – 7 presents the overlay of the boundary image over the remote sensing image of October 31. The model used to resample the October 31 image with respect to the boundary image was saved in a file. All the other remote sensing images (obtained after image-to-image registration) were geo-referenced with the boundary image using the similar model, since all of them were already geo-referenced with the October 31 image. This avoided the necessity of identifying control points for all the images separately. Results were checked by overlaying the boundary image over remote sensing images of different dates. The results were satisfactory in all the cases. This way, all the data, digitised from toposheets and remote sensing images were brought to the same co-ordinate and projection system.

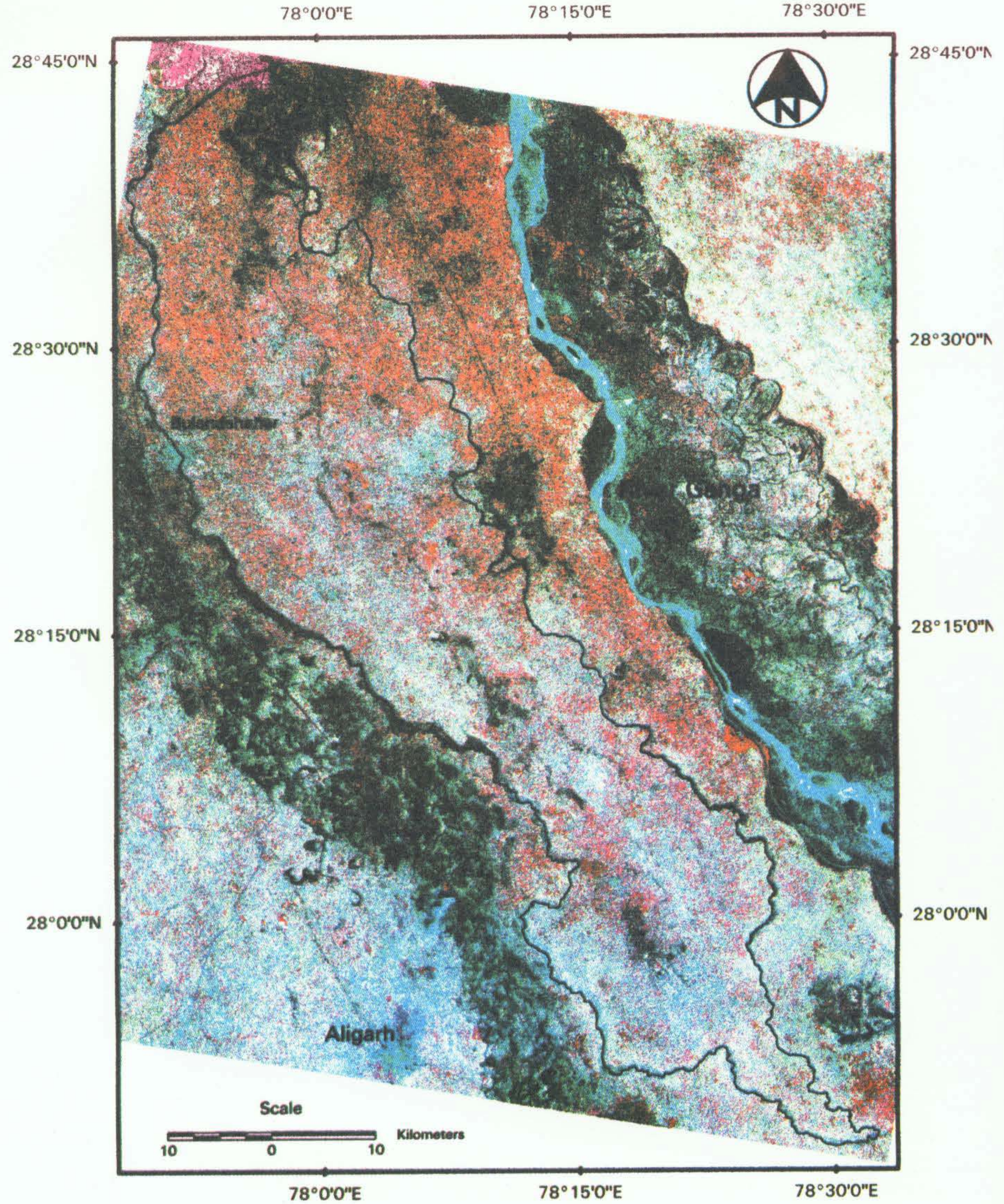


Fig. - 7 : Study Area in the Remote Sensing Image of October 31, 1998

4.5.3.3 Extraction of the Study Area

The area of interest in this study is a closed triangular polygon, bounded by the Kali river in the west, the Nim river in the east and the MGC in the north. To extract the information about various features, such as the area and location of different crop types, extent of waterlogged area etc., it was required to extract the study area from the full scene of the remote sensing image. Also, for the purpose of model application to the image data, it was required to exclusively separate the study area from the other surrounding area.

The boundary file, digitised in ILWIS, formed a closed polygon in segment form. This file was first converted from segment to vector format and then from vector format to raster format. The grids within the area were given a value, say "1" while the grids outside of the study area were given other value, say "0". The grid size of the raster image was kept same as that of remote sensing data (24 m). The rasterized boundary file was imported in ERDAS system and overlaid on the geo-referenced image of October 31. Then, using the multiple image data in the MODELER option of ERDAS, the study area was separated from the full scene and stored in a separate file. Similar steps were carried out for the other images and the remote sensing data for the study area was separated out for all the dates.

4.5.3.4 Identification of Plantations/Forest

The study area contains plantations of Babul and Oak and gardens of fruit trees, such as mango. There are some deciduous forests also in the area. These plantations have reflectance properties quite similar to the agricultural crops and, if not separated out, can be classified as an agricultural crop. Since the objective of the remote sensing analysis was to identify the actual cropping pattern in the area, the plantations and forests were identified and separated in the remote sensing images.

The toposheets contained the information about the plantations and forests in the area. The same were digitised and saved as a separate layer in ILWIS. This layer was converted into raster format and then imported in the ERDAS system. The rasterized plantation layer was overlaid on the remote sensing images of different dates.

Remote sensing signatures of plantations in different seasons of the year were observed. In the standard FCC of the command, the appearance of plantation grids was found to be quite distinct from the other vegetational grids. In the image of March 2, the plantation area looked grey and dull. In the images of October 9; October 31; and November 26, plantations appeared to be dark brownish in colour as compared to bright red appearance of crops. Deciduous forests that were difficult to identify in the March scene were quite distinct and clear in these images.

For identifying the plantations in the study area using remote sensing data, supervised classification technique was adopted. Two viewers were opened simultaneously: one, containing the image of October 31 with the plantation layer (digitised from toposheet) overlaid on it, and second, the image of October 31 alone for giving signatures for supervised classification. Based on the reflectance in the image and the information from the plantation layer, different training signatures were generated and the image was classified. Different combinations of signatures were tried till the classified plantation image covered most of the plantation area that visually appeared to be plantation in the remote sensing image and were simultaneously available in the digitised plantation layer. The classified image, obtained after supervised classification, contained small clusters (combination of one, two, three grids or so) of grids that did not appear to be plantations/forest. Such grids were removed by using the CLUMP and ELIMINATE utility of ERDAS software.

Though most of the grids, that were available as plantation in the toposheets, were found in the classified plantation image, yet it was observed from the visual appearance that some of the plantations have been removed and agriculture is being practised at those locations. A visit was made to the Lakhaoti command area and ground truth of the plantations at a number of places was collected. The plantations classified using the remote sensing data could be spotted in the field also.

The plantation area, identified using remote sensing data of 1998-99, is presented in Fig. – 8. Using the remote sensing data, it was possible to revise the plantation/forest map of the area. With the introduction of the canal system, some of the area has been converted into the agricultural land. However, such area is very small in proportion to the overall plantation area and most of the plantation/forest areas still exist in the command.

4.5.3.5 Identification of Crops in Lakhaoti Command

Though various Earth surface features, such as vegetation, soil and water, can be identified and differentiated quite accurately using remote sensing data, the discrimination of crop types is a difficult and tedious proposition.

A plant leaf reflects and transmits incident radiation in a manner that is unique characteristic of pigmented cells containing water solutions. The optical properties of crop or forest canopies depend mainly on the optical properties of leaves and the underlying soil, but in some cases, they are also affected by the optical properties of other parts of plants such as bark, flowers, fruits etc. All of the reflectance spectra of plant leaves (low crops or forest trees) have the same shape. Differences just appear in the magnitude of reflectance (Guyon and Riom, 1989). The spectral reflectance characteristics of typical vegetation, soil and water are shown in Fig. – 9. The reflectance, absorptance, and transmittance spectra of a typical plant leaf indicates that, based on the physical processes involved in the interaction of electromagnetic radiation, reflective region (0.35 - 2.5 μm) of the electromagnetic spectrum can be divided into six parts:

(i) 0.35 - 0.5 μm region characterised by strong absorption by chlorophyll.
(ii) 0.5 - 0.62 μm region which results in a higher reflectance than the adjacent blue and red regions which our eyes perceive as 'green'.
(iii) 0.62 - 0.7 μm region characterised by strong chlorophyll absorption.

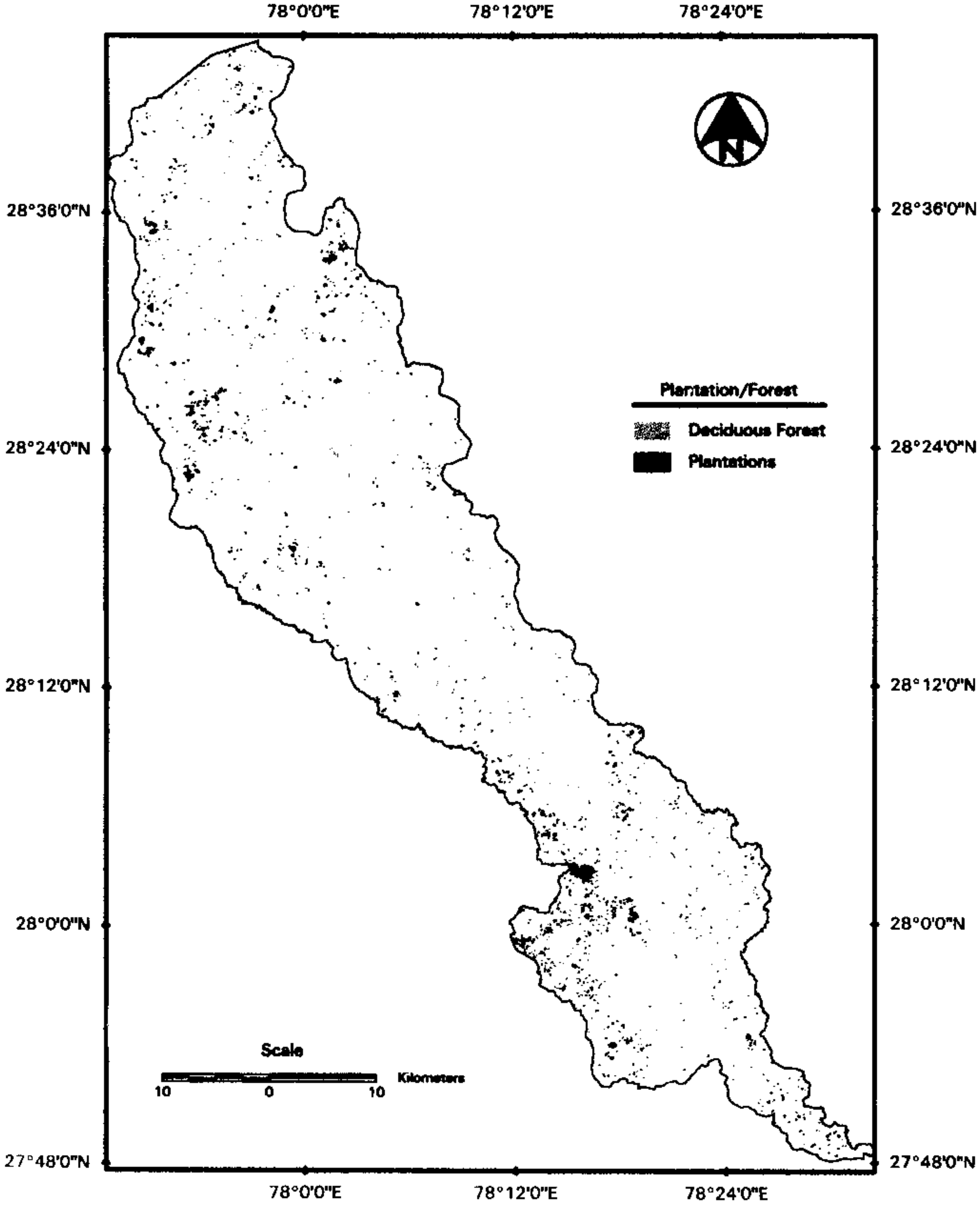


Fig. - 8 Plantations/Forest in the Study Area Derived from Remote Sensing Analysis

