Analysis of Hydrogeological System and Land Cover for Assessment of Risks to Irrigated Agriculture in Thar Desert: Charanwala System of the Indira Gandhi Canal Project

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by

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Abstract

IGNP-Indira Gandhi Nahar (Canal) Project, situated in the Thar Desert of North-Western India is one of largest irrigation projects in the world. Sustainability of irrigated agriculture is threatened due to hazard of 'Land Degradation'- manifested in the form of Waterlogging and Sand Dune Reactivation. The project command area lacks surface drainage and the sub-surface drainage is impeded by presence of a hydrogeological barrier composed of sticky and gypseous clays beneath the sandy surface soils. Simultaneously, inadequate and erratic irrigation supplies make irrigated agriculture unreliable for the farmers.

Understanding the surface-water (irrigation) and groundwater interaction in the command area of IGNP Stage-II is essential for assessment of risks to sustainability of irrigated agriculture in the Thar Desert.

This study aims at quantification of the interaction of surface-water and groundwater in upper reaches of the Charanwala System of Indira Gandhi Canal Project, through a distributed physically based model to understand the effect of irrigated agriculture system on groundwater regime.

For carrying out this investigation, the interaction between surface-water and groundwater in the Upper Charanwala System was conceptualized. Such an investigation involves a large data base creation about information on the groundwater recharge zone, frequency and quantity of irrigation application, depth to the hydrogeological barrier barrier from the ground, suitable digital elevation model, soil-hydrogeological parameters, and meteorological parameters, and ground coverage by the crops

The parameterisation of the model domain was carried out by ground surveys and existing scientific/ ancillary datasets. The land cover, seasonal area under crops, groundwater recharge zone and irrigation network were extracted using multi-temporal satellite imagery. The groundwater table was created by using the DGPS derived elevation data for piezometers in study area and the depth to groundwater data records. The soil-hydrologic parameters generated from ground investigation compaign and lab work were upscaled by linking them to land cover units. The ASTER DEM and SRTM DEM were compared. The SRTM DEM was found relatively more accurate and was chosen as the DEM for generating the hydrogeological barrier's DEM and the initial groundwater thickness above it for inputing into the model.

The model could be only partially calibrated. However, this initial attempt at modeling the complex irrigation input and groundwater table changes allowed some preliminary idea about groundwater movement.

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1. Introduction

1.1. Background

The last quarter of Nineteenth and much of Twentieth century witnessed the initiation of major\large irrigation projects in deserts of USA, former USSR, Egypt, Pakistan, India and Middle East. Arid and semi-arid lands were looked upon as last land frontier/empty land-banks and the Irrigation Projects as the harbingers of development, which brought these arid lands under the fold of agriculture, leading to rise in their economic potential by increasing the productivity manifold. This was also perceived as an answer to the ever-growing food and settlement needs of rapidly increasing world population.

While the techno-engineering challenge of damming rivers and large scale inter-basin transfer of water for blooming deserts with irrigation was successfully addressed, sustaining economically viable irrigated agriculture has proved to be much more difficult. The accumulating knowledge on large scale irrigation projects in desert regions testifies that long-term failure/ un-sustainability and uncertainty are built-in feature of these projects from the start. Waterlogging and salinization affect nearly all-major irrigation schemes situated in desert environments. For example, lower Colorado River lands in American West, northern Mexico, Punjab and Indus Valley Irrigation systems in Indian subcontinent, The Euphrates and Tigris basins of Syria are plagued by salinity hazard (Worster, 1992). The ancient hydraulic civilizations of Fertile Crescent, viz., Sumerian as well as Babylonia, which relied on irrigation of crops in a desert land, withered in the long run due to salinization, waterlogging and silt accumulation in agricultural land (Strahler and Strahler, 2002).

1.2. Indira Gandhi Nahar Project (IGNP)

IGNP-Indira Gandhi Nahar (Canal) Project (hereafter IGNP), earlier known as Rajasthan Canal Project, is one of largest irrigation projects in the world. IGNP meets the irrigation requirements of a vast area in the Thar Desert of North-Western India. The mighty Thar Desert has been immortalized in songs and legends as Maroosthal, the land of the unknown-hostile, harsh and merciless. IGNP was conceived to transform the dreary and desolate Thar into a land of prosperity and plenty. The Project was initiated in the late 50's and is situated in the districts of Sriganganagar, Hanumangarh, Bikaner, Churu, Jaiselmer, Barmer, and Jodhpur (Figure 1). On completion, it will have a Culturable Command Area (hereafter CCA) of 1.963 million hectares (mha). IGNP, owes its existence to the 'Indus Water Treaty' of 1958 between India and Pakistan, which allocated the water of three western rivers of Indus System Ravi, Beas, and Sutlej to India (Gulati, 1973). The transformation brought about by the project in poverty alleviation, improving agricultural productivity, providing livelihood, settling people, and providing drinking water, etc. has been remarkable (Kavadia and Hooja, 1994). Indira Gandhi Canal's (hereafter IG Canal) source is Harike Barrage in the State of Punjab, where the waters of Ravi and Beas rivers are stored (Figure 1). IG Canal is a gravity canal and runs at a distance of 40-50 km from the India-Pakistan border. The area on the west of the canal and between the canal and international border is the served by 'flow system'. The areas to the east of the main canal are too high to be commanded by gravity flow from the canal. These areas will be served by seven 'lift irrigation schemes'. Due to its extensive size the Project has been divided into two stages-

- Stage-I: It comprises of 204 km long Feeder from Harike Barrage in Punjab to Masitawali in Hanumangarh district in Rajasthan, and 189 km long main canal from Masitawali to Chattergarh in Bikaner district. It has 3454 km long distribution system to serve a CCA of 0.553 Mha; it has one 'lift canal'- Lunkaransar lift scheme.
- Stage-II: It comprises of 256 km long main canal from Chattergarh to Mohangarh in Jaiselmer district, and has 5606 km long distribution system to serve a CCA of 1.41 Mha (Table 1). It has six 'lift canals'- Sahwa lift scheme, Gajner lift scheme, Kolyat lift scheme lift, Bangarser lift scheme Phalodi scheme lift scheme, and Pokaran lift scheme (Gupta.A.K. et al., 2002).

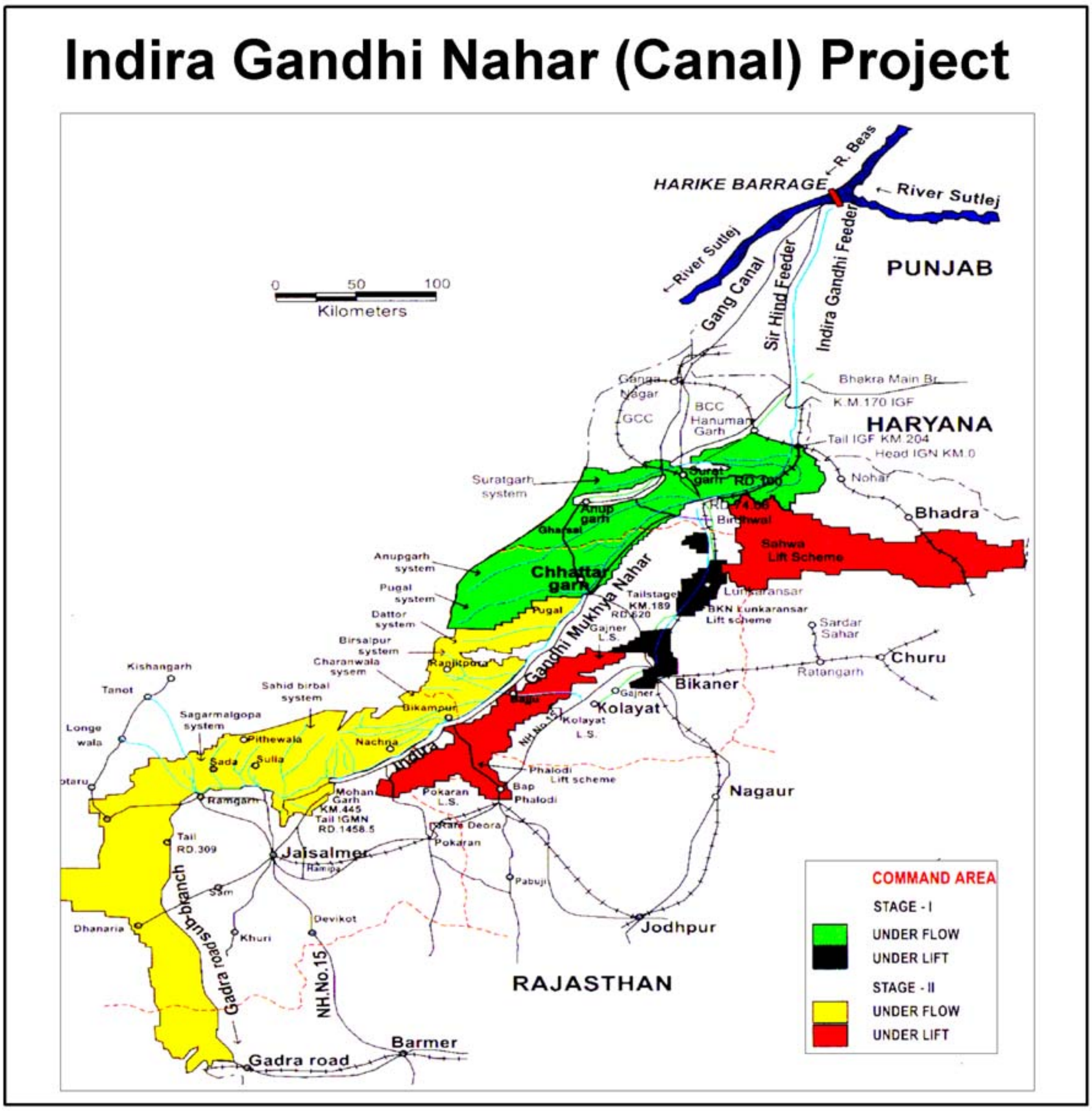


Figure 1.1 Index Map of Indira Gandhi Nahar Project

Source: Adopted form Gupta et. al. (2002)

Table 1.1 Culturable Command Area (in Mha) of IGNP Stage-I and Stage-II

Name of District	Stage I	Stage II	Total
Sriganganagar	190	-	190
Hanumangarh	180	92	272
Bikaner	183	412	595
Churu	-	115	115
Jaiselmer	-	652	652
Jodhpur	-	77	77
Barmer	-	60	60
Total	.553	1.410	1.963

Source: Gupta et.al. (2002)

1.3. Risks to Irrigated Agriculture

While the introduction of irrigation in the arid lands of Thar Desert opened up vast possibilities for development of agriculture, it has simultaneously posed several intriguing environmental, management and social challenges (D`Souza et al., 1998; Goldman, 1994; MacDonald and Dalal, 1999; MacDonald et al., 1999; Ramanathan and Rathore, 1994).

1.3.1. Waterlogging

The average depth to water table in the command area of IGNP in 1952, before inception of irrigation, generally ranged between 40 and 50 m below the surface. Irrigation commenced in IGNP Stage I in 1961 and within a few years the effect on ground water regime became visible in the form of rising water table and instances of waterlogging in patches. The following trends in groundwater levels have been observed in Stage I:

- A rise in water table of up to 1.17 m/year was observed during the period 1972-82.
- During the period 1982-92, the net rise in water table has been reduced to 0.76 m/year, but, a large area came under potentially sensitive and critical categories. The rate has reduced because sizeable areas were waterlogged, or became critical, enabling more water to evaporate from soil profile.
- In the years 1992-2002, the trend has been fluctuating .

A comprehensive study by Mott MacDonald (a consultant agency for State Government of Rajasthan for Indira Gandhi Nahar Project) indicated that in year 1995-96 around 10% of Culturable Command Area (CCA) of Stage-I became waterlogged (watertable within 0-1 meters from surface) and that potentially sensitive area (watertable within 1-6 meters from surface) increased from 9% in 1981 to 25% in 1990, and expressed the fear that by year 2000, extent of potentially sensitive area may go up to about 50% of the Stage-I, if no drainage solutions are provided for (MacDonald and Dalal, 1999).

Water was released in Stage II (from 189 km to 293 km or RD 620 to 961) in 1983 and subsequently (between 293km to 445km or RD 961 to RD 1459) in 1986. (In the IGNP records, the canal sections are expressed as 'R. D.'-'reduced distance'from the head of any channel. The head of channel is 0 RD and 1 RD is equivalent to distance of 1000 feet downstream from it). By 1991, pools of standing water became apparent at 127 locations along the IG Main Canal . The surface expression of waterlogging has declined considerably since then due to various reclamation measures, including Bio-drainage on account of large scale afforestation activity along the inundated areas and irrigation network, general decline in inflows, and opening up of newer irrigation settlements/colonies.

In the decade of 1980, when the crisis of waterlogging assumed serious proportion, The Indira Gandhi Nahar Board (IGNB), the apex planning and decision making body of the project, responded by adopting the strategy of 'extensive agriculture', i.e. spreading water as thinly as possible in the largest possible area. To put this into effect water allowance and irrigation intensities were reduced (Table1). Intensity of Irrigation has been defined in the IGNP as the amount of irrigated area out of the total Cultural Command Area. However, this strategy of thinly spreading water, in its wake brought in more problems.

Table 1.2 Proposed and Existing Water Allowance and Irrigation Intensities

Stage	Proposed Water Allowance	Proposed Irrigation Intensity	Existing Water Allowance	Existing Irrigation Intensity
Stage-I	3.5 cusec/1000 ha	100 %	5.23 cusec/000 ha	110%
Stage-I Lift	3.0 cusec/1000 ha	80 %	3.0 cusec/000 ha	100%
Stage-II Flow	3.0 cusec/1000 ha	80 %	3.0 cusec/000 ha	80 %
Stage-II Lift	2.0 cusec/1000 ha	60%	2.0 cusec/000 ha	60%

1.3.2. Sub-surface Hydrogeological Barrier Layer

The IGNP Stage-II, the area where the irrigation has been extended to implement the straegy of thinly spreading water, is underlain by a subsurface impermeable hydrogeolohical barrier layer (see section 3.5.1 for detailed discussion). It has been feared that Stage-II irrigated areas will succumb to waterlogging and salinization because of the presence of the barrier layer. However, the barrier layers depth from the surface is variable and irrigation authorities have argued that it could be beneficial in many locations as fresh groundwater resources may develop over this layer, which in turn could be tapped for coujuctive use with the surface irrigation. There is a need to scientifically investigate the impact of introduction of irrigation in the areas underlain by the hydrogeological barrier to assess, if there is a risk of waterlogging in the area.

1.3.3. Inadequate Irrigation Supplies

Water is the most precious natural resource in arid zones. The reduction of irrigation intensities and water allowances in Stage-I led to an assumption/belief that 'surplus water' is available in the IGNP system. This led to a scramble for irrigated agriculture in the remaining districts (Jodhpur,Nagaur, Barmer and Churu) of Thar Desert - not yet supplied/covered with irrigation, resulting in incessant revision and expansion of IGNP time and again. However, the assumed water resource availability of

7.59 Million Acer Feet, on which Project -Planning is based, is not reflected in the observed flows over last 25 years in the Ravi-Beas river systems, which supply IGNP with water (WCCR, 2002). The reason is that the assumed resourse of 7.59 Million Acer Feet is based on mean inflows in rivers and over years the precipitation in river catchments varies. Moreover, a part of the mean flows is contributed by the flood events in rainy season, all of which can't be stored. Thus, these expansions have made water scarcity, a built-in feature of IGNP. Given the reduced water allowances and irrigation intensities- in a very harsh environment, the margins for farmers are very thin. Erratic water supplies mean economic hardship for settlers. Since the year 2001, the state government has been declaring large parts of IGNP as drought hit areas, wherein drought relief operations are carried out.

1.3.4. Sand Dune Reactivation

Strong winds and undulating topography of Stage-II command expose it to the hazard of desertification. Mean wind velocities in Stage-II (Jaiselmer and Phalodi) in the months of June-July are 24-27 km/hour (during the frequent dust storms wind velocities soar above 50 km/hr) (WAPCOS, 1993). The menace caused by strong winds is augmented by agricultural activity. Sand load increases manifold for the aeolian processes from a field ploughed with a disc plough attached to a tractor than the field tilled by country plough. Field experiments conducted by CAZARI (Central Arid Zone Research Institute, Jodhpur) reported that during a dust-storm, the tractor-ploughed sandy plains lost more then 3000 tones of soil per hectare while the sandy plains with 10-12 percent of vegetation cover (desert scrub) suffered almost negligible erosion (Dhir, 1987; Dhir et al., 1992). High velocity wind regime unleashes the aeolian hazard in dry summer months and re-activates the semi-stable/stabilized sand dunes, which then chock the Irrigation Network and engulf the agricultural fields.

1.4. Surface–water and Groundwater Interaction Investigation

This study proposes to investigate the impact of the introduction irrigation on the groundwater table using a surface-water and ground water interaction model. The investigation of the irrigation/surface-water and groundwater interaction involves a large data base creation about information on the groundwater recharge zone, frequency and quantity of irrigation application, depth to the barrier from the surface digital elevation model, soil-hydrogeological parameters, and meteorological parameters, and ground coverage by the crops.

1.4.1. Groundwater Recharge Zone

The investigations for assessing the risk of the hazard of waterlogging in IGNP Stage-II undertaken as yet have assumed that the available irrigation inflows are evenly distributed over the entire CCA according to the designed irrigation deltas/duties as proposed in the irrigation planning. That certainly is not the case, since the actual irrigation is concentrated over a substantially small area. The allotted agricultural plots are of the size of 6.23 ha while most of the actual active plots are of the size 1 or 2 hectare and thus irrigation is concentrated into a smaller portion of the total planned CCA. Only 25% of the created irrigation potential in middle and lower reaches of IGNP was actually utilized between the years 2000-2005 in the summer season (Bhakar, 2005). Small active agricultural plots mean that the consumption of irrigation inflows by evapotranspiration is comparatively less then the assumed consumption and a fairly large proportion of inflows infiltrates through coarse sandy soils and contributes to recharge of groundwater. The the seasonal changes in the area under crop have to be mapped for demarcating the changes in groundwater recharge zone and this can be done using multi-temporal satellite imagery.

1.4.2. Digital Elevation Model

For modeling the surface water and groundwater interactions of perched groundwater bodies, the elevation model representing the depth and undulations of the barrier/impermeable base layer play an important role in determining the groundwater flow. This depth to barrier/impermeable layer from surface is estimated on basis of point measurements like borehole drillings or geo-electric soundings. This point data is converted into continuous/raster data layer by krigging or interpolation. It is important that the interpolated/krigged layer is compatible to the surface DEM, since the soil thickness and the initial groundwater levels above the barrier are measured in reference to this layer. Hence, a surface digital elevation model with good accuracy is preferable; else the modeled changes in watertable may be erroneous. For the present surface-water and groundwater interaction study the depth to the hydrological barrier layer, a layer based on hydrogeological survey by the irrigation authorities (see section 3.5.1) has to be estimated in reference to the satellite imagery based surface DEM and in this context the relative suitability of the SRTM DEM(90m) and ASTER DEM (15m), level 1A product from ERSDAC, will be compared.

1.4.3. Soil Hydrological Properties

The saturated hydraulic conductivity of the soils determines the percolation of applied irrigation through the soil profile. The data pertaining to soil hydrological properties is collected in the field at representative sample locatons. This point data can be krigged/interpolated for creating continous data layer. However, in the irrigated sandy desertic environments, where a new land cover has been imposed over the original, land cover boundaries are crisp and vary significantely over short distances,. In such situations soil hydrological properties may change significantely over short distances and upscaling (regionalization of point data) by linking it to land cover units may be an option. Present study will investigate the possibility of upscaling the soil hydrological data by linking it to the land cover units.

1.4.4. Intensity of Irrigation

Intensity of Irrigation i.e. the amount of irrigated area out of the total Cultural Command Area changes in response to the irrigation supply. The irrigation inflows in IGNP vary over years. No investigation using remote sensing has been undertaken as yet for the quantitative assessment of the changes in the intensity of irrigation in response to changes in irrigation supplies over different years. The same land cover information which is needed for demarcating the seasonal change in groundwater recharge zone can be used to assess the changes in intensity of irrigation/cropped area in the same season over more

then one year. This can be related to changes in available irrigation supply and can be used as a quantitative indicater of adverse impat to agriculture in situations of unreliable irrigation supplies.
The ascertaining the changing irrigation intensity over years can provide useful inputs for formulation of water distribution and management planning.

1.5. Problem Statement

Sustainability of irrigated agriculture in the Thar Desert is threatened due to hazard of 'Land Degradation'- manifested in the form of Waterlogging and Sand Dune Reactivation. Simultaneously, inadequate and erratic irrigation supplies make irrigated agriculture unreliable for the farmers. Understanding the surface-water (irrigation) and groundwater interaction and impact of erratic and fluctuating irrigation inflows in the command area of IGNP Stage-II is essential for assessment of risks to sustainability of irrigated agriculture in the Thar Desert.

1.6. Aims and Objectives

The overall objective of this study is quantification of the interaction of surface-water and groundwater through a distributed physically based model in Charanwala System of Indira Gandhi Canal Project, situated in the Thar Desert, to understand the effect of irrigated agriculture system on groundwater regime.

More specific objectives are:

- To conceptualize the interaction between surface-water and groundwater in Charanwala System.
- To parameterise the model domain using multi-temporal satellite imagery, ground surveys and existing scientific/ ancillary datasets.
- To calibrate the model and simulate the water table for different irrigation inflow scenarios.

1.6.1. Research Questions

- Is it possible to model the change in water-table in an irrigated arid land using a simple, distributed, physically-based surface-water and groundwater interaction model?
- Which is the appropriate method of upscaling the soil-hydrologic parameters in an irrigated desertic environment?
- Is it possible to extract the irrigation network details up to minor-canals level from medium resolution satellite imagery?
- To what extent can land cover maps derived through multi-temporal satellite imagery be used to delineate groundwater recharge zones and depict changes in irrigation intensity?
- Which satellite imagery based Digital Elevation Model (DEM) out of the SRTM and ASTER is more suitable for surface-water and groundwater interaction modelling of irrigation projects in dune dominated topography?

1.6.2. Research Hypothesis

- Distributed physically-based models provide reasonable quantification of the complex system of irrigation water supply and groundwater recharge for understanding the overall trend in groundwater levels.
- Satellite imagery provides vital spatial and temporal information about the terrain for generating different model input parameters.

1.7. Organization of the Thesis

The structure of the thesis follows the following sequence to achieve the objective of the study.

Chapter 2: Literature Review
This chapter engages the previous investigations and research carried out for hydrogeological understanding and assessment of risks associated with irrigated agriculture. Research studies focusing on earth observation (EO) techniques for evaluation of risks to irrigated agriculture have also been reviewed.

Chapter 3: Study area
The chapter gives a brief overview of the study area.

Chapter 4: Materials and Method
The chapter describes the data used and methodology adopted for data collection and database generation.

Chapter 5: Results and Discussion
The results of this study are discussed in this chapter.

Chapter 6: Conclusion
This chapter summarises the study and indicates the limitations and suggestions for further research in this area.

2. Literature Review

2.1. Risks to Sustainability of Irrigation Projects in Arid Zones

Arid and semiarid environments cover more than 40% of the global land surface . In the last century, many large irrigation projects have been initiated in the arid lands worldwide. Even though there has been a tremendous increase in food production, land degradation in form of salinization, waterlogging, and vegetation loss in the surrounding lands threaten to offsets the gain and investment in these projects, which may results in food shortages to feed the ever-growing population in dry lands, thereby leading to famines, deaths and human suffering on the whole. For example, lower Colorado River lands in American West, northern Mexico, Punjab and Indus Valley Irrigation systems in Indian subcontinent, The Euphrates and Tigris basins of Syria are plagued by salinity hazard (Worster, 1992)

Risk assessment is a technique for identifying, characterizing, quantifying and evaluating hazards. Hazard is an uncontrollable event like hurricane, flood, earthquake, landslide, draught, waterlogging and desertification that exposes people to the risk of death or injury and may damage or destroy property, agricultural or other developed land, and societal infrastructure. A natural hazard can also be due to lack of something, such as rain in the case of drought.

The sustainability of the Indira Gandhi Canal Project (IGNP) - the vision to bloom the Thar Desert, is threatened due to the hazard of 'desertification/land degradation' in form of waterlogging due to alarmingly rising groundwater levels and sand-dune reactivation. World Bank has been associated with irrigation projects served by the waters of Indus river system since 1950, when it offered its good office for negotiations of Indus water dispute between India and Pakistan, which was ultimately resolved in 1958 with the signing of Indus water Treaty in 1958. World Bank provided financial assistance and loans for the IGNP from 1973 to 1987; however, it became apprehensive about the sustainability of the project in view of fast rising water table, many settlements/ villages succumbing to the hazard of waterlogging. When irrigation authorities presented the strategy of 'extensive agriculture' and extension of the CCA of IGNP Stage-II in dunal tracts in Bikaner and Jaiselmer districts, Bank Mission observed that this development is contrary to accepted principles of irrigation and should be stopped immediately (Gupta.A.K. et al., 2002).

In view of Bank Mission's observation, Irrigation Authorities initiated about 16 evaluation and feasibility studies. Among these, studies by Water & Power Consultancy Services India Ltd. (WAPCOS), Institute of Development Studies (IDS), Operations Research Group (ORG), National Institute of Hydrology (NIH) and Mott MacDonald Limited (MML) are important. Review of these comprehensive feasibility and technical studies indicates that if the project has to survive as a viable prospect on a sustainable basis, its developmental plans have to urgently take account of the following findings:

- Project Command lacks drainage; extensive areas are bound to be affected by water logging and salt build-up in the long run.

- Stage-II areas are prone to strong winds; consequently aeolian processes render the water distribution network and agriculture fields vulnerable to sand encroachment.
- The assumed water resource availability, on which Project's planning is based, is not reflected in the observed flows of the Ravi-Beas river system over last 25 years (IDS, 1991; MacDonald et al., 1999; Mishra et al., 1995; ORG, 1989; WAPCOS, 1995; WAPCOS, 1996; WCCR, 2002).

Meanwhile, the project expansion in these hazard prone areas has continued and new kind of irrigated agricultural economy replaced the pre-existing semi-nomadic production mode in these lands (Goldman, 1994).

The evaluation of irrigation project performances is essential to plan viable project management strategies. With the advances made in applied and basic research, various options are available to prevent the water table rising to root zone by providing drainage solutions and thereby retarding the build-up of salts up to the levels that limit the productivity of soils. Remote sensing offers means for rapid assessment of agricultural performance. In this context it becomes imperative that the risk to the irrigation system form the hazards of waterlogging, secondary salinization and inadequate and erratic irrigation supplies should be evaluated so that remedial measures become part of planning process. The detection, monitoring and mapping of regions of areas under risk of waterlogging and secondary salinization is complicated matter because dynamic processes are involved. A brief survey of literature for land degradation assessment and irrigation system performance evaluation of irrigation systems operating in semi-arid and arid environments using earth observation/ remote sensing, ground water modelling, and GIS is presented.

2.2. Risk Assessment

Risk assessment attempts pre-crisis analysis with scenario formulation to answer the following question- if it happens, what consequences are expected? These scenario formulation provide inputs to develop strategies/action plans to mitigate the impact of hazard events However, scenario formulation is far from simple for the want of accurate high resolution spatio-temporal data requirements and multi disciplinary expertise. Westen (2005) terms risk assessment as the 'most complicated simple formula' and expresses it as product of - Hazard, Vulnerability, and Amount, where:

- Hazard (H) is the probability of occurrence of a potentially damaging phenomenon within a specified period of time and within a given area.
- Vulnerability (V) is the degree of loss to a given element or set of elements at risk resulting from the occurrence of a natural phenomenon of a given magnitude. It is expressed on a scale from 0 (no damage) to 1 (total loss).
- Elements at risk (E) include the population, properties, economic activities, including public services, etc. at risk in a given area.

Specific risk (Rs) is the expected degree of loss due to a particular natural phenomenon. It may be expressed by the product of H, V and costs C. Total Risk (Rt) is the expected number of lives lost, persons injured, damage to property, or disruption of economic activity due to a all natural phenomena. It is therefore the sum of the specific risks for all return periods and all types of events. It is usually only possible to express risk in monetary terms (Weston, 2005).

2.2.1. Desertification: Land-degradation in Dry Lands

Land degradation, or the loss of productivity of the land, one of the major environmental problems of our time, relates to reduction of land resource potential by one or a combination of processes acting on the land, including water and wind erosion, sedimentation, loss of soil structure and fertility, salinization, and other processes that result in long-term reduction in vegetation diversity and net primary production (Ward et al., 1988). The term 'Desertification' may be defined as the degradation of land in arid, semi-arid, and dry sub-humid areas caused primarily by human activities and climatic variations. Desertification leads to reduction of net primary productivity in these ecosystems (UNCCD, 1994). Desertification/land degradation is a slow-onset, creeping natural hazard that results in serious economic, social, and environmental impacts. Land degradation is not a recent phenomena; Dregne (2002) argues that land degradation in the dry lands has affected the world for millennia in Africa, Asia, and Mediterranean Europe and for last the two centuries in the Americas, and Australia. He identifies vegetation degradation in rangelands, salinization of irrigated lands, soil compaction, wind and water erosion as the principal degradation processes in arid and semi-arid lands (Dregne, 2002). However, there remains much confusion within the scientific and policy communities about its characteristics and assessment methodologies.

2.2.2. Changing Conception of Desertification

Herrmann and Hutchinson (2005) have presented a comprehensive review of the debate over the notion of 'Desertification' in context of changing understanding of climatic variability, vegetation responses to perturbation, social processes and desertification as a political process(Herrmann and Hutchinson, 2005). Veron et.al(2006) have reviewed the desertification assessment methodologies from- simple appraisals of the inter-annual movement of desert boundaries spuriously correlated with weather changes to; complex multivariate field surveys based on a number of field data on vegetation and soil yielding an index of desertification for each site surveyed as adopted by FAO/UNEP to; methodologies based on indicators of ecosystem functioning, such as rain use efficiency (RUE)- the ratio between annual aboveground primary production (the rate of aerial biomass accumulation by plants, ANPP) and annual precipitation. RUE-based approaches offered an attractive solution to the problem of desertification assessment at regional scale due to availability of both rainfall data and remotely sensed estimates of ANPP at adequate temporal and spatial scales (Veron et al., 2006).

2.2.3. Waterlogging and Salinization

Waterlogging and salinization are two of the major environmental problems associated with large irrigation systems of arid and semiarid tracts. The primary irrigation-induced waterlogging causes include leakage from poorly lined canals and reservoirs, excessive water application, and inadequate drainage of agricultural land . With flood irrigation, water table often rise fast, until a new equilibrium is established where it fluctuates close to the soil surface. When the water table rises within 1.5 m of the soil surface, the root zone available to plants becomes restricted, salts rise to the surface by capillary action, and the resulting salinization can render land unsuitable for agriculture. The areal extent of the problem is increasing worldwide. The area affected by these problems in the irrigation commands in India alone is estimated to cover about 5-6 Mha. While this figure is for the lands that have turned barren and are aptly described as wet deserts, quite a large area also experiences land degradation of various degrees resulting in crop yields far below the level anticipated for irrigated lands (Sharma and Gupta, 2006).

2.2.4. Bottlenecks in Land degradation Assessment in Dry lands

The methodologies for monitoring desertification based on indices as Rain Use Efficiency (RUE), may have some limitation due to sub-pixel mixing of land cover classes, more so in desert regions. Traditional digital remote sensing analysis has been based on the consideration that a pixel is uniformly covered. Therefore, classification techniques assigned each pixel to just one single category. In most environmental applications, this homogeneity is rarely confirmed. Usually, the area included in the instantaneous field of view of a satellite sensor is a composite of several land covers: grass, trees, shrubs, soils or manmade features. For desertification studies this is especially critical, since arid areas are commonly a combination of vegetation and soil in different proportions. One of the most promising –pixel classification techniques is known as SMA- ‘spectral mixture analysis’ which assumes that the reflectance of a pixel is a mixture of the reflectance of ‘pure’ covers (usually named ‘end members’) in proportion to the area that they cover (Collado et al., 2002)

Okin et al. (2001) enlists following hurdles in quantitative retrieval of vegetation type, cover, LAI using remote sensing in areas of low cover:

- A large soil background in arid and semiarid regions, where soils can be bright and mineralogically heterogeneous, masks the spectral contribution of plants ;
- Rapid movement of many desert shrubs through phonological changes in response to small amounts of spatially-discontinuous precipitation lead to high Spectral variability within shrubs of the same species, this makes the identification of the type of vegetation extremely difficult if not impossible ;
- Evolutionary adaptations to the harsh desert environment make desert plants spectrally dissimilar from their humid counterparts, in many cases lacking a strong red edge, exhibiting reduced leaf absorption in the visible spectrum- this may have implications for the interpretation of vegetation indices, desert shrubs often display open canopies which contribute to poor correlations with leaf area index (LAI)(Okin et al., 2001).

Similarly, assessing waterlogging and secondary salinization using remote sensing is troublesome as the satellite images don’t have information on the third dimension of the 3-D ground/soil body and more often than not groundwater is close to the surface rather then being at the surface. Moreover, hydrological conditions exhibit large spatial and temporal variability.

2.3. Remote sensing studies for monitoring Land degradation in Arid Lands

Dwivedi and Sreeniwas (2002) have attempted delineation and monitoring the long-term changes in the extent of waterlogged areas and vegetation cover in part of the Indira Gandhi Canal command area, during the period 1975 to 1995 using Landsat MSS and TM, and IRS-1A LISS-I data. Since, vegetation condition is altered in the event of the introduction of canal irrigation; it has been used as a surrogate measure for assessment of the impact of irrigation in the command area. After making several observations in the field, it was found that a NDVI value of 0.13 could be considered as a threshold value for segregating vegetated areas from non-vegetated ones. Having established the threshold NDVI value for a vegetated surface, a pixel-by-pixel comparison of changes in NDVI values during the period 1975–1995 was then made to assess the vegetation condition of the command area. This comparison has revealed two striking phenomena:

- the areas which were non-vegetated during 1975 were found supporting more and more vegetation, especially crops in successive years, due to introduction of canal irrigation; and
- the palaeo-channel (old river course) which supported very good crops during 1975 gradually became waterlogged during the 20 year period thereby resulting in the extinction of croplands therein (Dwivedi and Sreenivas, 2002).

Balakram and Chauchan (2001) have used multi-date IRS LISS-III data in conjunction with the topographical maps and field surveys to assess the changes in land use pattern in canal command areas in part of Hanumangarh District of Rajasthan. They reported that the emergence of waterloggin/ salinization hazard turned about 11,000 ha irrigated double cropped land into wasteland and a further 15,300 ha area is under critical limit of waterlogging. A number of village settlements are deserted and people have moved to nearby safer sites. To delineate land use changes LANDSAT imagery of 14.02.1975(rabi), IRS-IB LISS-II data of 30-9-94 and 1-10-94 (kharif) and 18-01-95 and 19-01-95 (rabi) and SOI toposheets of 1958 (1:63,360) and 1968 (1:50,000) were interpreted. Secondary data on land use, cropping pattern and crop production from 1969-70 onward are analyzed and correlated (Balakram and Chauchan, 2001).

The irrigated tracts in Faisalabad, which is part of the Indus Basin Irrigation system of Pakistan and facing extremely hydrosalinized land degradation problems, were investigated by Khan and Rastoskuev (2005) based on analysis of remote sensing data acquired from the IRS-1B and using a Geographical Information System. In order to map the areas under risk of waterlogging, they used the following 'water index':
WATER = (COMP124)/ (B4_STR) where, COMP124 is a composite image of the first, third and fourth spectral bands of LISS-II spectral data, and B4_STR concerns stretched satellite data received in the fourth spectral band (NIR regions)
The researchers believe that this water index is useful to accurately differentiate water objects and waterlogged areas. Further, they used Salinity Index [SI =$\sqrt{}$ (B1*B3)], Normalized Differential Salinity Index [NDSI) = (B3-B4)/ (B3+B4)], and Brightness Index [BI= $\sqrt{}$(B32+B42)] to delineate salinized areas (Khan and Rastoskuev, 2005).

Masod and Koike (2006) have used Remote Sensing to track down the progressive waterlogging and salinization of agricultural soils in intensively irrigated Siwa region, a tectonically induced closed depression, in the Western Desert of Egypt. A hydrological imbalance in the depression, created by intensive agricultural practices, overuse of irrigation water and improper drainage systems had resulted in rise of the water-table to the topsoil. Analysis of the multi-date(1987-2003) satellite imagery coupled with SRTM 30m DEM, and field observations, and using the principal component, vegetation indices, wetness index of the tasselled cap transformations, revealed presence of mainly nine land cover classes in the study area, namely, water bodies, wet salt crusts, dry salt crusts, vegetation, sand dunes, limestone, marl, carbonate-rich soil, and marl-rich soil. Spatio-temporal changes in different land cover classes, which were monitored, confirmed a gradual increase in the extent of the surface waters and salinization in most of the study area (Masoud and Koike, 2006).

