Trans. Inst. Indian Geographers
Vol. 30, No. 2, 2008

Delineating Spatio-temporal Distribution of Groundwater Recharge Zones Using Remote Sensing in an Irrigated Landscape of Thar Desert, India

Rajesh Bhakar, H.S. Sharma, S.K. Srivastav and Victor Jetten

Abstract

Because of poor rainfall, groundwater recharge in an irrigated sandy desert mainly takes place through the percolation of irrigation water applied to the agricultural fields, and seepage from the canal beds. The presence of an impermeable layer at shallow depth, common in such environment, impedes the subsurface drainage of percolated irrigation water resulting in the rise of groundwater table, ultimately leading to waterlogging and salinity problems. Accurate information about the area contributing to groundwater recharge as return flow from irrigation is, therefore, crucial for models simulating the risk of waterlogging. This research focuses on the delineation of temporally varying groundwater recharge zones in spatially distributed form in a dune dominated irrigated landscape of Thar Desert using multi-temporal satellite imagery. Supervised image classification and band-ratio (Normalised Difference Vegetation Index, NDVI) techniques are used for information extraction in conjunction with the aggregated crop area statistics obtained from the irrigation authorities. The spatially varying wetted perimeters of canals have been estimated by integrating the information obtained from the satellite data and longitudinal sections of canals. GIS is used to prepare and integrate the datasets. The study highlights the potential of geospatial technologies to generate reliable model inputs in a data-deficient situation.

Keywords: Groundwater Recharge, Remote Sensing, GIS, and Thar Desert

Introduction

Large scale irrigation projects initiated in the arid and semi-arid environments have provided assured irrigation, greater food security, and enhanced incomes enabling the growth rate of the agricultural sector to be higher than the population growth (Attwood, 2007; Kavadia and Hooja, 1994). However, these systems are prone to environmental degradation, which threaten the massive investments made, and the gains achieved by such schemes. Waterlogging and salinization of soils are two of the major environmental problems associated with large irrigation systems in arid and semi-arid tracts (Strahler and Strahler, 2002; Worster, 1992). The problem is partly due to the nature of the desert environments. In many parts of the sandy deserts, the impermeable layers often underlie permeable sand cover. Such impermeable layers act as hydrologic barriers for the subsurface drainage of irrigation induced groundwater recharge leading to waterlogging problems.

Moreover, when the groundwater table is within 1.5 m from the ground surface, i.e. within the root zone, due to high evapotranspiration rate prevailing in hot tropical and subtropical deserts, salts rise to the surface by capillary action resulting in salinization of soils, thereby rendering the land unsuitable for agriculture (Mishra et al., 1995; NIH, 1996). Moreover, the wasteful use of the scare irrigation resource including excessive water application (WAPCOS, 1995), leakage from poorly lined canals and reservoirs (Heuperman *et al.*, 2002), and inadequate drainage of agricultural land (MacDonald, 1998) exacerbates the natural causes.

Satellite imagery is often looked upon as an important source of information for assessment of desertification/land-degradation (Hellden, 1991; Okin *et al.*, 2001; Prince et al., 1998; Veron *et al.*, 2006); including waterlogging and salinization of soils (Balakram and Chauchan, 2001; Dwivedi and Sreeniwas, 2002; Fouad, 2003; Goyal and Arora, 2003; Khan and Rastoskuev, 2005; Masoud and Koike, 2006). However, as the groundwater table is often close to rather than being at the surface, the role of remote sensing data in assessing the future risk of waterlogging and secondary salinization is limited since satellite images do not provide direct information about the third dimension (subsurface) of the terrain. Generally, water table rise scenarios in response to induced recharge from applied irrigation are simulated using distributed, numerical, surface-water and ground water interaction models or groundwater flow models (Bastiaanssen and Molden, 1999; Gieske and Miranzadeh, 2002; Khan *et al.*, 2004; Singh *et al.*, 2006). Remote sensing and GIS databases are often used for accurate parameterization of the model domain, which is a pre-requisite for the reliability and utility of the model generated risk scenarios. GIS is used for deriving new data layer(s) needed as input to the models by processing a given data layer or by integrating different kinds of data layers, and also for visualization of the model results.