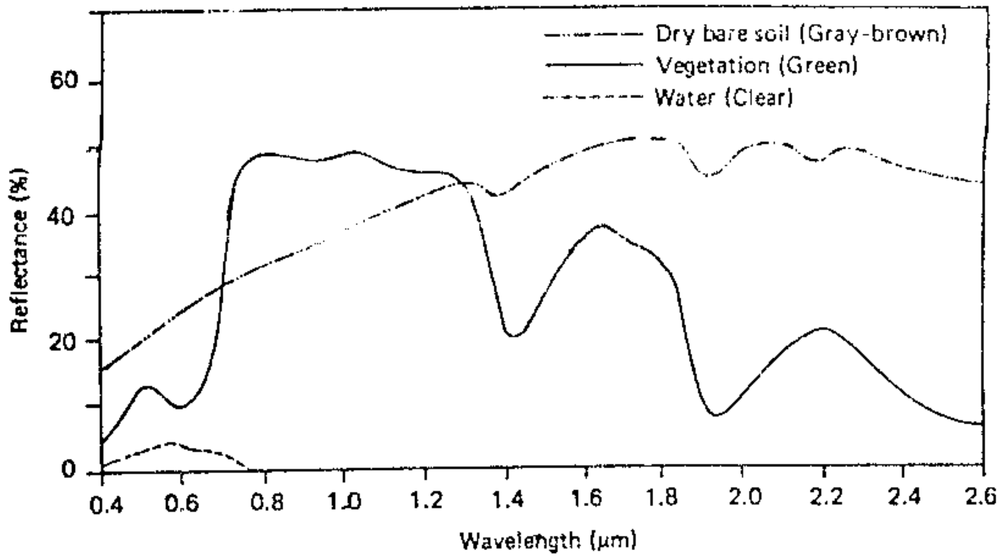


Fig. – 9 Spectral Reflectance Curves for Selected Earth Surface Features

(iv) 0.7 - 0.74 μm region characterised by the transition from strong chlorophyll absorption to high reflectance in the near-infrared (NIR) region.

(v) 0.74 - 1.3 μm region characterised by high reflectance. High reflectivity of leaves is caused by their internal cellular structure, which allows about 40-60% of the incident radiation to be scattered upwards as reflected radiation, whereas the remainder is scattered downwards. The amount of reflectance depends on the anatomical structure of the leaves, number of cell layers, size of cells, orientation of cell walls and the heterogeneity of their contents.

(vi) 1.3 - 2.5 μm region characterised by strong absorption by water present in the vegetation. In this spectral region, a strong relationship exists between the reflectance and the amount of water in the leaves.

Major factors which affect the leaf optical properties include the anatomical structure of leaves, leaf age, leaf water content, mineral deficiencies, pest and disease attacks and the reflectance of underlying soil. Soil background influences have been found to seriously hamper the assessment and characterisation of vegetation canopy covers.

The limitation of soil water availability of plants is a common environmental occurrence. This limitation of soil water availability to plants is referred to as "water stress" or "drought stress" which refer to the combination of abiotic conditions that produce serious plant water defects, which limit photosynthesis and restrict plant growth. Tucker (1980b) suggested that leaf water content changes can be more easily identified using remotely sensed data. Considering solar spectral irradiance and atmospheric transmission characteristics, he concluded that the 1.55 - 1.75 μm spectral interval is the most suitable band for monitoring plant canopy water status from space platforms.

In the present study, multi-temporal remote sensing data were utilised to identify and locate major crops in the command area. Since the crop reflectance depends on a number of factors as mentioned above, crop classification on the basis of reflectance signature alone posed complex problems. However, identification could be greatly enhanced by carefully selecting the timing and sequencing of images and having the knowledge of the crop calendar. A number of workers have stated a requirement for three to five good quality scenes if satellites are to realise their potential in agriculture. Various steps followed in the identification of crops are enumerated in the following.

a) Conversion of DNs to Radiance

Since the identification of crops relies heavily on the reflectance in the multiple bands of the spectrum, the DN values of the image were first converted into radiance. Using radiance values, it was possible to make a relative comparison of the reflectance in different bands with a common lower datum. For each band represented by wavelength λ, the digital radiance numbers, Q_{cal} on the satellite image were converted to radiance, L(λ) by:

$$L(\lambda) = L_{min}(\lambda) + [L_{max}(\lambda) - L_{min}(\lambda)] * (Q_{cal}/Q_{cal,max}) \qquad \text{... (16)}$$

The minimum and maximum radiance corresponding to minimum and maximum digital radiance numbers were obtained from the leader file supplied with the image data. Radiometric characteristics of IRS-1C LISS-III sensor, as used in this study, are presented in Table - 2 below.

Table - 2

Radiometric Characteristics of IRS-1C

Band	Wavelength Range (μm) in IRS-1C LISS-III	Satellite Radiance in (W m^{-2} μm^{-1} sr^{-1})	
		L_{min}	$L_{max.}$
1	0.52 – 0.59	1.76	14.45
2	0.62 – 0.68	1.54	17.03
3	0.77 – 0.86	1.09	17.19
4	1.55 – 1.70	0.00	2.42

A small model was developed using the MODELER option of the ERDAS system to convert the DNs to radiance. The model first finds the maximum DN value in a band and then computes the radiance for each grid in that band. The radiance was computed for all the bands separately and then a composite image of different bands was formed. To have the accuracy in computation, the output was obtained as a Float file, which provided the radiance estimates up to two decimal places. The radiance images were used in subsequent analysis.

b) Separation of the Agricultural Area

Since the aim of the analysis was to classify the crops within the agricultural area, it was first planned to separate out the agricultural grids from the full scene of the study area. As can be seen from Fig. – 9, the spectral reflectance characteristics of vegetation are quite distinct from that of bare soil, water, or built up area. In the red band (0.62 – 0.68 μm), the radiation is absorbed by the chlorophyll while in the NIR band (0.77 – 0.86 μm), the reflectance is quite high because of the cell structure of the plant leaves. This property was utilised for separating the agricultural grids from the other grids (bare soil, water, built-up area etc.).

Since the vegetation reflectance in red band is less and in NIR band is very high, the Vegetation Index (VI = Red/NIR) for an agricultural grid must be very high as compared to other grids. For the bare soil also, since the reflectance in NIR band is more than the red band, the VI will be greater than 1. However, the VI of the bare soil grid must be small in comparison to the vegetation grid (since the reflectance of soil in red band is greater and in NIR band is smaller than that of vegetation). So, there was a need to specify a threshold VI such that a grid above the threshold may be classified as an agricultural grid and that below the threshold may be recorded as a non-agriculture grid.

The VI images corresponding to images of different dates were computed and compared with the corresponding standard FCCs. Based on the visual inspection of the FCCs, threshold values of VIs for discriminating agricultural areas were finalised for images of different dates. Initially, a higher value of VI, such as 1.5, was assumed and corresponding agricultural area was compared with the FCC. The threshold was gradually decreased till almost whole of the vegetation area was covered under agriculture. This way, the threshold limits of VI were identified. For the images of June 3; July 23; October 9, October 31; November 26; and March 2, the threshold VI values for separating agricultural area were found to be 1.21, 1.43, 1.21, 1.21, 1.20, and 1.95 respectively. A model was developed in the MODELER and the condition to classify a grid as agriculture/no-agriculture was applied on the VI image. A grid having VI value less than the threshold was classified in the non-agricultural category and vice versa. Using VI thresholds in different images, the agricultural areas were extracted in the images of different dates.

It is possible that a grid with VI less than the threshold value (say 1.20 or 1.19 in the image of June) may also represent vegetation. However, it was assumed that such a grid may not represent a true crop location and, even if selected as agriculture, may be classified in either grassland, or vegetable or other miscellaneous category. It is also possible that such grids may represent mixed conditions at the boundary of the cropped area (with some area under crop and the rest under other land use). Based on the visual inspection of the FCCs, thresholds were selected such that most of the pure crop grids could find place in the classified agriculture area and the grids with mixed conditions could be kept separate. Fig. – 10 shows the FCC of the image of October 9 and the corresponding agriculture area extracted using the above procedure.

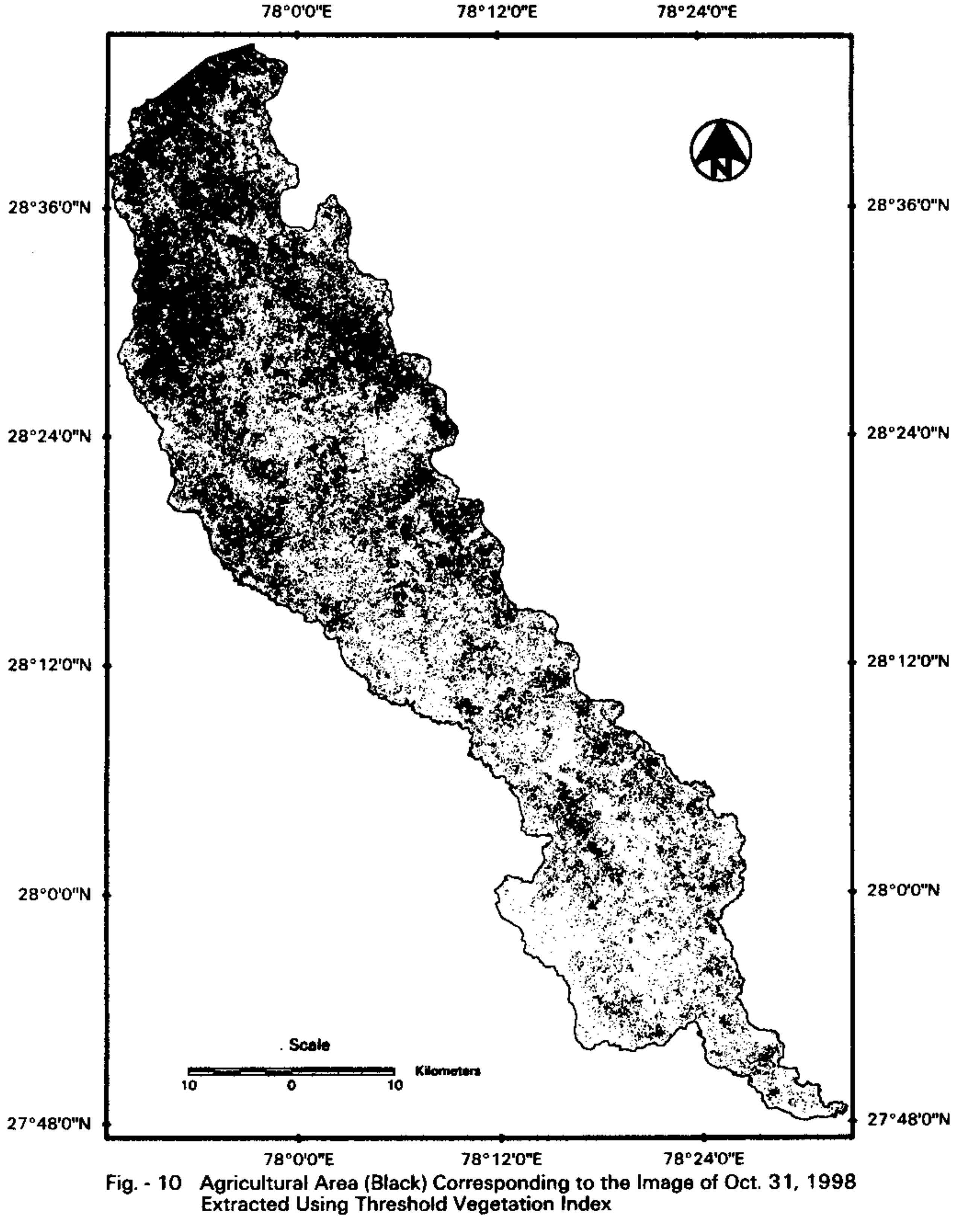


Fig. - 10 Agricultural Area (Black) Corresponding to the Image of Oct. 31, 1998 Extracted Using Threshold Vegetation Index

c) Separation of Plantations from Agricultural Area

Plantations and the forest area do not form part of the agricultural crop area and need to be separated from the vegetational area as described under (b) above. Plantations had been identified separately as mentioned under (a). Using the MODELER option, the plantation and forest area were eliminated from the agricultural areas of different dates. Thus, the net agricultural areas of different dates contained the major crops in the field and various other vegetation features, such as grassland, and vegetables etc. In the subsequent discussion, the term "image" shall refer to the radiance image of the net agricultural grids only.

d) Major Crops in Lakhaoti Command

The principal crops in the Lakhaoti command are Wheat, Sugarcane and Maize. As the canal supplies were not available earlier, the area under Paddy was very small. With the introduction of canal supplies, the area under Kharif paddy is proposed to be 48254 hectare, i.e. 25 % of the CCA. The existing cropping intensity during the monsoon season and winter-season are 39 and 75 percent respectively. Other major crops in the command are Gram, Guar, Arhar, Mustard, Berseem, Barley, and Potato.