For the waterlogging and salinity risk assessment, it is imperative that there should be a method for salinity assessment during the crop growth stage. Fouad (2003) has attempted to assess the soil salinity in the irrigated areas in the Balikh basin located in the northern part of Syria during the crop growth stage. This study dealt with the two different methods (empirical and biophysical) using broadband satellite data (Landsat7 ETM and ASTER) in two different crop calendar dates (immediately before the growing season and in the middle of it). In the first method, the empirical method, Salinity Index, derived from ASTER data: [(band4-bamd5)/ (band4+band5)] was used for overall salinity detection in the bare agriculture soils. In the second method, the biophysical method, SEBAL algorithm was used for salinity detection during the growing season. While the empirical method detected only the salts on the surface of the soil, the biophysical method indicated the condition and existence of salt in the entire soil section between the surface and the root zone (Fouad, 2003).

Collado et al. (2002) applied Spectral Mixture Analysis to monitor desertification processes in the central San Luis Province (Argentina), where two Landsat images, acquired in 1982 and 1992 were used for unmixing of the vegetation, water and sand components in areas of heterogeneous cover. Simple differences between unmixed images of sand or water revealed dune movement, re-vegetation trends and variations in water bodies. They argued that for the analysis of desertification/land degradation processes in dry lands, the spectral unmixing may provide better estimations of degraded areas than conventional techniques, since a clearer image of vegetation and soil proportions may be obtained. They observe that since the equations for spectral mixture analysis can only be solved when there are fewer pure categories than spectral bands provided by the satellite sensor, with the availability of hyperspectral sensors (capable of providing from a few dozens to few hundred bands, such as airborne visible/infrared imaging spectrometer (AVIRIS) or moderate resolution imaging spectrometer (MODIS)) makes it is possible to greatly increase its potential of SMA techniques (Collado et al., 2002).

Okin et al. (2001) employed multiple end member spectral mixture analysis (MESMA), high-quality field spectra, and AVIRIS data to determine how well full-range spectral mixture analysis (SMA) techniques can retrieve vegetation and soil information in dry lands. The study reported that in areas of low vegetation cover (cover of less the 30%) the use of MESMA with hyperspectral reflectance data leads to unreliable vegetation-type retrievals in arid areas, but vegetation cover in many circumstances can be estimated reliably (Okin et al., 2001).

The use of multispectral sensors, microwave sensors and techniques such as spectral unmixing, maximum likelihood classification, fuzzy classification, band ratioing, principal components analysis, and correlation equations for remote identification and mapping of salt-affected areas has been reviewed by Metternicht and Zinck (2003). The paper also presented modelling of temporal and spatial changes of salinity using combined approaches that incorporate different data fusion and data integration techniques However, they reported that the probability for obtaining a correct classification of the satellite images has shown to be strongly dependent on the season for all indicators analyzed (Metternicht and Zinck, 2003).

Land cover (woodland/forest, agriculture, savanna, and steppe land) performance in Senegal, Africa, has been evaluated using time series of rainfall data and normalized difference vegetation index (NDVI) for the period 1982–1997 by Li et.al. (2004), they found strong relationship between annual rainfall and season-integrated NDVI for all of Senegal. For agriculture, savanna, and steppe areas, high positive correlations portray ‘normal’ land cover performance in relation to the rainfall/NDVI association. Regions of low correlation might indicate areas impacted by human influence. The analysis identified three areas of poor performance, where degradation has occurred over many years. Use of the ‘Standard Error of the Estimate’ provided essential information for detecting spatial anomalies associated with land degradation (Li et al., 2004)

2.4. Modeling Irrigation induced Watertable Change Scenarios

While the analysis of time series satellite imagery helps in identifying the land degradation hazard and its extent in a cost-effective manner, its use for assessment of waterlogging hazard is rather limited due to the fact that water table fluctuates seasonally and in situations of rising water tables, the vulnerable areas can’t be identified before hand. Moreover only surface expression of waterlogged areas can be captured on the satellite imagery. Every crop has a critical water depth tolerance threshold. If water table rises above that threshold, crops would fail. There is always a definite trend of ground water movement and it is very slow movement when compared to surface waters. In areas where the water tables are rising, if this trend can be analyzed with some kind of certainty, remedial measures can be undertaken to mitigate the hazard. These remedial measures may include installation of subsurface drains, construction of regional outflow drains, evaporation ponds, bio-drainage, changes in cropping pattern and altering the amount of irrigation inflows etc. Hence, for the purposes of waterlogging risk assessment it is essential to undertake groundwater modelling to generate future scenarios and then integrate this information in GIS for carving out mitigation strategies.

Water table rise scenarios can be generated by use of numerical groundwater models which make use of equations derived from Darcy’s law. Important modeling packages are MODFLOW, AQUIFEM, and PLASM. Depending on the nature of problem, 1D, 2D and 3D models could be employed (Anderson and Woessner, 2002). The information on water table fluctuation and aquifer parameters, viz. hydraulic conductivity, transmissivity, specific yield and storage, porosity, is needed for modeling of fluxes in ground water regime and generating scenarios. This information comes from water table measurements in the wells, test wells, piezometer readings, borehole logs (Rushton, 2003). Remote Sensing data provides following information in spatially distributed form for modelling purposes for assessment of Waterlogging Risk:

- Recharge/sink/source (irrigation network and irrigated fields),
- Discharge (water logged) zones,
- Saline Zones indicating watertable close to the surface,
- Water consumption/use: crop growth, evapotranspiration by measuring the energy,
- Fluxes (weekly/ monthly basis),
- Digital Elevation Model, etc.

This information can be integrated and visualized in GIS.

The following studies have followed the modelling approach to gain insight into groundwater regime and the risk of hazard of waterlogging in various areas.

The performance and sustainability of the irrigation system in Sirsa Irrigation Circle, India was studied using satellite remote sensing, GIS and Ground Water Modelling by Bastiaanssen and Molden (1999). IRS LISS-II Satellite data were employed to obtain essential agronomic characteristics during Rabi 1995/96. Crop yields were obtained from information of crop cuts and NDVI values. A grid was imposed on remote sensing images of the study area to form cells, each of which contained several crop types and fallow land, and hydrologically similar cells were grouped into 46 model units. FRAME, a hydrologic modelling package, was employed to perform hydrologic computations for each cell for the period 1977-90 for study area. FRAME is composed of several sub-models describing the hydrologic sub- processes of an irrigation system. The lateral connections between the 46 units were established with a groundwater model (SGMP), a surface water allocation and distribution model (DESIGN), and a regional drainage model (REUSE). The interaction between surface and groundwater systems was formulated empirically so that leakage losses from the canal network and the Ghaggar River into the phreatic aquifers are taken into account. The hydrologic model was calibrated for 1977-81 using observed water table data. The period 1982-90 was used for validation. The model parameters considered in the calibration process were soil water-holding capacity, on-farm conveyance losses, and the effective porosity of the aquifer. Hydrologic analysis was aided by a geographic information system (GIS) that synthesized information obtained from ground data, remote sensing, and computer modelling (Bastiaanssen and Molden, 1999).

The major rice growing areas situated in Murray Valley Irrigation areas, Southern New South Wales (Australia) comprising of a total area of around 150,000 hectares along the rivers and creeks are experiencing the problem of rising water table and soil salinity threatening the sustainability of irrigated agriculture. This study by Khan and King (2004) describes how GIS, remote sensing and hydrology can be integrated for evaluating environmental management options in the rice growing areas. The rice growing areas were extracted by classification of LANDSAT imagery using NDVI and on screen digitizing of Spot Panchromatic imagery.The rice growing areas were overlaid on soils maps and electro-magnetic survey maps to identify leaky paddocks contributing to groundwater recharge to shallow watertable. Lithology of aquifers - including top and bottom elevations and hydraulic characteristics, vertical interactions (leakage) between the aquifers, recharge due to irrigation and rainfall , groundwater abstractions from different aquifer layers, leakage to and from the supply channels with the adjoining aquifers, leakage to and from the drainage channels and the Murrumbidgee river were represented in GIS.

These hydrogeological themes provided input to the surface-groundwater interaction model in the irrigation areas using MODFLOW, which simulated aquifer dynamics on a detailed (750 m*750m) grid under different irrigation scenarios. Groundwater model simulations gave predictions of watertable heights under different scenarios and help identifing groundwater hotspots in the irrigation areas. The study demonstrated the use of Groundwater models coupled with Remote Sensing and GIS databases as powerful tool for the environmental management of irrigation areas (Khan and King, 2004).

A groundwater modelling study carried out by Gieske and Miranzadeh (2002) in the Lenjanat District south of the Zayandeh Rud, Iran, to determine the magnitude of the main components of the water balance: recharge, abstraction by wells, qanats and springs, and groundwater losses to the Zayandeh Rud, if any. This study didn't deal with rising water table and waterlogging, on the contrary it investigated the declining water tables due to over abstraction of ground water. It is relevant from the perspective of a methodology for understanding surface-water & ground-water interaction using Remote Sensing, modelling and GIS. A steady-state model was developed using PMWIN as pre- and postprocessor for MODFLOW. The Lenjanat Southern Plains Aquifer was delineated by interpretation of two ASTER Images. The Zayandeh Rud River was taken as a constant head boundary, whereas all other boundaries were no-flow boundaries. The aquifer was modelled as a single layer confined system with a thickness of 50 m. Recharge was considered to take place as direct infiltration of precipitation, as lateral subsurface inflow and as mountain front recharge into the coarse colluvial cones at the foot of the mountains. Aquifer transmissivity and storativity values were derived from pumping tests. It was assumed that the direct vertical recharge is much smaller than the lateral recharge across the aquifer boundaries. (Gieske and Miranzadeh, 2002).

The first numerical modeling study inIGNP command was conducted in 1988 to understand the behavior of groundwater and test the viability of developing conjunctive use of surface and groundwater resources and under various scenarios (Sehgal and Vyas, 1994). A finite difference single layer digital model of pilot area was developed. The area modelled covers the middle reaches of IGNP command in the Flow Command (areas to the west of Main Indira Gandhi Canal in Bikaner district) and covers an geographical are of the extent of 8650 km^2, with boundaries defined on south-east by the IG main canal, and north-west by the Indo-Pak border. An impermeable base layer of sticky clay forms the base of the aquifer and groundwater occurs under phreatic conditions. The depth of the base layer from surface is between 5 to 40 meters. The model used in study was developed by Prickett and Lannquist (1971) and later modified by Texas Water Development Board (1974). The water table levels of June 1986 were used as initial heads. Irrigation in this reach of IGNP was introduced in 1983. Model was calibrated in two stages- steady state and transient state. The value of permeability ranged between 6m/day to 12m/day and specific yield ranged between 8% and 11% over the model area. Several possible irrigation developments were simulated to provide quantitative information on aquifer capacity to hold and transmit water on introduction of irrigation. The model predicted a rise of 2 to 5 meters in 81% of model area after 20 years of irrigation under conditions of no conjunctive use of groundwater; under the conjunctive use scenario, the rise was found to be almost nil (Sehgal and Vyas, 1994).

The Lift command areas of IGNP in Jaiselmer, Bikaner, and Jodhpur districts of IGNP command are considered to be prone to waterlogging due to presence of a hydrological barrier very close to the surface(within 5 meters in 90% of the area). The evolution of water table in case of introduction of

irrigation has been investigated by National Institute of Hydrology (NIH), Roorkee using a lumped groundwater balance model (Mishra et al., 1995). This study predicted that for the designed annual irrigation applications of 3.0 cusecs per thousand acres, waterlogging condition commences 49 months after introduction of irrigation and water table stabilizes at a depth of 0.73 meters.
Since the specific storage and conductivities vary spatially, the evolution of watertable\groundwater flow in the modelled area was also investigated using MODFOW, a modular three-dimensional finite difference groundwater flow model developed by (Macdonald and Harbaugh.A.W., 1988).The study area discretized into 14*28 grid squares of 2km side. The aquifer up to the hardpan was divied into two layers having distinctly different order of magnitude of hydraulic conductivity and storage coefficient. Both layers were assumed to be isotropic. The main IG canal was taken as constant head boundary and the high elevation areas beyond which no irrigation is possible as no flow boundary. External stresses in the form of areal recharge due to irrigation, canal seepage and rainfall, and areal evapotranspiration were considered. Model simulated a period of 40 years, divided into uniform 480 stress periods-each of 30 days. Each stress period was discretized into 15 uniform time steps for obtaining head variations and volumetric budgets. The model runs indicated that for the designed annual delta of 0.41233m water table will rise to less then 1 meter from surface just after 4 years of initiation of irrigation and a dynamic equilibrium will be reached (Mishra et al., 1995).

These studies didn’t have any input from earth observation/remote sensing. One modelling study in IGNP command has employed remote sensing generated data for evaluation of the groundwater in upper reaches (Suratgarh Branch) of the system (Goyal and Arora, 2003). Expected groundwater levels and fluxes for the next 20 were simulated using the MODFLOW code to indicate the changes in the extent of waterlogged and saline area. IRS LISS-III dataset was classified to obtain land use information as input in the conceptual model, which was developed by generating various information layers in GIS environment. These layers were then transferred into finite difference grid based model employing the MODFLOW code. The findings of study suggest that a rapid and accurate assessment of the waterlogged area can be made by the use of remotely sensed data.

Distributed eco-hydrological modelling not only simulates the watertable, also provides the means to evaluate the performance of irrigation systems at different spatial and temporal scales. The soil–water–atmosphere–plant (SWAP), an eco-hydrological model, based on deterministic and physical laws for hydrological, chemical and biological processes occurring in the soil–water–plant–atmosphere continuum has been employed to evaluate the performance of irrigation systems in Sirsa district in terms of water productivity, net groundwater recharge and salt build-up (Singh et al., 2006). The study area covers 4270 km2 in the western part of Haryana State (India), which faces typical problems of canal water scarcity, poor groundwater quality, rising and declining groundwater levels, and sub-optimal crop production. The field scale model SWAP was extended in a distributed manner to quantify the required hydrological and biophysical variables during the agricultural year 2001–2002. Field experiments, satellite images and existing geographical data were used to aggregate the representative input parameters of all homogeneous ‘simulation units’ and their boundary conditions. The study revealed a large variation of net groundwater recharge and salt build-up over different canal commands. In the central commands, the high intensity of water demanding wheat and rice crops and relatively low canal inflow, inducing high groundwater extraction resulted in declining groundwater levels. In the northern canal commands, the relatively high canal inflow and low groundwater pumping resulted in negligible negative to positive net groundwater recharge, which corresponds to rising groundwater levels. The simulated mean annual evapotranspiration (689 mm) over the entire Sirsa district was 15% lower as compared to the mean annual evapotranspiration (809 mm) estimated by independent remote sensing approach. The discrepancy in the actual evapotranspiration estimated by the remote sensing algorithm SEBAL and the distributed SWAP modeling over the bare soils shows the importance of proper land use classification A low accuracy in the land use classification can mislead the parameterization of the eco-hydrological model, which subsequently can result in unrealistic water and salt balances.

STARWARS, as described by Sekhar (2005) is a slope hydrology model developed by van Beek (2002), which simulates the spatial and temporal dynamics of moisture content and perched water levels in response to rainfall and evapotranspiration. This model was used to simulate the water table changes as an input to another model for simulating the debris flow in Kerala. It models percolation through the unsaturated zone and lateral saturated flow over a semi-pervious bedrock contact. Both the saturated and unsaturated zones are assumed freely draining and the groundwater levels unconfined. In the model, any rainfall is prone to interception by the vegetation canopy. A fraction reaches the soil surface unhampered as bulk throughfall, whereas the remainder is intercepted and is only passed on as leaf drip when the maximum canopy storage is exceeded. The intercepted rainfall can be lost to the potential evapotranspiration, thus freeing storage capacity for the next rainfall event. After the evaluation of any interception of rainfall by the canopy, rainfall and potential evapotranspiration are passed to the soil. If surface detention is already available, it is liable to evaporation and the remaining potential evapotanspiration that can be lost from the soil is modified accordingly. The net rainfall is added to any remaining surface detention, which can infiltrate. Any surface detention in excess of infiltration or return flow is passed on as surface runoff. The soil profile is subdivided into three vertical layers to allow for variations in the soil properties with depth and the perched water table can move freely within the soil column, thus reducing the depth of the unsaturated zone. In the model infiltration is added to the upper most unsaturated layer or in the case of full saturation to the saturated zone directly. Percolation through the unsaturated zone proceeds from layer to layer and is driven by gravitational unsaturated flow only. However, some leakage at the base of the soil column can occur and this can lower the water table or prevent its formation altogether as long as the percolation rate from the unsaturated zone is insufficient. Imposing a constant flux into a fourth, infinite layer, simulates this base loss. After evaluation of the vertical changes in water height for the current timestep, saturated lateral flow is considered. The elevation of the water table is used as the total head to calculate the gradient of the saturated flow in the X- and Y-directions of the grid using a simple explicit, forward finite difference solution. The resulting lateral flow leads to a new water level and change in the depth of the unsaturated zone. If the soil becomes fully saturated any water in excess of the available storage ex-filtrates as return flow to the surface (Sekhar, 2006)

3. Study area

Charanwala System of the IGNP Stage-II was chosen for this study for the following considerations:

- Along the Charanwala Branch (hereafter CWB), water table rise was sharp in the early 1990's. Two villages, '2CWB' and '3CWB', close to the take-off of the Charanwala Branch from IG Main Canal, and few low lying areas further downstream, succumbed to waterlogging by 1991.
- A dense network of piezometers was laid in IGNP Stage-II between the years 1988 to 1994. A large number of these piezometers have either been converted to hand pumps to tap potable water by farmers, as there is a scarcity of drinking water in the summer months, or have been damaged. In the Charanwala system, however, a good number of piezometers are still intact and, therefore, relatively better data on the water table changes are available.
- The population density in the flow command areas before the initiation of irrigation was below 5 persons per km2 and in many systems most agricultural plots were allotted to 'entrepreneur' farmers from neighbouring irrigation projects for colonization of empty lands. Farmers have to level their land as preclude to irrigation. Land levelling in this region means levelling of the low dunes, i.e, spreading loose sands over a wider area. Such activities accelerate the aeolian hazard. In the dry summer months of May, June and July, wind velocity is quite often above 25 km/hr, which transforms the loose sand from the levelled fields into unstable dunes, which chock the irrigation network and engulf their agricultural plots. Most of these settlers have abandoned their fields due to the harsh environment and colonization/settlement rates are poor in many systems. In the Charanwala system, most farmers are locals, belonging to the 'Bishnoi' community, settled in the dunal tracts for last couple of centuries. Hence, this system is representative of the best possible adaptation to a new kind of agriculture in this harsh environment. Irrigation started in this branch in 1986 and over the last two decades, the new production mode- settled irrigated agriculture- has firmly established itself, replacing the old semi-nomadic pastoral economy of the area.

3.1. Location and extent

Charanwala System of Indira Gandhi Canal is situated between latitudes 27^0 42' 13"N and 28^0 08'44"N, and longitudes 71^0 32'22"E and 72^0 28'39''E. This Irrigation system is sub-divided into a hierarchy comprising of branch, distributaries, minor, sub-minor, and sub-sub-minor (Figure 3.1). The total culturable command area (CCA) is 110573 ha. The length of these channels and CCA served by each is given in table- 3.1.

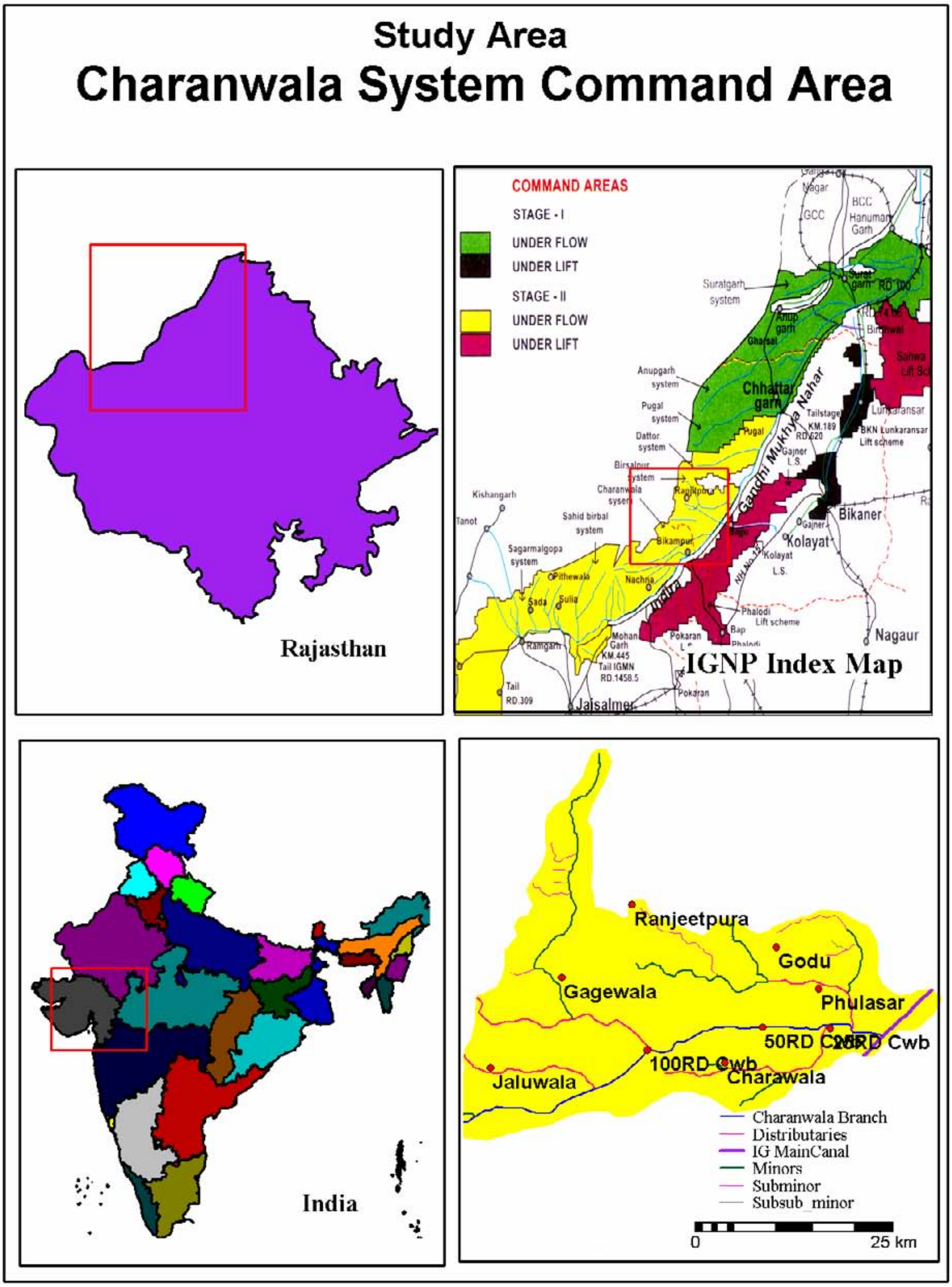


Figure 3.1 Location map of study area.

Table 3.1Length & CCA of irrigation channels in Charanwala System.

S.No	Channel	Length (Km)	CCA (ha)	S.No	Channel	Length (Km)	CCA (ha)
1	Charanwala Br	81.95	16875	17	Meghwala Mr.	5.27	1792
2	Phoolasar Disty	15.09	5165	18	Maruti Mr.	11.18	3004
3	Godu minor	18.56	4311	19	Raichandwala Mr	9.14	1439
4	Godu sub minor	4.34	1267	20	Jalluwala Disty	18.23	7216
5	Phoolasar Mr. I	20	3905	21	Devawala Mr.	4.11	2202
6	Phoolasar Mr. II	7.32	918	22	Dhakalwala Mr.	5.1	1087
7	Phoolasar Sub Mr.	14.81	2404	23	Akalwala Disty	9.75	3479
8	Khara Disty	21.95	3024	24	Thakarwala Mr.	3.81	683
9	Narainsar Mr.	7.62	1256	25	Jiyawala Mr.	17.13	3980
10	Charanwala Br	1.6	790	26	Bharawala Mr.	6.52	2202
11	Khara Minor	11.43	2703	27	Khariya Mr.	11.43	2915
12	Kheruwala Disty	22.86	6346	28	Mehrabkhan Disty	15.43	4345
13	Gajjewala Mr.	27.93	5638	29	Summer Mr.	4.93	1933
14	Gajjewala Sub Mr.	3.2	788	30	Sekhuwala Disty	10.66	3792
15	Dholla Mr.	3.47	728	31	Mehrabkhan Mr. I	14.99	6287
16	Bhottowala Mr.	4.27	1230	32	Mehrabkhan Mr. II	15.27	6869
					Total	429.35	110573

Source: (IGNP, 2006)

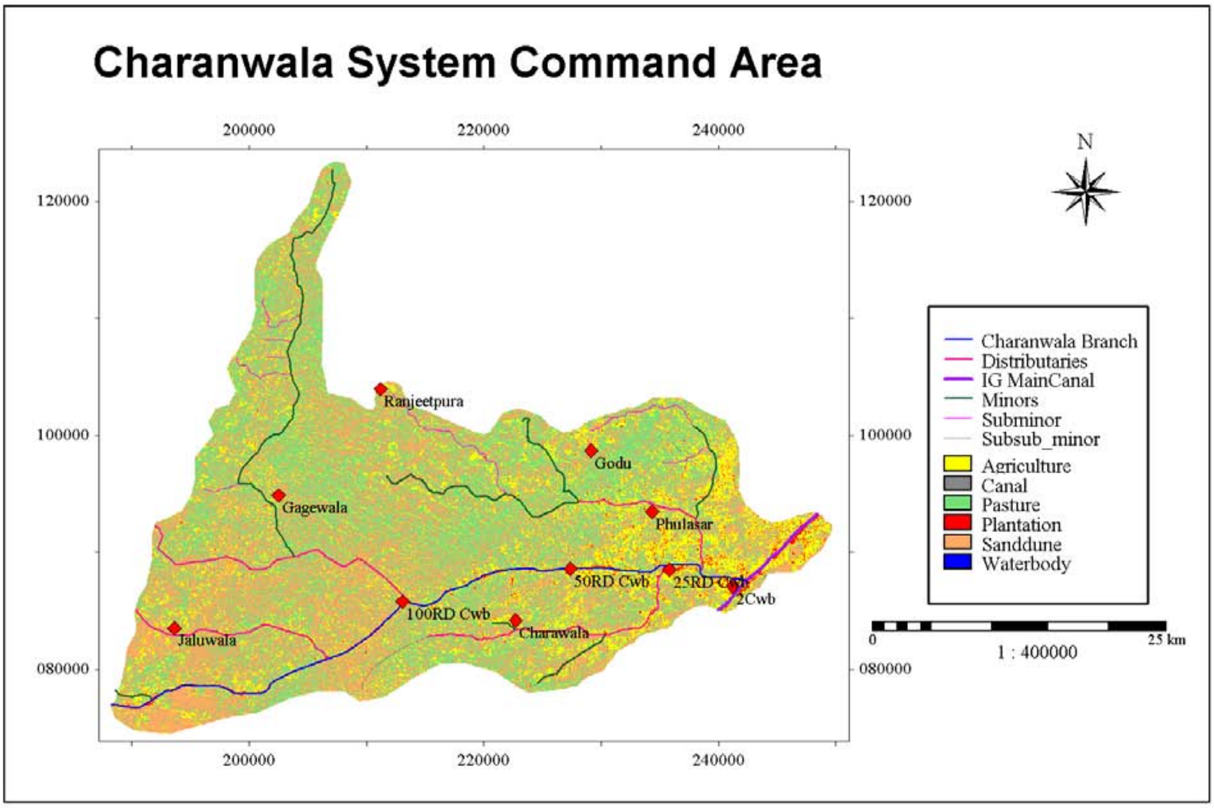


Figure 3.2 Cultuable command area served by Charanwala Branch

3.1.1. Upper Charanwala System: irrigation and groundwater interaction modelling area

Irrigation/ soil water and groundwater interaction modelling is carried out for an area of 33319 ha in the head/upper reaches of the Charanwala system and is served by Charanwala Branch(CWB), Phulasar Distributary (PSD), Khara Distributary (KD), Godu Minor (GM) and Naryansar Minor (NM) (Figure3.2). Out of the total area of 33319 ha, the planned/designed culturable command area (cca) is 19016 ha. The CCA in the 'tail' portions of the above mentioned irrigation channels has been excluded as at spatial resolution of 50 meters, data/information requirements for each grid cell makes it a very heavy/ time consuming model. The choice of the size of model area is also restrained by the location of gauge stations recording the outflow in network beyond them and/or off-takes of channels lower in hierarchy (minor or sub-minor) of network to ascertain the CCA served, and location of piezometers for validation of the results. Details of the area investigated are given in Table 3.2.

Table 3.2 CCA of irrigation and groundwater interaction model area

Name of Channel	Length of Channel (meters)	CCA Served (ha)
Charanwala Branch	26860	7310
Phulasar Distributry	16800	4354
Khara Distributary	25280	3878
Godu Minor	9090	2522
Naryansar Distributary	6350	952
Total	84380	19016

(Source: IGNP,2006)

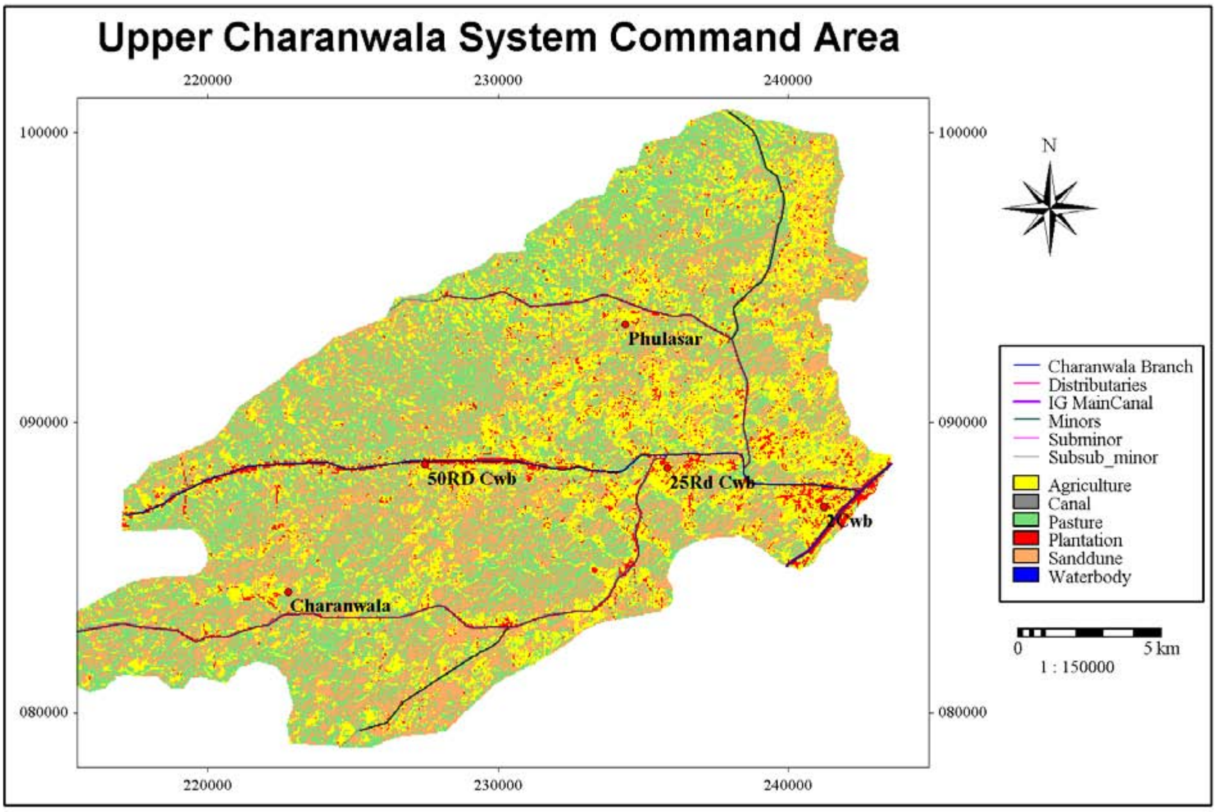


Figure 3.3 Irrigation and Groundwater Interaction Modelling Area

3.2. Topography

Surface of Charanwala system is a blanket of wind deposited sand, which completely conceals the rocks underneath. The topography of the area consists of sand dune fields, inter-dunal flats, and aeolian plains. The elevations range between 192 m close to east of the Indira Gandhi Main Canal to 107 m close to India-Pakistan border (Figure 3.4). The area slopes in a northwesterly direction towards the Indus River (in Pakistan). The average slope is around 1.5 meter per km.

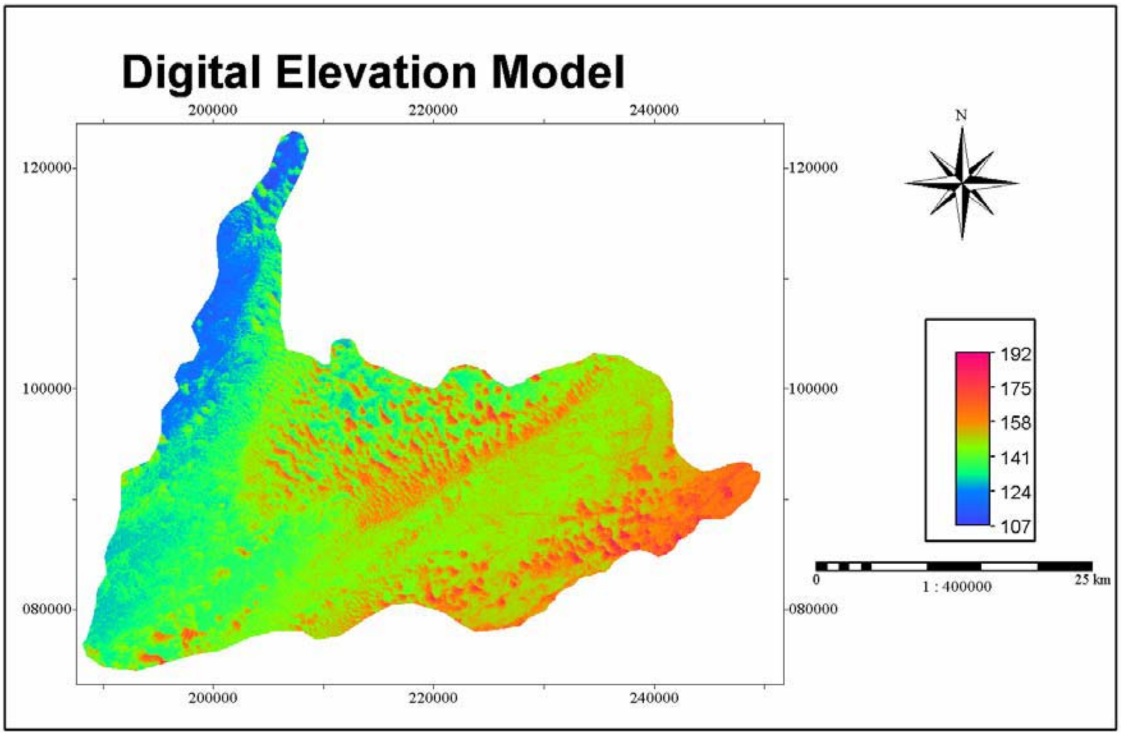


Figure 3.4 Digital elevation model (DEM) of the study area (Data source: GLCF)

The internal relief (m per hectare) map of the Charanwala Command given below in figure 3.5 provides a general idea about the undulating terrain in the area of area.