The average area under various crops before the introduction of the canal system and as proposed by project authority after the introduction of canal system under the conjunctive use plan are shown in Table – 3. The crop calendar of various crops that is broadly followed in this area is presented in Table - 4.

e) Crop Classification

In this study, various computer-based algorithms were used to identify different crops in the command area. After finalising the agricultural crop area (after step ©), image visualisation was enhanced using histogram equalisation and the difference between various crop types was observed. However, since the crop reflectance depends on a number of factors besides crop type, it was not possible to find significant visual difference among various crops. Next, the principal component analysis for the agricultural image was carried out and most of the variation within the four band data was condensed in a single band. The first principal component was visualised alone and in combination with the red and NIR band of LISS-III but useful inferences about crop classification could not be drawn.

Then, the Tasselled Cap transformation was applied on the radiance image of four bands and the transformed image was visualised. Coefficients of corresponding bands of TM sensor were used for LISS-III sensor. The FCC corresponding to the Brightness, Greenness, and Wetness layers was prepared and visualised. This process also did not yield much information for differentiating various crop types. Next, a vegetation index that eliminates the background soil effect from the reflectance of a crop (Soil Adjusted Vegetation Index) was utilised to generate a soil adjusted crop reflectance layer. The first principal component of the radiance image of agricultural area was also prepared. It was planned to prepare a FCC with the first principal component as band 1, greenness layer of Tasselled cap transformation as band 2, and the soil adjusted vegetation index (SAVI) as band 3. It was opined that since the

Table – 3
Cropping Pattern Before & After Canal Introduction in Lakhaoti Command

S. No.	Name of Crop	Crop Area Before Canal		Crop Area After Canal		Yield
		(in ha)	(as %)	(in ha)	(as %)	(Qt/ha)
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	10950	5.7	10950	5.7	10
5.	Guar	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 – 4
Crop Calendar of Major Crops in Lakhaoti Command

S. No.	Name of Crop	J	F	M	A	M	J	J	A	S	O	N	D
1.	Sugarcane	←	—	—	—	—	—	—	—	—	—	—	→
2.	Moong			←	—	→							
3.	Urad				←	→							
4.	Rice						←	—	—	—	→		
5.	Maize						←	—	—	→			
6.	Arhar						←	—	—	—	—	→	
7.	Guar							←	—	→			
8.	Gram	←	—	→							←	—	→
9.	Mustard	←	—	→								←	→
10.	Potato	←	→									←	→
11.	Wheat	←	—	—	→								↔
12.	Barley	←	→									←	→

first principal component contains the maximum information of the four bands of LISS-III, greenness layer of tasselled cap enhances the vegetational information, and the SAVI eliminates the soil background effect, the combination of the three layers might infer useful information about different crop types in the command area. However, most of the agricultural area appeared bright and the variation within the crops could not be obtained. Then, the unsupervised classification of this FCC was carried out for classification in some finite number of classes (say, 5). The signatures of different classes were found to be similar in the principal component and SAVI bands and variation could be observed in the green band of tasselled cap only. Based on these observations, it was decided not to utilise the digital processing techniques on a single date image for crop classification and to resort to the use of multi-temporal data in conjunction with the crop calendar. The procedure used to identify different crops in the area is described in the following:

i) Sugarcane

Sugarcane is one of the major crops of Lakhaoti command. It is sown in the month of December and it remains in the field throughout the year. For the identification of sugarcane in the command area, the images of June, July and October 9 were utilised. From the crop calendar, it can be seen that in the image of June 3, 1998, the major crops in the command must be Urad, Moong and Sugarcane. The Urad and Moong will be in their senescence stage on June 3 and their VI will be lower than the active chlorophyll crop of sugarcane. Hence, it can be expected that on June 3, sugarcane is the only major crop in the field that will have appreciable VI as compared to other crops or vegetation. Based on this reasoning, the image of June 3 was utilised to separate the agriculture grids into two broad classes: sugarcane with pronounced signatures of vegetation, and rest others, with feeble signature of vegetation, say grassland, vegetables, or others.

Unsupervised classification was carried out on the June 3 image. Though, the interest mainly lied in the discrimination of the agricultural grids into two classes, the image was classified into more number of classes (say, 10) to visualise the difference in the signatures of the various classes formed. The signatures were analysed and it was found that there were two broad classes. The classes one to seven were merged as a single class as sugarcane while the classes eight to ten were merged and classified as others. One more check was applied on the sugarcane grids. The sugarcane grids, present on June 3 in the field, must be present as agricultural grid in the subsequent images also. So, the sugarcane grids, classified above, were checked for their presence in the subsequent images of July and October 9. Most of the sugarcane grids were found in both these images. Those grids, which were classified as sugarcane in the June 3 image and were present in the subsequent images also, were finalised as sugarcane. The sugarcane area in the command came out to be 17878 ha which is quite close to the proposed area of this crop.

ii) Rice

Sugarcane was the first crop to be classified as it was the major crop exclusively present in the field on June 3, 1998. Next, the rice crop in the command was identified by using the images of July 23 and October 9. It is well known that rice needs standing water in the field, at least in the early stages of its development. During this period, the growth of rice plant is quite small and remote sensing signatures mainly represent the water characteristics at such locations. After the full development of the plant, the canopy reflectance takes over and the reflectance characteristics represent vegetation signatures at the same locations.

This fact was utilised to identify and classify the rice grids in the Lakhaoti command. A comparison of the agriculture images of July and October 9 revealed that a lot of area, which is not classified as agriculture in the July scene, is classified as agriculture in the October scene. From the original FCCs (radiance image) of July and October 9, it was found that many grids, which represent agriculture in the October 9 scene and are not classified as agriculture in the July image, bear water signatures. Such locations were confirmed to be rice. So for classification of rice in the command, the following condition was applied: "if a grid is not classified as agriculture in the July scene and the same is represented as agriculture in the October 9 scene, it may be classified as rice". As the rice crop needs large amount of water, most of the rice locations in the command were found to lie near the main canal and along the distributaries. This further confirmed the classification. The radiance FCC of October 9 with the agriculture image of July 23 overlaid is presented in Fig. – 11. The map of classified rice crop is presented in Fig. - 12. The cropped area of rice came out to be 43887 ha which is very close to the proposed area in the command.

iii) Arhar

Of the various Kharif crops grown in the Lakhaoti command, arhar is the only major crop that remains in the field up to November. To identify this crop, the image of October 31, and the classified images of sugarcane and rice were utilised. On this date, the major crops in the field will be sugarcane, rice (not harvested), arhar and others. Though, the gram crop of Rabi season is sown in the month of October, it is expected that the plant development will be in its initial stage and it may not find place in the agriculture area in the image of October 31.

From the agriculture image of October 31, the images of sugarcane and rice were subtracted so that the remaining agriculture area may represent only the arhar crop and other miscellaneous vegetation. Unsupervised classification algorithm was applied to the remaining agricultural area and two major classes were identified. Based on the spectral signatures of the two classes, the class with prominent vegetation signature was identified to be arhar. Based on this procedure, the cropped area of arhar crop came out to be 9148 ha while the projected proposed area of this crop is 10950 ha.

iv) Maize/Guar

As per the crop calendar, maize crop is planted in the month of June and the guar crop is planted in July. Both these crops are harvested by the end of September. It was felt that some area under these crops could be present in the image of October 9, but not in the image of October 31. For identification of maize and guar, the images of July and October 31 and the classified images of sugarcane and rice were utilised.

From the agriculture image of July, the classified image of sugarcane and rice and the agriculture image of October 31 were subtracted. The image of July was found to contain a large agricultural area not covered under the sugarcane, rice, and arhar crops. This area pertained to the maize and guar in the command area. For the separation of these two crops, the unsupervised classification algorithm was applied and two different classes were obtained. One class was assigned to the maize crop and the other to the guar crop. The area under maize came out to be 38330 ha and that under guar 2360 ha. It is seen that before the canal introduction, the area of maize was 37551 ha. From the remote sensing analysis, it is concluded that maize crop is still being grown in the command area to the similar extent.

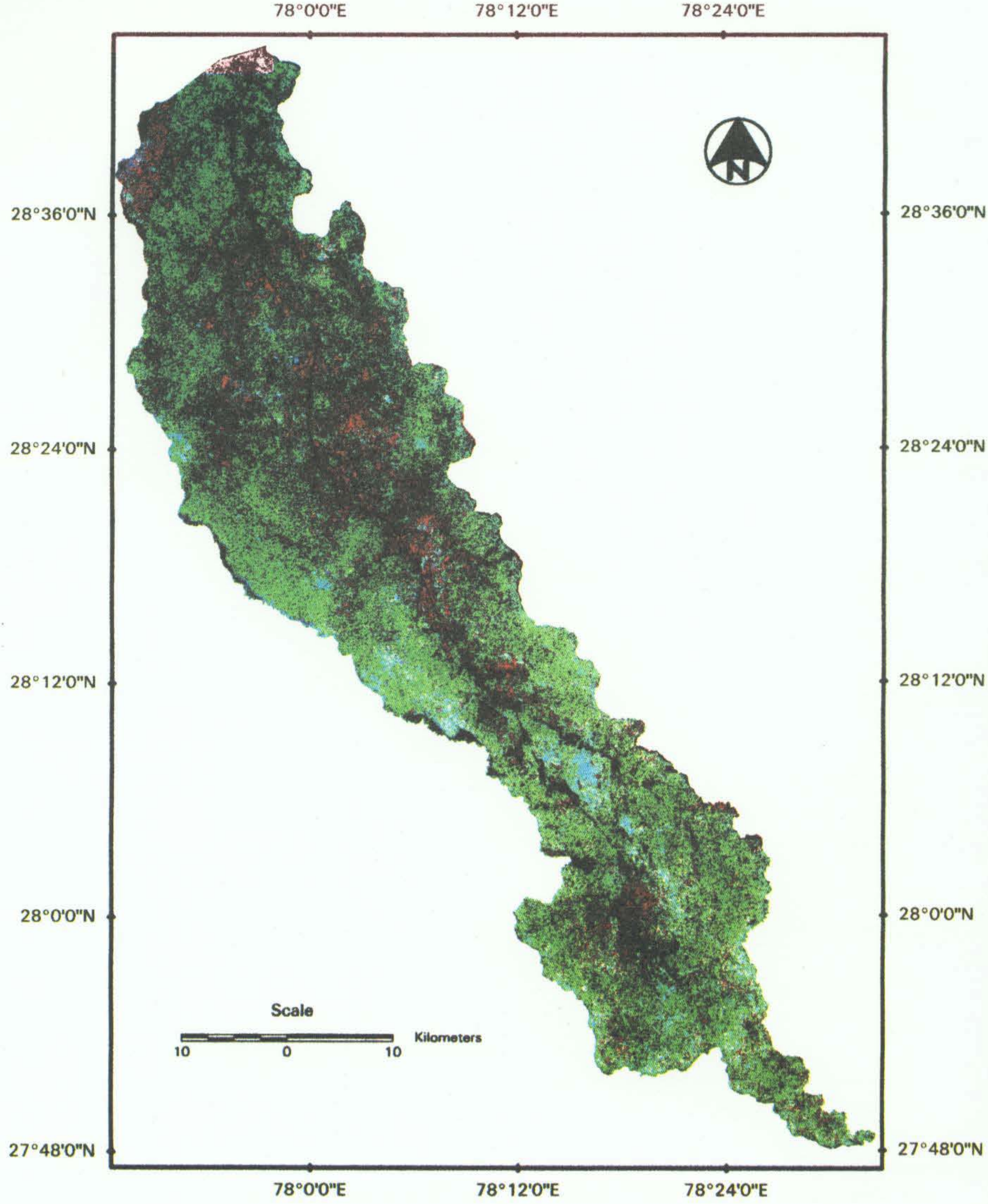


Fig. - 11 : FCC of Image of Oct. 9 Overlaid with Agriculture Area (Green) of July 23, 1998 and Lakhaoti Branch Canal (Black)

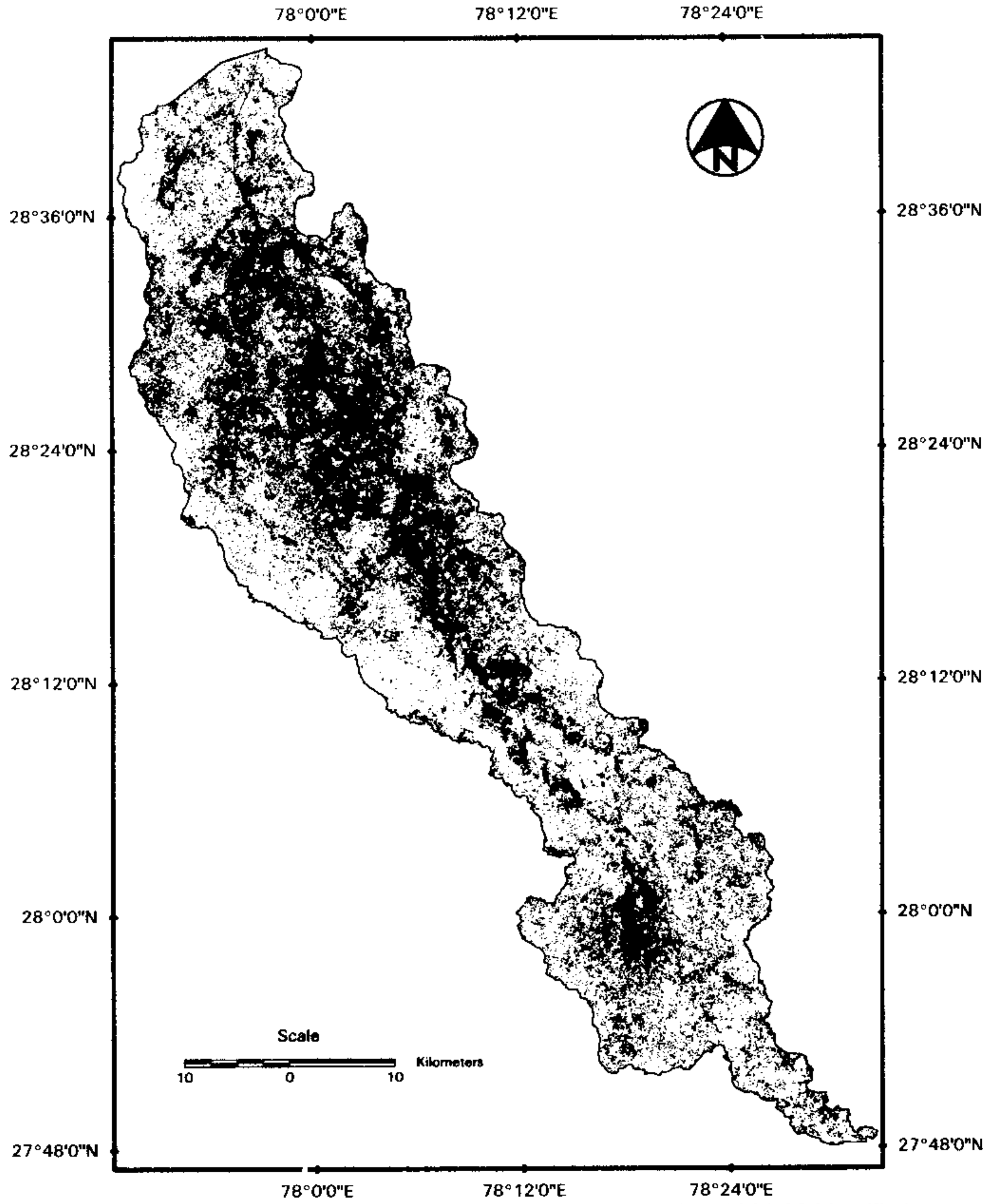


Fig. - 12 Rice Crop (Black) in the Lakhaoti Command in Year 1998-99 Identified Using Remote Sensing Analysis with Branch Canal (Magenta) Overlaid

v) Wheat/New Sugarcane

Wheat is the major Rabi crop in the command area and is sown in the month of December. During the Rabi season, the remote sensing data were available for only two dates, i.e. 26 November and 2 March. From the crop calendar, the image of November was assumed to contain crops of gram, mustard, potato and barley while the image of March was assumed to contain gram, mustard, wheat and new sugarcane planted in the month of December. Since the potato and barley are harvested towards the end of February, the subtraction of the agriculture area of November from that of March clearly separated out the wheat and new sugarcane crops from the rest of the Rabi season crops in the command area.

Based on these observations, the image of November agriculture was subtracted from that of March. Unsupervised classification algorithm was applied and two crop classes were obtained. Based on the signatures and extent of the area of two classes, one class was represented as wheat and the other class as new sugarcane. The VI of wheat grids was higher than that of new sugarcane. The signatures of the two classes were distinctly different. The area of wheat came out to be 64700 ha while that of new sugarcane came out to be 26129 ha. Because of the limitation of images of subsequent dates, these areas could not be confirmed.

vi) Gram/Mustard

Crop of gram is sown in October while that of mustard is sown in Early November. Both these crops are harvested by the end of March. It was assumed that these crops must be represented in both the images of November and March. Based on this reasoning the agricultural grids present in the agricultural areas of November and March were identified and classified in two categories to separate gram from mustard. The area of mustard came out to be 7176 ha while that of gram was found to be 2360 ha.

vii) Potato/Barley

Potato and barley are two Rabi crops that are sown in early November and harvested by the end of February. It was assumed that these crops would be included in the agricultural image of November and not in the image of March. For identifying potato and barley, the image of November and the classified crops of sugarcane, arhar, mustard and gram were used. From the agricultural area of November, the classified areas of sugarcane, arhar, gram, and mustard were subtracted. The remaining crops left in the agricultural area in November were potato, barley, and other miscellaneous vegetation. So, the remaining agricultural area was classified into 3 categories using the unsupervised classification algorithm. Based on the signatures and the corresponding areas, the potato and barley crops were identified in the command. The area of potato and barley came out to be 4156 ha and 8035 ha respectively.

f) Discussion of Remote Sensing Analysis

In the present study, remote sensing data have been used as ancillory data for incorpoating spatial crop type variation the Lakhaoti command. The classification of remote sensing data and the identification of different crops is primarily based on the availability of multi-temporal data and the crop calendar in the command area. The extensive ground truth verification of the remote sensing analysis was lacking in the present study. However, the acreage of most of the crops as found from remote sensing analysis came out to be quite close to the proposed acreage in the new regime after canal introduction. The results of classification were also compared with the records available at the DM office. The difference between the two was quite significant. For example, the DM records showed the acreage of rice crops as 8543 ha in the year 1998-99 while the estimation using remote sensing was 43843 ha. The rice crop in the command has been identified using a very convincing logic. In the image of July 23, 1998, a lot of area around the canal network represents the signatures of water. The same area in the October 9, 1998 scene gives very high reflectance in the NIR band representing a clear vegetation signature at that location. Since the rice fields require standing water, at least in the initial growth period of the crop, and the crop growth takes some time before it dominates the soil and water background influence, it seems highly certain that such fields represent rice crop. Further, such fields have been found to be located very near to the canal network in the Lakhaoti canal system. Thirdly, the accumulated area of such grids comes out to be very close to the proposed area of the rice crop in the present setup. There is no other interpretive factor used in the identification of rice crop. All these factors suggest to believe that the identification of rice crop in the present study using remote sensing is not very far off from the actual field situation. However, in the light of these observations, it is realised that extensive ground truth verification must be made for the analysed remote sensing data.

It needs to be mentioned here that remote sensing data are used in the present study as a substitute for the field record with regard to the crops grown in different fields. In actual practice, it can not substitute but only confirm the validity of the available records. Further, sufficient remote sensing signatures of actual crops are obtained after the crops have grown to maturity which may take some time (weeks or months). So it is emphasized that the application of the water balance model must be made for the actual crop records at the field level and the remote sensing data must be used to corroborate the field records after the crops have obtained sufficient maturity to be identified and discriminated in the remotely sensed images.

g) Composition of Kharif & Rabi Image

Location and extent of various crops in the Lakhaoti command were identified as discussed above and saved in separate files. The basis of classification of different crops was purely based on the crop calendar and the multi-temporal attribute of remote sensing. In addition, multi-spectral attribute was also used to classify an image in to different categories using unsupervised classification. The accuracy of classification depends on the exactness with which the crop calendar has been followed in the field. First, those crops were identified that could be classified on some logical basis (sugarcane, rice, arhar, wheat etc.). These crops were then, separated from the rest of the agriculture. Unsupervised algorithm was applied only in those instances where individual segregation was not possible. The signatures obtained under unsupervised classification were quite distinct to classify the rest of the crops in to different categories. The final areas of the crops obtained from classification are matching quite close to the corresponding areas proposed in the command.

After the finalisation of different crops, two composite images were formed, one for the Kharif season and another for the Rabi season. The individual crops of sugarcane, maize, rice, arhar and guar were merged together in one image and different numbers were assigned to different crops (sugarcane – 1, maize – 2, rice – 3, arhar – 4, and guar – 5). Thus, the Kharif image contained the locations of all the crops grown in the command during the Kharif season. The Kharif map of the command area is shown in Fig. – 13. Similarly, the individual crops of gram, mustard, potato, barley, wheat and new sugarcane were merged together and different numbers were assigned to them (gram – 6, mustard – 7, potato – 8, barley – 9, wheat – 10, and new sugarcane – 1). Thus, the Rabi image contained the locations of all the crops grown in the command during the Rabi season. The Rabi map of the command area is shown in Fig. – 14. These images were used as one layer of information (spatial crop variation within the command) for spatial water balance modelling of the root zone and for finding real-time demands.

4.5.4 Characteristics of Crops

Different crops have different characteristics associated with them, such as crop factors at different crop stages, maximum root depth, time to reach maximum root development, starting week of the crop, crop duration, standing water requirement (if any), and the fraction of the available water without affecting the yield of the crop. After the classification of crops in the Lakhaoti command, various characteristics associated with different crops in the area were identified and saved in a separate data file.

Crop factors of different crops at different growth stages were taken from the Circular No. 25 of M.P. Irrigation Department. Root depth characteristics and the fraction of available water for different crops were obtained from the FAO – IDP 24 (1977). In between the period of starting of crop to the time of maximum root depth, linear variation of root depth was assumed. Various characteristics of the crops and the fortnightly values of crop factors, that were used in this study, are presented in Table – 5.