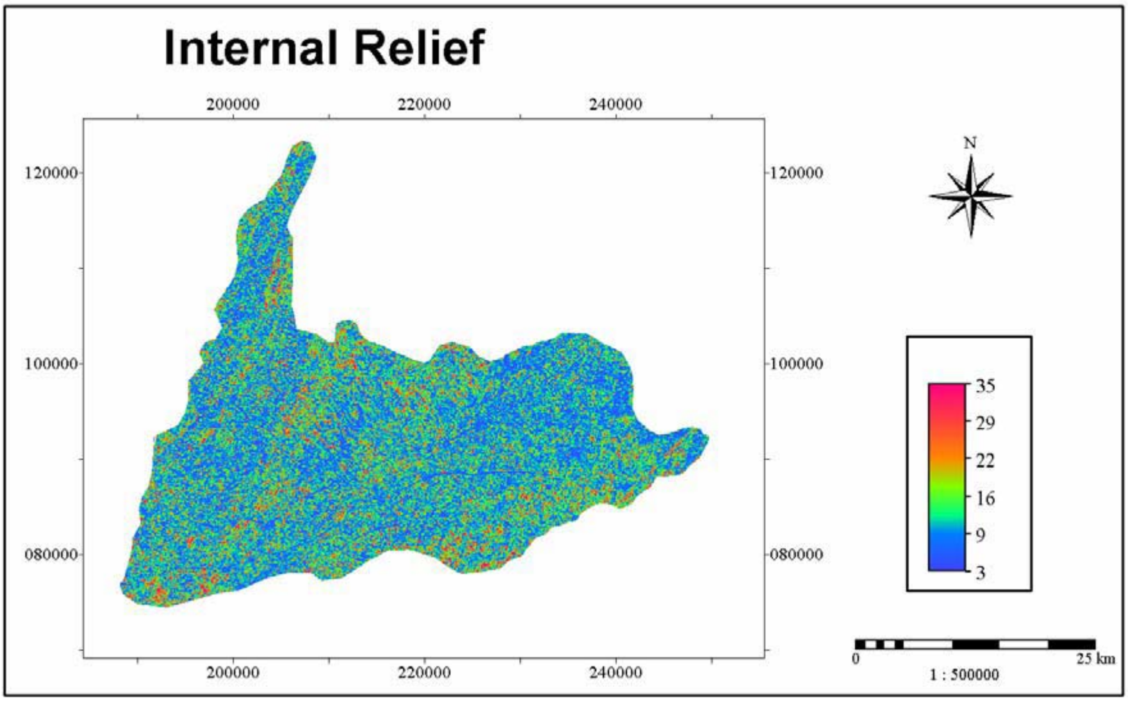


Figure 3.5 Internal relief (m/ha) of the study area

3.3. Drainage

Charanwala System has no surface drainage. Though the area slopes in a north-westerly direction towards the Indus River (in Pakistan), there are very few rainfall events (less then 20) in the entire year and whenever it rains, the intermittent sand dunes block the overland flow resulting into formation of small puddles, which disappear soon on account of high infiltration rates in coarse sandy soils and high potential evapotranspiration rates prevailing in the area.

3.4. Soils

The soils in the area are of aeolian origin consisting of sandy plain, inter-dunal flats and dunes. They are deep, coarse textured and infiltration rates are high. They are low in fertility and highly susceptible to wind erosion. The semi-detailed soil survey and land irrigability classification was carried out in the Stage II areas of IGNP by the UNDP-FAO (UNDP-FAO, 1971). Soils of Charanwala System, which were surveyed in the above mentioned survey, are classified as aE (deep fine sand to loamy sand with average infiltration rates of 164 mm/hr) or DA (deep sand to fine sand with infiltration rates of 296 mm/hr) (MacDonald and Dalal, 1998).

3.5. Hydrogeology

The geological formations in the Charanwala System of IGNP stage-II area belong to Quaternary & Tertiary periods (CADA, 1991).The hydrogeological formations/lithological assemblages, on the basis of their mineralogical composition, may be classified into 3 different layers:

- Layer1- Quaternary formations comprising of loose pale brown to yellowish wind blown surface sand.
- Layer2- Quaternary alluvial horizons comprising of partly consolidated sand and clay with kankars (calcium carbonate nodules), and sticky gypsum dominated clays.
- Layer3- Tertiary formations comprising of shale and sandstone.

The most important geological formation in study area controlling the water table is hydrogeological barrier composed of sticky and gypseous clays (ORG, 1989).

3.5.1. Hydrogeological Barrier Layer

Barrier layer has been defined as any layer having a radial hydraulic conductivity (i.e. permeability or in simpler terms movement of water through deep soil layers) less then 1/5 of the strata lying above at the surface (CADA, 1999). This definition is given by The US Bureau of Reclamation and has been adopted by the Groundwater Wing of Command Area Development Authority (hereafter CADA) for ascertaining the depth to the hydrogeological barrier.

Barrier layer in IGNP Stage-II has been determined by integration of geological, hydrogeological and geophysical surveys carried out by the Groundwater Wing of the IGNP CADA. Reconnaissance studies were taken between 1989 and 1990 (CADA, 1991). Table 3.3 provides a summery of the extent of barrier areas in IGNP Stage-II.

Table 3.3 Extent of barrier areas in IGNP Stage-II

S.N.	Name of command	Depth to the barrier from surface (m)	Barrier area (ha)	Barrier area as % of the area investigated
1	Flow command	0-5	149220	12.97
		5-10	312025	27.13
		10-15	197077	17.14
		> 15	4691678	42.75
2	Lift Commands			
(a)	Pokaran	0-5	2700	100
(b)	Phalodi	0-5	56750	100
(c)	Kolayat	0-5	77750	100
(d)	Gajner	0-5	49540	100
(e)	Bangarsar	0-5	0	0

Source:(CADA, 1999)

Detailed studies in the Upper Charanwala System Command for a section along the Charanwala branch were taken up in 1992 and 1993. One borehole were drilled in every 5 km^2 and one geo-electric sounding was made for every 1 km^2 area (CADA, 1993). On the basis of geophysical investigations and lithological assemblages as indicated by borehole logs, it has been generalized that the barrier layer in Charanwala system belongs to Layer 2 of the above defined classification (CADA, 1993; Sehgal and Vyas, 1994). The sticky clay, sand and kankar (calcium carbonate nodules) mixed layer, generally encountered between 10-25 m below the ground level act as a hydrogeological barrier in this reach of IGNP. The overlying formation is highly permeable and has very poor water holding capacity. The barrier layer is underlain by thick argillaceous formation of Tertiary age. The depth to barrier from the surface ranges between 5 and 35 meters in Charanwala System.

The hydraulic conductivity values for the surface soils and barrier layers are available for the Charanwala area as well as for Pokaran and Phalodi lift command areas, situated on east of the IG Main Canal and Charanwala area (Tables 3.4 to 3.7). IGNP authorities determined the hydraulic conductivities of the Tertiary shale formations (layer 3) in the Charanwala System area by the analysis of core samples in the laboratory using Jodhpur permeameter. These surface infiltrations tests for Charanwala area were conducted with double ring infiltrometer, while for Pokaran and Phalodi lift areas, hydraulic conductivity was determined by Guleph permeameter.

Table 3.4 Surface layer hydraulic conductivity in Charanwala System.

Sample No	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Ksat(m/day)	1.008	5.976	3.6	1.224	2.088	3.816	3.96	2.592	3.6	4.24	2.52	2.16
Sample Number	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
Ksat(m/day)	2.16	3.81	3.264	5.976	2.88	2.88	6.12	2.088	6.336	2.544	5.04	5.353

Source:(CADA, 1993)

Table 3.5 Surface layer hydraulic conductivity m/day in Pokaran and Phalodi Lift areas.

Sample No	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Ksat(m/day	1.5342	4.4567	3.3592	1.6249	2.4825	3.5218	5.0389	2.0773	0.244	1.175	1.784	5.772

Source: (Mishra et al., 1995)

Table 3.6 Tertiary Shale layer hydraulic conductivity in Charanwala System.

Sample No	**1**	**2**	**3**	**4**	**5**	**6**
Ksat(m/day)	0.000997	0.000192	0.000149	0.000123	0.000107	0.000179

Source:(CADA, 1993)

Table 3.7 Barrier layer hydraulic conductivity in Pokaran and Phalodi Lift areas.

Sample No	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Ksat(m/day)	0.00001	0.00067	0.00042	0.0018	0.007	0.0018	0.011	0.0021	0.009
Sample No	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**
Ksat(m/day)	0.00078	0.0017	0.0228	0.001	0.0344	0.039	0.0078	0.004	0.007
Sample No	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**
Ksat(m/day)	0.064	0.0056	0.00146	0.0015	0.0048	0.0046	0.00203	0.0023	0.001
Sample No	**28**	**29**	**30**	**31**	**32**	**33**	**34**	**35**	**36**
Ksat(m/day)	0.00024	0.014	0.00109	0.073	0.015	0.0027	0.00049	0.2776	0.0874

Source:(Mishra et al., 1995)

3.5.2. Depth to water table and extent of waterlogging

The groundwater in study area occurs under phreatic conditions. The initiation of irrigation has completely changed the groundwater hydrology. The depth to water table in the IGNP command area generally ranged between 40 and 50 m below the surface before introduction of irrigation. The native groundwater was highly saline with EC more than 8000 micro-Siemens/cm. With the introduction of irrigation in Stage-I in 1961, the water table started to rise. During1981-1992, the average water table rise was 0.92 m/yr. Water was released in IG Stage-II area from 189 km to 293 km (or RD 620 to RD961) in 1983 and beyond 293km to 445km (or RD961 to RD 1459) in 1986. By 1991, pools of standing water became apparent at 127 locations along the Indira Gandhi Main Canal . However, due to various reclamation measures such as plantations for Bio-Drainage, opening up of newer irrigation settlements/colonies and consequent spreading of inflows over a larger area, and overall decline in inflows after year 2000, the surface expression of waterlogging has declined considerably. In June 2000, the number of inundated areas declined to nine . The depth to groundwater, close to Indira Gandhi main canal is about 5 meters while towards the tail of the Charanwala branch in the west it is 30 to 40 meters. The EC of fresh groundwater which has developed above the hardpan or above the dense native water table is reported to be around 2000 micro-Siemens/cm (Gupta.A.K. et al., 2002). Table 3.8 gives a temporal picture of the extent of waterlogged areas n\in IGNP Stage-II.

Table 3.8 Extent of waterlogged area in IGNP Stage-I

Section (km)	June 1991 (ha)	June 1993 (ha)	June 1995 (ha)	June 1997 (ha)	June 2000 (ha)
229-293	337	35	24	11	3
293-342	533	471	83	4	3
342-416	30	24	20	6	1
Total	900	530	127	21	7

3.6. Climate

Thar Desert is a typical hot, arid desert. There is no meteorological station within the huge command area of IGNP. In the year 2000, three automatic weather stations were installed in IGNP command area in Suratgarh (Sriganganagar district), Bikampur (Bikaner district) and Ramgarh (Jaiselmer district) in IGNP command area. Unfortunately, they were not maintained and stopped functioning in less than two years of installation. The climatic information about the Charanwala system is based on interpolation of data of the meteorological stations of Bikaner (118 km from 25 CWB) and Jaiselmer (178 km from 25 CWB). Some of the climatic indicators in Bikaner and Jaiselmer areas is given in Table 3.9. The moisture index of Jaiselmer and Bikaner are (-)90.9% and (-)83.4% (CADA, 1991).

3.6.1. Temperature

The daily mean temperature ranges from 13^0 C to 18^0 C in winters to 34^0 C to 37^0 C in summers. The Charanwala area of IGNP in particular and IGNP command area in general are considered as the areas with minimum of clouding and maximum of solar Radiation in India (WAPCOS, 1993). Maximum temperature hovers between 42^0 C to 45^0 C and at times shoots up to 49^0 C. Minimum temperatures are recorded in December and January and range between 4^0 C to 6^0 C, but occasionally touch the freezing point.

3.6.2. Rainfall

The rainfall data is collected at each tehsil headquarters in the study area. Rainfall in deserts is highly erratic spatially. About 70% of the total rainfall is received in the months of August and September. Total rainy days are usually about 10 to 12 in the entire year (CADA, 1991). Major rainfall events do occur close to each other (temporally) at different stations. The rain events in the same week were clubbed together for the same day so as to get a reasonable average estimate of the rainfall in the study area.

3.6.3. Winds

Wind in the Charanwala area is most important meteorological phenomena, adversely impacting the agricultural activities. Winds blow from southwest to northeast during the dry summer season from mid-march to October beginning. The average wind speed during May, June and July is between 15km/hr to 25 km/hr, however, during the dust storm events which frequent the area in summer months, wind attain velocity of the order of 45km/hr. From October to mid March, winds blow form northeast to southwest with velocity less the 8 km/hr.

3.6.4. Potential/reference evapotranspiration.

The command of IGNP has the maximum Potential Evapotranspiration (ETp) in India. The annual ETp for Bikaner is 2151 mm/year and further increase to 2527 mm/year in Jaiselmer.

Table 3.9 Climate indicators in Bikaner and Jaiselmer.

	Potential Evapotranspiration (mm)		Mean Monthly Rainfall (mm)		Mean Wind Speed (Km/h)		Days with wind speed above 20Km/h	
	Bikaner	Jaiselmer	Bikaner	Jaiselmer	Bikaner	Jaiselmer	Bikaner	Jaiselmer
January	83	106	5.6	2.1	3.3	6.9	0	5
February	107	129	7.3	1.2	4.3	7.6	1	5
March	179	207	6.2	2.6	6	10	1	7
April	214	237	4.6	1.5	6.7	11.3	1	7
May	274	332	7.5	5.2	9	16.6	4	12
June	278	353	27	6.8	13.3	25.3	6	18
July	243	265	86.8	89.5	11.9	21.3	4	18
August	208	229	104.5	85.8	10	18.9	2	16
September	206	237	44.6	13.9	8.1	15.4	1	12
October	169	195	5.7	1.3	4.8	8.2	0	5
November	107	129	2.6	4.9	3.7	6.7	0	4
December	83	108	2.3	2.2	3.6	7.2	0	4
Total	2151	2527	304.7	217				

Source:(WAPCOS, 1993)

3.7. Land cover

Pastures, agricultural plots, plantations along the irrigation channels and sand dunes constitute the main land cover units/ types in Charanwala system. The ground photographs of different land covers are given below (Figures 3.7 to 3.11).

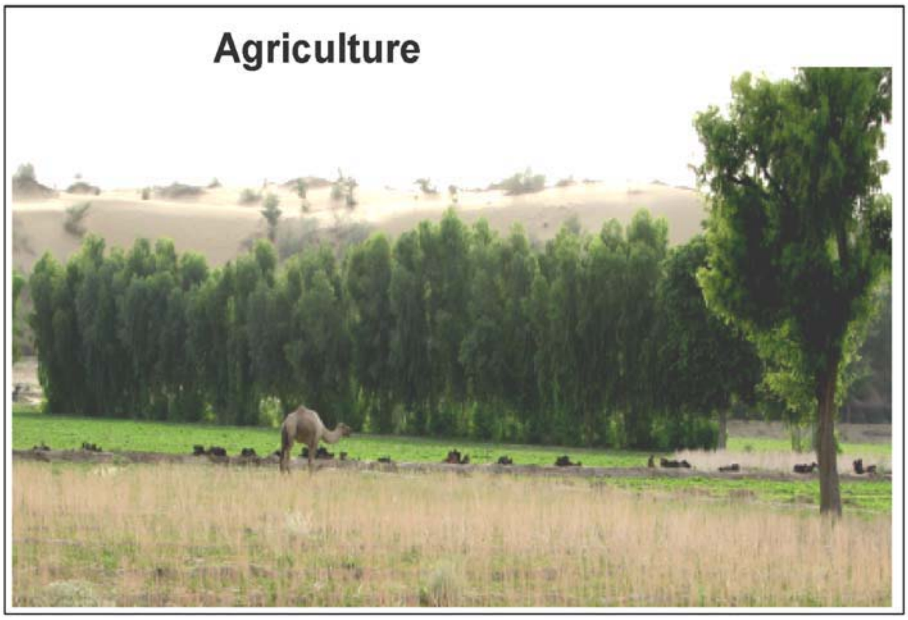


Figure 3.6 Ground photograph showing agricultural field near village 3CWB.

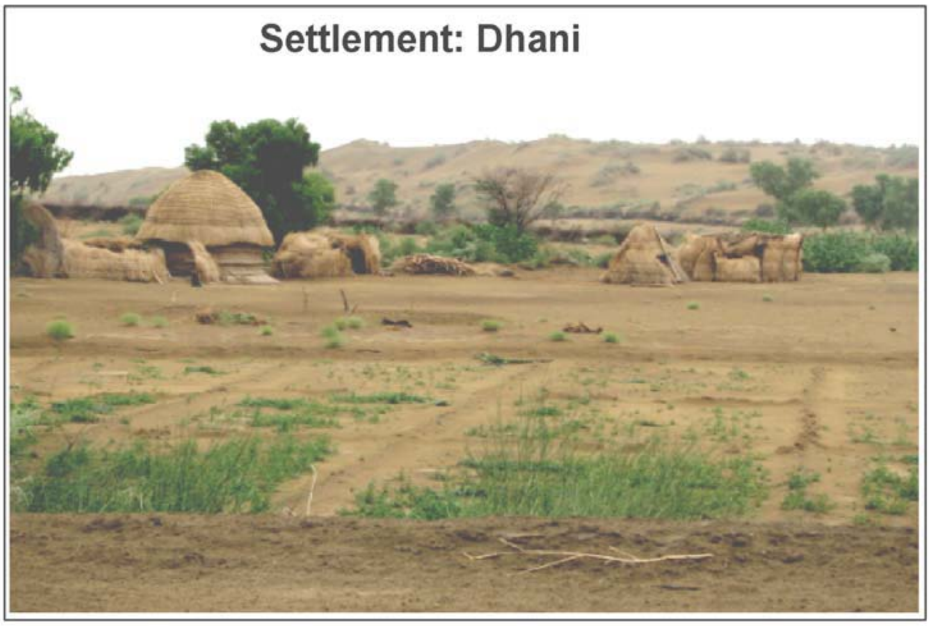


Figure 3.7 Ground photograph showing a settlement/Dhani near Naryansar village.

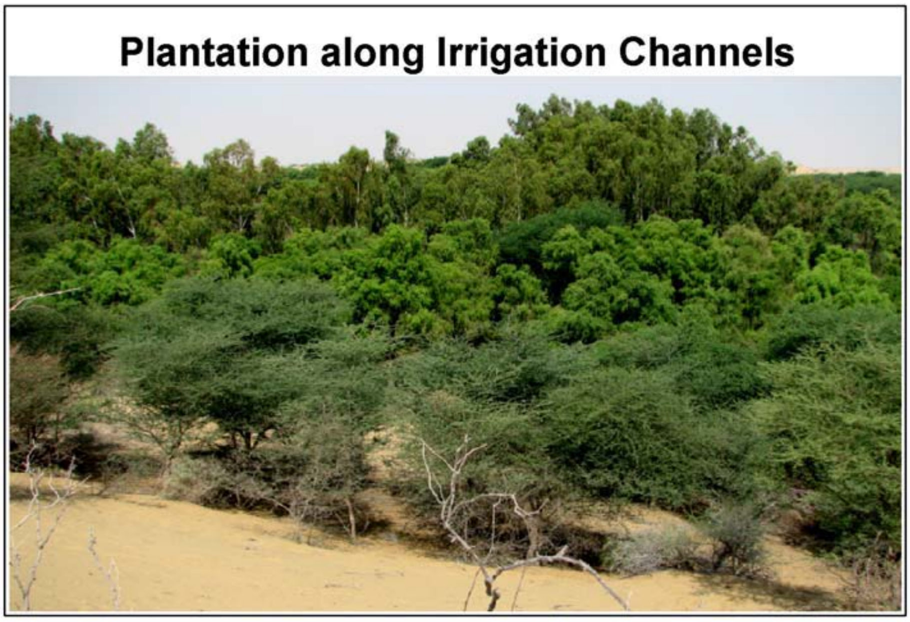


Figure 3.8 Ground photograph showing plantations close to the off-take of Charanwala Branch.

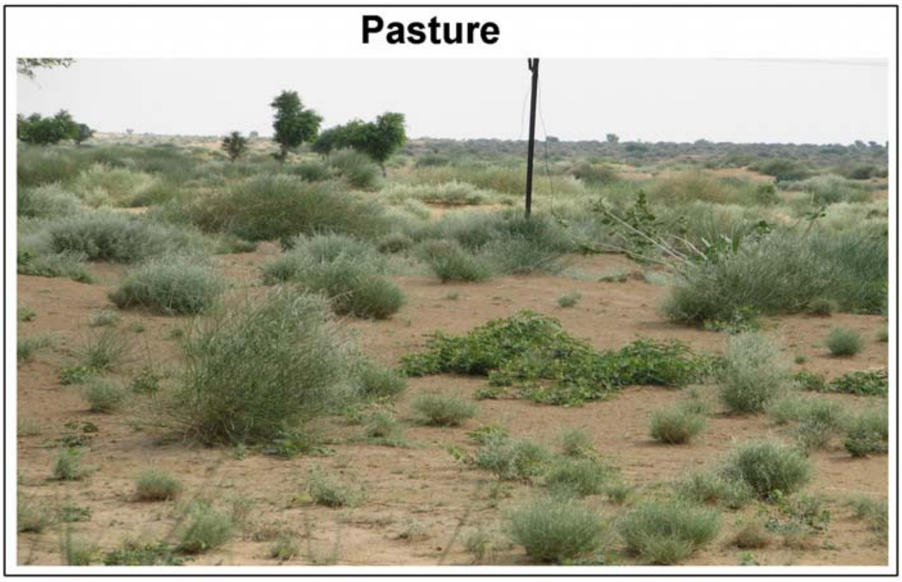


Figure 3.9 Ground photograph showing pasture near village 20PSD.

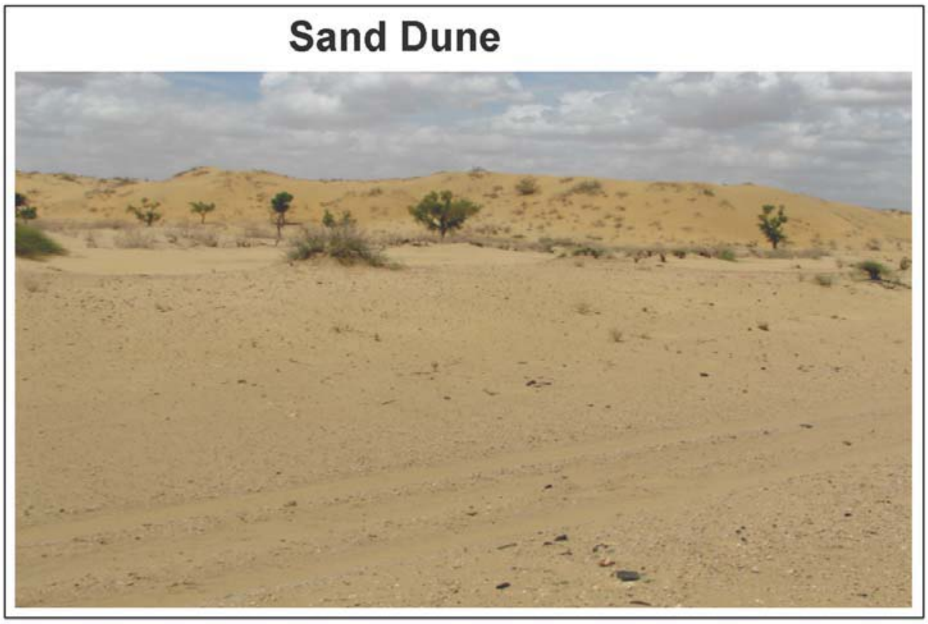


Figure 3.10 Ground photograph of sand dunes to the left of Khara Distributary

Figure 3.11 Ground photograph of inter-dunal agricultural field and pasture.

3.8. Vegetation

The area's natural vegetation is xerophytic desert shrubs and grasses. Fog (*Calligonum polygonomides*), Akra (*Calotropus procera*), Jal (*Salvadora persica*), Bui (*Avera tomentosa*) and Kair (*Capparis decidnal*) are the dominant shrubs of the area. During the rainy season, grasses also grow. Sewan *(Lacirius sindicus*) is the most important grass species found in the area. Bharut (*Cenchrus catharticus*), morant (*Chloris rosburglina*) and ganthil (*Dactyloctenium Aegyptium*) are the other grass species found here. In between some trees are also found. Khejri (*Prosopis cincenraria*), and Rohira (*Tecomella undulata*) are the important tree species (WAPCOS, 1993).

Apart from the natural vegetation, a massive afforstation program is undertaken to protect the canals from wind blown sand deposit by creating effective shelterbelts. Moreover, they also contribute to solution of drainage problems on account of Bio-drainage. The main tree species planted in irrigated areas are Eucalyptus camaldulensis, Dalbergiasissoo and Acacia nilotica. The afforestation activities have received financial support from international organizations, such as the World Food Programme (WFP), the International Development Agency (IDA), International Fund for Agriculture (IFAD) and Overseas Economic Cooperation Fund, Japan (OECF). The afforestation schemes included canal side plantation, block plantation, sand dune stabilization, pasture development, roadside plantation and environmental plantation. Continuous strips of land of the following widths have been reserved for canal side plantation on both sides of all canals (Table 3.10).

Table 3.10 Mandatory Plantation Strips along Irrigation Channels

	Width:East & South (m)	**Width: West & North (m)**
Main Canal	200	100
Branch Canals	100	50
Distributaries	50	50
Minor & Sub-minors	25	25

Source:(Soni, 1994)

3.9. Cropping pattern

In the pre-irrigation period, economy was semi-pastoral. In the years with good rainfall in the Kharif (summer) season, millets- Pearl millet or bajara and sesamum, were the main kharif crop: pulse- moth and moong (Phaselous radiatous) were also sown (Chatterji and Saxena, 1988). With coming of irrigation, these crops are gradually being replaced and Cluster bean is the most important Kharif crop, with fodder, groundnut, and cotton also grown. In the Rabi (winter) season, wheat, mustard, chickpea and berseem (rabi fodder) are main crops. Cattle rearing/animal husbandry is still important, but practice is increasingly shifting towards feeding cattle with agricultural residue and fodder.

3.10. Population

The population density, in IGNP Stage-I of Sriganganagar and Bikaner districts were 30/km2 and 16/km2 in 1958, when irrigation started (these districts account for about 41% of the total CCA irrigated/ utilized as of the year 2000). In Stage II, irrigation ensued in 1983, and Jaiselmer had population density of 11/km2 in 1981. In the flow areas (Charanwala System is a part of the Stage II flow area) of Stage-II, had population density was as low as 3 persons in 1981. These population densities are inadequate from the perspective of introduction of intensive irrigated agriculture. This extraordinary project has envisaged developing the desolate dreary desert by taking both water and people there. The population of Bikaner has increased to 44/km2 and 62/km2 in 1991 and 2001. While in Jaiselmer, the corresponding increase has been 9/km2 and 13/ km2 (Census, 1991).

4. Materials and Method

The investigation of the impact of the introduction irrigation on the groundwater table using irrigation/surface-water and groundwater interaction involves a large data base creation about information on the groundwater recharge zone, frequency and quantity of irrigation application, depth to the barrier from the surface digital elevation model, soil-hydrogeological parameters, and meteorological parameters, and ground coverage by the crops. First the model is described and this will be followed by the procedures adopted to generate the required information layers from collected and acquired data.

4.1. Model

The model chosen for conducting the surface-water and groundwater interaction study is a modified version of the physically based STARWARS (version 2.3) model, originally developed by vanBeek(van Beek, 2002).This model simulates the spatial and temporal dynamics of 'moisture content' and 'perched water levels' in response to gross rainfall and evapotranspiration. The model outputs are in turn used in another model to assess the the stability of steep slopes mantled with loose material in humid environments.

Though originally developed for vegetated humid regions, model was chosen for present study as it can be adapted to various data availability conditions and can be applied to all kinds of situations in which percolation is impeded by a less permeable layer(Sekhar, 2006).

4.1.1. Salient features of the model

The description of the main/salient features of the model described below are adopted from Sekher (2006).

- The evapotranspiration losses are calculated by routing the rainfall though the canopy interception and subtraction of any evaporation from the canopy, representing the water that never enters the soil. The balance/remaining rainfall and potential evapotranspiration are passed to the soil/ground underneath the vegetation. If surface detention is already available, it is liable to evaporation and the remaining potential evapotanspiration that can be lost from the soil is modified accordingly. The net rainfall is added to any remaining surface detention, which can infiltrate. Any surface detention in excess of infiltration or return flow is passed on as surface runoff.
- The proportion of rainfall, which infiltrates, passes through the soil profile. The soil profile is subdivided into three vertical layers of variable thickness to allow for variations in the soil properties with depth. In the model, infiltration is added to the upper most unsaturated layer.

- The percolation from each layer to the next layer is determined by the unsaturated hydraulic conductivity, k(□E), based on the soil water retention curve (SWRC) model of Farrel and Larson(1972) (Personal communication, Prof V. Jetten):

$$h = h_A \exp[\alpha(1-\theta_E)$$ --**Equation 4.1**

- where h is the matric suction (m), hA is the air entry matric suction (m) and □ is the dimensionless slope of the log-linear relationship between ln(h/hA) and (1-□E). This relation is true when h < hA (both are negative).
- The unsaturated hydraulic conductivity is then expressed as the relative unsaturated hydraulic conductivity, kr(□E) (-). Together with the SWRC model of Farrel and Larson, the unsaturated hydraulic conductivity becomes:

$$k_r(\theta_E) = \theta_E{}^{\tau} \frac{\exp(2\alpha\theta_E) - 2\alpha\theta_E - 1}{\exp(2\alpha) - 2\alpha - 1}$$ -----------------------------**Equation 4.2**

- Where □ is the "tortuosity", which is set to 4/3 (-). The relative unsaturated hydraulic conductivity forms an analogue with filled capillaries that represent filled pores in the soil at different suction levels. It is zero at the residual soil moisture content and unity when the soil is completely saturated. By multiplying the relative unsaturated hydraulic conductivity with ksat (m·s-1), the absolute unsaturated hydraulic conductivity, k(□E), is calculated:

$$k(\theta_E) = k_{sat} \cdot k_r(\theta_E)$$ --Percolation from each layer is calculated by multiplying the absolute unsaturated hydraulic conductivity with the time increment □t:

$$Perc = k(\theta_E) \cdot \Delta t$$ ---**Equation 4.4**

- Evapotranspiration and percolation lead to a change in the saturated storage that translates into a rise of the water table that depends on the available unsaturated pore space.
- To ensure numerical stability, the actual flux is calculated using a central finite difference solution including the additional changes in the unsaturated storage that arise from transpiration (lumped with soil evapotranspiration) and infiltration/percolation.
- Some leakage at the base of the soil column is allowed. This base loss is simulated by imposing a constant flux into a fourth, infinite layer.
- Groundwater is assumed as unconfined and both the saturated and unsaturated zone as freely draining.
- After evaluation of the vertical changes in water height for the current timestep, saturated lateral flow is considered. The elevation of the water table is used as the total head to calculate the gradient of the saturated flow in the X- and Y-directions of the grid using a simple explicit, forward finite difference solution. The resulting lateral flow leads to a new water level and change in the depth of the unsaturated zone. The effective degree of saturation of the overlying unsaturated layer is used if a fully saturated layer cavitates. If the soil becomes fully saturated, any water in excess of the available storage exfiltrates as return flows to the surface.

- The potential or reference evapotranspiration (Ep, mm/day) is carried out outside the model and the values are provided as a time series file. The model corrects the Ep to the actual evapotranspiration using the crop coefficient approach proposed by Allen al. al.(1998), thereby accommodating the fact of limited soil water availability and the presence of vegetation.

- The model provides temporal volumetric moisture contents and water levels as outputs.

4.1.2. Modifications to the original model

In order to suit the requirements of present study involving the surface water and groundwater interaction in an irrigated arid environment in Thar Desert, the original model has been modified. The important changes are following:

- The model was modified to enable the input of irrigation in terms of 'extra gift of rainfall' to the cells in the model area, which receive irrigation. The irrigation gift is provided as a time series file.
- The original assumption in the model was now was that the relation between actual ET (ETa) and mositure content is linear, i.e. when the soil is saturated, the ET equals the potential ET (ETp) and when it is zero, the ETa equals 0. This assumption resulted in extremely low evapotranspiration losses (ETa). Therefore in order to increase the relation between ETa and moisture content was assumed to be non linear, so that Eta = ETp * ThetaRel ** (2*(1-ThetaRel)).ET is directly subtracted after each irrigation gift from the cells that have irrigation, and the remaining water then infiltrates.
- In original model, the horizontal saturated conductivity was calculated as a weighed average from ksat3, ksat2, ksat1 depending on the groundwater was rise in these layers. This provision has been modified and the horizontal saturated conductivity is made spatially uniform and homogeneous.
- Lateral Groundwater outflow has been accommodated.

4.1.3. Model inputs

The execution of the modified STARWARS model described above, requires following data information in the spatial (map) and non spatial (table) formats (Table 4.1)

The information layers are needed as inputs by the model for simulating the surfacewater and groundwater inreraction are enlisted in the table below.

Table 4.1 Data information required for model execution.

Model inputs	Data Type	Source
DEM.map	Digital Elevation Model	SRTM DEM
Ksat1.map	Saturated Hydraulic Conductivity,top soil layer	Infiltration test
Ksat2.map	Saturated Hydraulic Conductivity,second soil layer	Soil texture analysis and soil watercharacteristic calculater
Ksat3.map	Saturated Hydraulic Conductivity,third soil layer	Soil texture analysis and soil water characteristic calculater
Pore1.map	Porosity, Top soil layer	Soil texture analysis and soil water characteristic calculater
Pore2.map	Porosity, Second soil layer	Soil texture analysis and soil water characteristic calculater
Pore3.map	Porosity, Third soil layer	Soil texture analysis and soil water characteristic calculater
Soildepth.map	Soil thickness layer	Barrier map and SRTM DEM
Gwinit.map	Groundwater above the barrier layer	DGPS data, Groundwater table, Barrier map and SRTM DEM
KsatBC.map	Barrier layerKsat	Adopted from NIH study
Landuse.map	Map with area under crop in different season	Time series LISS-III imagery and Crop area statistics
Production.map	Map showing Agricultural fields receiving irrigation	Time series LISS-III imagery and Crop area statistics
Channel.map	Map with the width of irrigation channels	L-section of irrigation channels
Mateo.dat	Text file with Daily ET(p) and Precipitation mm/day)	
Irrigation.dat	Text file with daily irrigation inflow in m3/day	Daily Irriagtion inflow timeseries (IGNP)
Covet.tbl	Text file with fraction of ground coverd by crop at different crop growyh stages	Daily Meteo data (IMD)

4.2. Data base preparation

Table 4.2 Provides thw list of data elements required and their sources for generation of the different types of information layers needd for model execution (as described in table 4.1

Table 4.2 Data elements needed, type, sources and purposes.

Sl No.	Data Elements	Type	Source	What for
1	Piezometer Location Map	Analog/ paper map	CADA	Locating piezometers in field for measuring groundwater levels and piezometer elevations
2	Depth to barrier layer Map	do	do	Genertion elevation map of impermeable/barrier base layer impeding percolation
3	Groundwater levels	Time series	do	For generation of groundwater

				table maps, initial grondwater levels and calibration of model results
4	L-section of irrigation channels	Analog/ paper graphs	IGNP	For quantifying the wetted perimeters of irrigation channels and comparison of relative accuracy of satelite imagery based DEM
5	Cropped Area Satistics	Time series	CADA	For broad comparision of satellite based area under cultivation and actual cultivated areas
6	Daily Irrigation Inflows	do	IGNP	For inputs to the surface-water and groundwater interaction model
7	Meteorological parameters:	Time series	IMD	For inputs to the surface-water and groundwater interaction model (Etp, precipitation)
8	infiltration rates	Primary data for 27 sites	Ground measurement	For estimation of Ksat of surface layer
9	Soil texture	do	Ground/ laboratry measurement	For estimation of Ksat in sub-surface layer
10	Ksat of saturated zone	Primary data for 12 sites	Ground measurement (slug tests)	Model input
11	Base map	Raster map	TERRA-ASTER image of December 2005	do
12	Land use/land cover	Raster map	Multi-temporal LISS-III, ASTER images	Area under cultivation/crop
13	DEM	Raster map	SRTM/ ASTER	For determining the barrier layer elevation, soil thickness and initial groundwater levels
14	Porosity	Raster map	Ground/ laboratry measurement	Model inputs for surface and sub-surface soil layers
15	Piezomete/canal offtake Elevation	Primary data	Fiedwork-DGPS	Generation of watertable map
16	Crop Calander	Ancilliry data	Interview with farmers and WAPCOS (1995)	For estimating the temporal ground coverage by vegetation/crops to compute Intereption and ETa
17	Precipitation at local levels	Time series	District Revenue Administration	Model input

4.2.1. Fieldwork

To collect the required data, fieldwork was planned and was conducted in two phases.

First phase: 23rd July to 9th August

- Determined the location of Piezometers and Canal /Branch Off-takes using Leica 500 Differential GPS for 52 sites.
- Measured depth to water table at 62 sites using a water level indicator.
- Collected L-Sections of IGMC and Charanwala System form irrigation authorities.
- Collected ground truth information for various Land cover classes.

Second phase: 23rd July to 9th August

- Conducted infiltration tests carried out at 27 sites for surface soil Ksat,
- Collected soil core sample at different depths at 27 sites for texture analysis,
- Conducted Slug tests at 12 sites,
- Collectedstatistics of Culturable Command Area served by different channels within the Charanwala System,
- Collected irrigation inflows (time-series) from IGNP authorities.
- Collected irrigated area statistics from CADA,
- Collected information on crops grown, sowing and harvesting dates from informal interviews with farmers,
- Collected report of Hydrological Barrier Studies (1992-93) from CADA,
- Collected basic data records (BDR) of piezometers from CADA,
- Collected automatic weather station data.
- Collected precipitation data at the tehsil headquarters in Bikaner District from District Magistrate's Office.

4.2.2. Irrigation Inflows

The irrigation inflows data within the Charanwala System were acquired from the IGNP authorities (IGNP, 2006a; IGNP, 2006b). The logs have been maintained for every three hours at the head of the Charanwala Branch (961RD IGMC) and distributaries off-taking from it. The logs for minors and sub-minors are not maintained and as such the area served by the minor and sub-minors located at the tail of Distributaries) in Upper Charanwala System were excluded to reduce the time involved in modelling effort. The distribution for the study area was worked out in consultation with the IGNP engineers associated with the water distribution regulation in Charanwala System (personal communication, Bhuwal and Sahu, 2006). The three hourly inflow data for the Upper Charanwala area, i.e. till RD 80 of the Charanwala Branch in cusecs (cubic feet per second) were aggregated for daily time step and converted to cumec (cubic meter per second) and finally to cubic meter (m^3) per day. The inflow data is provided to the model as a timeseries. The inflows are then equally distributed over the total area under crop in the entire system. This is added to the surface storage in the script, and after accounting for the evapotranspiration, the remainder infiltrates.

4.2.3. Groundwater table

Groundwater Wing of CADA maintains record of the watertable through biannual observations of the network of piezometers. These data provide information about the changes in the depth to groundwater from surface. The location (latitude and longitude) and elevation information of piezometers is not made public. However, without this information watertable map can't be created, which is essential to understand the overall groundwater flow direction and setting up the initial and boundary conditions for modelling. Topographical maps can't be used to fill this data gap because of their classified nature as the study area is located. To overcome this problem DGPS data collection was planned and data for 52 sites was collected using Leica GPS 500. These sites include: piezometer locations, irrigation channel off-takes and road intersections.

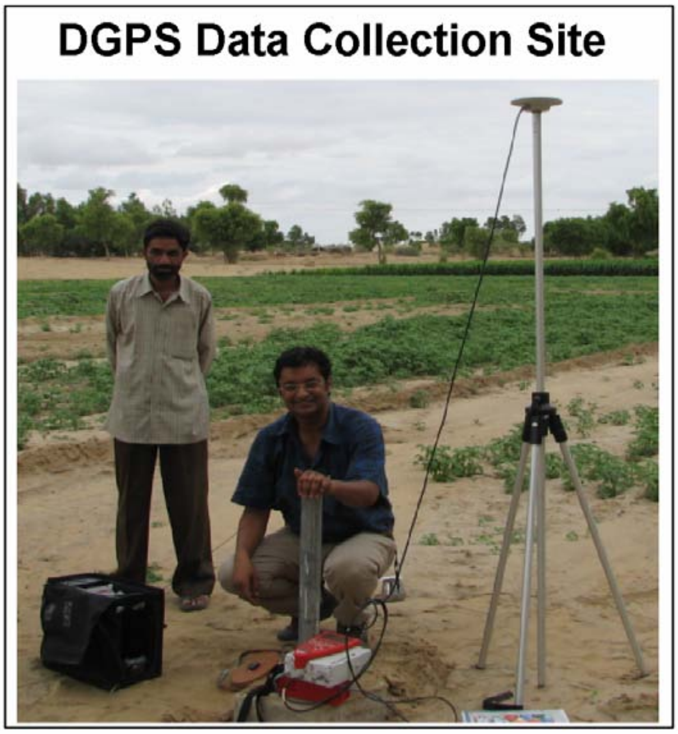


Figure 4.1 Ground photograph showing DGPS data collection near a piezometer.

UTM (zone 43) was specified as the projection, and WGS 84 as the datum and ellipsoid for the DGPS data collection. Observations at every site lasted for 20-25 minutes. Due to a technical snag with the instrument, only code measurements were recorded which processed using Ski Pro processing software.

Since conversion parameters from the Indian datum to WGS datum are not available (Indian datum parameters being a state secret) the base station's data (Khara Distributary's off- take from 25RD

Charanwala Branch), where the data were logged for the longest duration, was processed using the single point positioning technique. The base station value was used as the reference for the creation of baselines to stations logged by the rover. The elevation values range between 90m and 126 m.

In the present study relative height accuracy between the points is more important then the absolute accuracy. The DGPS measurements were compared with the SRTM DEM, ASTER DEM and Indian datum elevation values. The ASTER DEM turned out very erratic while SRTM DEM was found to be better and therefore, was used as input for preparation of different data layers such as barrier layer elevation and soil thickness etc. (see Chapter 5 for detailed discussion).

For four of the canal off-take sites, for which the DGPS data was also colleted, the Indian Datum elevations were extracted from the longitudinal sections (L-Sections) of irrigation channels in the area. L-sections not only have information about the slope and cross-section of the channels, but also have elevation information for the canal bed and canal banks. However, the L-sections don’t provide information about the latitude and longitude of the canal sections. The geocoded ASTER scene, which is used as the reference image in this study, was used to assign the latitude and longitude to these canal off-takes. Elevation values from these three sources-the DGPS generated elevation values, the Indian datum values and the SRTM DEM values for the above mentioned canal off-takes sites were compared to find the relative shift between these sources of elevation information (Table 4.3)

Table 4.3 Comparision of elevation information obtained from DGPS, Indian Datum, and SRTM DEM for channel off-take points

Site	DGPS ID	Coordinates	DGPS derived elevation (m)	Indian datum elevation (m)	Relative shift (DGPS vs Indian datum) (m)	SRTM elevation (m)	Relative shift (Indian Datum vs SRTM) (m)
RD961 IGMC	CANAL 002_1327537	27 53 21.279682 N 72 23 3.114068 E	122.15	169.08	46.93	166	3.08
RD957 IGMC	CANAL 0021_2111264	27 53 43.885347 N 72 23 34.000620 E	123.34	169.2	45.86	168	1.2
RD14 CWB	CANAL 0031_1753460	27 53 43.795334 N 72 20 36.572220 E	119.24	166.2	46.96	169	-2.8
RD25 CWB	SITE 0049_1803288	27 53 56.915400 N 72 18 59.661660 E	119.51	165.7	46.19	166	-0.3
Average Shift				46.49			

It is observed from above table that there is a relative shift ranging between 45.86m to 46.96m (positive only) between the DGPS values and the Indian datum values. All the fourofftake sites are within 10 km from the base station. The accuracy of differential processing of data using code only measurements is reported between 3 to 12 meters horizontally and vertically at 95% probability, a significant improvement considering that the single point code measurement’s vertical accuracy is

156m at the same probability (Geomatica, 1992; Lachapelle et al., 1991). The relative accuracy achieved in relation to the above four points is good as the shift is consistent. The Indian datum elevation values have a rather good fit with the SRTM DEM (though at 90 m spatial resolution); the difference between two range between –2.8 to 3.08 m. However, when the SRTM DEM altitude was plotted against canal bank sections for lagre number of points, it showed undulations ranging between 10 m above the canal banks to 10 m below the canal banks (See Chapter 5).

The average difference of 46.49 between the DGPS values and Indian Datum values was added to all the DGPS data record so as to make the water table, soil depth and other data layer relatively more compatible to the SRTM DEM; although, it is a risky to do so without the datum conversion parameters. However, if the DGPS data was used as it is, the water table would have been below the barrier layer.

The piezometers were assigned shift corrected elevation (WGS84 datum) and location values collected by differential GPS. The depth to groundwater, as provided by CADA, was subtracted from the piezometer elevation values to determine watertable elevations at different piezometer sites (Table 4.4.)The resulting values were interpolated using inverse distance moving surface method to create the watertable layer (Figure 4.2).

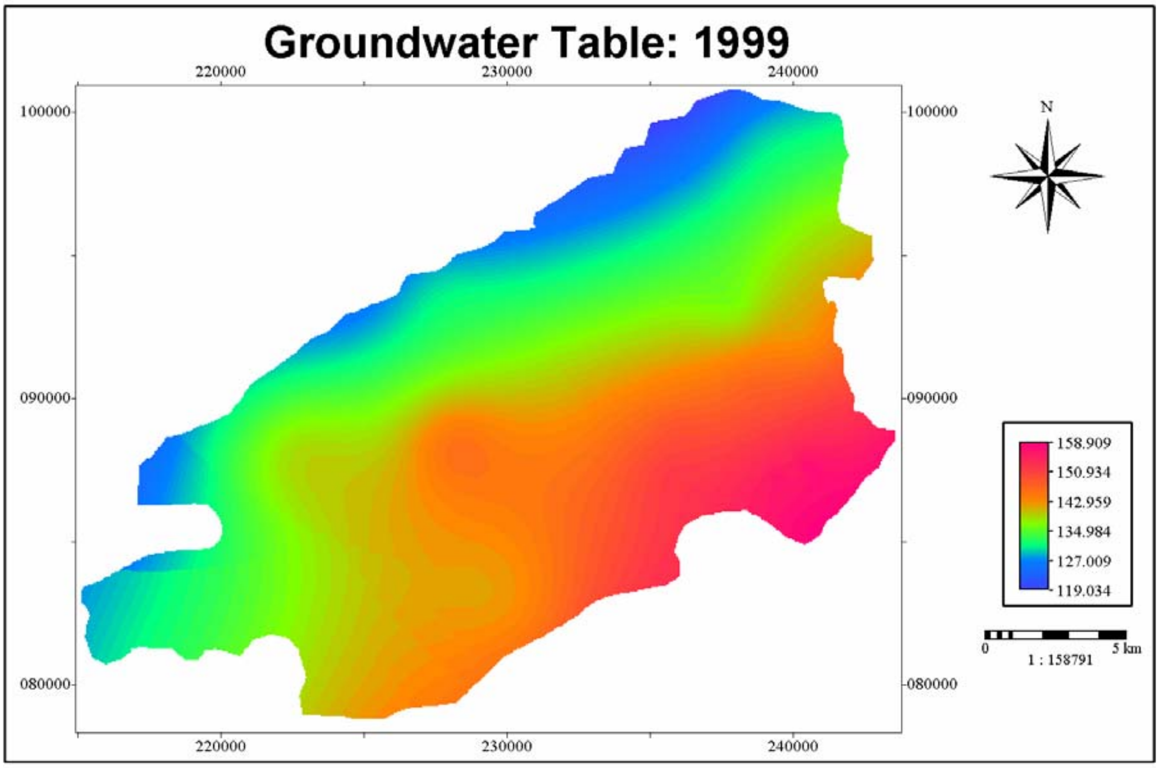


Figure 4.2 Groundwater table map (elevation in meters above MSL) for the Upper Charanwala System during pre-monsoon period of 1999-2200

Table 4.4 Depth to groundwater table and watertable elevations at different piezometers locations during pre monsoon period of 1999, 2000, and 2006

S.No	Point_id	Coordinate	Elevation	GwtDepth	GwtDept	GwtDepth	Watertable	Watertable	Watertable

				1999 (m)	2000 (m)	2006 (m)	1999 (m)	2000 (m)	2006(m)
1	**C_923RD_IGMC**	(250951,3095672)	163.49	5.4	5.3	5.4	158.09	158.19	158.09
2	**C_940RD_IGMC**	(247219,3092126)	162.81	5	5.1	5	157.81	157.71	157.81
3	**C_957RD_IGMC**	(243377,3088373)	162.39	5.6	5.7	5.6	156.79	156.69	156.79
4	**C_961RD_IGMC**	(242494,3087639)	162.29	5.5	5.7	5.5	156.79	156.59	156.79
5	**C_980RD_IGMC**	(238833,3083463)	161.82	5.6	5.7	5.6	156.22	156.12	156.22
6	**W_995RD_IGMC**	(237609,3081298)	164	8	7.5	12	156	156.5	152
7	**C_995RD_IGMC**	(235492,3080746)	161.45	4.8	4.9	4.8	156.65	156.55	156.65
8	**W_BAAJU_MINOR**	(251527,3093052)	158.9	14.3	14.8	15	144.6	144.1	143.9
9	**P_4BJM**	(249573,3093726)	159.1	7.87	7.97	13.1	151.23	151.13	146
10	**P_MITH_TAIL**	(247013,3089260)	158	6	5.8	14.3	152	152.2	143.7
11	**32RD_KHARA_DS**	(230362,3082931)	153.2	10.45	9.95	8.6	142.75	143.25	144.6
12	**P_62RD_KHARA_DS**	(219119,3081370)	148.86	15.72	14.89	14.5	133.14	133.97	134.36
13	**P_69RD_CWB**	(222895,3088541)	148.96	10.6	9.2	7.9	138.36	139.76	141.06
14	**P_51RD_CWB**	(228245,3088617)	147.86	2.75	2.5	3.5	145.11	145.36	144.36
15	**P_6RD_PSD**	(238447,3090164)	153.66	6	5.64	6.1	147.66	148.02	147.56
16	**P_16RD_PSD**	(237995,3093002)	151.56	14.2	12.35	10	137.36	139.21	141.56
17	**P_3PSD_CHK**	(240457,3091975)	152.46	9.55	8.95	7.8	142.91	143.51	144.66
18	**P_20PSD_CHK**	(227874,3093790)	150.36	19.85	18.95	16.9	130.51	131.41	133.46
19	**P_13RD_PSM_I**	(224523,3092941)	149.06	22.68	22.45	22	126.38	126.61	127.06
20	**P_3KM_BK_RNG**	(217584,3099956)	137.16	32.6	32.58	29.6	104.56	104.58	107.56
21	**P_19GMR_CHK**	(229910,3099951)	141.86	27.8	26.1	24.2	114.06	115.76	117.66
22	**P1_LADHURAM**	(240465,3087716)	159.46	2.54	2.4	5.5	156.92	157.06	153.96
23	**P_42GODUMINOR**	(234589,3102121)	142.76	33.1	31.25	27.7	109.66	111.51	115.06
24	**P_25RD_CWB**	(235916,3088683)	156.36	6.9	6.65	7.2	149.46	149.71	149.16
25	**P_23RD_GODU**	(239255,3098952)	148.66	18.35	16.76	14.1	130.31	131.9	134.56
26	**P_4GMR_CHK**	(240289,3096556)	149.46	13.3	12.72	10.8	136.16	136.74	138.66
27	**P4_PRATAPRAM**	(240066,3087355)	157.06	1.7	1.6	2.9	155.36	155.46	154.16
28	**P22_TAKTHARAM**	(238257,3087344)	156.46	2.9	2.65	2.4	153.56	153.81	154.06
29	**P19_BHIANRAM**	(239416,3087345)	164.86	8.98	8.6	9.5	155.88	156.26	155.36
30	**W_5CWB_CHK**	(235767,3087710)	152.06	0.9	0.6	1.5	151.16	151.46	150.56
31	**P16_MEGHARAM**	(240523,3086055)	158.66	0.9	0.7	1.9	157.76	157.96	156.76

Source: CADA, field information

4.2.4. Soil Depth Layer

The calculations for the changes in the groundwater levels, in the model, are made in reference to an initial water table perched above sub-surface barrier layer.. This layer was created from 'Depth Barrier map' of IGNP Stage-II (provided by the IGNP authorities) SRTM DEM, and DGPS measurements using the following procedude.

The 'Depth to Hardpan/barrier' analog map was prepared by the Groundwater Wing of CADA from information extracted from geophysical surveys of the IGNP Stage–II (as described in section 3.5). This map was scanned, and registered to ASTER image of the area. The depth contours for the Charanwala System area were screen digitized. These contours were interpolated to obtain a raster map (50 m pixel size) showing the depth to barrier layer (Figure 4.3).

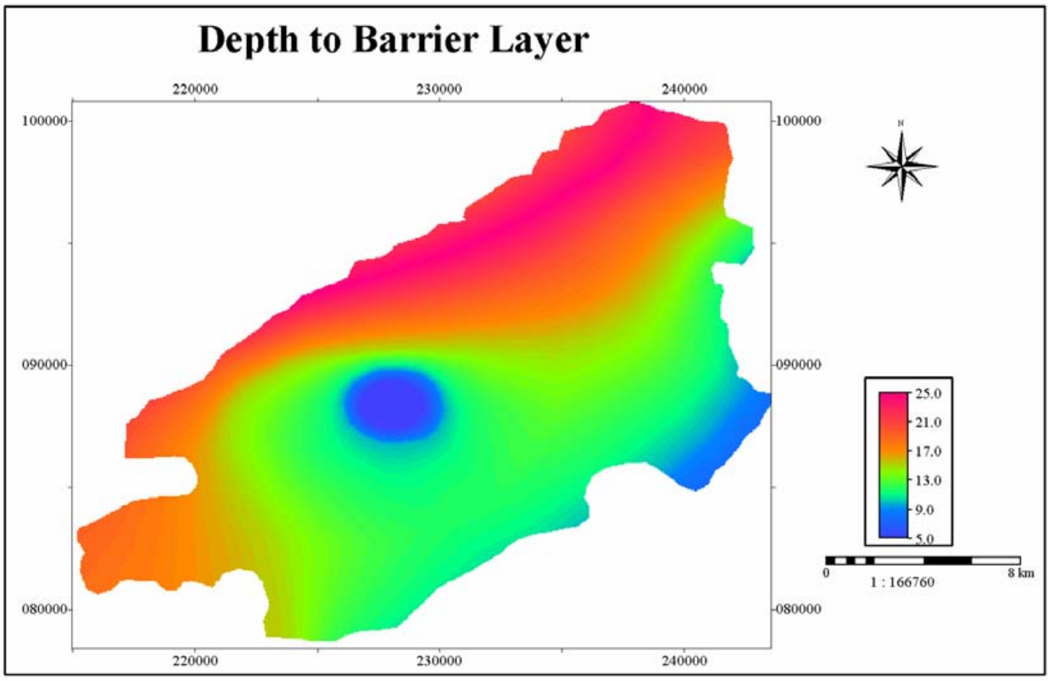


Figure 4.3 Depth to barrier layer (in meters below ground).

Source: CADA (1995)

However, the map was not useful in its original form, because when the geophysical surveys were carried out to ascertain the depth to barrier, the high elevation areas, i.e. sand dunes, which couldn't be brought under irrigation, were completely ignored as the mandate of the survey was to collect the information relevant for assessment of threat of waterlogging to the irrigated areas. In simple words, the depth barrier layer is determined from a hypothetical surface, which, laterally cuts through the base of high dunes, i.e. ignoring the surface topography.

To get around this problem, it is required that the depth to the barrier be determined in terms of the WGS84 datum and then, that layer be subtracted from the DEM. To do that the piezometer elevation were interpolated using inverse distance moving surface method and a hypothetical surface 'Initial Reference Surface'(Figure 4.4) was created.

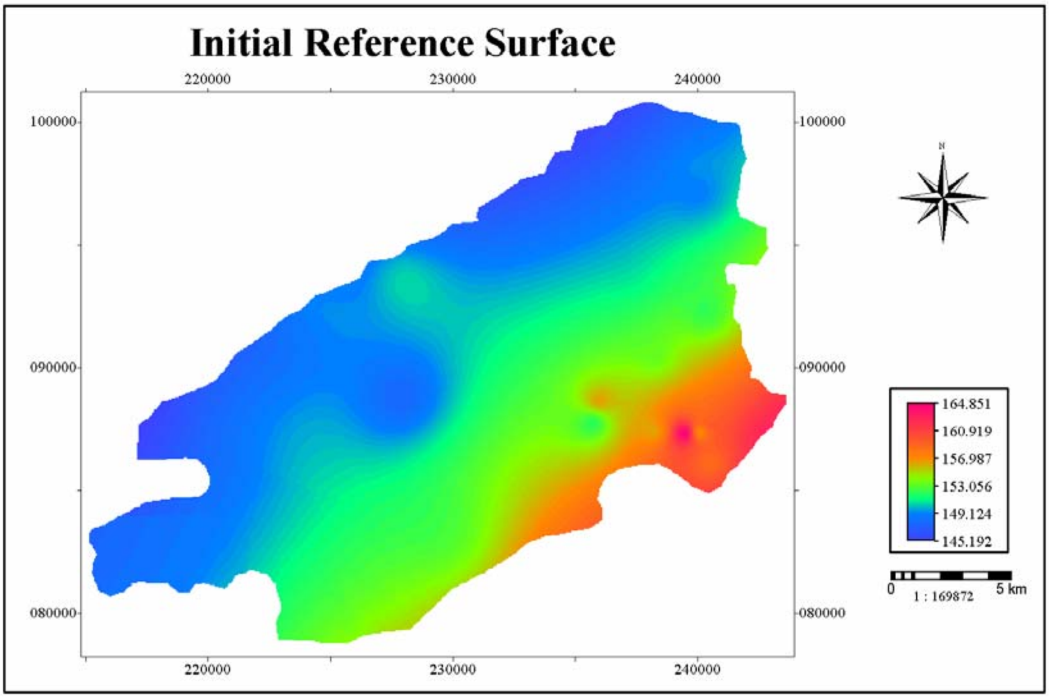


Figure 4.4 Hypothetical initial reference surface created using piezometer elevations.

The DEM and 'Initial Reference Surface' are not similar, DEM being higher in the dunal tracts and lower in the depressions. Another layer 'Final Reference Surface' was created (Figure 4.5). This layer retained the 'Initial Reference Surface' in the dunal areas (i.e. wherever the DEM was higher) while in the low lying depressions (where DEM was lower) the 'Initial Reference Surface' was replaced by the DEM. From this layer the original 'Depth to Barrier Layer' (Figure 4.6) was subtracted resulting in layer 'Barrier Elevation' (Figure 4.7).

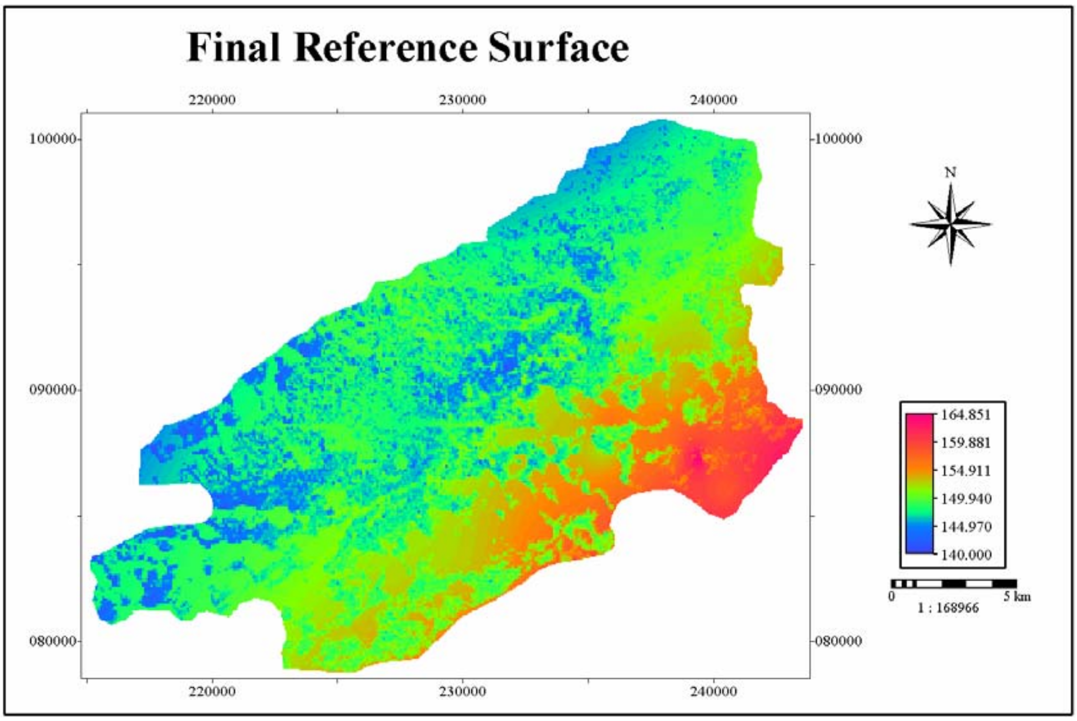


Figure 4.5 Final hypothetical reference surface.

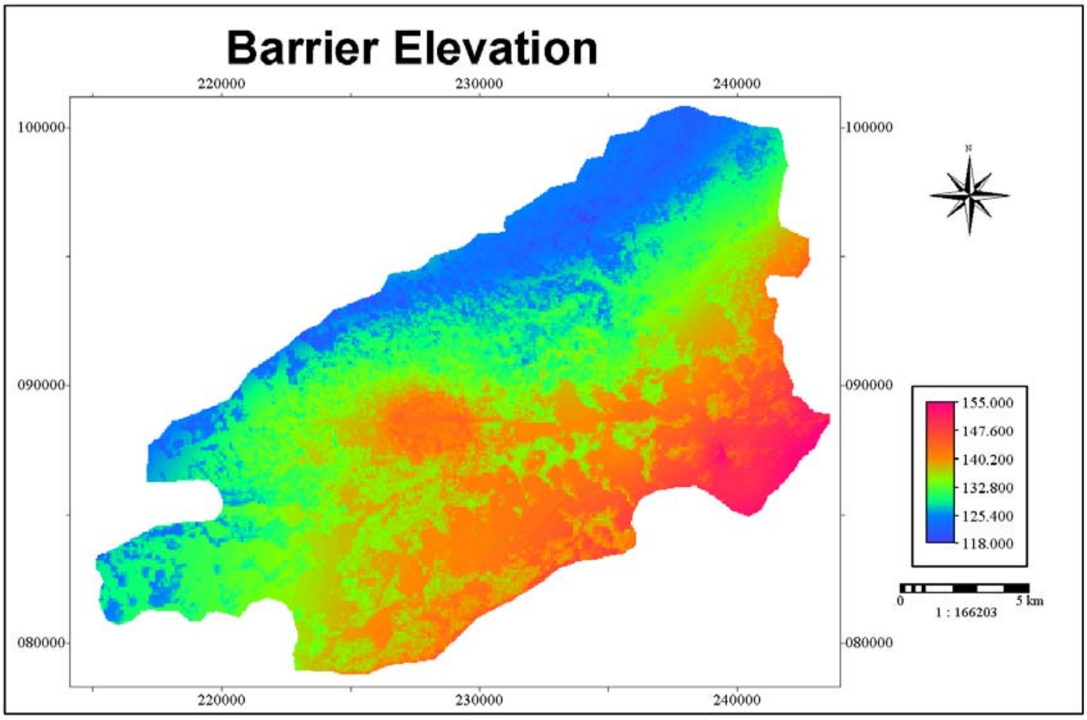


Figure 4.6 Map showing barrier layer elevations (in meters above MSL, WGS84 datum)

Information layer Soil depth was obtained (Figure 4.7) by subtracting the 'Barrier Elevation' (Figure 4.6) from the SRTM DEM.

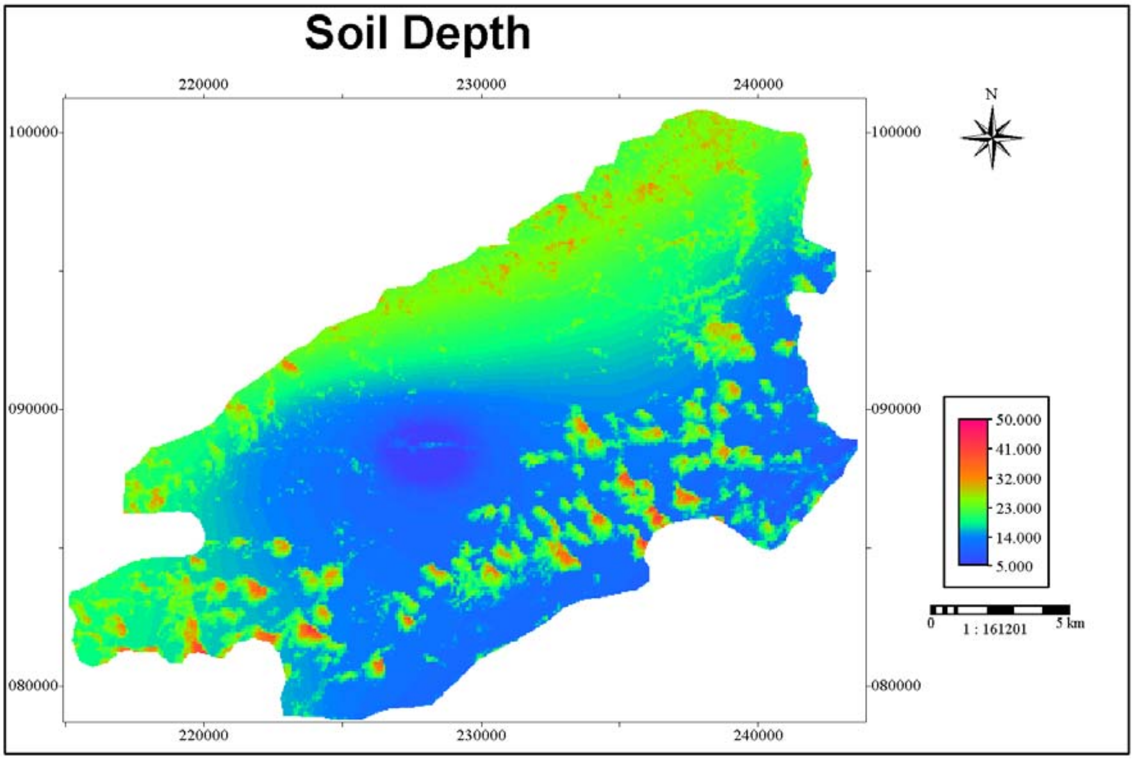


Figure 4.7 Map showing soil depth (in meters below ground level).

4.2.5. Initial groundwater level

The 'Initial Groundwater Level', represents the thickness of groundwater in meters above the barrier layer. It was derived (Figure 4.8) by subtracting the layer 'Barrier Elevation' from the layer 'Groundwater Table: 99'.

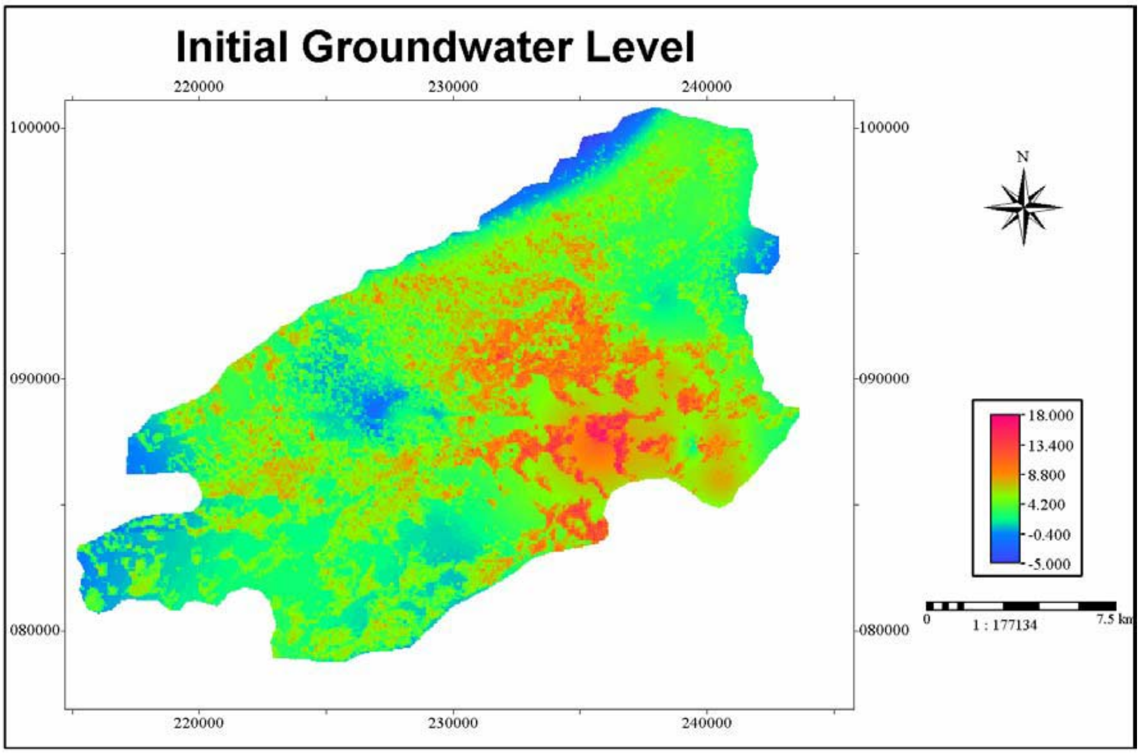


Figure 4.8 Map showing initial groundwater level in meters above the barrier layer.

Considering the fact that, the Barrier layer is based on a survey with one observation every 1 km2, (see section 3.5) and the inaccuracy in the SRTM DEM, this layer is could be erroneous. This may result in groundwater moving towards the 'artificial depressions' created due to above procedure.

4.2.6. Irrigation channels and their wetted perimeters

The wetted perimeter of the irrigation channels is required to specify the leakage from the channels. The wetted perimeter for each channel in the study area, but for the exception of the IG Main canal, decreases downstream. The following procedure was adopted to prepare the required model layer.

The irrigation channels- IG main canal, Charanwala Branch, Phulasar Distributary, Khara Distributary, Godu Minor, and Naryansar Minor- were screen digitized as separate channel maps using ASTER image of 14th December 2005. Each segment map was converted to a point map, with points stored at every 5 meters. These maps were opened as tables and distance from the off-take (i.e. head to the tail) were read for each point coordinate using the following command:

Distance = (%R-1) * 5

Where, %R is a predefined variable in ILWIS and refers to these record index of the coordinates of point map (ITC, 2002). The formula results in distances in meters from the channel off-take. The wetted perimeter of the channels was calculated from canal cross-section parameters- bed width, side slope and full supply depthobtained from the Longitudinal section of the irrigational channels (source: personal communication, Chief Draftsman, IGNP, 2006). The wetted perimeter information was added as an attribute to each of the record index in the table and point maps were created using wetted perimeter attribute. These point maps were rasterized and resampled to 50-meter cell size, and finally glued together into one map showing channels with their weyyed perimeters in meters (Figure 4.9).

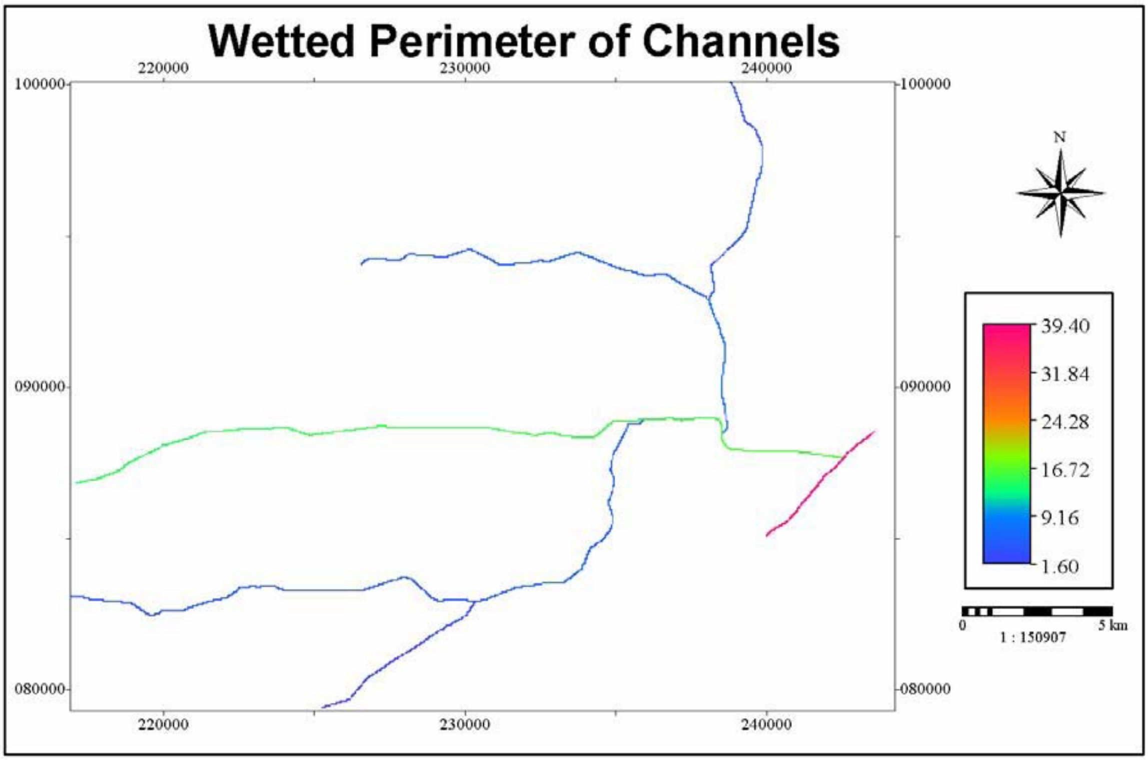


Figure 4.9 Map showing irrigation channels with wetted perimeters (in meters).