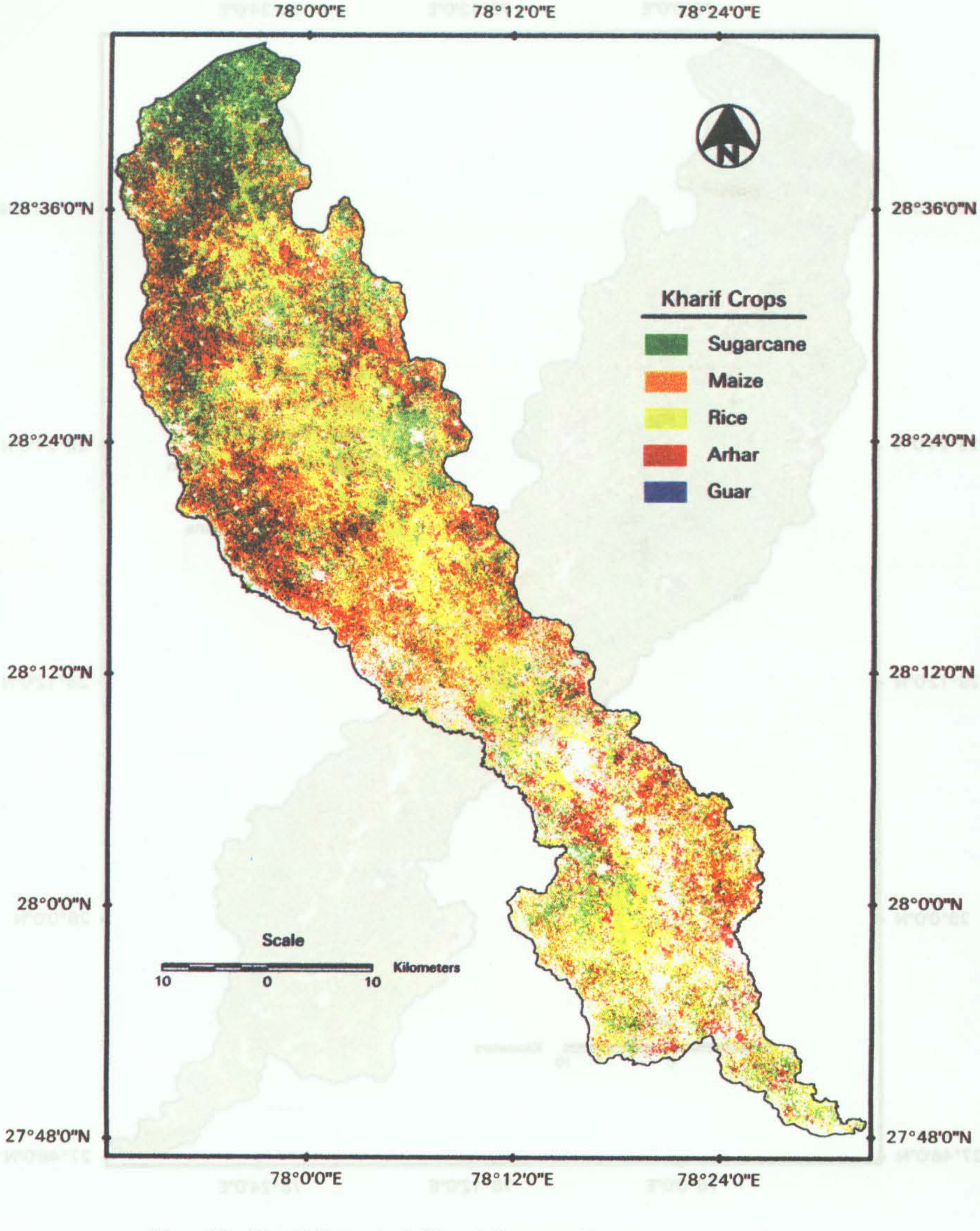


Fig. - 13 : Kharif Crops in Lakhaoti Command During the Year 1998-99

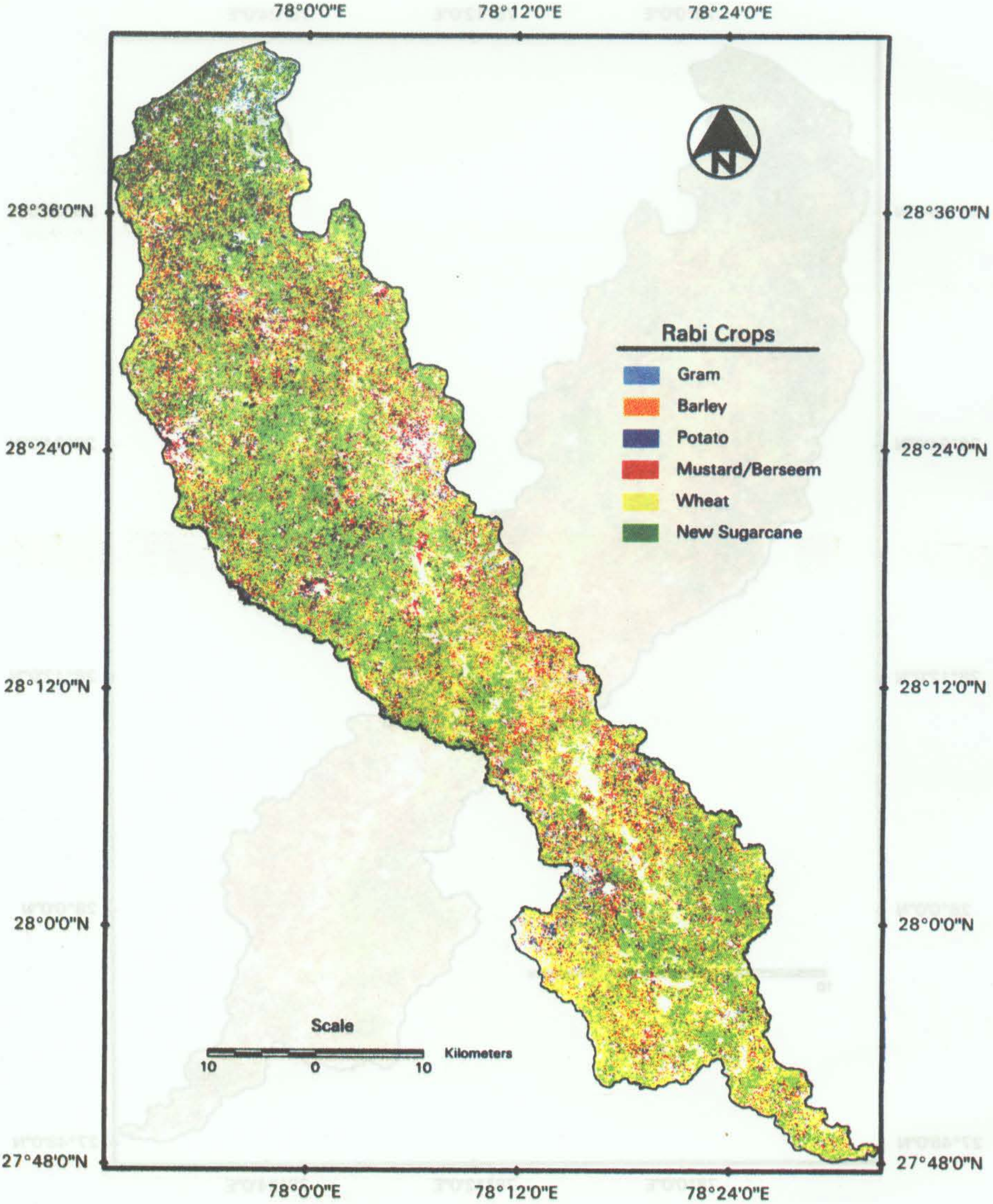


Fig. - 14 : Rabi Crops in Lakhaoti Command During the Year 1998-99

4.5.5 Soil Map of Lakhaoti Command

Properties of soil and its spatial variation have a significant effect on the water balance in the root zone. In addition to the crop type and the evapo-transpiration, the water content at a place depends on the saturation capacity of the soil, its field capacity and the water content at permanent wilting point. For these reasons, the variation of soil type in the command was an important input to the water balance model.

Table – 5

Crop Characteristics of Major Crops in Lakhaoti Command

Crop Characteristic	Sugarcane	Maize	Rice	Arhar	Guar	Gram	Mustard	Potato	Barley	Wheat
Fraction	0.65	0.60	1.00	0.50	0.50	0.50	0.50	0.25	0.55	0.50
Max. Root Depth (mm)	1200	1000	600	1200	1000	1200	1200	500	1000	1000
Time to Max. Root Depth (Cal. Week)	15	9	9	9	6	9	9	9	9	9
Starting Week	47	22	24	24	26	41	45	45	45	48
Period of Crop (Week)	52	20	20	21	15	19	19	17	19	17
Max. Standing Water Req. (mm)	0	0	100	0	0	0	0	0	0	0
Crop Coefficients										
January (I)	0.57					1.04	1.10	1.15	1.10	0.92
January (II)	0.59					0.89	1.10	1.15	1.07	1.10
February (I)	0.61					0.63	1.09	1.11	0.87	1.10
February (II)	0.64					0.41	0.93	0.86	0.50	1.10
March (I)	0.66					0.41	0.52			0.92
March (II)	0.70						0.52			0.53
April (I)	0.7									0.53
April (II)	0.81									
May (I)	0.87									
May (II)	0.92									
June (I)	0.96	0.49								
June (II)	1.00	0.59	1.05	0.40						
July (I)	1.05	0.91	1.10	0.47	0.49					
July (II)	1.09	1.10	1.10	0.65	0.63					
August (I)	1.10	1.10	1.10	0.99	0.91					
August (II)	1.10	1.01	1.13	1.03	1.05					
September (I)	1.10	1.01	1.15	1.05	1.05					
September (II)	1.10	0.71	1.15	1.05	0.96					
October (I)	1.10	0.71	1.10	1.03	0.64					
October (II)	1.06	0.71	0.98	0.89		0.23				
November (I)	1.02		0.98	0.48		0.29	0.31	0.34	0.31	
November (II)	0.51					0.83	0.48	0.42	0.42	
December (I)	0.53					1.05	0.50	0.72	0.80	0.31
December (II)	0.55					1.05	1.09	1.00	1.08	0.44

The soils in the Lakhaoti command are recent alluvium, deposited by the Ganges and its tributaries. The texture of these soils is light to medium loam and clay loam. Although there are large local variations, the same soil types and associations occur almost throughout the command. There is no salinity problem in the area. The thickness of fertile soil at top varies from 1.5 m to 2 m. The soil map of U.P. at a scale of 1:5,000,000 was obtained from the National Bureau of Soil Survey and Land Use Planning, New Delhi.

The soil map was geo-referenced in the same co-ordinate and projection system as that of other data. A segment map was created by digitising the boundaries of various soil types such that each soil type forms a closed polygon. The map shows nine different types of soils in the command area. The segment map was polygonized so that each polygon may represent a single type of soil and different identifiers were specified for different polygons. The polygon map was rasterized and similar values were given to the grids of similar soils. The soil map extended beyond the study area. So, the soil map of the study area was extracted from the whole map by using the rasterized boundary map of the area.

The soil map of the study area is presented in Fig. – 15 (a). Values from 1 to 9 were assigned to different soils.

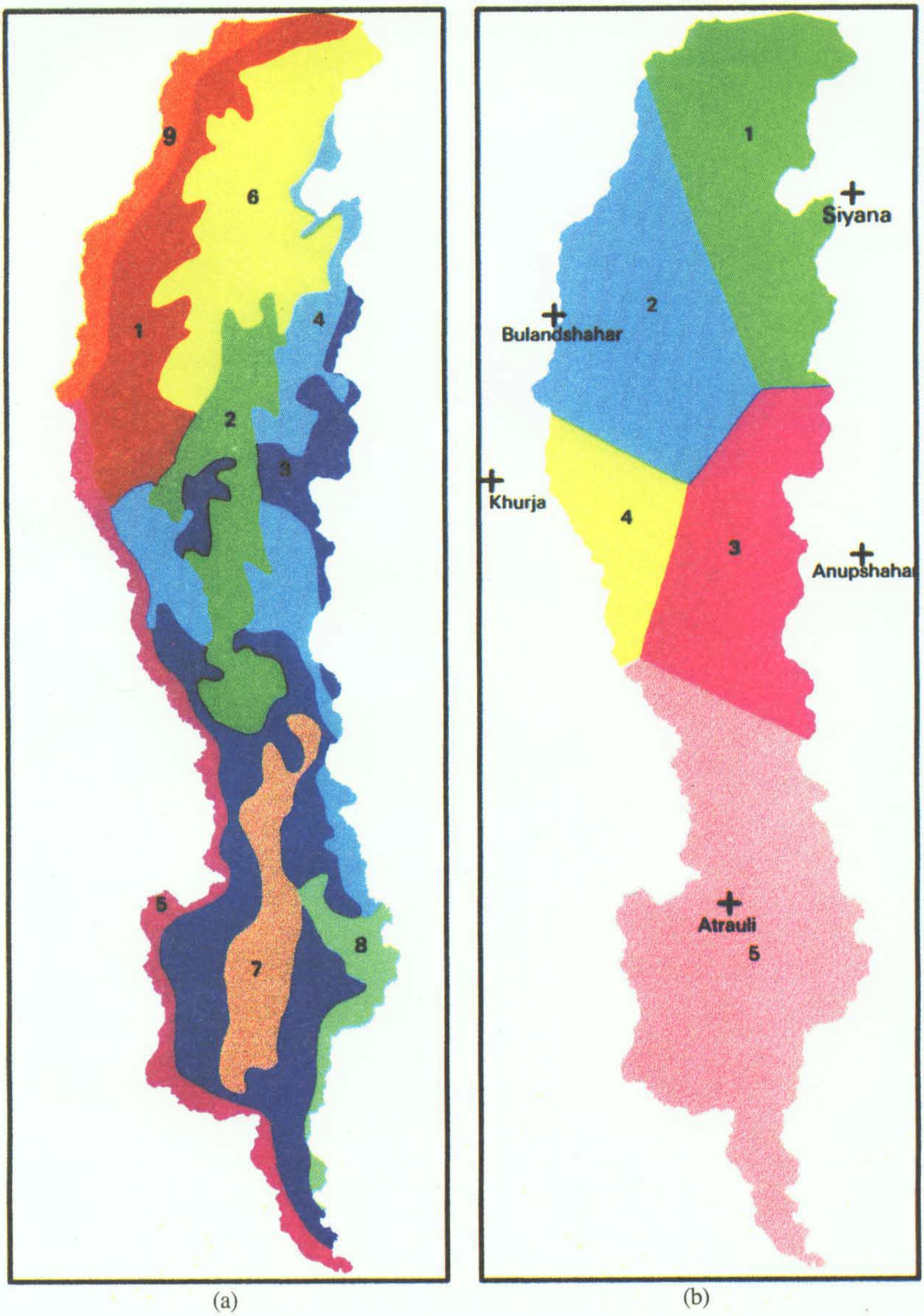
4.5.5.1 Identification of Soil Parameters

The capacity of soil to hold water is related to surface area as well as pore space volume. Hence, water-holding capacity is related to both structure and texture of the soil. In general, fine textured soils have the maximum total water holding capacity, but maximum available water is held in medium-textured soils. In this study, the soil properties of interest were: a) porosity, b) field capacity, c) permanent wilting point, and d) apparent specific gravity. Based on the location of various soil types in the Lakhaoti command, field visits were made and the samples were collected for all the varieties of soils. Three samples were collected from different depths at a site; at a depth of 15-20 cm from the ground surface, 50-60 cm from the ground surface, and about 1 m from the ground surface. The first two samples were taken out with an augur while the third sample was collected with an undisturbed sampler. These samples were analysed in the laboratory for finding the parameters of interest. The grain size distribution of the samples was also found out. Identification of various parameters is briefly described in the following:

a) Particle Size Distribution

Particle size distribution is an attempt to determine the relative proportion of different grain sizes that make a given soil mass. The relative proportion of sand, silt and clay determines the soil texture. The diameter of the particles present in the soil sample makes the soil to be coarse, medium and fine. The soil texture triangle is then used to convert quantitative data from detailed gradation analysis to textural class names of soils.

To carry out the particle size distribution, the oven dried soil sample is first washed through the sieve of number 200. The portion of the soil particles retained on sieve is



(a) (b)

Fig. - 15 (a) Rotated Map of Different Soil Types in Lakhaoti Command
(b) Rotated Map of Thiessen Polygons for Lakhaoti Command

subjected to sieve analysis. In sieve analysis, the portion retained on each sieve is collected and weighted. The percentage of soil sample retained on each sieve on the basis of total weight of soil sample and the percentage of weight passing through each sieve is calculated. Sedimentation analysis is used for the fraction of soil finer than 75 micron. In this study, particle size distribution was determined for all the soil types. Fig. – 16 shows the distribution for the soil number 88. Based on the USDA soil texture classification, all the soils in Lakhaoti command fall in the "Silty Loam" texture class.

b) Soil Moisture Characteristic Curve

Soil moisture retention curve, also called moisture characteristic curve, is the plot of moisture content versus suction head. It shows the amount of moisture in a given soil at various tensions. The moisture characteristic curve of a soil sample can generally be determined by equilibrating a soil sample at a succession of known tension value and each time determining the amount of moisture. The graph is plotted between the tension and corresponding soil moisture value to obtain the soil moisture characteristic curve. Different soil types give different characteristic curves.

Pressure plate apparatus is a standard method for obtaining the soil moisture characteristic curves. It consists of a pressure chamber in which a saturated soil sample (either disturbed or undisturbed) is placed on a porous ceramic plate through which the soil solution passes but no soil particle or air can pass easily. The soil solution, which passes through the membrane is in contact with atmospheric pressure. As soon as the air pressure inside the chambers are raised above the atmospheric pressure, it takes excess water out of the soil mass through the membrane outlet. Soil water flows out from the soil sample until the metric potential of the unsaturated flow is same as the applied air pressure. The air pressure is then, released and the moisture content of the soil is gravimetrically determined for that particular tension. When air pressure in the chamber is increased flow of water from the sample starts again and continue until a new equilibrium is reached. The same procedure is repeated at various pressures. The pair of pressure and moisture content data so obtained is used to construct the soil moisture characteristic curve.

Soil moisture characteristic curves are useful to understand the amount of water that is available to plants, the water that can be taken up by the soil before percolation starts, and the amount of water that must be used for irrigation. 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 (Henry, 1984). In this study, moisture contents were evaluated corresponding to soil suction pressures of -0.1, -0.33 bar, -1 bar, -3 bar, -5 bar, and –10 bar. Soil moisture characteristic curves were prepared, exponential relations were fitted and moisture content corresponding to –15 bar were obtained for all soil types. Soil moisture characteristic curve for soil number 99 is shown in Fig. – 17.

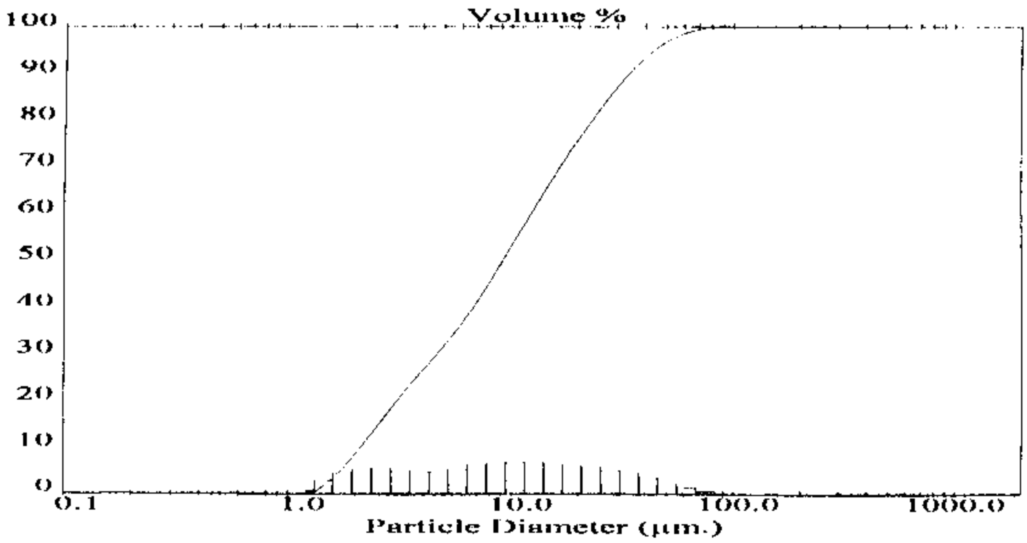


Fig. – 16 Particle Size Distribution for the Soil 88

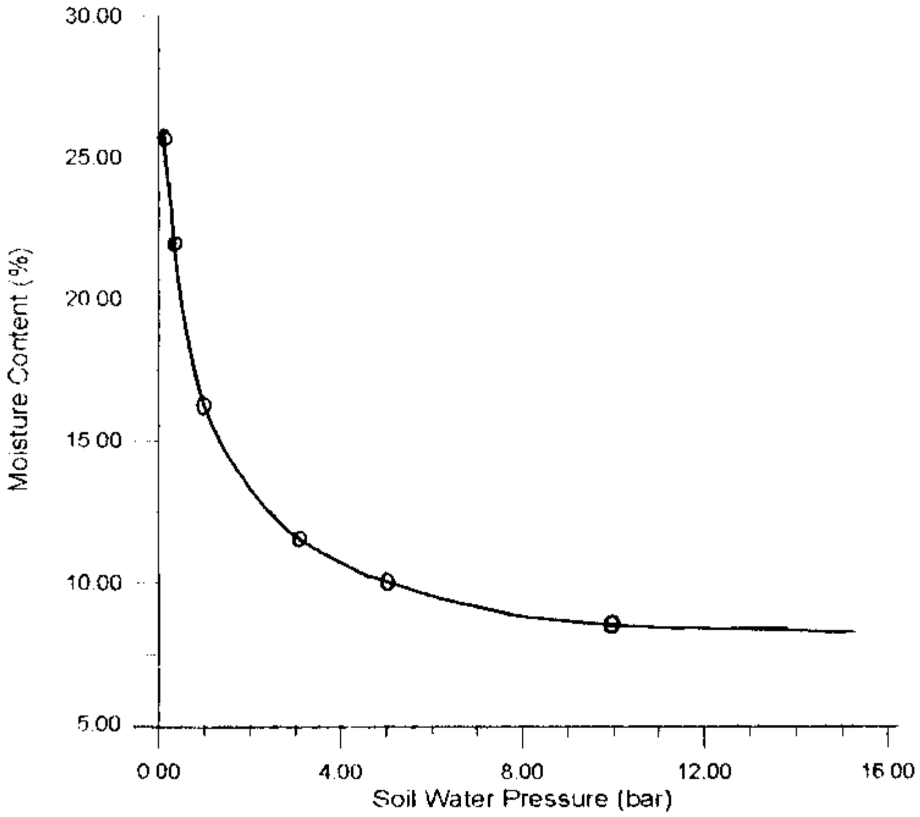


Fig. – 17 Soil Moisture Characteristic Curve for Soil 99 *c) Apparent Specific Gravity*

Specific gravity (G) is defined as the ratio of the 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 the soil particles and takes into account the voids within the soil mass. Apparent specific gravity is defined as the ratio of the weight of a given volume of soil mass to the weight of an equal volume of water. Apparent specific gravity is related to the specific gravity by the following relation:

$$G_a = (1 - n) * G$$

where n is the porosity of the soil. The specific gravity for different soil types were 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.

Table – 6

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

4.5.6 Rainfall 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 were available for the year 1998-99. The data were collected from the office of the District Magistrate, Bulandshahr.

Various rainfall stations were marked on a map and the Thiessen polygon map of the area was prepared and geo-referenced to the same co-ordinate and projection system. A segment map of various Thiessen polygons was digitised such that each polygon forms a closed area. The segment map was polygonised and rasterised. In the raster map, the grids under different stations were given different values. The Thiessen polygons of Siyana, Bulandshahr, Anupshahr, Khurja, and Atrauli were given values of 1, 2, 3, 4, and 5 respectively. The study area portion was extracted out of the full map using the raster boundary map of the Lakhaoti command.

Thiessen polygon map of the Lakhaoti command is shown in Fig. – 15 (b). Using the Thiessen polygon map, different grids in the Lakhaoti command were associated with different rainfall stations and their rainfall data were used for the purpose of water balance modelling in the root zone. The daily rainfall data of the various stations were entered and stored in a data file such that each row represented the rainfall of a day corresponding to station 1 through 5.

4.5.7 Rotation & Export of Image Data

Three data layers were prepared in the image form: a) crop map, b) soil map, and c) Thiessen polygon map. These data layers were to be exported in ASCII format so that the Fortran program could use these data and carry out the distributed water balance modelling in the command area.