4.2.7. Land cover

The land cover map was needed to know the spatial distribution of different covers in the area and also to test the feasibility of upscaling the soil hydrological.

ASTER (on-board TERA satellite) scene 'AST3A1_0512140554100624623' captured on 14th December 2005 was used for the preparation of land cover map using supervised image classification technique- maximum likelihood classifier. The ASTER scene was chosen for the preparation of the base land cover map as the high spatial resolution of 15 meters helps to reduce the area covered by mixed pixels/circumvent the mixed pixels which is often the case in arid regions (Collado et al., 2002).

The important land cover units in the study area are:

1. Agriculture: Both under 'crop' and 'fallow'
2. Plantation: Afforestation along the Irrigation Channels,
3. Sand Dunes: Bare Sand Dunes,
4. Pasture: Pastures (sand dunes dotted with shrubs),
5. Canal: Irrigation Network.

Training set was prepared on the basis of ground truth collected during the fieldwork and knowledge of study area for the following classes:
'Plantation', 'Pasture'. 'Sand dune', 'Fallow', and 'Crop'

The feature space occupied by different land cover units is shown in Figure 4.10.
The class 'agriculture' posed a problem, as the fieldwork was conducted in July-August and the image being classified was of December. In December, the agricultural plots are either under fallow after the 'Kharif' harvest of late October–November or the 'Rabi' (winter) Crop is under the 'establishment' or 'initial development' phase. However, this provided the opportunity for extraction of the land cover unit 'Plantation' with ease, as it can be assumed that healthy green vegetation with more then 50% of the ground cover fraction in December belongs to the class 'Plantation'.

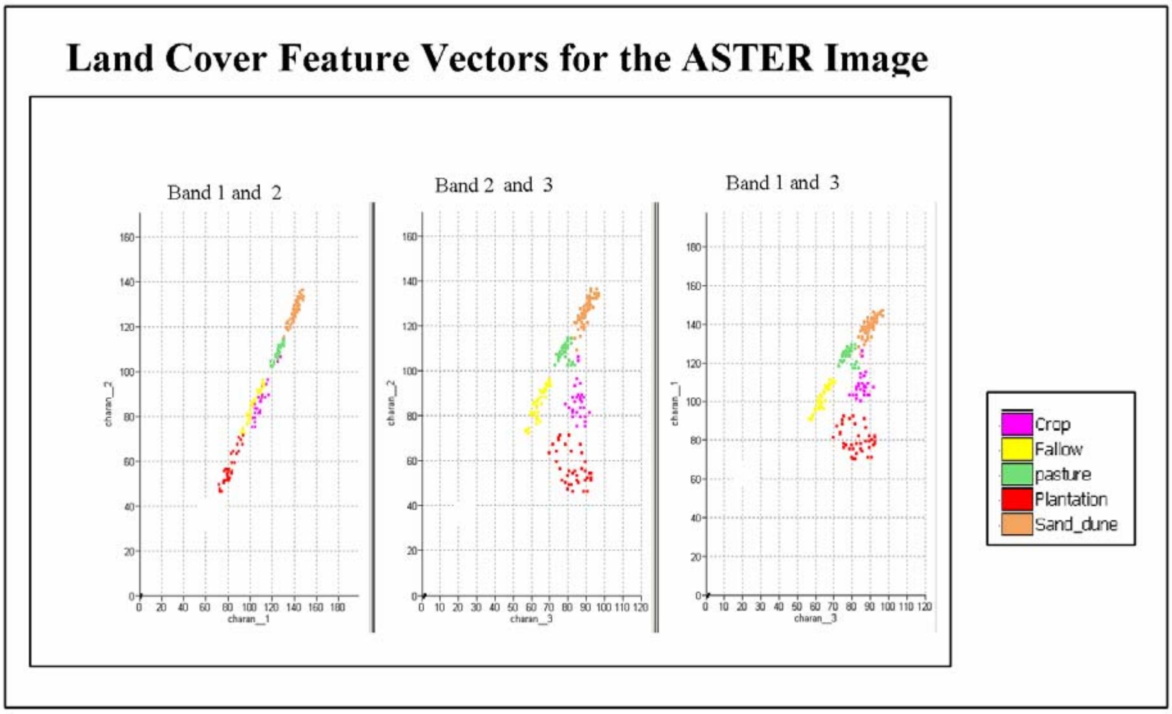


Figure 4.10 Feature space occupied by different land cover classes.

The classified land cover map of Upper Charanwala is shown in Figure 4.11, and land cover statistics is given in Table 4.5. Both 'Fallow' and 'Crop' were classified as separate classes and later merged as the class 'Agriculture'. The feature vectors of irrigation channels (width between 4-10 m apart from the IGMC (width above 20 m) mixes with the classes 'Fallow' and 'Pasture' and thus, couldn't be accurately classified. Hence, the network was extracted by on screen visual interpretation and overlaid on the classified image.

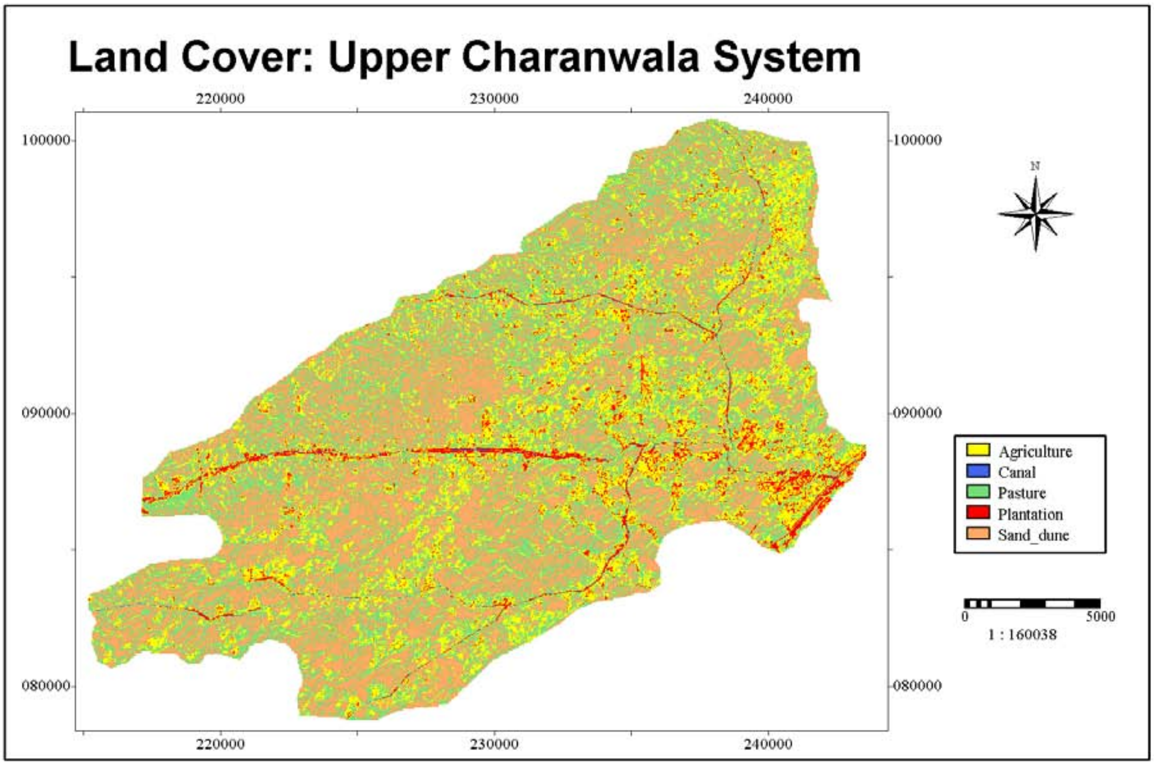


Figure 4.11 Classified land cover map of the Upper Charanwala System

Table 4.5 land cover statistics of Upper Charanwala System

Landcover class	No of pixels	Percentage Area	Area (ha)
Agriculture	279504	18.96	6288.8
Canal	5445	0.37	122.5
Pasture	502750	34.11	11311.8
Plantation	63215	4.29	1422.3
Sand dune	623069	42.27	14019.0

The accuracy of classification was tested on the basis of ground truth collected during the fieldwork, using confusion matrix (Table 4.5)

Table 4.6 Confusion matrix of classified land cover

	Agriculture	Pasture	Plantation	Sand Dune	Accuracy
Agriculture	59	4	12	0	0.79
Pasture	27	45	1	8	0.56
Plantation	4	0	56	1	0.92
Sand dune	2	9	0	50	0.82
Reliability	0.64	0.78	0.81	0.85	

Average Accuracy = 77.00 %
Average Reliability = 76.91 %
Overall Accuracy = 75.54 %

The class 'plantation' was extracted more accurately with only 4 ground truth pixels of 'plantation' were excluded from class 'Plantation', and were misclassified under the the class 'Agriculture'. For the, class 'Plantation' accuracy is 0.92 and reliability is 0.81. The two classes 'Agriculture' and 'Pasture' were misclassified into each other. Their producer's accuracy was 0.79 and 0.56, while the user's accuracy/reliability was 0.64 and 0.78. The possible reason is that the spectral signature of fallow agricultural fields and pastures are close to each other in the feature space. The pastures essentially are, dunes dotted with shrubs, which cover 10% to 25% of the ground. The class 'agriculture/, especially fallow fields, mix with pasture as the shrubs are green only for a brief period after the rainy season in August and September.

4.2.8. Crop Area Statistics

The information about area the quantum of agricultural area under different crops (referred as 'Landuse' layer in model is required to:

- Estimate the distribution of irrigation inflows,
- Estimate crop fractions for calculation of interception and ET, and
- Estimate the groundwater recharge zone in different seasons..

NDVI thresholds were used to decide upon the area under crops. The thresholds were arrived upon the basis of the agricultural statistics of the Charanwala system for the agricultural years 1999-2000 and 2000-2001(summer and winter saperately) as obtained from the CADA (Table 4.7). The available statistics was consolidated information for the entire Charanwala system. The agricultural areas served by the canals are part of different revenue tehsils (districts) and it was not possible to disaggregate the data on channel by channel basis with the available time. On the suggestion of the CADA authorities (personal communication, M.L.Godara, Asst. Director Agriculture Extension, CADA, 2006) it was assumed that the Upper Charanwala area's contribution to the total area under crops in the entire Charanwala System is about 25% -30%. the crop area statistics for the agricultural year 1999-2000 is given in the table below

Table 4.7 Crop area statistics for agricultural years 1999-2000 and 2000-2001 for entire Charanwala System

	Cluster bean	Groundnut	Cotton	Wheat	Gram	Mustard	Fodder	Total
1999-2000(summer)	16122	660	112	0	0	0	406	17300
1999-2000(winter)	0	0	0	5808	9153	4597	1109	20567
2000-2001(summer)	12615	134	21	0	0	0	894	13664
2000-2001(winter)	0	0	0	2198	5826	426	385	8835

Table 4.8 Assumed area under crops statistics for agricultural years 1999-2000 and 2000-2001 for the Upper Charanwala System

Year/ crop	Total Area Under Crop in Charanwala System	Assumed Share of Upper Charanwala System (30%)
1999-2000(summer)	17300	5190
1999-2000(winter)	20567	6170.1
2000-2001(summer)	13664	4099.2
2000-2001(winter)	8835	2650.5

Since, most of farmers of the Charanwala System Command area have more than one crop in the same field at the same time, multi-crop maps can't be generated without extensive 'ground-truth' collection, i.e. field information coinciding with the growth cycle of the crops grown. In the present study, summer crop and winter crop maps were generated by combining-

- Information extracted from satellite based NDVI values for summer and the winter seasons,
- Land cover map (Figure 4.13) to mask out the Plantations and Canals, and
- Crop area statistics supplied by IGNP authorities to draw broad comparison of the crop area extracted from imagery and actual cultivated area.

IRS LISS-III(spatial resolution 23.5 m) images of 14thSeptember99, and 11th February2000 were used to quantify the cropped area in Kharif(summer) and Rabi(winter) seasons. The images were registered by image-to-image registration to with ASTER image. The RMS of registration 'sigma' was 0.25 for the September image and 0.24 for the February image. NDVI indexes were generated for both the scenes (Figure 4.12 and 4.13) and the pixels with NDVI value of 0 and above for February 2000 image and –0.04 and above for the September 1999 image were assumed to represent the ground covered by vegetation. From these pixels the area under class 'Plantation' and 'Canal' as determined by the classification of ASTER imagery was masked out, and the remaining area represented the area under the 'summer' and 'winter' crop on respective images.

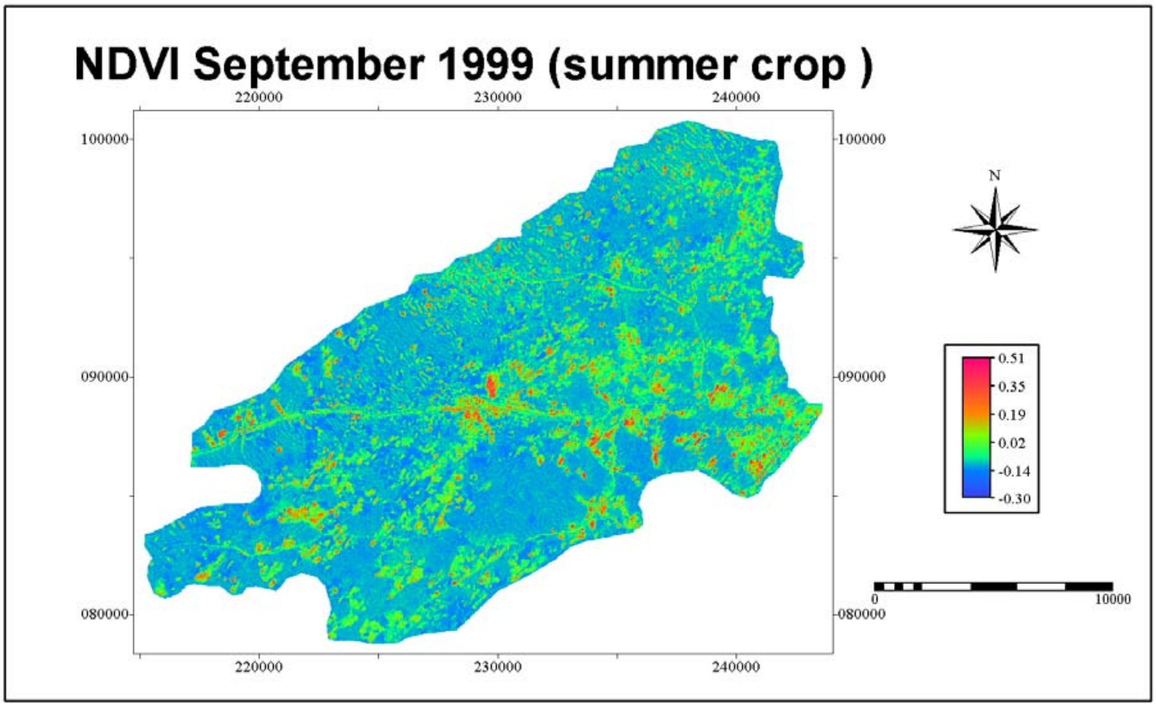


Figure 4.12 NDVI image of Kharif (summer season) of the Upper Charanwala System.

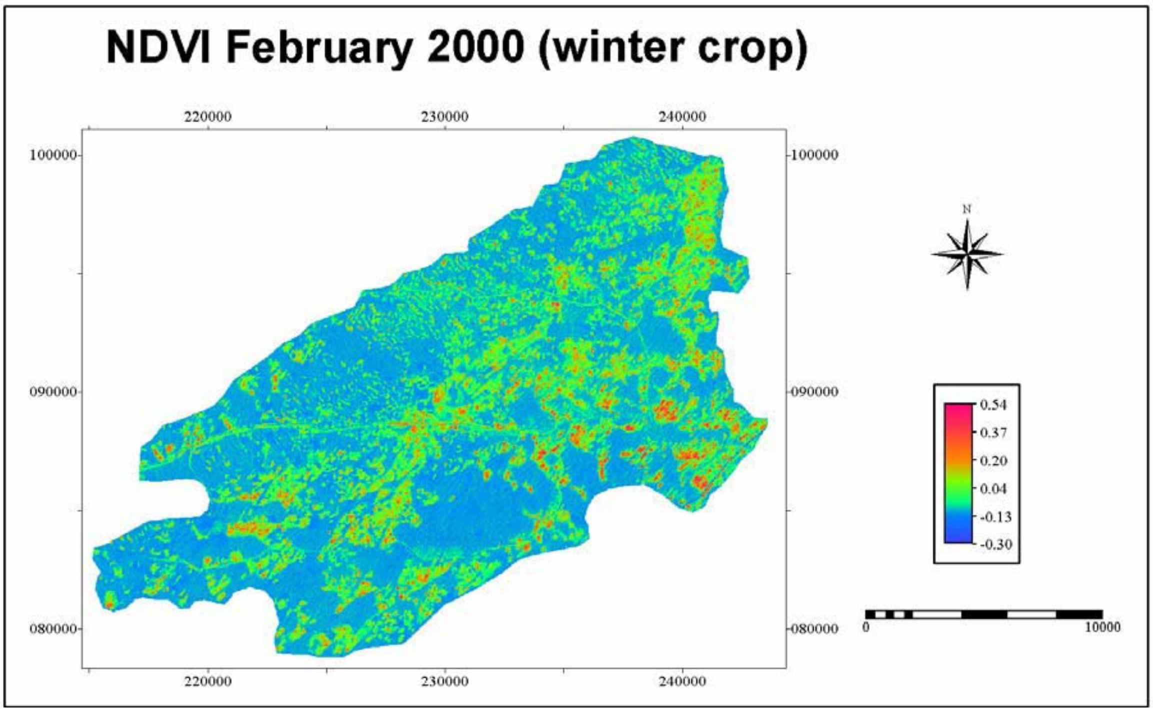


Figure 4.13 NDVI image of RABI (winter season) of the Upper Charanwala System.

The ‘winter’ and ‘summer’ crop maps were combined and a single crop map termed as landuse map in the model was prepared (Table 4.9). The following codes were assigned to the crop categories:

0: Area under no crop,
1: Area under crops in both winter and summer season.

2: Area under crops in the summer season.
3: Area under crops in the winter season.

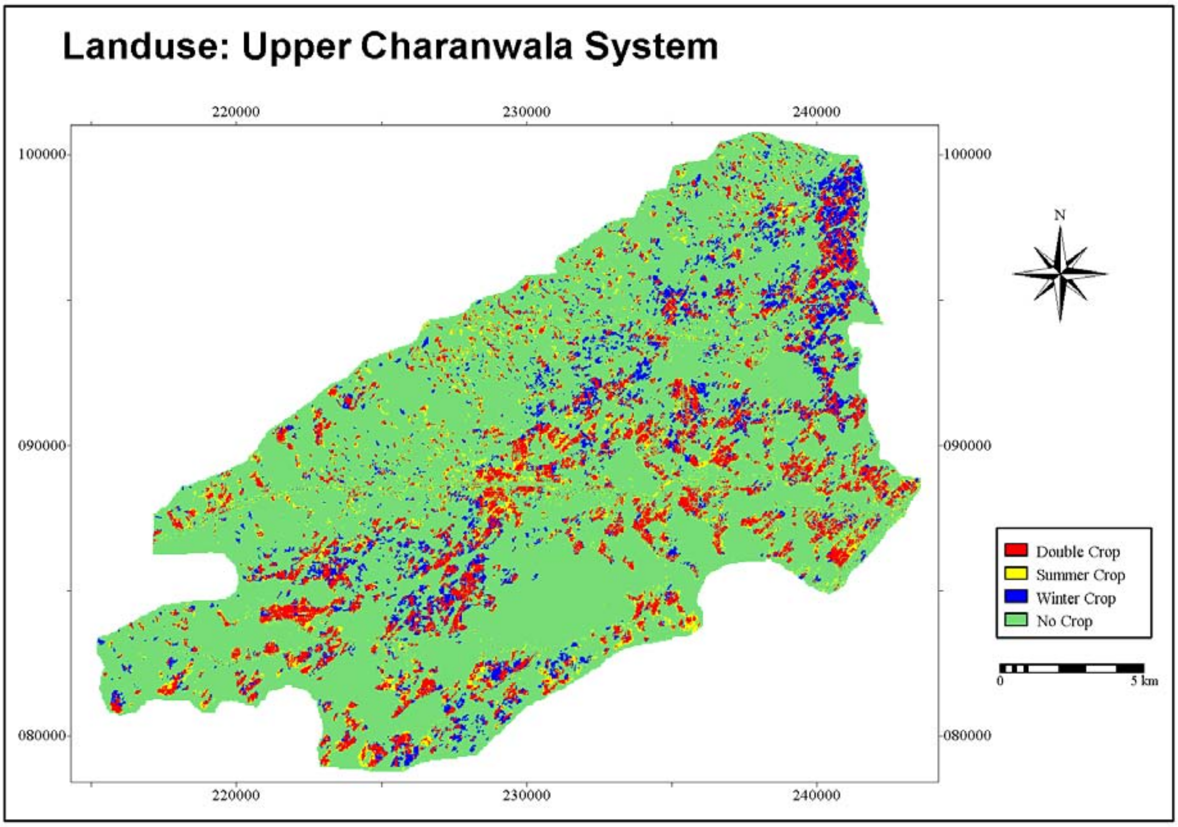


Figure 4.14 Crop map showing area under crops during the agriculture year 1999-2000.

Table 4.9 Crop area statistics derived from satellite images- Upper Charanwala System

Crop Category	No of pixels (Resolution 23.5 m)	Pixel percentage	Area (ha)
No Crop	465645	77.54	25715.24
Double Crop (area under crop both in Rabi and Kharif season)	63998	10.66	3534.28
Kharif/Summer only Crop (area under crop only inKharif season)	28708	4.78	1585.39
Rabi/ Winter only (area under crop in Rabi season only	42203	7.03	2330.66

The cropped area as extracted from satellite imagery in the Upper Charanwala System is about 28% of the total cropped area of Charanwala system in the agricultural year 1999-2000. It uses about 30% to 35% of the inflows on account of its location in the head reaches (personal communication, Sahu, 2006).

4.2.9. Reference Evapotranspiration/ Potential Evapotranspirtion (ET_{ref} /ET_p)

Reference Evapotranspiration/ Potential Evapotranspirtion (ET_{ref} /ET_p) is the maximum possible evaporation of a reference crop (usually clipped grass) according to prevailing atmospheric conditions and constant bio-physical properties. The reference crop has a horizontally homogenous coverage, is optimally supplied by soil moisture and free from disease. ET_{crop} is the sum of transpiration by the crop and evaporation from the soil surface. Just after sowing and during the early growing period, when ground cover by plant foliage is less, evaporation from the soil surface, ET_{soil}, may be considerable. During full ground cover, ET_{soil} is negligible.

Following methods have been developed for estimation of ET_{ref} /ET_p:
Blaeny-Criddle,
Radiation,
Pennman Monteith,
Pan-evaporation.

The choice of the method is based on the type of meteorological data available and on the accuracy needed in determining the water requirements. ET_{ref} /ET_p for present study was calculated using the modified Pennman-Monteith standard equations (Allen et al., 1998; Doorenbos and Pruitt, 1977; Gieske, 2003). The computation was made using the daily values of the following meteorological parameters:

- Temperature- minimum and maximum,
- Precipitation,
- Average relative humidity,
- Sunshine hours, and
- Average wind velocity.

There is no weather station in the study area. Automatic weather stations were installed at three stations; Suratgarh in Sriganganagar district, Bikampur in Bikaner District and Ramgarh in Jaiselmer district in IGNP command in the year 2000. The data for these stations was acquired from State Irrigation Ministry; unfortunately many of the data files were corrupt, as the stations were not maintained. These stations stopped functioning altogether after 2002. The nearest weather stations maintained by the India Meteorological Department (IMD) are at Bikaner 118 km from study araae and Jaiselmer 176 km from the study area. Meteorological data for these stations was obtained from the IMD for the period 1st April 1999 to 31 March 2000. The values of ET_{ref} /ET_P for these two station were linearly interpolated for the point 25RDCWB, a centrally located place in u\Upper Charanwala area. Rainfall data were available for 5 stations. Daily average estimates were made taking into account these stations. The total ET_{ref} /ET_p for the year 1999-2000 is 2246.1 mm and precipitation is 207.52 mm. The ET_p and precipitation data were inputed as timeseries in the model.

4.2.10. Plant cover fraction:

The 'plant cover fraction' is used in for calculation of the interception and evapotranspiration in the model. The crop fraction varies, between 0 and 1. The ground covered by crops /vegetation depend on the natural or managed phenological cycle of the vegetation under consideration and varies significantly not only spatially (from one region to another), but also on the current meteorological condition (Jensen, 2003). The crop fractions for the study area were arrived at using the rule of thumb that less then 10% ground is covered in the establishment phase. The coverage sharply increases to

50% during the initial development phase, then further rises to 100% by the maturity and remains so till the harvest.

Table 4.10 Cropping calander of Charanwala System.

Indian name	Latin name	Standard sowing date	Crop duration	Establis-ment	Early season	Mid season	Maturity
Cluster Bean	*Cyamopsis tetragonoloba*	1 June	125	20	30	45	30
Cotton	*Gossypium arborenm*	1 April	190	30	25	45	90
Kharif Fodder		1 May	150	20	40	30	40
Groundnut	*Arachis hypogea*	5 May	140	35	45	30	30
Wheat	*Triticum aestivum*	11 November	140	25	30	55	30
Chick-Pea	*Cicer arietinum*	15 October	145	25	40	50	40
Mustard	*Brassica juncea*	25 October	145	25	35	50	35
Berseem	*Triticum aestivum*	1 October	180	20	40	30	90

(Source: WAPCOS, 1995)

Information about plant cover growth stages (i.e. phenological cycle of crops) in study area was adopted from WAPCOS(1995) and informal conversation with farmers about the sowing dates and ground covered in different stages of crop growth/months for the dominant crops (WAPCOS, 1995). The dominant crops are the ones having the highest share in the total area under cultivation.

The landuse or crop is linked in the model script to a crop fraction table for the calculation of ET and interception. Since a majority of area under crops overlaps in both seasons, the crop fractions for overlapping area are based on the predominant crop, crop with highest acreage, in the respective season. The crop areas without overlap have crop fraction for the second most important crop in respective season.

4.2.11. Soil Hydrological Parameters

4.2.11.1. Infiltration tests for surface soil saturated hydraulic conductivity

Detailed soil survey of the study area hasn't been carried out. A semi-detailed soil survey of of the flow areas of IGNP Stage II (including the Charanwala Branch) was conducted by the FAO/UNEP (1971), however, the maps couldn't be traced out. In the absence of detailed soil maps, the other option was to conduct infiltration tests and collect soil core samples, for texture analysis in laboratory.

An effort was made to select the sites at fairly distributed locations in the study area. The choice of location of infiltration test sites was limited on account of the following:

- The sandy soils have high infiltration rates; hence, large quantity of water is required to conduct the infiltration tests. The canals are the only source of water in these areas. The areas away from canals are generally inaccessible as the road network also follows the irrigation network.
- The 'cut' sections (the spots where high dunes were leveled to make way for the irrigation channels) of the canals pass through the sand dunes and pastures, hence these land cover units are also accessible close to the channels.
- Since the different Land cover classes occur in close vicinity to each other, at few sites, tests were conducted for all the classes. This not only limited the travel time but also facilitated comparison of the variation in infiltration rates in close by land cover units to observe if the changes in land cover have had any substantial impact on the soil hydrologic properties.
- Samples of agriculture plots are higher in number, as only these plots receive irrigation. Next are the plantations. These two land cover types are imposed over the original land cover consisting of the Dunes/pasture, and indicate the impact changing land use practices over the soil characteristics.

Infiltration tests were conducted at 27 sites in study area. These sites include 10 agricultural plots, 9 forest plantation sites, 4 sand dune sites, and 4 pasture sites (Figure 4.14). A double-ring infiltrometer was used for determining the rate of infiltration into soil. The rings were driven about 10cm into the ground, the tests were conducted as a falling head test, and measurements of the drop in water level were taken at regular intervals until a steady infiltration rate is observed. Infiltration tests lasted for 2 to 4 hours (See chapter 5 for detailed discussion). The infiltration rates measured at point scale were to get saturated hydraulis conductivity (Ksat map) of the study areafor surface soil cunductivity.

Figure 4.15 Ground photograph showing the Infiltration test on a pasture.

4.2.11.2. Soil texture analysis for porosity and sub-surface saturated hydraulic conductivity of sub-soil layer

The porosity, and saturated hydraulic conductivity of sub-soil layers, for which direct measurements couldn't be made, were estimated from soil texture using the 'Soil Water Characreristics' software (Saxton and Rawls, 2005). This model uses soil water characteristic equations based on the available variables of soil texture- sand, silt, clay percentages. Soil core samples for texture analysis were collected at spots close to the infiltration test sites (Figure 4.16). The samples were collected at following depths.

- 10-20 cm,
- 40-50 cm,
- 80-90 cm,
- 120-130 cm,
- 160-170 cm,
- 200-210 cm,and
- 250-260 cm.

Figure 4.16 Ground photograph showing soil sample pits.

Particle size analysis was carried out to determine the soil texture in the laboratory. Soil samples were first passed through 2 mm sieve to separate the gravel (>2mm) and then samples of 50 gram were taken and 200 ml of distill water and 10 mg of Hydrogen Peroxide was added. The samples were heated at 120 degree C temperature for 1.5 hours on hot plate, for the organic matter to evaporate and later were mechanically stirred by a high speed-stirring machine to break apart the soil aggregates. Next, the solution was transfered to the settling cylinder. After about 30-40 seconds, the largest particles in the soil (the sand) settled down from the soil/water mixture on to the bottom of cylinder. The amount of sand was determined using the Bouyoucos hydrometer, which measures the density of the liquid in the cylinder, since, the sand settled down first, the 40 second ,i.e. the Ist reading indicates 'grams of silt and clay in suspension' and the percent sand is determined by subtraction from the total amount of soil used (50g). As the temperature of the liquid increases, the soil particles fall faster then if the liquid was colder. The hydrometer is calibrated at 20^0 C, and 0.4 g/L is added or subtracted for each degree above or below 20^0 C. After 2 hours another observation was carried out to read 'grams of clay in suspension' and the percent clay and was determined by subtraction from the total amount of soil used.

Given the soil texture values derived fro soil-texture analysis; the'Soil Water Characreristics' software calculated the bulk density (g/cm3) and Ksat (mm/hr). The ksat values of the samples below 1 m were adopted for the sub-surface Ksat layer 'Ksat2' which were then upscaled for the study area (see chapter 5 for detailed discussion)

Porosity was estimated from the bulk density values derived above using the equation:

$P = 1 - (Pb / Ps)$ --Equation 4.5

Where P is porosity, Pbis the bulk density and, Ps is Mean Particle Density (2.65 gm/cm3)

4.2.11.3. Hydraulic conductivity of saturated zone

No soil samples could be collected for depths below 2.6 meters as it was not possible to dig furthr meters with the limited time and equipment available. Therefore slug tests were conducted to assess the hydraulic conductivity of the saturated zone (ksat 3). A slug of the radius 2.1 cm and 1.86 m long was introduced in the piezometers (Figure and the readings for the recovery of head were made with a handheld water level indicater. These tests were performed at 12 sites. In the slug tests the most important period is the initial 1/3 time of the recovery of head. 10 out of the 12 tests were over before 2 minutes. The initial 30% recovery was within 1-2 seconds and without an automatic transducer these readings couldn’t be recorded. Only a very general qulatiative impression can be gathered from the results of these tests- Ksat of the soil column above the barrier is high. It was decided not to use the slug test data and Ksat 3 was adopted as an average value of the Ksat2 values, which was later changed during model caliberation.
Since there was no quantitative information was available for the Ksat3, it is assumed that soil profile is similar to the second layer. A general trend observed during the fieldwork was that soils gradually become coarse and sandy with depth below the root zone.

Figure 4.17 Ground photograph showing the slug test

4.2.11.4. Leakage to barrier layer

The barrier layer is defined in relative terms (see section 3.5.1) and the values representing the leakage into the barrier were adopted from the NIH study of the nearby Pokaran and Phalodi lift area (Mishra et al., 1995) . This initial value was also adjusted during model caliberation.

4.2.11.5. Ground water recharge zone

The seasonal changes in the groundwater recharge zone were estimated by the land cove change map derived using IRS LISS III images of 12th May 1999, 14th September 1999, and 11th Feb 2000 (See chapter 5 for detailed discussion).

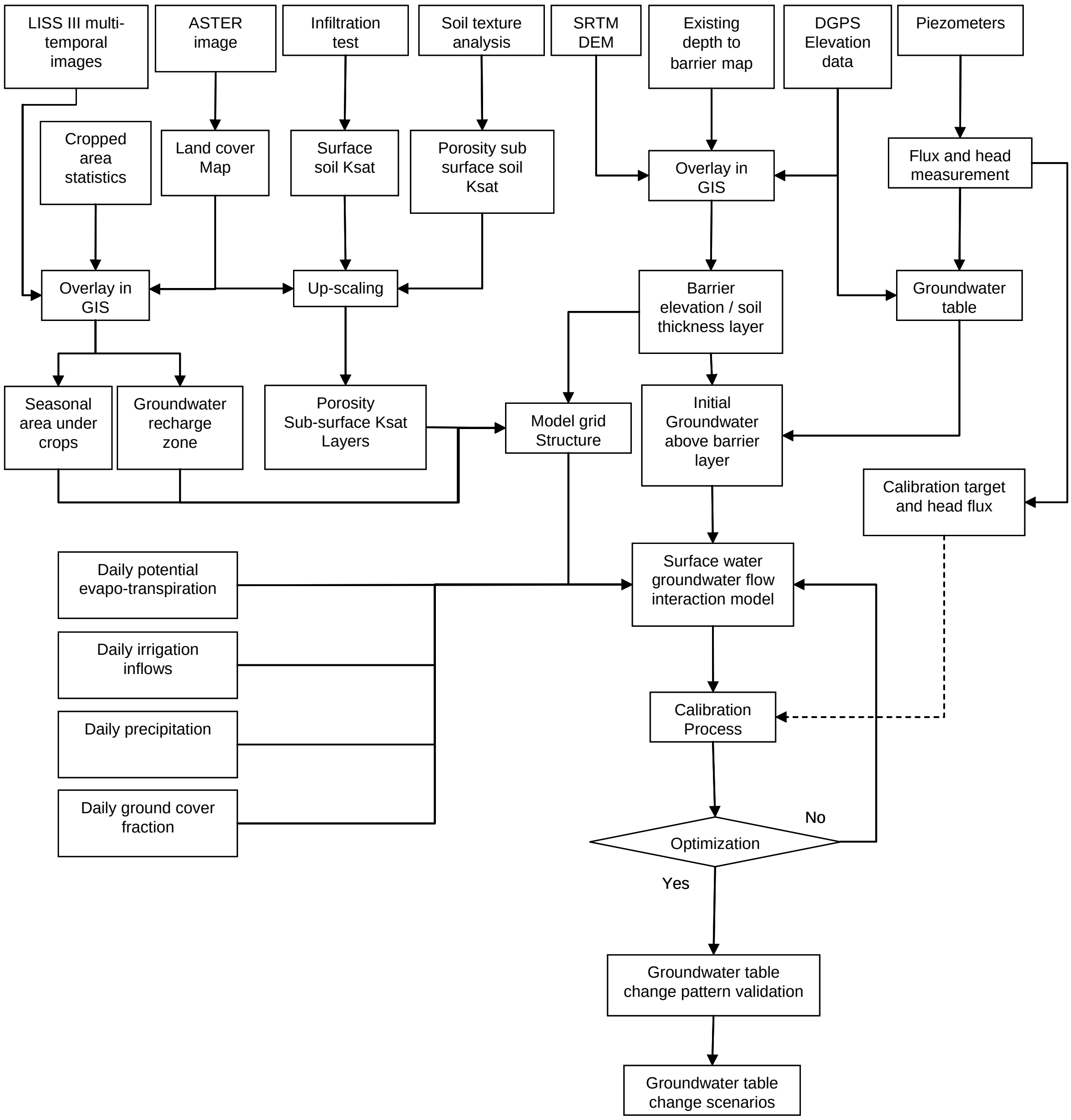
4.3. Choice of the year

Irrigation commenced in Charanwala system in 1983. By the early 1990s some patches in the Upper Chranwala System command- 2CWB chak, 3CWBChak amd 50 RD Charanwala became waterlogged. One of the reasons was excessive irrigation. The system down-stream was being developed and the head reaches were utuilzing all the available water. Reclamation measures in form of Bio-drainage by bulk 'Plantation' along the canals and critical areas, and pumping of ponded waters stabilized the conditions by 1996. Since the year 2000-2001, the inflows have reduced and a lot of abstraction through wells has begun. No data about the abstraction of groundwater has ever been collected. The decline in inflows coupled with the abstraction has resulted in decline in water table the areas close to the off-take of Charanwala Branch, while in the middle and tale reaches, the water table is still rising. To avoid modelling such a complicated situation, especially when groundwater abstraction data are not available, the year 1999-2000 was chosen. Till this year, no abstraction in the system by the wells had commenced.