With the true co-ordinate and projection system, the Lakhaoti command area was covered in 3006 columns and 4356 rows. From the visual inspection of the boundary map, it can be seen that the shape of the command area is longitudinal but since it lies in slanting position, a large amount of redundant area gets associated with it. When this command map was converted into the ASCII format, the size of file was approx. 67 MB. For using files of this dimension for modelling, similar dimensions had to be specified in the Fortran program. Such large dimensions caused problems in the compiling of the program and its memory space was exceeded.

To reduce the dimensions of the data, different data images were rotated clock-wise by 30° so that the command area position becomes longitudinal in vertical direction with minimum associated redundant area. The results were saved in another image file. After rotation, a subset of the image was formed which contained only the study area. The upper and lower X co-ordinates of the subset were 175.75 and 345.35 respectively. Similarly, the upper and lower Y co-ordinates of the subset image were –28.83 and –643.99 respectively.

The grid size and the co-ordinate system of the rotated image were different from the true values as used throughout in this study. So, the rotated images were geo-referenced again with respect to the original image and then re-sampled to a grid size similar to that of the original image, i.e. 24 m. The FCC of the study area was used to finalise the geo-referencing model and the same was saved in a file. This model was used for re-sampling different data layers of crop, soil, and Thiessen polygon. Using the rotated data, the command area was covered in 1143 columns and 4142 rows and the file size, in ASCII format, was approx. 24 MB. With these dimensions, the Fortran program could be easily compiled and worked with.

After finalising the image layer in the ERDAS system, the file was, first, exported in the TIF format and then, converted to ASCII format using the ILWIS system. The ASCII data were used as input data for the water balance program.

4.5.8 Estimation of Evapo-transpiration

The meteorological factors that are useful in the water balance computation include rainfall and potential evapo-transpiration (PET). Daily PET depends on several factors such as maximum and minimum temperature during the day, maximum and minimum relative humidity, sunshine hours, average wind speed, time of the year and the latitude and altitude of the place. The water consumption by the plants is computed on the basis of daily/weekly PET in the area. A number of methods are available in the literature for the estimation of PET. These include Penman method, Penman-Monteith (PM) method, Hargreave's method, Blaney Criddle method etc. PM method is the most advanced resistance based method of evaporation used in hydrology. However, the application of Penman or PM methods requires data on temperature, humidity, wind, and sunshine duration or radiation. The expert committee of FAO (1991) recommended the use of PM method for the estimation of PET.

Where extensive data on climatic parameters are not available, other methods such as Hargreave's have to be resorted to. Hargreave's method is a temperature based method and is represented as:

$$E_{rc} = 0.0023 * S_o * \delta_T * (T + 17.8) \text{ mm per day} \qquad \ldots(17)$$

where S_o is the water equivalent of extraterrestrial radiation in mm per day for the location of interest, T is the temperature in °C and δ_T is the difference between mean monthly maximum and mean monthly minimum temperatures. In cases of data scarcity, this equation has been shown to provide reasonable estimates of reference crop ET. Kotsopoulos et al. (1997) have provided analytical equations for finding parameters used in calculating PET. These equations include expressions for adjustment factor "C" in the Penman's method, saturation vapour pressure "e_s", slope of saturation vapour pressure with respect to air temperature "Δ", extraterrestrial radiation "R_a", declination of the Sun "δ", relative distance of the earth from the Sun "d_r", and the maximum possible sunshine duration "N".

Using these expressions, a computer program was developed to estimate the evapo-transpiration from the climatic data. Three methods of computation have been used: the Penman method, PM method, and the Hargreave's method. Based on the availability of data, any one of the methods can be chosen.

For the Lakhaoti command, the climatic data at Bulandshahr or Aligarh were not available. So, the climatic data of a station near Meerut were used. This station is located in the Modipuram Campus of the G. B. Pant Agriculture University. Records of maximum and minimum temperature and relative humidity were available. Due to the non-availability of the reliable wind and sunshine records, the Penman or PM methods could not be utilised. With the available data, the Hargreave's method was used to compute the reference crop evapo-transpiration. Daily values of E_{rc} were computed for the year 1998-99.

* * *

CHAPTER – 5

ANALYSIS AND RESULTS

The water-resources system is conceived to be a public utility system in all parts of the world. Water resources are a limiting factor in crop production in many parts of India and water for irrigation is becoming, both, scarce and expensive. Irrigation water is a very valuable commodity and needs to be conserved and managed efficiently. Mathematical models are developed to simulate the physical processes of crop-soil-water systems for providing the knowledge of the amount and timing of water needed and the crop's yield.

Hydrologic parameterisation in lumped regional models uses spatially averaged conditions. The space and time dependence inherent in some components of these models limit their applicability. It is well-known that processes of evapo-transpiration, infiltration, percolation and runoff vary significantly in space due to heterogeneity in soil, vegetation and topographic conditions. In this study, an analytical model of soil-water balance, that is distributed in space and time, is developed.

5.1 COMPUTER PROGRAM FOR WATER BALANCE COMPUTATION

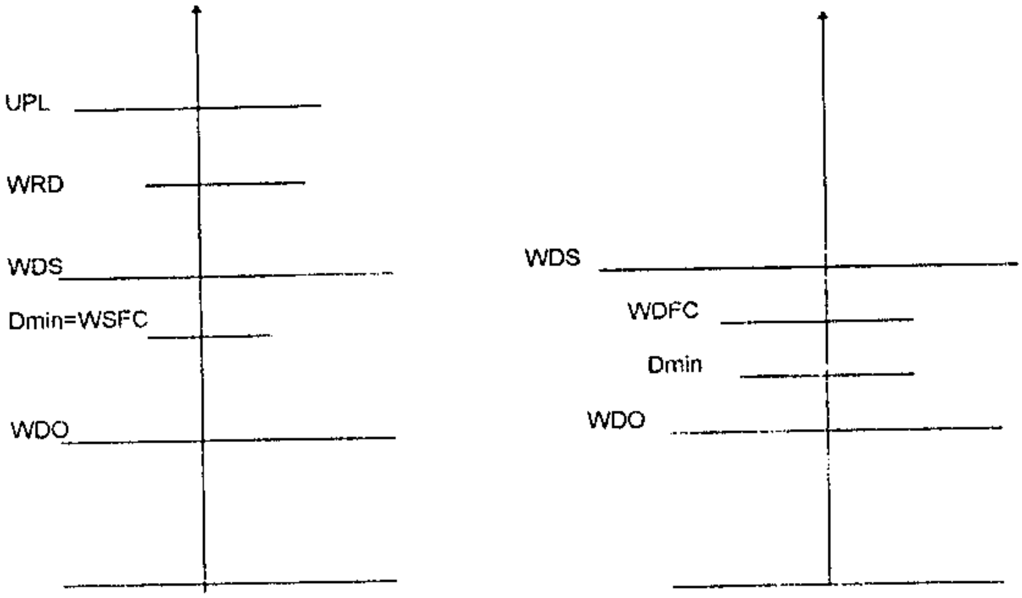
A computer program was developed to carry out the water balance computations in the root zone of a command area. The water balance procedure is described in Chapter 2. The program performs grid-wise computations and uses the raster as well as attribute data of different variables. Two time steps can be chosen: daily or weekly.

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

For computing the water balance in the root zone, initial moisture content needs to be specified. For the first time step, it is assumed that the initial moisture content in the root zone for all the grids lies midway between field capacity and permanent wilting point. For the subsequent time steps, the final water depth of the previous week becomes the initial moisture content of the current week. In this study, the computations were started for the around the first half of June when the initial moisture in the root zone can be assumed to be low because of the dry and hot weather of May and June. After receiving a few spells of heavy shower in the monsoon months, the effect of assumption of initial soil moisture becomes marginal.

During its run, the program prompts for two pieces of information. First, it requires the calendar day/week for which the simulation is to be carried out. Second, it queries whether computations need to start afresh. For fresh computations, the initial moisture content (WDI) for all the grids are calculated by the program itself (midway between field capacity and permanent wilting point). Otherwise, the initial soil moisture data are read from an input file. After this, the program reads various data files one by one and the data type being read is displayed on the screen. The reading of distributed data types takes some time and for such files, the row being read is displayed. If the program terminates midway due to some error in the data files, the location of the error and the corresponding data file can be spotted.

After reading the input data files, the computations are performed for different grids. Based on the day/week of simulation and the crop type at a particular grid, the program identifies whether the crop is present during the period of simulation or not. If present, then the growth stage of crop and the corresponding root depth are calculated. Effective soil depth is assumed to be higher of the root depth or 75 mm for all the time periods. Based on the effective soil depth, soil properties, and the crop properties at a particular grid, the program computes the water depth at saturation (WDS), water depth at field capacity (WDFC), water depth at permanent wilting point (WDO), upper limit of water depth, minimum depth required without causing stress (D_{min}), and the maximum required water depth. Based on the reference crop ET, crop type, and the simulation period, potential crop ET is calculated. After this, the water balance computations are started. Fig. – 3 is presented here again for easy reference to various water depths.



5.1.1 Determination of Actual Crop Evapo-transpiration

First, the water balance computation is made by assuming potential crop ET and the final water depth (FWD) at the end of the period (day/week) is calculated. It is assumed that above D_{min}, crop ET occurs at potential rate and at/below the WDO, the crop ET is zero. In between D_{min} and WDO, the crop ET varies linearly from 100% to nil. Different scenarios of initial and final moisture contents in the root zone are possible and the actual crop evapo-transpiration may vary for different scenarios. These scenarios are discussed in following:

a) WDI $\geq D_{min}$ & FWD $\geq D_{min}$

In this case, the crop will be in the normal conditions and the actual crop ET will be equal to the potential crop ET.

b) WDI $\geq D_{min}$ & FWD $< D_{min}$ & FWD $>$ WDO

Since the final water content falls below the D_{min}, the crop will be under stress and the actual crop ET will be less than the potential (PET). In this case, the ET is divided in two parts: up to D_{min} (AET1) and below D_{min} (AET2). Up to D_{min}, the crop ET will be at potential rate and is calculated as:

$$AET1 = WDI + Rain - D_{min} \qquad \ldots(18)$$

Below D_{min}, the stress coefficient (SC) is calculated and multiplied by the remaining of the crop ET to get AET2. Following equations are used:

$$SC = (1 + (FWD\text{-}WDO)/(D_{min}\text{-}WDO))/2 \qquad \ldots(19)$$

$$AET2 = SC * (PET - AET1) \qquad \ldots(20)$$

Total actual crop ET is calculated as the sum of AET1 and AET2.

c) WDI $\geq D_{min}$ & FWD $\leq$ WDO

In this case also, the crop will be stressed as above. The actual crop ET is divided in two parts. Above D_{min}, AET1 is calculated by using the equation (18). Since the FWD reaches WDO, the SC will be equal to 0.5 and the AET2 is calculated by using the equation (20). It is assumed that below WDO, crop ET will be zero. Total actual crop ET is calculated as the sum of AET1 and AET2.

d) WDI $< D_{min}$ & WDI $>$ WDO & FWD $\geq D_{min}$

In this case, the crop is initially in stress but the water input brings it in the normal range. For this scenario, the calculation of AET1 and AET2 is made in the same way as under (b) above. However, for the calculation of SC, WDI is used instead of FWD in equation (20). Total actual crop ET is calculated as the sum of AET1 and AET2.

e) WDI $< D_{min}$ & WDI $>$ WDO & FWD $< D_{min}$

Since the initial and final water depths remain below D_{min}, the crop will be under stress. However, two scenarios are possible in these conditions. One scenario is that the water input (rain) is sufficient to bring the water content above D_{min} and then the crop ET again lowers the water content below D_{min}. Second scenario is that the rain is not sufficient to bring water content above D_{min}. These are discussed separately in the following:

i) (WDI+Rain) ≥ D_{min}

In this case, AET1 is calculated in the same way as given by equation (18). The stress coefficient is calculated for the rising and falling phases separately. During the rising phase, the initial stress coefficient (SC1) is worked out for WDI using the following equation:

$$SC1 = (WDI-WDO)/(D_{min} - WDO) \qquad ...(21)$$

The final stress coefficient (SC2) during the rising phase will be equal to 1.0 as the water content rises above D_{min}. So, the average stress coefficient during rising phase (SCR) becomes average of SC1 and SC2.