4.4. Software Used

PCRaster was chosen as the modelling environment. The software is capable of modelling diverse dynamic environmental scenarios and allows the researcher to write or adapt an existing script according to the requirements of the research being undertaken. The preparation of model input layers was carried out in ILWIS 3.3(Integrated Land and Water Information System) GIS with Image Processing capabilities (Integrated Land and Water Information System) developed by the ITC.

Flowchart of methodology



5. Results and Discussion

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5.1. Parameterisation of model domain

5.1.1. Visual Extraction of irrigation network upto sub-minor level from medium resolution satellite imagery

The automatic /digital extraction of the irrigation channels is not possible (see section 4.2.7). Medium resolution satellite imagery of ASTER (spatial resolution 15 m) and IRS LISS-III (spatial resolution 23.m) were used to visually extract the Irrigation network up to minor level. The irrigation network of IGNP is divided into a hierarchy of channels with following width.

Table 5.1 Width of Irrigation channels In IGNP system

Class	Width(m)
Main canal	35
Branches	10-14
Distributary	4-7
Minor and Sub-minor	2-4

5.1.1.1. Irrigation network extraction from ASTER image

It is possible to extract the network up to sub-minor level with the ASTER image (Figure 5.1) with visual interpretation mainly on the basis of knowledge of study area, help of analog maps and interpretation keys of- shape, and association (e.g. plantations close to the irrigation channels). No edge enhancement filter was needed to enhance the images.

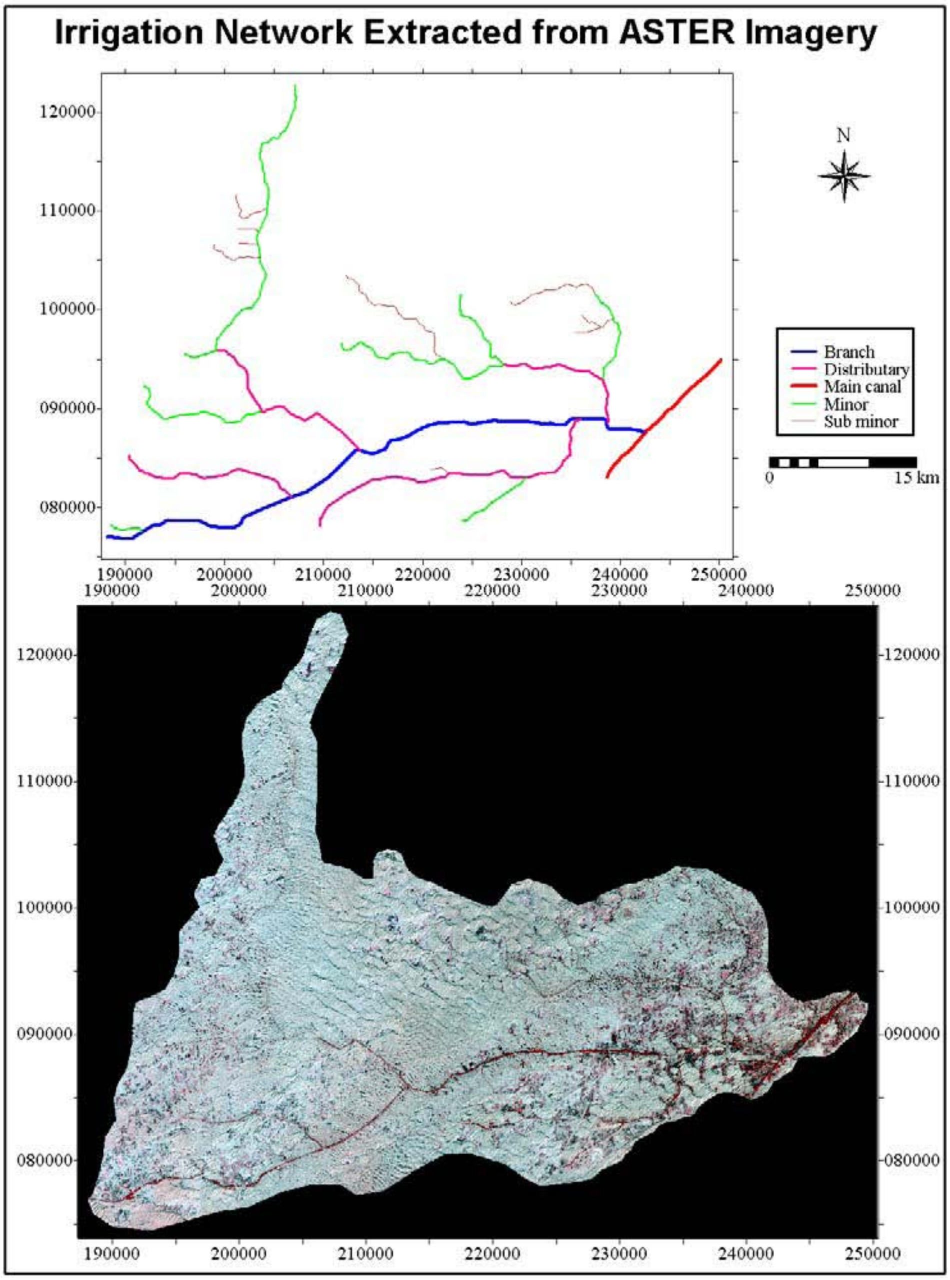

Figure 5.1 Irrigation network extracted from ASTER image

5.1.1.2. Irrigation network extraction from LISS-III image

With IRS LISS-III image it is possible to extract the network up to the 'distributary' and minor level in irrigation channels hierarchy without any edge enhancement procedure. However, in the case of sub-minors, and in some cases even for minors in areas where there is little vegetation cover close to the canals, the channel lines mix with the linear dune chains making the extraction with visual interpretation difficult. A Laplacian high pass filter 'Laplas plus' (Table 5.2), was created and applied to the 4th band of the LISS –III image. It made possible the extraction of the network up to the sub-minor level from the LISS-III imagery.

Table 5.2 Edge enhancement Laplace plus filter

0	-1	0
-1	5	-1
0	-1	0

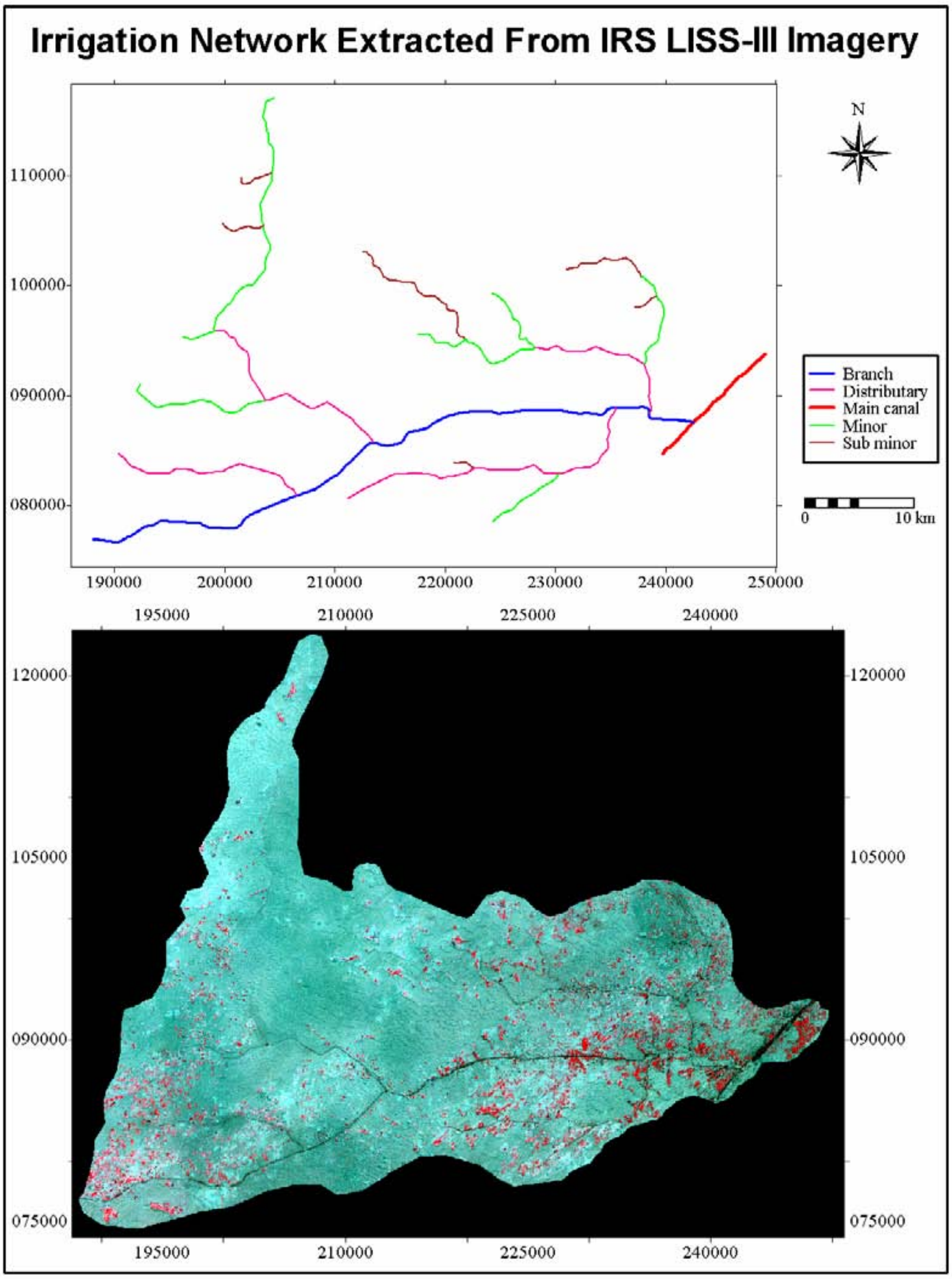

Figure 5.2 Irrigation Network Extracted from LISS-III image.

5.1.1.3. ASTER and LISS-III comparision

Overall it can be said that the ASTER imagery, with higher resolution of 15m, is comparatively advantageous for extraction of linear features like irrigation channels, then the LISS-III. However, the ASTER image is of the year 2005 and LISS image is of the year 1999, when development of the lower reaches of he Charanwala system was still going on. Hence, the interpretation key of association couldn't be used for those regions and a comparison of the two data products of the same period should also be done.

5.1.2. Upscaling of soil-hydrologic parameters

No detailed soil maps of the study area are available, therefore primary data was collected by conducting infiltration tests at 27 locations (Figure 5.3) and collecting soil sample for texture analysis (see section 4.2.11). One of the objectives of the study was to upscale the soil hydrological parameters point data collected during the fieldwork.

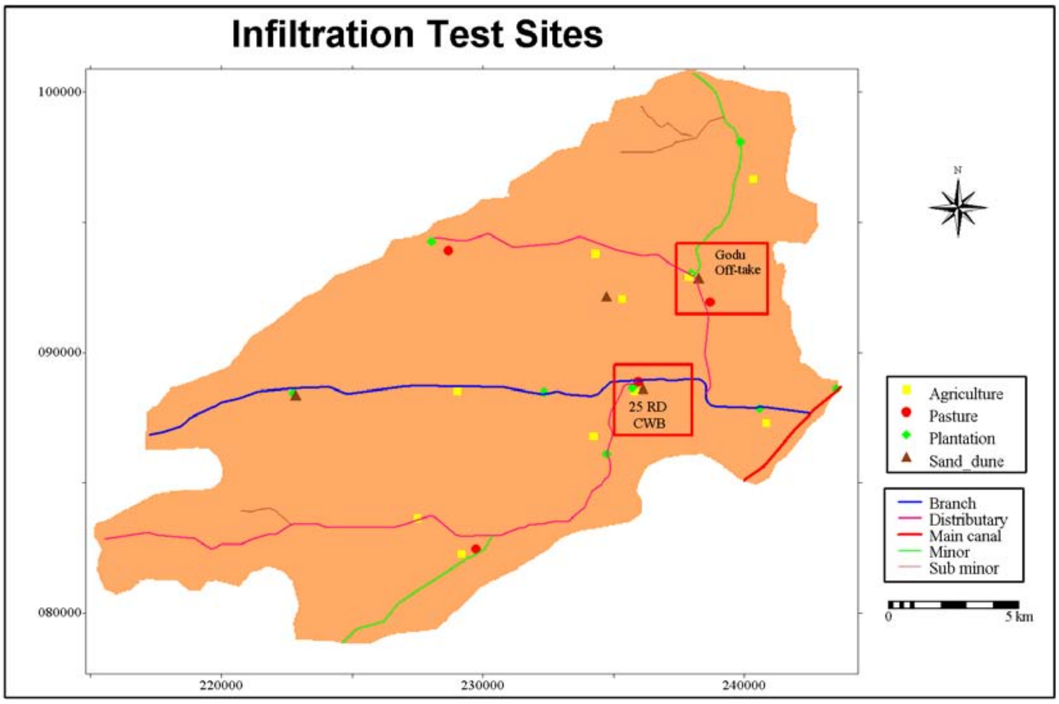

Figure 5.3 Point map of infiltration test sites in Upper Vharanwala System command area (Inset are locations where tests for all the land cover units were conducted)

5.1.2.1. Saturated hydraulic conductivity of surface soils

The average infiltration rates for the land cover units 'Agriculture', 'Plantation', Pasture' and Sand dune' are 0.71m/day, 1.098 m/day, 2.02 m/day and 1.74 m/day respectively (Table 5.3).

Table 5.3 Infiltration test statistics

Statistics	Plantation	Agriculture	Sand dune	Pasture
No. of observations	9	10	4	4
Minimum (mm/hr)	37.6	21.4	76	64.6
Maximum (mm/hr)	51.2	46	94	80.2
Range (mm/hr)	13.6	24.6	18	15.6
Mean Ksat (mm/hr)	45.8	29.6	84.3	72.6
Standard Error	1.46	2.57	3.94	3.70
Median (mm/hr)	46	27.6	83.65	72.8
Standard Deviation	4.38	8.14	7.88	7.4
AvKsat (m/day)	**1.098**	**0.71**	**2.02**	**1.74**

The infiltration rates for different land cover units were overlaid over the FCC of ASTER image to visually interprete the posiblity of krigging. At two sites different land cover were represented close to each other.

5.1.2.2. Infiltration rates at 25 RD CWB

At 25RD CWB, a location close to the off-take of Khara Distributary tests for all the four Land cover units in the study area were conducted (Figure 5.3 and Figure 5.4).

The infiltration rates at these sites are as follows:

- Agriculture: 24.4 (mm/hr)
- Plantation: 51.2 (mm/hr)
- Pasture: 68.2 (mm/hr)
- Sand dune: 87 (mm/hr)

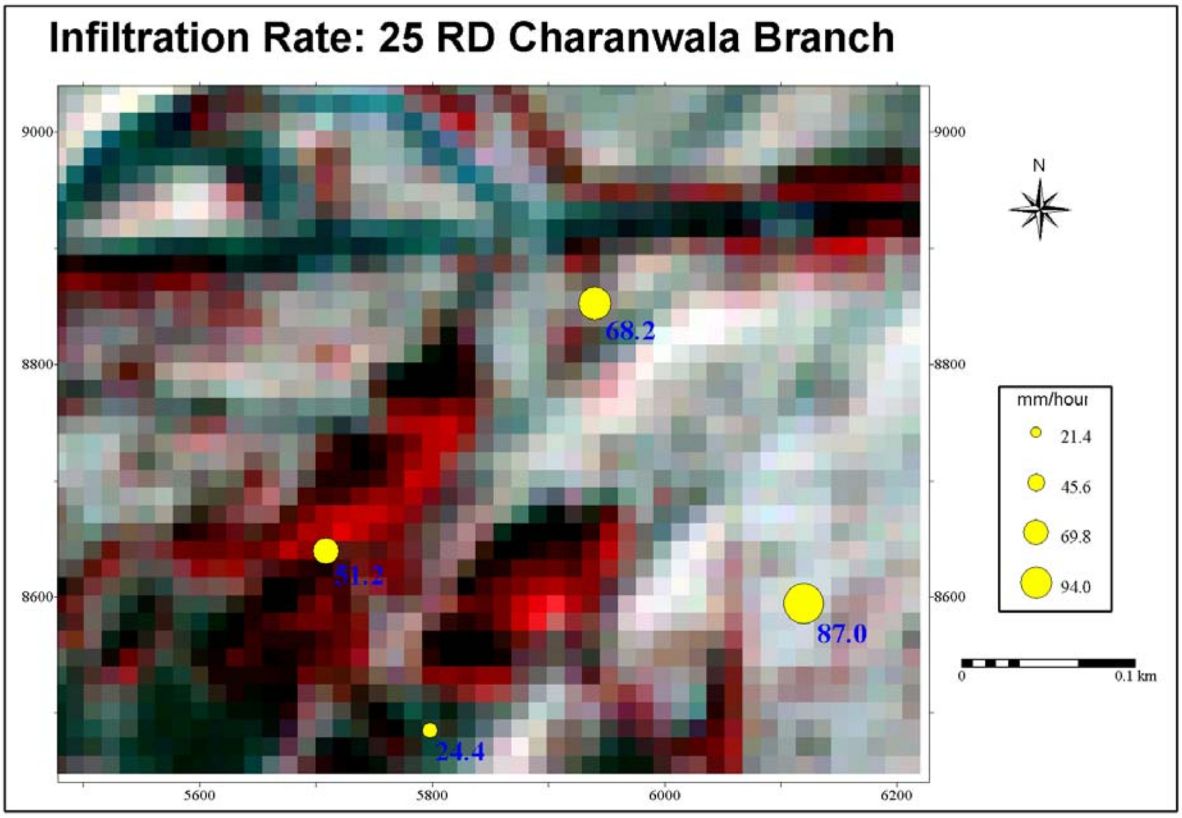

Figure 5.4 Infiltration rates of different land cover units overlaid over the ASTER image FCC.

5.1.2.3. Godu minor off-take

Similarly, at a location close to the off-take of Godu minor (Figure 5.3 and Figure 5.5) test were conducted for three land cover units and the infiltration rates are:

- Agriculture: 25.2 (mm/hr)
- Plantation: 42.8 (mm/hr)
- Pasture: 80.3 (mm/hr)

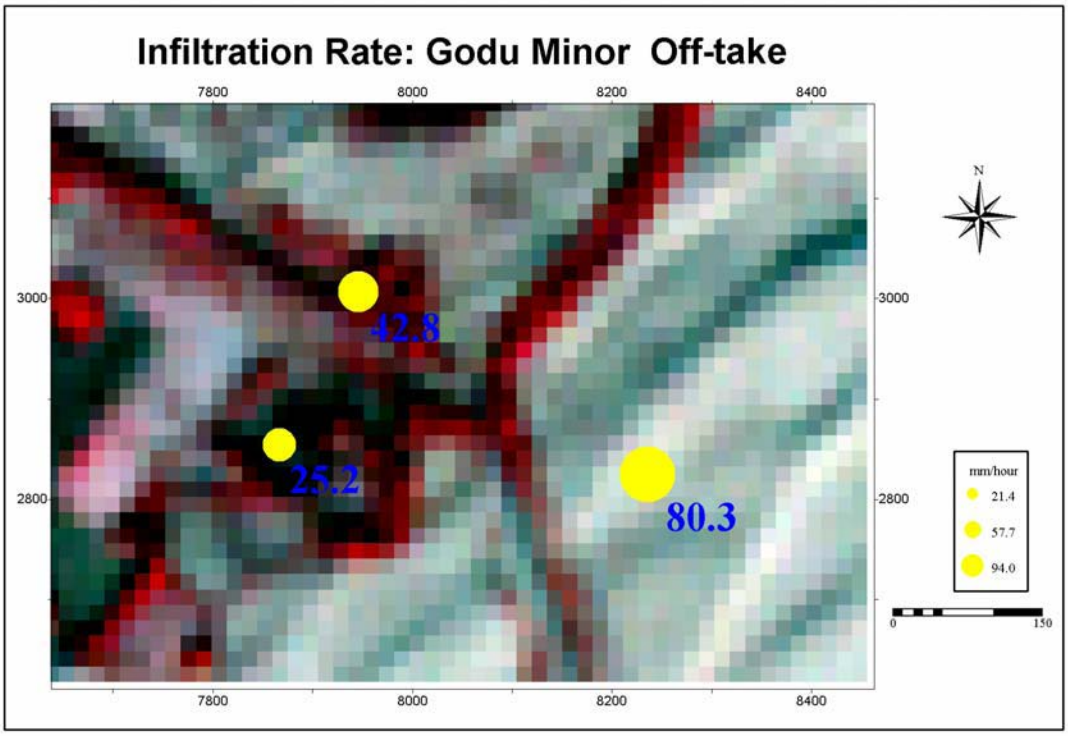

Figure 5.5 Infiltration rates of different land cover units overlaid over the ASTER image FCC

5.1.2.4. Saturated hydraulic conductivity of the sub surface soil layer

For the subsoil level saturated hydraulic conductivity soil texture values were derived in laboratory and subsequently the conductivity and porosity values were derived using the Saxton soil characteristic calculator. 29 samples of the 'Plantation', 29 samples of 'Agriculture', 13 of 'Pasture' and 8 samples of the 'Sand dune' class were used for determining the Texture information for the subsoil layer (below the depth of 1 meter). During the texture analysis iself it became apparent that with increasing depth the impact of land cover diminishes as the percentage of sand in the soils started rising.

Table 5.4 Sub-soil layer hydraulic conductivity statistics.

Statistics	Agriculture	Plantation	Pasture	Sand dune
Sum	1599.31	1939.52	1427.29	1209.82
No. of observations	29	29	13	10
Minimum(mm/hr)	30.46	38.94	72.56	95.44
Maximum(mm/hr)	92.56	121.74	220.54	130.8
Range	62.1	82.8	147.98	35.36
Mean/AvKsat2 (mm/day)	55.14	66.88	109.79	120.98
Standard Error	2.98	4.05	11.42	4.27
Median	55.08	59.35	92.56	127.12
Standard Deviation	16.07	21.82	41.18	13.52
Av Ksat (m/day)	1.32	1.61	2.93	1.45

5.1.2.5. Ksat2

The above values indicate that on one hand the average values of saturated conductivity of agriculture and plantations are close to each other and on the other the rates of sand dune and pasture are also tend to be similar. On this basis it was decided to provide a single Ksat2 value of 1.46 for the land cover units 'Plantation' and 'Agriculture' and value of 2.77 m/day to the land cover units 'Pasture' and 'Sand dune'.

5.1.2.6. Ksat3:

Initially it was assumed that the third layer of the soil profile is similar to the second layer as no tests or data was collected for it, however, later the, average of the second layer values was adopted as representing the saturated hydraulic conductivity for the third soil layer.

5.1.2.7. Porosity

As for porosity the values range in between 0.38 to 0.41. The average for the samples from land cover units 'plantations' and 'agriculture' was 0.389 and that for the 'pasture' and 'sand dunes' was 0.40. Similar values were assigned to all the three layers of the soil profile.

5.1.2.8. Upscaling of the parameters

The above analysis indicates that land cover influences the hydraulic conductivity of surface layer and to some extent that of the sub-surface layer, representing the soil profile below the root zone of crops. It is also evident that land cover has sharp variations within very short distances. Hence, it can be concluded that up-scaling of soil hydrological parameters i.e. The regionalization of point data, according to the land cover units is preferable over krigging or interpolation methods in the irrigated sandy deserts. The Ksat1 (Figure 5.6) and Ksat2 layers (Figure 5.7) were created by linking the average Ksat1 and average ksat2 values to the land cover units.

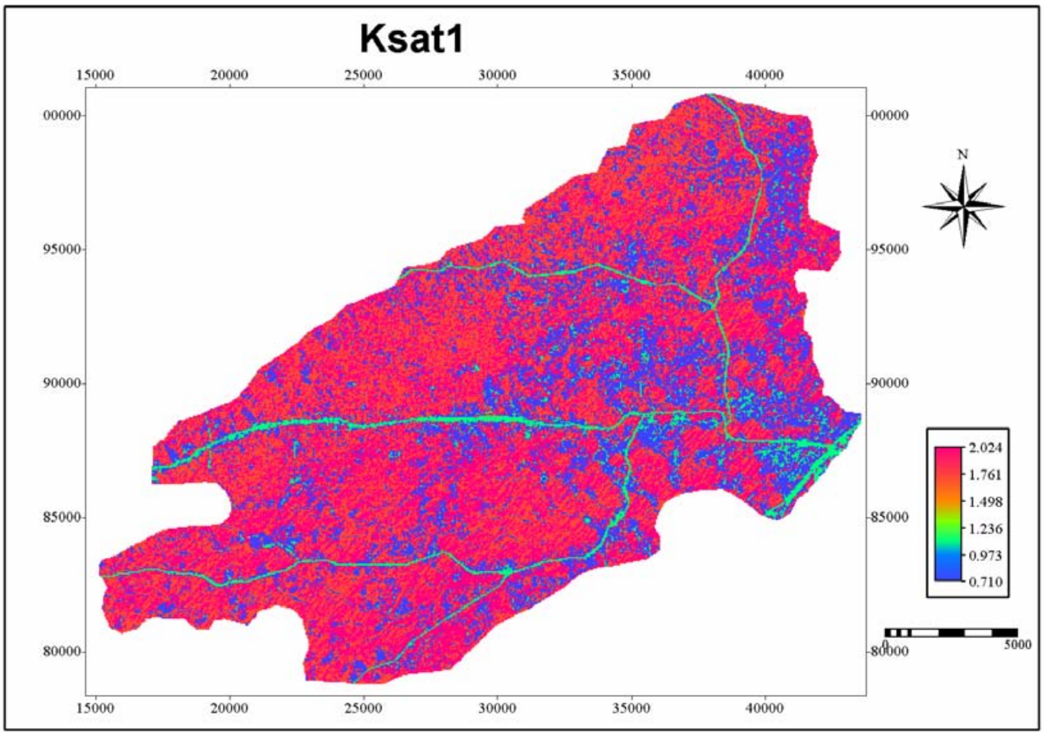

Figure 5.6 Saturated hydraulic conductivity of the Surface soils in Upper Charanwala area.

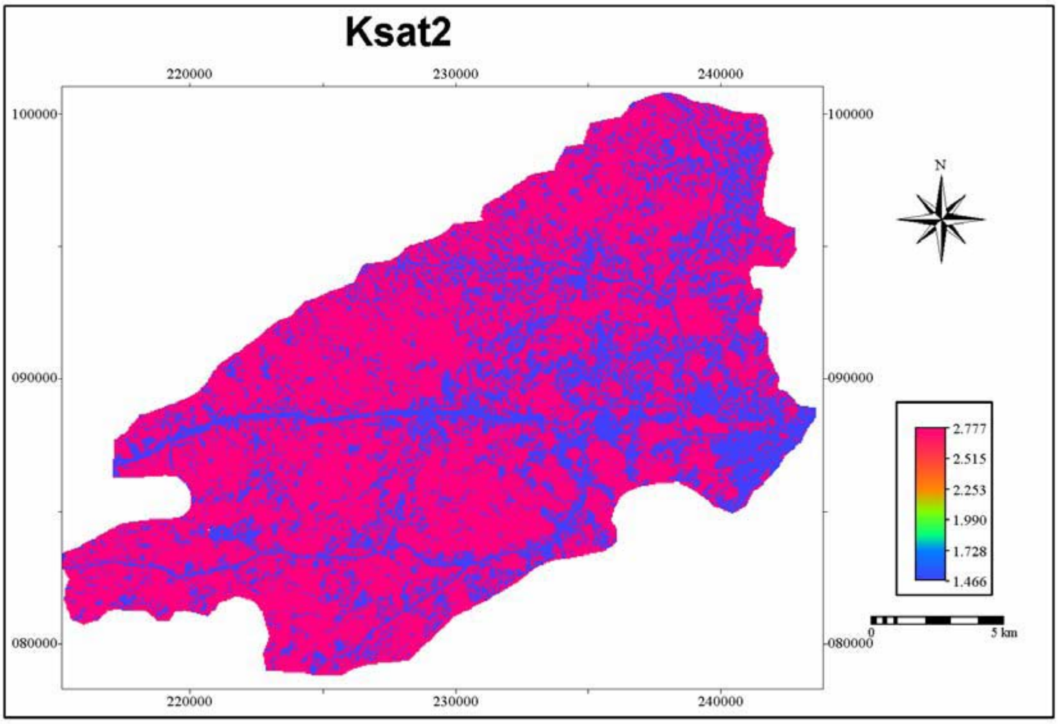

Figure 5.7 Saturated Hydraulic Conductivity for the Sub-soil Layer (mm/hr)

5.1.3. Mapping groundwater recharge zone from satellite imagery

Groundwater recharge takes place from:

- The percolation of irrigation applied to the agricultural fields,
- Leakage from the canals and precipitation.

The objective was to quantify the seasonal changes in the extent of the area contributing to the groundwater recharge using land cover/ area under crops information derived from multi-temporal satellite imagery.Simultaneously it was also attempted to quantify the changes in the area under crops during the same crop growth period over two different years and consequently the groundwater recharge zone in response to any substantial change in irrigation supply.

5.1.3.1. Groundwater recharge zone

The Groundwater recharge zone was quantified by extracting the information on area under crops from the satellite imagery, which was also needed for the preparation of the model input layers- ‘Landuse.map’ and ‘Production.map’(see section 4.2.8 for the procedure adopted). The width of the irrigation channels was added to the area under crops get the total groundwater recharge zone. Following NDVI thresholds were applied to estimate the area under crops:

- May is month of scorching summer heat and strong winds (Table 3.9) with little area under crops except for some fodder grown by farmers. This is the period for the preparation of fields or sowing of crops like cotton and groundnut and fodder (Table 4.10), though not much area is devoted to these crops. The NDVI threshold of ‘–0.05 and above’ was used to extract the groundwater recharge zone form the May1999 LISS-III imagery (Figure 5.8).
- For the Kharif 1999-2000 season the NDVI threshold of‘–0.04 and above’ was used to extract the groundwater recharge zone form the September 1999 LISS-III image (Figure 5.9),
- For the Rabi 1999-2000 season, the NDVI threshold of ‘0 and above’ was used to extract the groundwater recharge zone form the February 2000 LISS-III (Figure5.10).
- For the Rabi 1999-2000 season, the NDVI threshold of ‘0 and above’ was used to extract the groundwater recharge zone form the February 2001 LISS-III (Figure5.11).

The secsonal changes in the extent of the groundwater recharge zone are indicated in the table below.

Table 5.5 Groundwater Recharge zone in upper Charanwala area (1999-2001) extravted from satellite imagery

Period	Type of Area	No of pixels (Resolution 23.5m)	Area (ha)
May 1999	No Recharge Area	594032	32805
May 1999	Groundwater Recharge Area	6522	360
September 1999	No Recharge Area	505612	27922
September 1999	Groundwater Recharge Area	94942	52431
February 2000	No Recharge Ares	492117	27177
February 2000	Groundwater Recharge Area	108437	5988
February 2001	No Recharge Area	554006	30594
February 2001	Groundwater Recharge Area	46548	2570

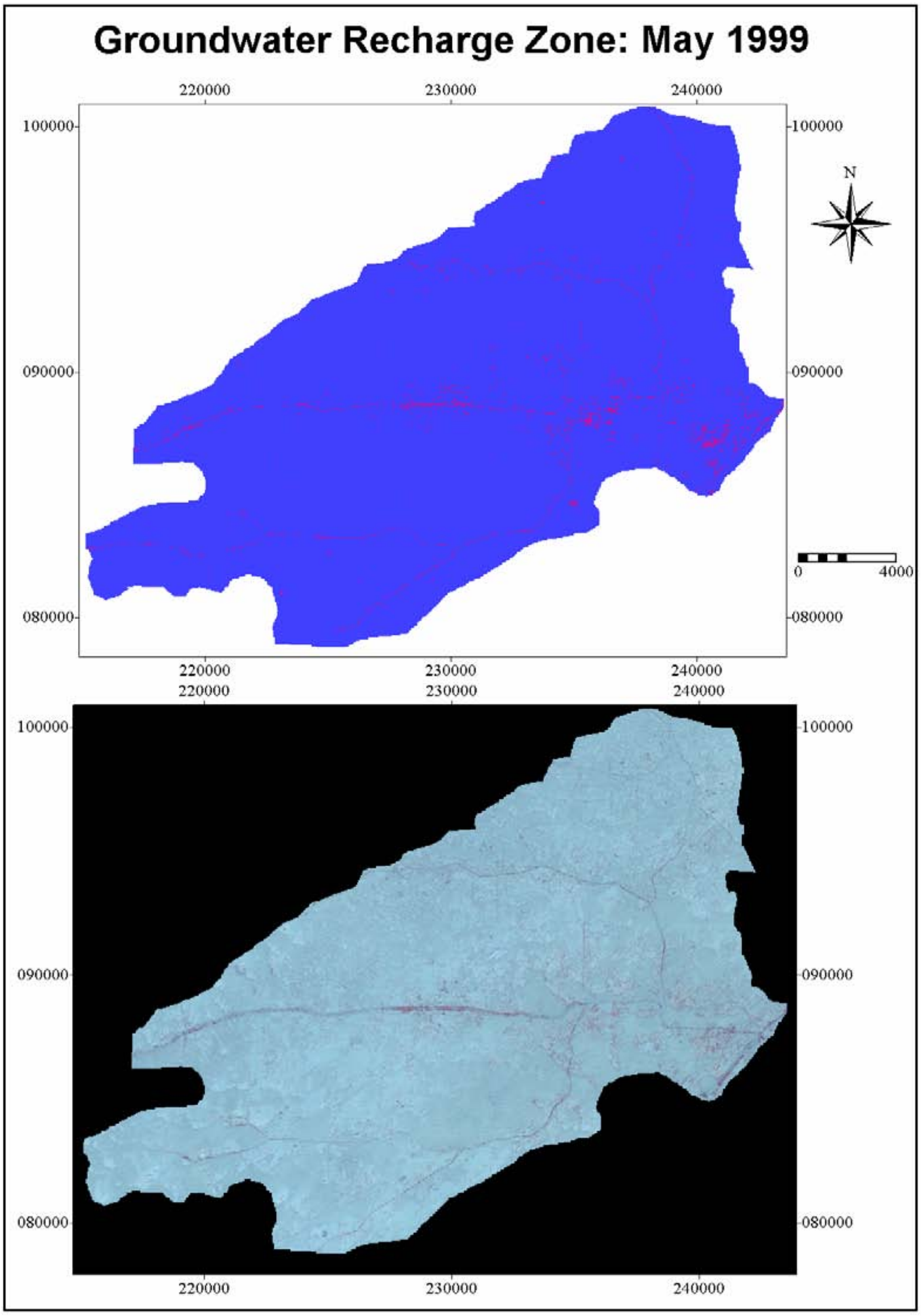

Figure 5.8 Groundwater zone extracted from LISSS-III image of May 1999

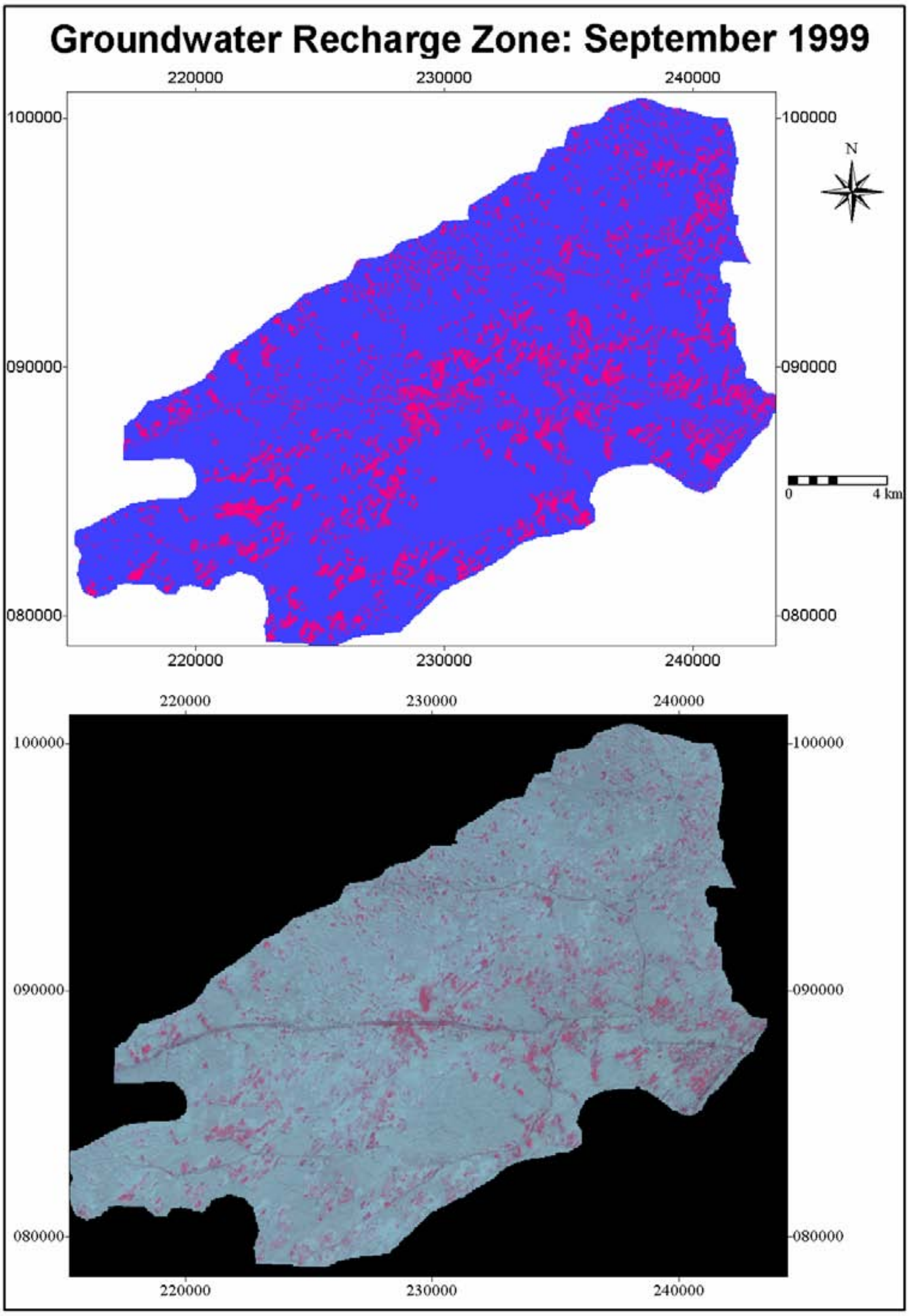

Figure 5.9 Groundwater recharge zone extracted from LISS-III image of September 1999.