During the falling stage, the initial stress coefficient becomes 1.0 as the water content starts from above D_{min} and then lowers down to SC3 given by:

$$SC3 = (FWD-WDO)/(D_{min} - WDO) \qquad ...(22)$$

Average stress coefficient during the falling phase (SCF) will be average of SC2 and SC3. The overall stress coefficient in this case is worked out by averaging the stress coefficients during the rising and falling stage. The actual crop ET during the stress phase (AET2) is calculated using equation (20). Total actual crop ET is calculated as the sum of AET1 and AET2.

ii) (WDI+Rain) < D_{min}

In this case also, the stress coefficients are calculated for the rising and falling phases separately. During the rising phase, the initial stress coefficient (SC1) is worked in the same way as under (i) above. During the rising phase, as the water content remains below D_{min}, the final stress coefficient (SC2) is given by:

$$SC2 = (WDI+Rain-WDO)/(D_{min} - WDO) \qquad ...(23)$$

The average stress coefficient during rising phase (SCR) becomes average of SC1 and SC2. During the falling stage, the initial stress coefficient remains SC2 and then lowers down to SC3, which is worked out in the same way as given under (i) above. Average stress coefficient during the falling phase (SCF) will be average of SC2 and SC3. The overall stress coefficient (SC) is worked out by averaging the stress coefficients during the rising and falling stage. The actual crop ET is calculated using the following condition:

$$AET = \text{Minimum of} (SC * PET, WDI+Rain-WDO) \qquad ...(24)$$

f) WDI $\leq$ WDO & FWD $\geq D_{min}$

The crop remains initially under stress but the water input brings it in the normal range. For this scenario, the calculation of AET1 and AET2 is made in the same way as under (b) above. However, value of SC in this case will be 0.5. Total actual crop ET is calculated as the sum of AET1 and AET2.

g) WDI $\leq$ WDO & FWD $< D_{min}$

The computation of actual crop ET in this scenario is similar to that explained under (e) above. The only difference is that during the rising phase of water content, the initial stress coefficient (SC1) will be taken equal to zero. As mentioned under (e), two scenarios are possible but the computations in both the cases are similar.

After the first run, the actual crop ET value gets modified. Using this revised value, water balance computations are made again. This process is iterated till the value of water depth at the end of the day/week and the actual crop ET converge within a specified limit. After getting the stabilised value of end of period water depth, recharge depth and the final water depth are calculated. Recharge at a paddy field is assumed to occur at a maximum rate of 3 mm per day. At other crop locations, it is calculated by subtracting water depth at field capacity from the end of period water depth. On the basis of end of period water depth and recharge, final water depth is calculated. The results of final water depth and recharge are stored in separate files. Final water depth of this period is used as input (initial moisture content) for the simulation of the next period.

The moisture condition at a crop location is classified in three states. First is *NORMAL* state when the final water depth is at or above the minimum depth requirement (D_{min}). Second is the *STRESS* state when the final water depth is in between the D_{min} and permanent wilting point (WDO). Third is the *WILT* state when the final water depth is at or below WDO. The stress results are stored in a separate file. Further, the supplementary water requirement is calculated by subtracting the final water depth from the required depth and the results are stored in a separate file.

Thus, four output files are generated: a) supplementary water requirement, b) final water depth, c) stress condition, and d) recharge. The importance and utility of these results are discussed in the following:

5.1.2 Supplementary Water Requirement

This requirement is worked out by subtracting the available water depth at the end of a day/week from the total water depth required (to reach up to saturation plus standing water depth in case of paddy and field capacity in case of other crops). If the overall efficiency of water application from the head of the canal system up to the field is known, the water requirement at the canal head can be worked out. The overall water requirement in the command area of the canal can be worked out by adding the water requirement of all individual grids.

5.1.3 Final Water Depth

Final water depth is the depth of water available in the effective soil depth at the end of the current day/week. Final water depth, as such, does not provide any useful information to the canal operator. However, this variable is carried forward to the subsequent week for the water balance computations. Thus, the final water depth of the current week becomes the initial water depth for the next week. Final water depth needs to be calculated and saved as separate file for all the weeks.

5.1.4 Stress Condition

As defined earlier, three different conditions have been assumed to occur in a crop – Normal, Stress, and Wilt. In the present study, stress conditions at different grids are evaluated and the results are presented in map form.

The information of spatial stress conditions within the command can guide the system operator in deciding the priority areas for allocation of available water so that the crops at any place may not reach the wilting stage at all. Some crops are more tolerant to stress and their yield is marginally affected up to a particular limit of stress. Based on the stress-yield relation for different crops, different options of allocation can be simulated such that the yield from the command area is maximized and the crop failure is minimum.

5.1.5 Recharge

Recharge is calculated at all the grids by subtracting the final water depth from the field capacity. For the paddy fields, recharge rate of 3 mm per day is assumed. While calculating the recharge, it is assumed that the soil zone below the root depth is at saturation and the moisture content above the field capacity will join the water table as recharge.

The recharge computation is useful for the modelling of the water table in the canal command. If conjunctive operation of the canal water and ground water is to be planned in a command area, then the spatial evaluation of recharge can be used to find the revised water table. Based on the watertable position and the available water supply, the conjunctive operation can be planned in the command area.

5.1.6 Presentation of Output

The result files, as described above, are generated in a format that cab be converted into maps and displayed in any GIS system, such as ILWIS. The space taken by the result file as a map is less than half the space taken as an ASCII file. Further, the interpretation and decision making in the map form becomes much easier as compared to the conventional record form or tabular form.

The results of the weekly water balance computation for the week June 17 – 23, 1998 and September 3 – 9, 1998 are shown in Fig. – 18 through Fig. – 20. The computations were started during the week June 10 - 16, 1998. Before and during the week June 17 – 23, 1998, the rainfall in the command area was very less and as envisaged, the supplementary water requirements are very high and most of the command is in stress and wilt stage. Fig. – 18 shows the variation of the supplementary water requirement (SWR) and final water depth (FWD) in the command. SWR varies from 7.9 mm (Blue) to 423.6 mm (Red) while the FWD varies from 6.2 mm (Red) to 452.3 mm (Blue). There is no recharge during the week. The stress condition in the command is presented in Fig. 19 (a) with Green representing Normal, Blue representing Stress and Violet representing Wilt conditions. Just before and during the week September 3 – 9, 1998, the area received appreciable amount of rainfall and consequently, the irrigation water requirements get lowered and stress conditions are better. Fig. – 19 (b) shows the stress conditions during the week September 3 – 9, 1998 with similar colour representations. Fig. – 20 shows the SWR and recharge in the command during the week of September 3 – 9, 1998. SWR varies from 17.3 mm (Red) to 385.8 mm (Blue) while the recharge values varies from 2.1 mm(Red) to 21 mm (Blue). Most of the recharge is from the rice fields. From the output it can be realised that besides the crop types, the spatial variation of the soil type and rainfall affect the water requirements and recharge to a large extent. Similar computations have been made for all the weeks but the results of only two weeks are presented here for the sake of illustration. It needs to be mentioned here that computations must be carried out as a continuous time series starting from the first week. However, only the results of final water depth need to be stored for all the intermediate weeks. If one wants to make the computations for an intermediate week, the final water depth of the previous week can be input and the values of other three variables can be obtained.

For the real-time evaluation of demands in the command area, the program can be run either on daily or weekly basis. If the rainfall and meteorological (for ET computation) forecasts are available for the next time step, then the demands for the subsequent day/week can be forecasted. Otherwise, normal daily/weekly values of rainfall and evapo-transpiration can be obtained from the historical records and can be used for the evaluation of irrigation requirements. With the availability of the actual data, the demands can be updated.

5.2 SELECTION OF TIME STEP

Selection of time step is an important consideration in the accuracy of estimation of irrigation demands. While making the water balance computations, it is assumed that various inputs and outputs from the soil reservoir occur instantly, e.g. rainfall, crop ET, recharge etc. However, this does not happen in real practice. For example, in case of weekly time step, it is assumed that all the rainfall during the week occurs instantly. It may happen that all of the rainfall occurs on the last day of the week and the crop may remain under stress during the initial period of the week. So it is always better to select as short a time step as possible. Using the daily time step, one may overcome this problem but it increases the computational time and the data input.

Hence, if one wants to go for detailed computation, daily time step can be chosen and better estimates of actual crop ET, final water depth and recharge can be found. Though for agriculture purposes, periods as short as one week are considered quite sufficient for operational applications, yet the accurate determination of recharge, stress etc. must be obtained using the daily time step.

* * *

CHAPTER – 6
SUMMARY

The dynamics of water within the unsaturated zone of the soil is a complex phenomenon dependent on properties of the atmosphere, soil and vegetation. It is an important component in the modelling of agricultural systems, since the processes of infiltration, redistribution, drainage and evapo-transpiration (ET) affect both the amount and timing of irrigation applications. As a result, for agriculture water management, it is necessary to have models that accurately predict the behaviour of soil moisture. The general objective of this study was to simulate the dynamics of soil moisture within the root zone. The focus was given to incorporate the spatial variation of crop, soil and rainfall in the dynamics of soil-water-plant interaction for irrigation management.

A distributed conceptual model of soil water balance was developed and applied to field data of the Lakhaoti command area under the Madhya Ganga Canal system. The data inputs to the model include rainfall, potential evapo-transpiration, crop characteristics such as root depth variation, crop coefficient etc., and soil characteristics. Three important inputs of the model, i.e. rainfall, soil type, and crop type have been considered to be spatially distributed. The command area is discretized into a finite number of rectangular grids and water balance computations are made for each grid. Root zone depth is a major sensitive parameter in such computations that depends on the type of crop in each grid. Since the actual crop data at the scale of individual field were not available, the actual cropping pattern for the year 1998-99 is determined using the multi-temporal remote sensing data. When dealing with relatively large agricultural systems, remote sensing is useful as an information source and can be used as an ancillary data in conjunction with the field records. Soil type is a major factor in ascertaining the water holding capacity at a place. Based on the soil survey maps and the laboratory analysis of different soils in the command area, various parameters such as field capacity, permanent wilting point, apparent specific gravity etc. were determined and the soil type in each grid was defined. A Thiessen polygon was generated around each raingauge station in/around the command area and each grid was attached to a particular polygon based its proximity.

The model is 'coupled' with the spatial database to simplify data input and provide an efficient way to display and manipulate results. It also makes the processes clear for the user to understand and modify for different conditions. Because of its features, a GIS is a suitable tool to aid in the management of water resources.

The model works either at daily or weekly time step. Effective soil depth is assumed to be the root zone depth in a grid which keeps on increasing with time till it attains a maximum value. The model estimates the actual evapo-transpiration and the soil moisture content at the end of each day/week using the available information on soil water availability, rainfall, potential evapo-transpiration and the plant water uptake. The output of the model is the actual evapo-transpiration during the day/week, the soil moisture content at the end of the week, supplementary water requirement, water stress condition in the crop, and the recharge. If the overall efficiency of water application from the head of the canal system up to the field is known, the water requirement at the canal head and the overall water requirement in the command area of the canal can be worked out. Final water depth, as such, does not provide any useful information to the canal operator. However, this parameter is carried forward to the subsequent week for the water balance computations. The information of spatial stress conditions within the command can guide the system operator in deciding the priority areas for allocation of available water so that the crops at any place may not reach the wilting stage at all. Some crops are more tolerant to stress and their yield is marginally affected up to a particular limit of stress. Based on the stress-yield relationship for different crops, different options of allocation can be simulated such that the yield from the command area is maximized and the crop failure is minimum. The recharge computation is useful for the modelling of the water table in the canal command. If conjunctive operation of the canal water and ground water is to be planned in a command area, then the spatial evaluation of recharge can be used to find the revised water table.

The model is effective in predicting spatial distribution of average soil moisture conditions in a command area. A computer program was developed to perform the water balance computations for each grid in the command area. A computer program was also developed to estimate the reference crop evapo-transpiration from the meteorological data. The developed program will allow us to estimate the spatial and temporal distribution of crop water demand in the command area that can be usefully incorporated into larger computer-based irrigation management models. The system also permits display of information on maps for easy handling. This visualisation allows users to more readily participate in decision-making processes.

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