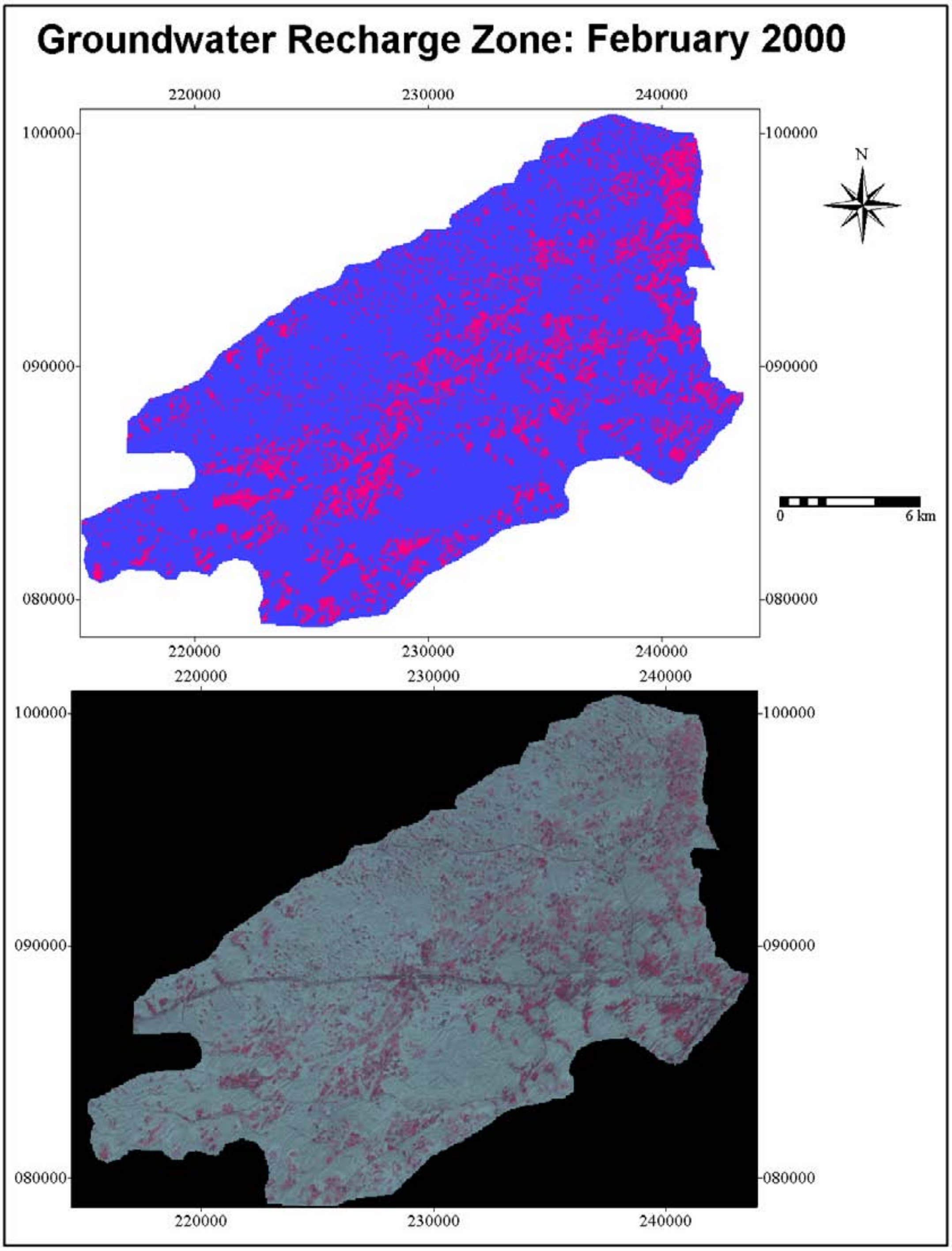

Figure 5.10 Groundwater recharge zone extracted from LISS-III image of February 2000.

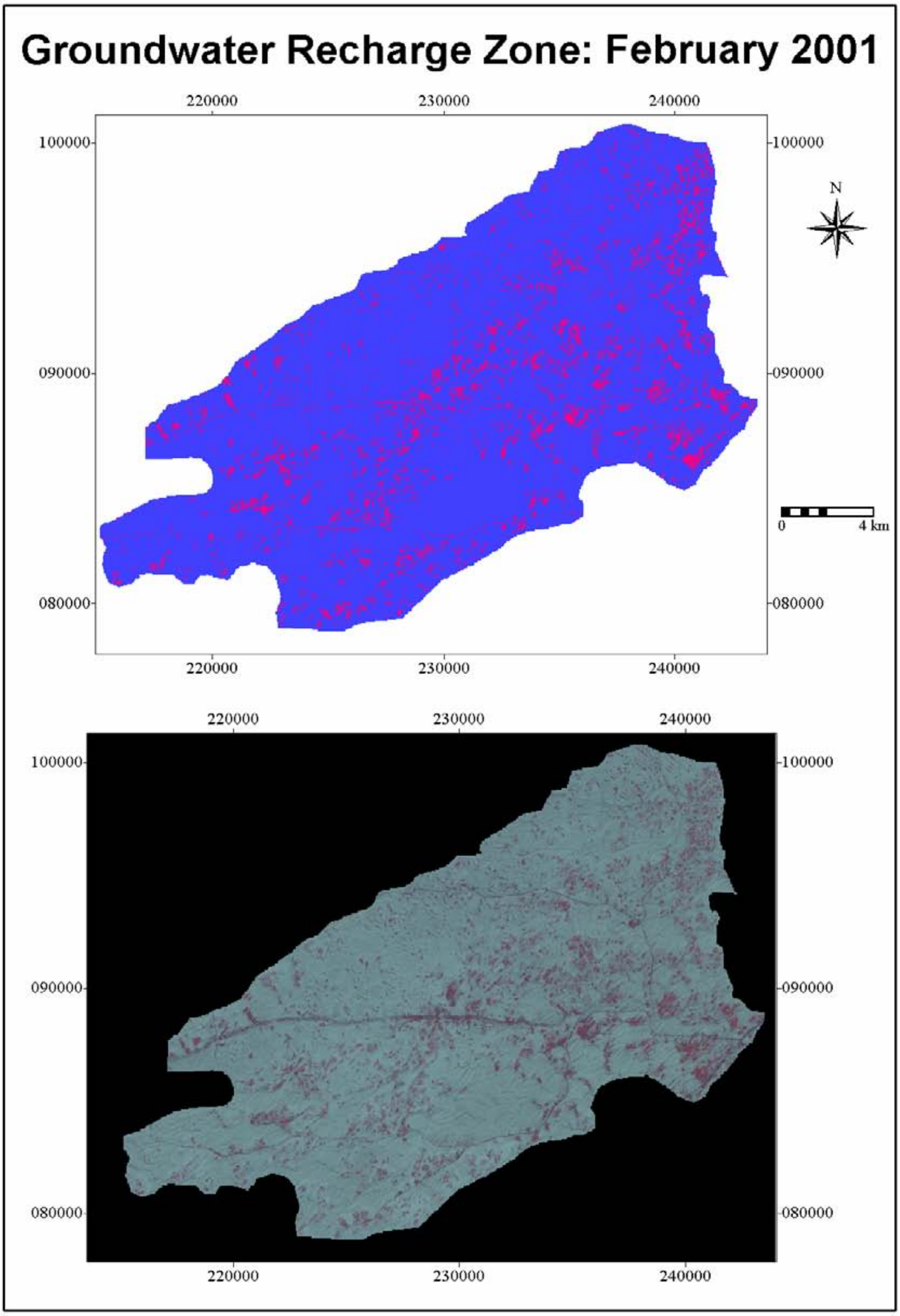

Figure 5.11 Groundwater recharge zone extracted from LISS-III image of February 2001

5.1.3.2. Change in cropped area in response to changes in irrigation supply

During the agricultural year 2000-2001, the irrigation inflows declined. The area under crop/groundwater recharge zone was extracted for the 'Rabi' crop from the LISS-III image of Feb2001. NDVI threshold of '0 and above', (same NDVI threshold was used for the Rabi 1999-2000 crop) was applied was applied to extract the area under crops for the 2000-2001 Rabi crop from the February 2001 LISS-III image (Figure 5.11).

The area under crops as extracted from the images declined to 2447.13 ha in the Rabi 2001 from 5864.95 in Rabi 1999-2000 season (Table 5.6). The area under crop in the Rabi 2000-2001 season is about 41.7% of the previous year. This decline matches with the crop area statistics from CADA (see Table 4.7).

Table 5.6 Rabi crop area extracted from the LISS-III Imagery (1999-2000 and 2001).

Year/ crop season	Area under crop extracted from LISS-III images (ha)	Area under crop as per CADA (2002) (ha)	
		30% Share of Entire Charanwala System	25% Share of Entire Charanwala System
1999-2000 (Rabi/winter)	5864.95	6170.1	5141.75
2000-20001(Rabi/winter)	2447.13	2650.5	2208.75

Total irrigation inflow in the Rabi 2000-20001 seasons had reduced to33483978 cubic meters as against 47268669 cubic meters in the Rabi season of the previous year (1999-2000). The decline of is of 29.2 %. The impact of decline in inflows is high as the inflows were little erratic in the months of October, November, and December when the different Rabi crops are sown. Erratic supplies mean certain farmers miss on their their turn to apply irrigation to their fields, which are fixed for the entire year on specified days in the week.
Overall, it can be said that the seasonal changes in groundwater recharge ares can be extracted form satellite imagery in conjunction with ancillary information about the cropped area statistics.

5.1.4. Relative accuracy of SRTM DEM and ASTER DEM vis-a-vis reference canal bank elevations

Initially it was decided to use ASTER DEM- 3A relative DEM (product id-AST3A1_0512140554100606240623), from ERSDAC lab with the assumption that because of its higher spatial resolution of 15m, it will be more accurate then the 90m SRTM DEM. As per the ASTER user handbook, the 3A relative DEM is reported to have relative vertical accuracy up to 10 m (Abrams et al.).

During the fieldwork it was realized that the ASTER DEM along the sections of the Indira Gandhi Main Canal, was highly erratic and undulating. The canals have plantations along them and initially the apprehension was that the ASTER DEM is representing those values. However, later that was ruled out because the width of Indira Gandhi Main Canal is 35m and the bank width on each side is at least 8m, hence the ASTER DEM with a resolution of 15m cannot be expected to representing the plantations. SRTM DEM's resolution is 90 m and each pixel is larger then the canal width, hence undulations were expected.

To draw broad generalizations about the relative accuracy of the ASTER DEM vis-a-vis the SRTM DEM, cross-sections for both the DEM's were created by digitizing segments along the irrigation channels of the IGNP system. These segments were opened as point map, with one point representing distance for every 5m length of the section from the start of to the end of the segment. For these points elevation information was recorded for both the DEM's. This elevation information was plotted on a graph against the distance.

The Indira Gandhi main Canal has a slope of 1: 12000 and the elevation information of the canal bed and canal banks above the mean sea level in Indian Datum with high accuracy was available form the longitudinal sections of the irrigation channels provided by the irrigation authorities(IGNP, 2006c). The canal bank elevations were also plotted along the DEM altitude sections to find the relative undulations in both the DEM's and their fit to the Indian Datum.

Four sections were generated:

1. 23.5 km long section along the Indira Gandhi main canal.
2. 30.7 km long section along the Charanwala Branch. The sections along the Charanwala branch are to be treated cautiously, because the combined width of the channel and the banks is about 20m.
3. 600 m long section with no Plantation close by the IGMC.
4. 550 m long section with no Plantation close by the Charanwala Branch.

The small sections, without any plantations in close vicinity were selected to rule out the impact of the plantations.

Before making any generalization about the relative accuracy of the two DEM's along sections of IGMC and Charanwala Branch, it would be prudent to mention that the landscape traversed by the canal is dunal and the topography of the area is undulating (see figure 3.4 and 3.5) and the canal structure has two kinds of sections:

- 'Fill sections', representing the low inter dunal depression, which were filled up during canal construction
- 'Cut sections', where a large dune crossed the canals course and which was removed or flattened to make way for the canal.

5.1.4.1. Section along the Indira Gandhi Main Canal

Along the 23.5 km long section along the IGMC (Figure 5.12 and Figure 5.13) the canal bank elevations, range form 169.506 m at the start of the section to 167.506 m at the end of section, a fall of about 2 m for entire length (the slope of canal is 1:12000). In this section the SRTM values range between a low of 160 m to a high of 175 m, while the range for the ASTER DEM is from 47m to 158 m.

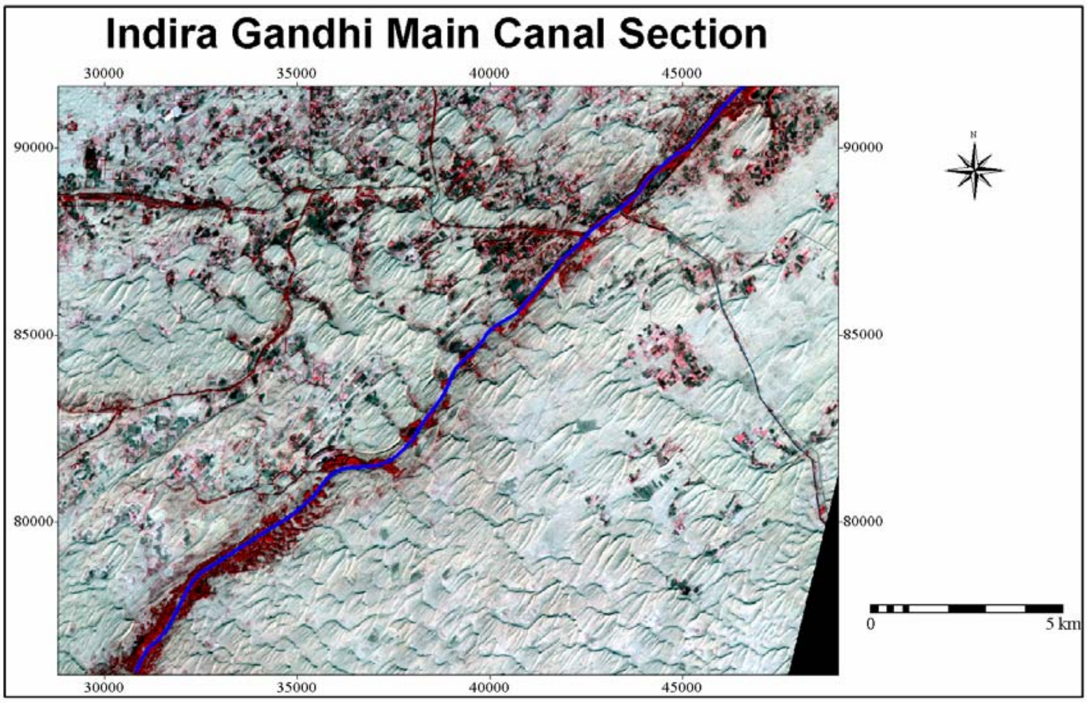

Figure 5.12 Section along the Indira Gandhi Main Canal

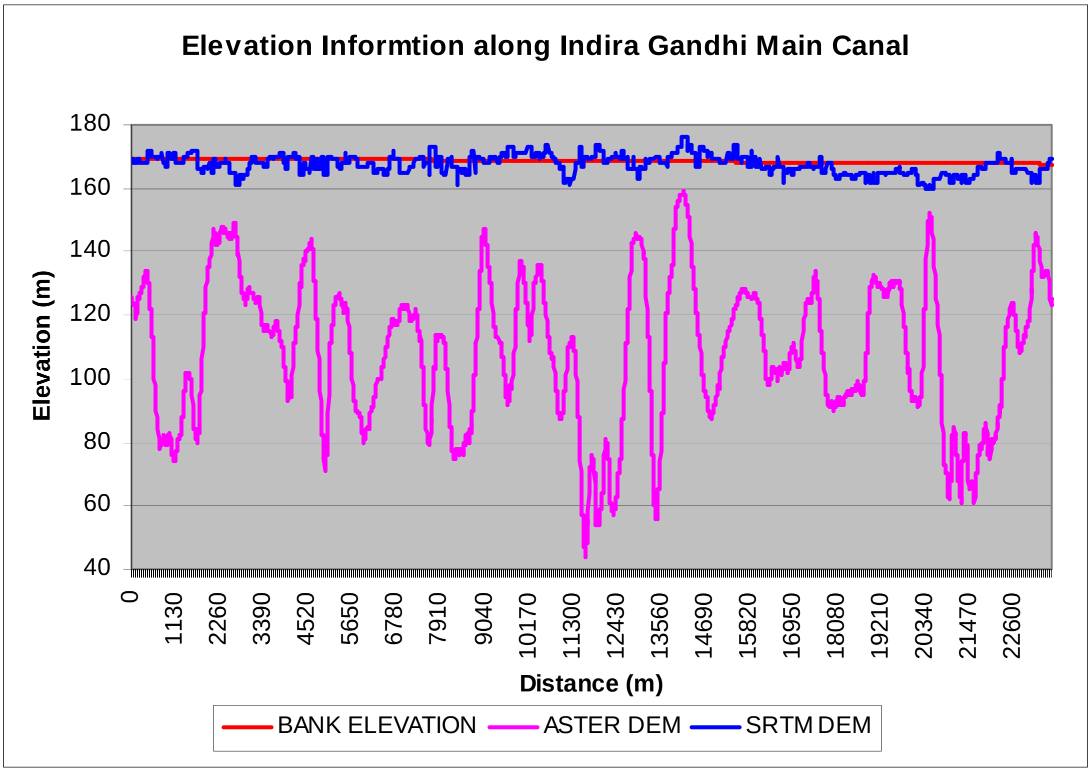

Figure 5.13 Plot of elevations (m) from the SRTM DEM, ASTER DEM and canal bank along a section of Indira Gandhi main canal

5.1.4.2. Plantation free section along the Indira Gandhi Main Canal

A small section of 600m (figure 5.14 and 5.15), along the Indira Gandhi Main Canal where there are no 'Plantations, the canal bank elevation range between168.159m to 168.11 m. The SRTM DEM elevations range between 171m to 176 m. in this section the ASTER elevations are between 127 m to 158m.

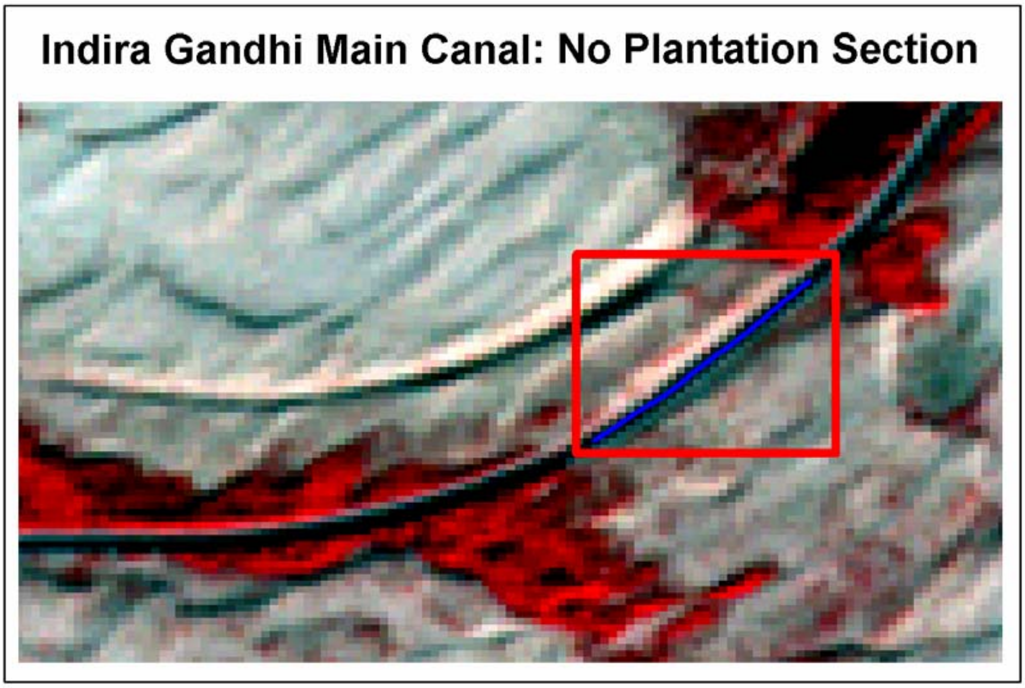

Figure 5.14 Plantation free section along the Indira Gandhi Main Canal

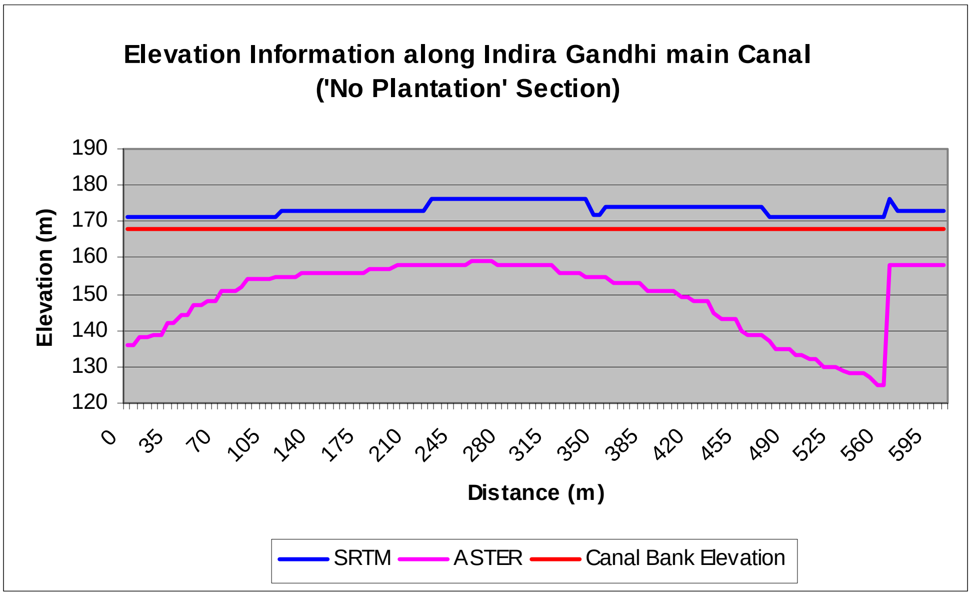

Figure 5.15 Plot of elevations (m) from the SRTM DEM, ASTER DEM and canal bank along a plantation free section of Indira Gandhi main canal

5.1.4.3. Section along the Charanwala Branch

Similarly a long 30.7 km section was generated along the Charanwala branch (figure 5.16 and figure 5.17).The bank elevation at the beginning of the section is 162.29m and at the end of section is 146.44m, a fall of 15.5m (the branch and minor channels have a bed slope of about 1:5000 to 1:6000). The range of SRTM DEM elevations in this section is between 144m to 170 m and that of the ASTER between 80m to 120m, although at one spot it plummeted to about 50m, but that isolated spot can be ignored as an aberration.

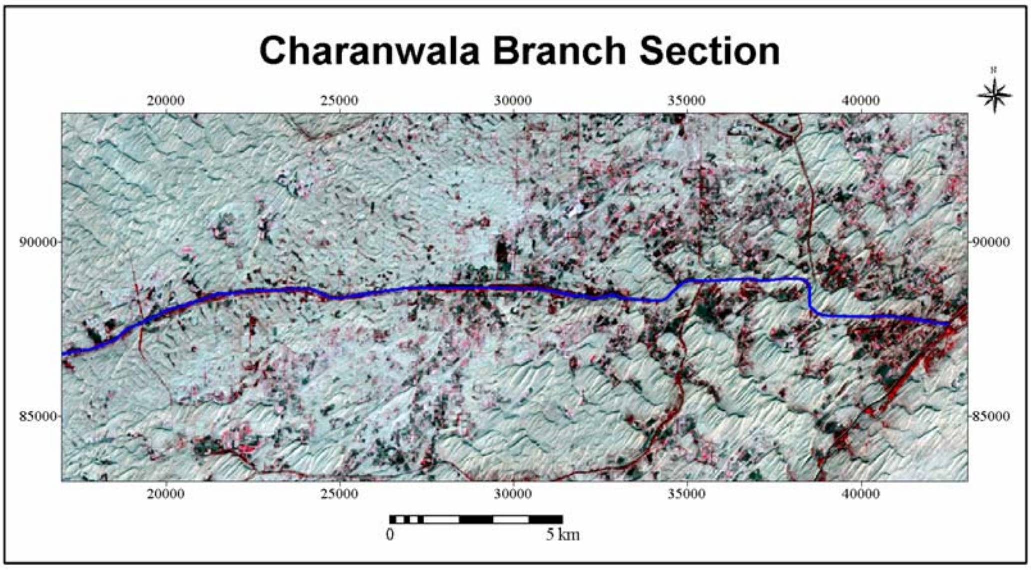

Figure 5.16 Section along the Charanwala branch

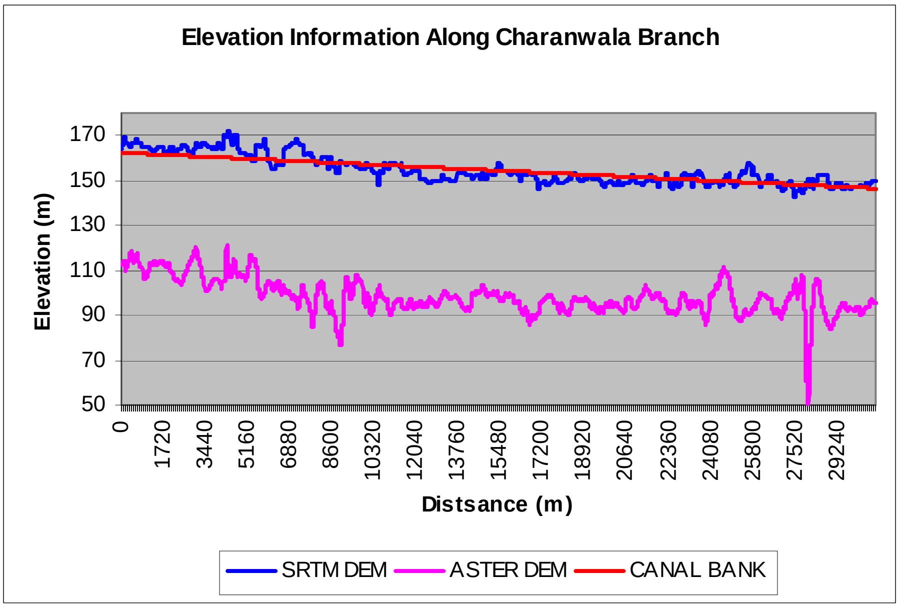

Figure 5.17 Plot of elevations (m) from the SRTM DEM, ASTER DEM and canal bank along a section of Charanwala Branch

5.1.4.4. Plantation free section along the Charanwala Branch

A small plantation free section was also generated along the Charanwala Branch (figure 5.18 and figure 5.19). The bank elevation decline from 157.78m to 157.5m, SRTM DEM ranges between 153m to 159 m. The ASTER DEM values range from 78m to 107m.

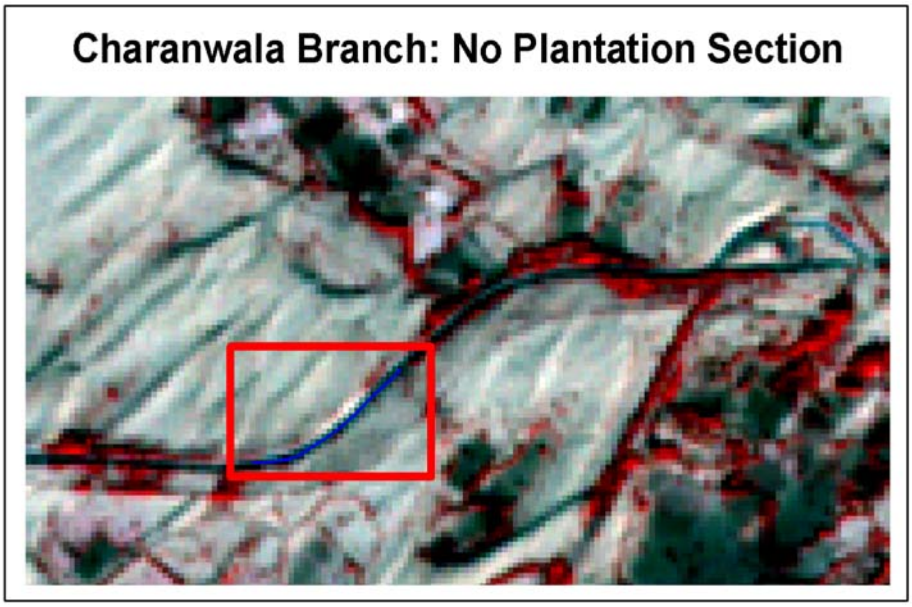

Figure 5.18 Plantation free section along the Charanwaka Branch

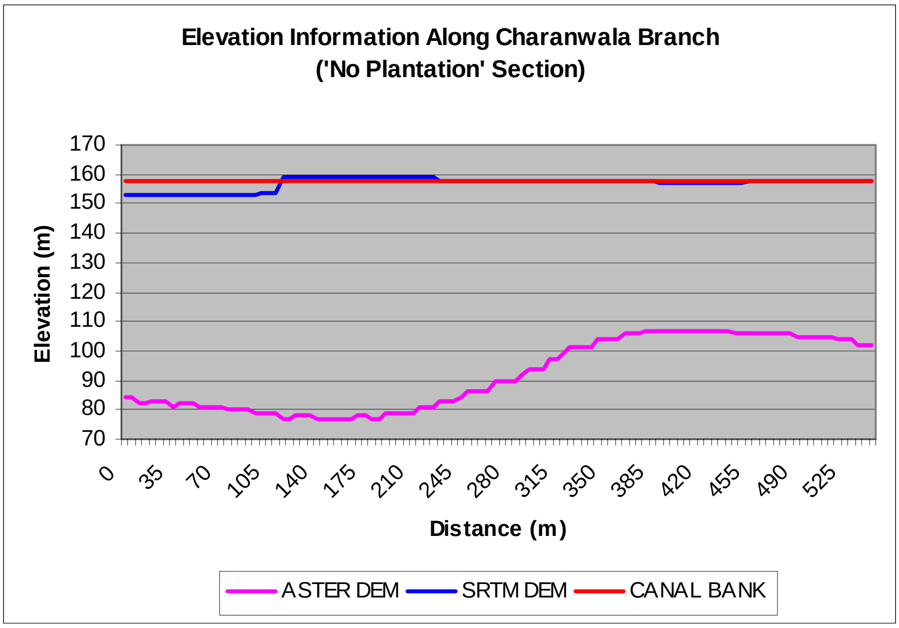

Figure 5.19 Plot of elevations (m) from the SRTM DEM, ASTER DEM and canal bank along a plantation free section along the Charanwala Branch

The above analysis of the two DEM's indicates that the SRTM Dem is relatively more suitable then the ASTER DEM for the surface water groundwater interaction study as its values mostly are in a range of 10 meters above or below the reference canal bank elevations. The range of fluctuation for the ASTER DEM is much more then the SRTM DEM. Moreover, the SRTM has better fit with the elevation data along the irrigation channels as compared to the SRTM DEM. Apart from the undulations the ASTER DEM appears to have a relative shift of more then 40m with respect to the canal bank, and the SRTM DEM. On this basis, the SRTM DEM was used for the generation of model input layers- ''Soil depth' (see Figure 4.7) and 'Initial Groundwater Level' (see Figure 4.8) layers.

5.2. Model Calibration

The surface-water groundwater interaction model was run for the agricultural year 1999-2000. Each time step was of 6 hours and the total no of timesteps was 1460. The model takes about 8 hours with a Pentium 4, 1.8 GHz processer with 1 GB RAM.

For achieving calibration, the 'trial and error strategy' was adopted. The calibration targets were the observed groundwater levels above the barrier at the sample locations for the year 2000.The original script, which assumed a linear realation between ETp and ETa (see section 4.1.2) resulted in very low ETa. The script was modified. Model was run each time with slight changes in the parameters of Klat (lateral hydraulic conductivity of the saturated zone), EdgeKsat (outflow rate from the western boundary), and KsatBC (leakage to barrier).

Model was also run as closed system, without the input of irrigation, rainfall and output/losses in terms of evapotranspiration and groundwater outflow for the initial stabilization of the groundwater levels. This was attempted to address the concerns about the barrier layer elevation and the thickness of the initial groundwater levels above it on account of the methodology adopted (see section 4.2.4 and 4.2.5). Next the model runs were conducted considering the 'stabilized groundwater level' as the initial groundwater level. However, the results were better with the initial groundwater level, inputed in the model as 'Gwinit' layer (see Figure 4.8), arrived at by subtracting the 'Barrier Elevation' layer (see Figure 4.6) from the Groundwater table of the year 1999 (see Figure 4.2).

The model allows the lateral outflow of the groundwater from the system. The outflow takes place from the western boundary. The value of outflow- EdgeKat was set at 1.3m per day, less then the Klat which was set at 2.4 m per day. The reason for setting the Edgeksat low is that beyond the western boundary of the model area, the 'Barrier' starts to rise and probably restricts the lateral groundwater flow. Since, this rise is outside the the model area boundary, it is not accounted in the simulated groundwater levels. Hence, the EdgeKsat was set to 1.3 to account for the effect of the Barrier.

The Ksat1 were derived from field observations, and were not altered. The Ksat2 values based on ltexture analysis had sharp boundaries and were modified to make them smooth using a moving window. Similerly the irrigation inflows in upper Charanwala System- 33% of the entire inflows in the Charanwala System- were assumed to be correct and were not interfered with (although they range in between 30% to 35% of the total inflows in the Charanwala system and, in future runs could, be altered for the caliberation purpose). Similerly, the parameters of ETp and, leakage from the irrigation channels, groundwater recharge zone and ground covered by plants were kept constant.

At a later stage caliberation was also attempted with another modified script, which calculated ETa only for the seasonally active agricultural fields, which actually is the case, however , the initial results were little erratic and due to paucity of time it was decided to stick to the second version of the script.

The best results were arrived by specifying the following values to parameters:

- EdgeKsat (outflow rate from the western boundary) = 1.3 m/day
- Klat (lateral hydraulic conductivity of the saturated zone) = 2.4 m/day
- KsatBC (leakage to barrier) = 0.0198

The simulated groundwater levels above the barrier were compared to the observed water levels above the barrier at 14 locations for which water table observations were available. The groundwater rise data from CADA, for one of the observation points '23RD Godu' was found to be inconsistent and this observation location was excluded from the analysis of model results. Overall, the simulation resulted in rise in groundwater levels in the study area (Figure 5.21, 5.22 and 5.23). The Root Mean Squared (RMS) Error (the average of squared differences in observed and simulated heads) is 0.58. However, when compared to the actual observed groundwater rise it has underperformed, i.e. simulated groundwater levels above the barrier are less than the actual observed groundwater levels (Figure 5.20).

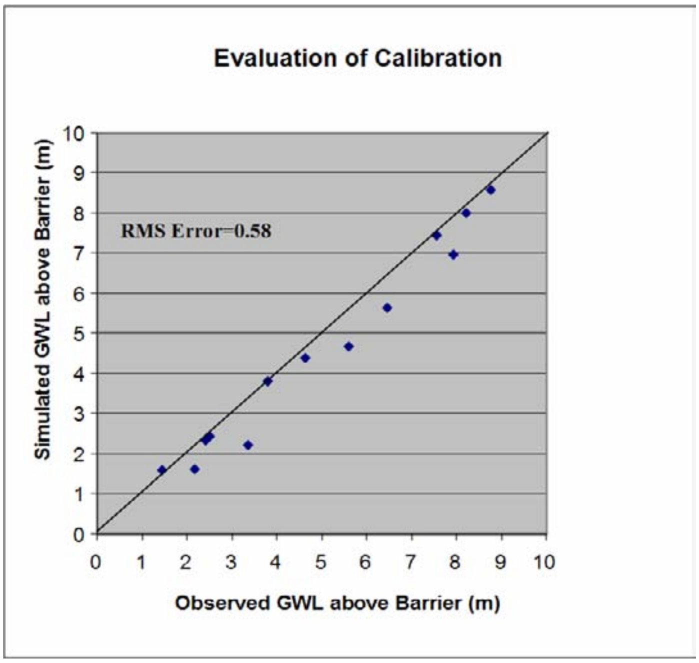

Figure 5.20 Model calibration evaluation.

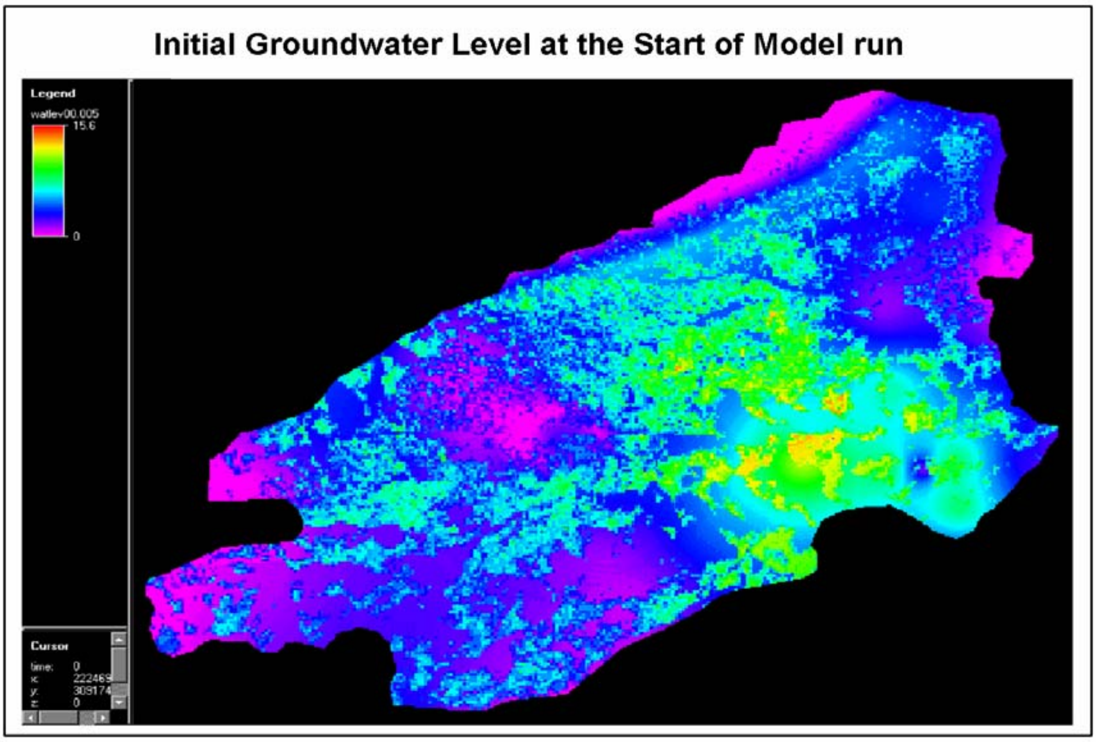

Figure 5.21 Groundwater table at the start of model calibration.

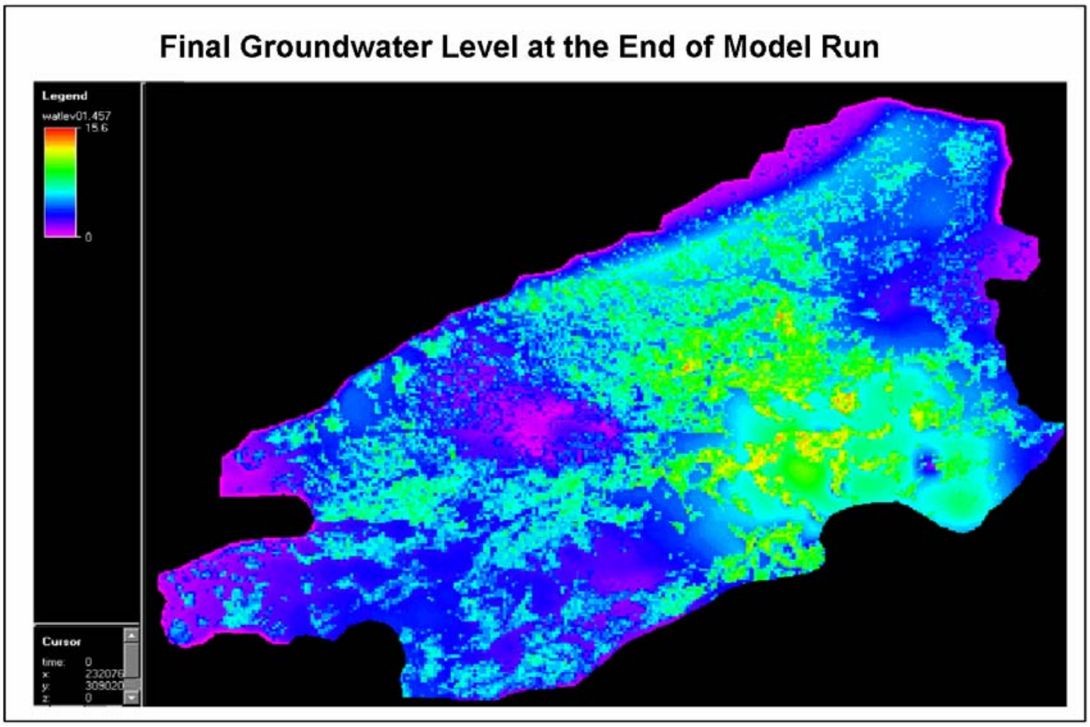

Figure 5.22 Groundwater table at the end of calibration run

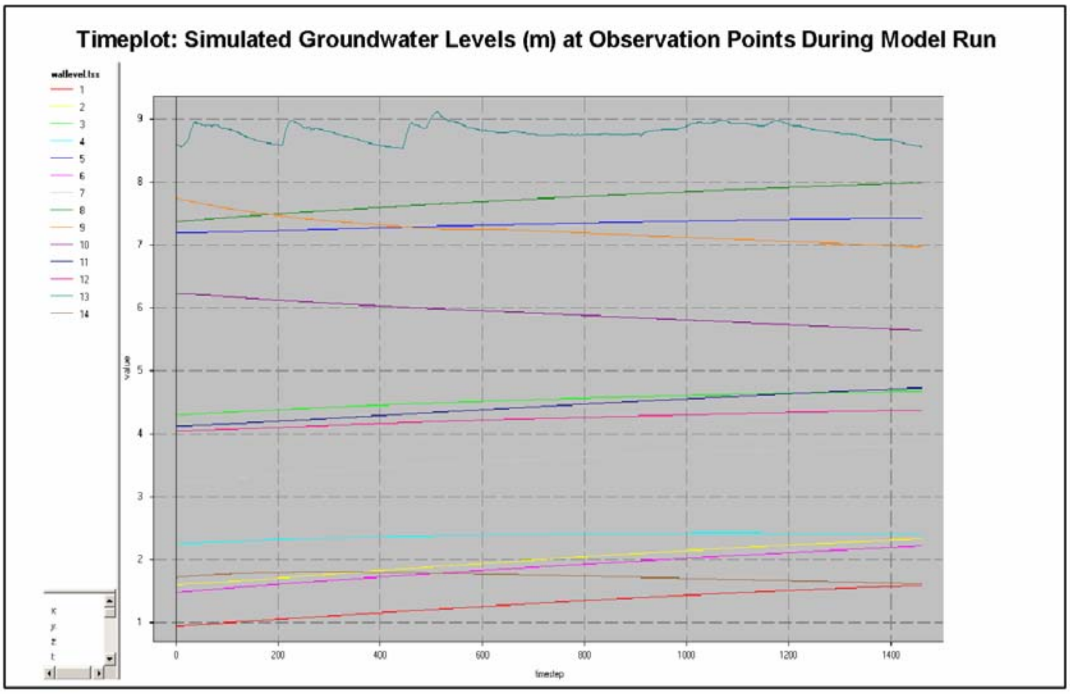

Figure 5.23 Plot of simulated groundwater levels at observation locations during the calibration run

The low RMS result show that, the caliberation was good, however, the errors have cancelled out each other, since at few locations there was a slight decline and at rest of the places there was a rising trend. These results could well be interpreted as no caliberation at all. However, that is not the case as the reason for decline in the simulated groundwater levels at the four observations can be explained.

The main reason for the decline of groundwater at 4 of the 14 observation locations is there location close to the eastern boundary of the system (Figure 5.24). The groundwater flows in the system from east to west. In the model, for avoiding complexity, the eastern boundary was assumed to be no flow boundary. This has caused the simulated groundwater levels at these locations to decline below the initial groundwater levels above the barrier.

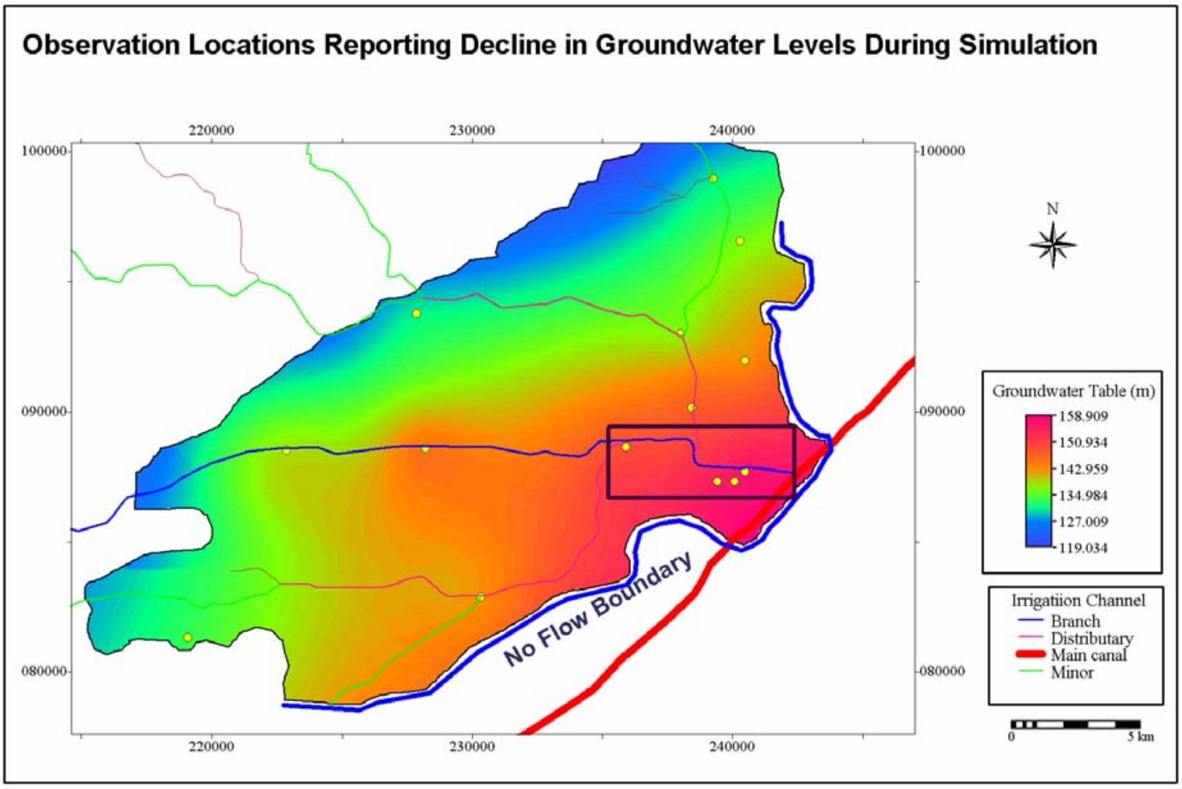

Figure 5.24 Observation locations reporting decline in groundwater levels during simulation

At all other 10 observation locations the groundwater levels have shown a rise during calibration which is in conformity with the observed groundwater levels. Overall it is concluded that there is a need for further calibration.

5.2.1. Observed trends in groundwater table

The groundwater levels at the observation locations close to IGMC have gone down sharply since 1998(Figure 5.28).

The decline in the piezometers close to IGMC is on account of heavy abstraction of groundwater since the year 2000-2001. During fieldwork, some farmers in the Chack 2CWB (village) told that they have abandoned their dug cum bore wells, due to the fall in the water levels. On an average every second farmer has a shallow, dug cum bore well in this zone. Moreover there are thick stands of ecuplatus plantations in this area and there is substantial abstraction by them on account of biodrainage.

Table 5.7 Depth to groundwater (m) from surface for observation locations close to IGMC

	May-96	May-97	May-98	May-99	May-00	May-2001	May-02	May-03	May-04	May-06
P1 LADHURAM	2.41	2.85	2.75	2.54	2.4	2.89	3.02	NA	NA	4.88
P4 PRATPRAM	NA	1.6	1.8	1.7	1.6	2	2.61	2.73	2.8	2.5
P19 BHIANRAM	8.6	8.75	8.4	8.98	8.6	8.85	9.15	9.35	9.77	9.53
P 25RD CWB	6.41	6.5	7	6.9	6.65	7.2	7.2	7.1	7.4	7.2

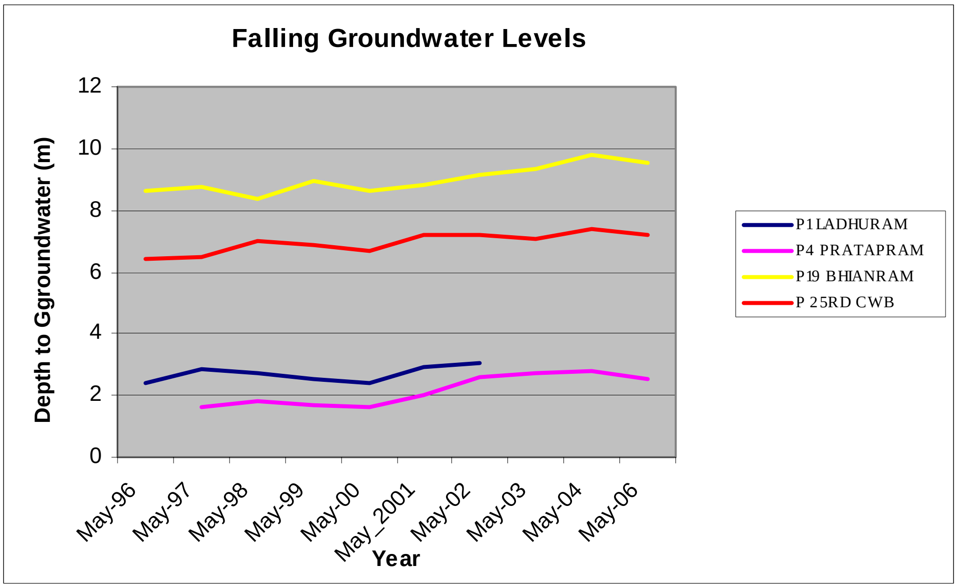

Figure 5.25 Falling groundwater levels close to IGMC indicated by increasing depth (m) to groundwater from ground surface (1998-2006).

Whereas, the rest of the piezometers still show a gradually rising trend (Figure 5.7). The rise in the barrier elevations beyond the upper Charanwala acts as an obstacle to the lateral flow of the groundwater, and this appears to be the reason for the rising groundwater patterns, but this needs to be investigated further.Moreover, areas towards the western boundary, except those served by the Godu minor, have comparatively less density of active ageicultural fields and conscequently lesser wells and abstraction. Also, the 'Plantation' stands are thinner.

Table 5.8 Depth to groundwater (m) from surface for observation locations close to western boundary of Upper Charanwala System

	May-98	May-99	May-00	May-01	May-02	May-03	May-04	May-06
P 16RD PSD	14.72	14.2	12.35	11.04	11.07	11.38	11.13	10
P 20PSD CHK	20.4	19.85	18.95	18.2	17.97	17.91	17.73	16.9
P 4GMR CHK	14.55	13.3	12.72	12.14	12.18	11.67	11.75	10.8
P 23RD GODU	18.47	18.35	16.76	16.6	15.92	15.42	15.36	14.1
32RD KHARA DST	10.1	10.45	9.95	9.7	9	8.98	8.7	8.6
P 62RD KHARA DST	16.01	15.72	14.89	14.25	14.37	14.02	13.37	13.5
P 69RD CWB	10.87	10.6	9.2	8.3	8.74	8.68	8.89	7.9

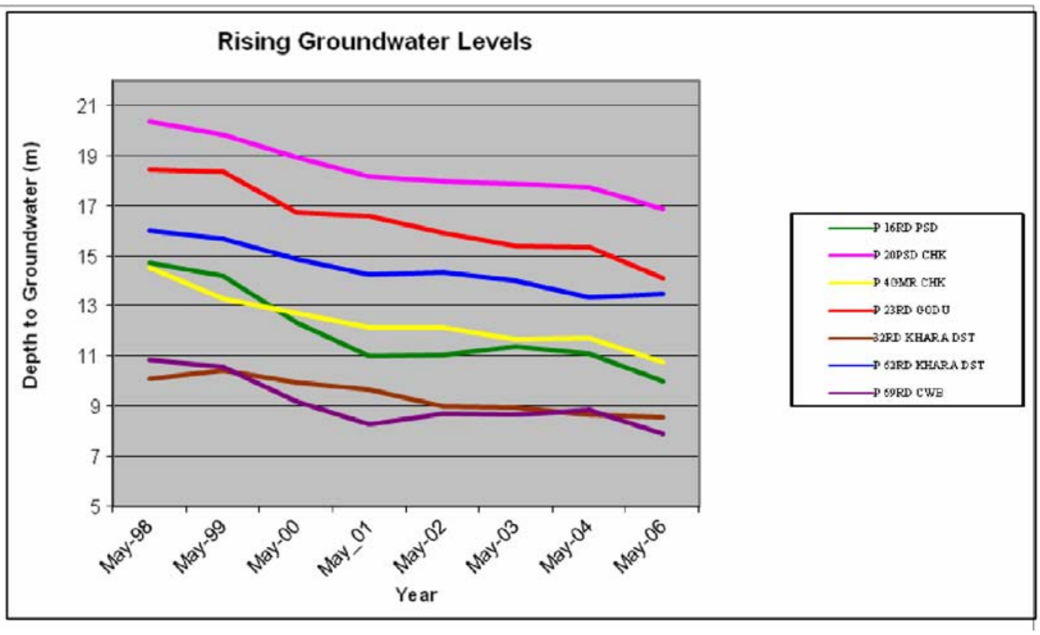

Figure 5.26 Rising groundwater levels in rest of Upper Charanwala System indicated by decreasing depth (m) to groundwater from ground surface (1998-2006)

6. Conclusions

6.1. Results of Research questions

6.1.1. Is it possible to model the change in water-table in an irrigated arid land using a simple surface-water and groundwater interaction model?

The surface-water and groundwater interaction couldn't be fully calibrated. Though, considering the limited available time for calibration and the fact that it was the initial attempt at modeling this complex water demand and supply environment, it was possible to model the complex irrigation input and water table changes and get some preliminary idea about groundwater movement.

6.1.2. Which is the appropriate method of upscaling the soil-hydrologic parameters in an irrigated desertic environment?

Upscaling of soil hydrological parameters according to the land cover units generated from the satellite imagery is preferable over krigging or interpolation methods in the irrigated sandy deserts as infiltration rates depend on land cover which changes abruptly within a small area.

6.1.3. To what extent can land cover maps derived through multi-temporal satellite imagery be used to delineate groundwater recharge zones and depict the changes in irrigation intensity?

The changes in groundwater recharge zone were quantified by extracting the information on area under crops from multi-temporal satellite imagery. It was also evident that changes in cropping intensity (total area under crops) in different years on account of change in the inflows could be captured by the using multi-temporal satellite imagery.

6.1.4. Is it possible to extract the irrigation network details up to minor-canals level from medium resolution satellite imagery?

It is possible to extract the canal network upto the minor canal level by visual interpretation of the TERRA ASTER and IIRS LISS-III satellite imagery.

6.1.5. Which satellite imagery based Digital Elevation Model (DEM) out of the SRTM and ASTER is more suitable for modelling of perched groundwater tables in

dune dominated topography using a simple surface-water and groundwater interaction model?

The analysis conducted to ascertain the relative accuracy of the two DEM's vis-a-vis reference canal bank elevations indicates that the SRTM DEM is relatively more suitable than the ASTER DEM for modelling of perched groundwater tables in dune dominated topography using a simple surface-water and groundwater interaction model, as its values mostly are in a range of 10 meters above or below the reference canal bank elevations. The range of fluctuation for the ASTER DEM is much more than the SRTM DEM.

6.2. Recommendations

6.2.1. Modifications in the model

The model can be modified/ adapted to allow spatially flexible assignment of the following input parameter:

- To spatially vary the leakage to the barrier layer.
- To spatially vary the irrigation inputs.
- To assign variable outflow values to different sectors of the lateral outflow boundary.
- To allow the groundwater inflow from the eastern boundary.

6.2.2. Modelling strategy

A modeling strategy could be adopted in which the study area is divided into smaller areal units, and each is modeled and calibrated individually. At a later stage the model script should be modified to take into account the needed spatially variability in input parameterisation and an attempt could be made to model the entire study area as a single unit. Although this can only be possible when the irrigation inflow inputs to the smaller units could be worked out with reasonable accuracy.

6.2.3. Data collection

The data collection procedures for the soil-hydrologic parameters could be improved upon. For the present study, a double ring infiltrometer was used. Infiltration tests with a Guleph permeameter will enable better quantification of this parameter.

For the the lateral groundwater movement, slug tests with a automatic transducer could be conducted for a large number of piezometers and on the analysis of their results, representative samples could be chosen for pumping tests.

The results for the groundwater change at few observations locations were erratic; for these places, more realistic parameterization should be done through ground investigation.

The DEM, in reference to which the depth to hard pan and in turn the initial groundwater levels are measured, needs to be reasonably accurate. The study showed that ASTER DEM can’t be used for that purpose.The 90 m spatial resolution SRTEM DEM proved to be more useful; an attempt can be made using the 30 m spatial resolution SRTM DEM or other better resolution DEMs.

For estimation of the the area under crops in different seasons, ground truth collection during the crop growth stages may allow to arrive at a more reasonable NDVI threshold for the estimation of the area under crops.

Reference

Abrams, M., Hook, S. and B., R., ASTER user handbook, 2. CIT, JPL.

Allen, R.G., Pereira, L.S., Raes, D. and M., S., 1998. Crop Evapotranspiration. Guidelines for computing crop water requirements. FAO Publication number 56. 56, FAO, Rome.

Anderson, M.P. and Woessner, W.W., 2002. Applied Ground Water Modeling: Simulation of Flow and Adevective Transport. Acedemic Press, SanDiego, California.

Balakram and Chauchan, J.S., 2001. Impact Assessment of IGNP Canal on Land use in Hanumangarh District, Rajasthan Using Remotely Sensed Data. Indian Cartographer, 20(2): 47-52.

Bastiaanssen, W.G.M. and Molden, D.J., 1999. Remote Sensing and Hydrologic Models for Performance Assessment in Sirsa Irrigation Circle, India. 27, International Water Management Institute, Colombo, Sri Lanka.

Bhakar, R., 2005. Re-evaluating the Sustainability of Irrigated Agriculture in Arid zones:A Case Study of Indira Gandhi Nahar Pariyojna. In: S.C. Kalwar, M.L. Sharma, R.D. Gurjar and S.K. Wadhawan (Editors), Geomorphology and Environmental Sustainability. Concept Publishing Company, New Delhi, pp. 300-313.

CADA, 1991. Hydrological Barrier Studies:1989-1990, Command Area development-Indira Gadhi Nahar Project, Bikaner.

CADA, 1993. Intensive Hydrological barrier Studies; Digga , Sultana, and Charanwala (Flow command), and Madasr,Newa, Awai,and Ajasar, Askandra (Lift areas), IGNP Command Area Development Authority, Bikaner.

CADA, 1999. Paper for finalising the Term and Conditions for Allotment of Land Underlain by Barrier Layer for Afforestation, IGNP Command Area Development Authority, Government of Rajasthan, Bikaner.

Census, 1991. District Census Handook 1991: Bikaner, Census of India, New Delhi.

Chatterji, P.S. and Saxena, K.S., 1988. Canal Irrigation in arid zone of Rajasthan and its ecological implication. In: I. Praksah (Editor), Desert Ecology. Scientific Publisher, Jodhpur.

Collado, A.D., Chuvieco, E. and Camarasa, A., 2002. Satellite remote sensing analysis to monitor desertification processes in the crop-rangeland boundary of Argentina. Journal of Arid Environments, 52(1): 121-133.

D`Souza, R., Mukhopadhyay, P. and Kothari, A., 1998. Re-evaluating Multi-Purpose River Valley Projects: A Case Study of Hirakund, Ukai and IGNP. Economic and Political Weekly, 33(6): 297-302.

Dhir, R.P., 1987. Flux in Indian Desert. In Desert Ecology. In: Prakash.I. (Editor), Desert Ecology. Jodhpur: Scientific Publishers., Jodhpur.

Dhir, R.P., Kolarkar, A.S. and Singh, H.P., 1992. Soil Resources of the Thar. In: A. Kar, R.K. Abichandani, K. Ananthram and D.C. Joshi (Editors), Perspectives on the Thar and the Karakaum. Department of science and technology ,Govt of India, New Delhi, pp. 60-85.

Doorenbos, J. and Pruitt, W.O., 1977. Guidelines for predicting crop water requirements, Irrigation and Drainage Paper 24, FAO, Rome, Italy.

Dregne, H.E., 2002. Land Degradation in the Drylands. Arid Land Research and Management, 16(2): 99 - 132.

Dwivedi, R.S. and Sreenivas, K., 2002. The vegetation and waterlogging dynamics as derived from spaceborne multispectral and multitemporal data. International Journal of Remote Sensing, 21(3): 519-531.

Fouad, A.K., 2003. Soil Salinity Detection Using Satellite Remote Sensing, ITC, Enschede.

Geomatica, 1992. GPS positionin Guide. Geomatica Canada, Geodatic Survey Division, Natural Resources Canada, Ottawa, 78 pp.

Gieske, A., 2003. Operational Soiutions of Actual Evapotranspiration. In: I. Simmers (Editor), Understannding Water in Dry Environment. Balkema Publishers.

Gieske, A. and Miranzadeh, M., 2002. Groundwater Resources Modelling of the Lenjanat Aquifer System. 28, IEARI,EARC,IWMI.

Goldman, M.R., 1994. There's A Snake On Our Chests: State and Development Crisis in India's Desert. Ph.D. Thesis, University of California, Santa Cruz, 254 pp.

Goyal, R. and Arora, A.N., 2003. Use of Remote Sensing in Ground Water Modeling. G.I.S Development.

Gulati, N.D., 1973. Indus Water Treaty:An Exercise in International Mediation. Allied Publishers, Bombay.

Gupta.A.K. et al., 2002. History of Indira Gandhi Nahar: A Venture to Turn Desert of Rajasthan into Granary, Indira Gandhi Nahar Board, Bikaner.

Herrmann, S.M. and Hutchinson, C.F., 2005. The changing contexts of the desertification debate. Journal of Arid Environments
Special Issue on The "Greening" of the Sahel, 63(3): 538-555.

IDS, 1991. Equity and Productivity Issues in IGNP- A review of Literature, Institute of Development Studies, Jaipur.

IGNP, 2006a. Charanwala System:Cultural Command Area Statistics. IGNB, Bikampur.

IGNP, 2006b. Irrigation Inflow Log in Charanwala System:1999-2004. In: R. Bhakar (Editor). IGNB, Bikaner, pp. Three hourly inflow logs in the charanwala system.

IGNP, 2006c. L-Section's of Indira Gandhi Canal Stage-II. In: R. Bhakar (Editor). IGNB, Bikaner, pp. Graphs displaying the discharge, bed eleveation andwidth, bed slope, full supply depth, bank elevetion and width.

ITC, 2002. Using Digital Elevation Models. In: ITC (Editor), ILWIS 3.0 User’s Guide. ITC, Enschede.

Jensen, J.R., 2003. Remote Sensing of Environment: An Earth Resourse Perspective. Pearson Education, New Delhi, 544 pp.

Kavadia, P.S. and Hooja, R., 1994. Indira Gandhi Canal Project(IGNP):Components,Impacts and Planning Issues. In: P.S. Kavadia and B. Hooja (Editors), Planning for Sustainability in Agriculture:Command Area Development and Indira Gandhi Canal Project. Rawat Publications, Jaipur
New delhi.

Khan, N.M. and Rastoskuev, V.V., 2005. Assessment of hydrosaline land degradation by using a simple approach of remote sensing indicators ". Agricultural Water Management, 77(1-3): 96-109.

Khan, S., P. and King, 2004. Role of GIS, Remote Sensing and Hydrology In the environmental Management of Rice growing areas. Australia.

Lachapelle, G., Kielland, P. and Casy, M., 1991. GPS for Marine Navigation and Hydrrography, Forth Biennial Canadian Conference, Rimouski.

Li, J., Lewis, J., RowlandbJ., TappanbG. and TieszenL.L., 2004. Evaluation of land performance in Senegal using
multi-temporal NDVI and rainfall series. Journal of Arid Environments, 59: 463-480.

MacDonald, M. and Dalal, C., 1998. IGNP Studies for the State of Rajasthan : Draft Final Report; Annex F- Sustainable Land Irrigability Classification, Mott Macdonald (Consultans for the Government of Rajasthan for Evaluation of IGNP), Bikaner.

MacDonald, M. and Dalal, C., 1999. IGNP Studies for the State of Rajasthan: Annex G -Review of North West Drainage Study.

MacDonald, M., Dalal, C. and I.I.S., 1999. IGNP Studies for the State of Rajasthan : Main Report, Mott MacDonald Limited.

Macdonald, M.G. and Harbaugh.A.W., 1988. A moduler three Dimensional Finite Difference Groundwater Flow Model-Techniques of water Resource Investigation, 06-A1. USGS, 576 pp.

Masoud, A.A. and Koike, K., 2006. Arid land salinization detected by remotely-sensed landcover changes: A case study in the Siwa region, NW Egypt. Journal of Arid Environments, 66(1): 151-167.

Metternicht, G.I. and Zinck, J.A., 2003. Remote sensing of soil salinity: potentials and constraints. Remote Sensing of Environment, 85(1): 1-20.

Mishra, G.C., Singh, S.K., Kumar, C.P., Kumar, S. and Shukla.M.K., 1995. Assessment of Impact of Irrigation Application in a Part of IGNP Stage-II Command Area Underlain by Hydrological Barrier, National Institute of Hydrology, Roorkee, India.

Okin, G.S., Roberts, D.A., Murray, B. and Okin, W.J., 2001. Practical limits on hyperspectral vegetation discrimination in arid and semiarid environments. Remote Sensing of Environment, 77(2): 212-225.

ORG, 1989. Groundwater Systems Study of Pilot Area: IGNP Command-Stage-II, Operations Research Group, Baroda.

Ramanathan, S. and Rathore, M.S., 1994. Sustainability of Indira Gandhi Canal and theNeeds for Correct Responses:A Social Scientist Perspective. In: R. Hooja and P.S. Kavadia (Editors), Planning for Sustainability in Irrigation. Rawat Publishers, Jaipur, pp. 277-299.

Rushton, K.R., 2003. Groundwater Hydrology:Conceptual and Computational Models. John Wiely and Sons.

Saxton, K.E. and Rawls, W.J., 2005. Soil warer Characteristic.

Sehgal, M.M. and Vyas, A.C., 1994. Conjuctive Usr of Surface and Groundwater in the IGNP: Digital Model of a Pilot Area. In: R. Hooja and P.S. Kavadia (Editors), Planning for Sustainablity in Irrigation. Rawat Publications, Jaipur, pp. 130-142.

Sekhar, L.K., 2006. Effect of Vegetation on Debris Flow Initiation:Conceptualisation and Parameterisation of a Dynamic Model for Debris Flow Initiation in Tikovil River Basin, Kerala, India, using PCRaster. Master of Science in Geo-information Science and Earth Observation,Specialisation: (Hazard and Risk Analysis) Thesis, ITC-IIRS, Ensched and Dehradun, 117 pp.

Sharma, D.P. and Gupta, S.K., 2006. Subsurface Drainage for Reversing Degradation of Water of Waterlogged Saline Lands. Land Degradation & Development.

Singh, R., Kroes, J.G., van Dam, J.C. and Feddes, R.A., 2006. Distributed ecohydrological modelling to evaluate the performance of irrigation system in Sirsa district, India: I. Current water management and its productivity. Journal of Hydrology, 329(3-4): 692-713.

Soni, R.G., 1994. Afforestation in Indira Gandhi canal Project. In: R. Hooja and P.S. Kavadia (Editors), Planning for Sustainability in Irrigation. Rawat Publication, jaipur, pp. 97-103.

Strahler, A. and Strahler, A., 2002. Physical Geography:Science and Systems of the Human Environment. John Wiley and Sons, Singapore.

UNCCD, 1994.
Desertification, United Nations Convention to Combat Desertification.

UNDP-FAO, 1971. Soil Survey and Water Management Research and Demonstration in Rajasthan Canal Area., FAO, Rome.

van Beek, L.P.H., 2002. Assessment of the influence of changes in landuse and climate on landslide activity in a Mediterranean Environment. PhD Thesis, Utrecht University, Utrecht, 363 pp.

Veron, S.R., Paruelo, J.M. and Oesterheld, M., 2006. Assessing desertification. Journal of Arid Environments, 66(4): 751-763.

WAPCOS, 1993. Ecological and Environmental Studies for Integrated Development of Indira Gandhi Project Stage-II, Wateer and power Consultancy Services(India)Limited, New Delhi.

WAPCOS, 1995. Indira Gandhi Nahar Project, Stage-II : Feasibility Report, Water and Power Consultancy Services, New Delh.

WAPCOS, 1996. Study of Availability of Water in IGNP, Water and Power Consultancy Services, New Delhi.

Ward, D., Ngairorue, B.T., Kathena, J., Samuels, R. and Ofran, Y., 1988. Land degradation is not a necessary outcome of communal pastoralism in arid Namibia. . Journal of Arid Environments, 40: 357–371.

WCCR, 2002. Important Data and Decisions of Ravi and Sutlej Complex, IV Edition, Water Controller Cell for Rajasthan-Government of Rajasthan, Chandigarh.

Weston, C., 2005. Introduction Risk Assessment, pp. docs/lectures/19_09_2005.

Worster, D., 1992. Rivers of Empire:Water Aridity and Growth of Amserican West. Oxford University Press, New York, 402 pp.