In the irrigated sandy deserts, accurate information on the spatio-temporal distri-bution of the areas contributing groundwater recharge as return flow from irrigation is crucial to the models simulating waterlogging risk scenarios as recharge from rainfall is extremely low. In addition to return flow from irrigation, recharge also takes place through seepage from canal beds for which information on the spatially variable wetted perimeter of canals is required. The present study contributes to generate such information using multi-temporal satellite imagery in the Charanwala irrigation system of Indira Gandhi Nahar Project (IGNP), situated in the Thar Desert. The underlying hypothesis is that the area under irrigated crops in a desert environment could be considered as a surrogate measure of the groundwater recharge zone from where irrigation water percolates downward and meets the groundwater system. The study forms a part of the surface-water and groundwater interaction modelling study initiated in the area. The agricultural year 1999-2000 was selected for modelling because since the agricultural year 2000-2001, irrigation supplies have reduced in the Charanwala area and as a consequence groundwater abstraction through dug-cum-bore wells has begun. No data about the abstraction of groundwater has ever been collected. The decline in irrigation supply, coupled with the groundwater abstraction, has resulted in decline in groundwater table in the areas close to the off-take (upper reach) of Charanwala Branch, while in the middle and tail reaches, the groundwater table is still rising. To avoid modelling such a complicated situation, especially, when groundwater abstraction data are not available, the agricultural year 1999-2000 was chosen. Till that year, irrigation inflows were stable and abstraction in the system by the wells had not commenced.

Study Area

The study area constitutes the upper reaches of the Charanwala irrigation system of the IGNP. It lies between latitudes 27° 48 11 N and 28° 00 30 N, and longitudes 72° 06 28 E and 72° 23 47 E in Bikaner district of Rajasthan (Figure 1). Topography of the area is dominated by high and low sand dunes, interspersed with interdunal flats/ depressions (Dhir *et al.*, 1992; Kar, 2005). The important land cover units in the area are agriculture, plantation, pasture (low sand dunes with shrubs), and sand dunes (high, almost bare). Topography exercises a strong control over the occurrence and distribution of different land covers. For example, agriculture and plantation areas occur in the interdunal flats or depressions, whereas pasture occurs over undulating sand dunes. The surface soils are of aeolian origin, coarse-textured (fine sand to loamy sand) having high infiltration rates (UNDP-FAO, 1971). The return flow from irrigation water supplies and seepage from canal sections, coupled with lack of surface drainage and presence of hydrologic barrier at shallow depth have led to the problem of waterlogging at places in the IGNP command (CADA, 1993; ORG, 1989) including the study area. The Charanwala branch (CWB), Phulasar distributary, Khara distributary, Godu minor and Naryansar minor are the canals serving the area. Out of the total area of 33165 ha, the designed Cultural Command Area (CCA) is 19016 ha.

Data Used

(a) Remote Sensing Data

- ASTER (Advanced Spaceborne Thermal Emission and Reflectance Radiometer) imagery, on-board TERRA satellite, captured on 14th December 2005.
- LISS–III (Linear Imaging Self-scanning Sensor–III) imagery, on-board Indian Remote Sensing Satellite (IRS), captured on 12th May 1999, 14th September 1999, 11th February 2000, and 20th February 2001. The images of 1999 and 2000 were selected because the agricultural year 1999-2000-2001 was chosen for modelling.

(b) Ancillary Data

- Consolidated statistics of the cropped area (source: Mr. M.L. Godara, Assistant Director, Agriculture Extension Wing, CADA, IGNP, personal communication
- Interviews with farmers during field work time and; cropping calendar for choosing the relevant dates for acquisition of the satellite imagery (source: Mr. Dalbir Singh, Agriculture Extension Officer, Agriculture Extension Wing, CADA, IGNP, personal communication.

- Longitudinal-sections of canals (source: Mr. K.L., Dhattarwal, Chief Draftsman, IGNP, personal communication.

Mapping groundwater recharge zones

Groundwater recharge in an irrigated area takes place through the percolation of irrigation applied to the agricultural fields, seepage from the canals, and rainfall. The annual rainfall in the area is scanty (<30 cm), most of which is confined to monsoon season. The poor rainfall coupled with high evapotranspiration rates makes the groundwater recharge from rainfall to be very low, though, it is more or less uniformly distributed all over the area. Thus, the return flow from applied irrigation and the seepage from canal beds form the main source of groundwater recharge.

The irrigation water supplied through canal systems is used for growing the crops in interdunal depressions/flats. Two crops are raised every year in the project command area: one in the monsoon season, known as 'kharif' crop; and second in the winter season, known as 'rabi' crop. Since the land parcels under the crop cover change seasonally in this 'two crops in a year' agricultural system, groundwater recharge zones also vary spatially from season to season. During the summer months (15th March to 10th June), groundwater recharge almost ceases, as there is very little area under crops.

The area under crop during the maturity phase (ground coverage more than 75%) of the crop growth cycle lends itself for quantification using satellite imagery (Jensen, 2003). It is thus considered as a surrogate indicator of the groundwater recharge zone as a source of return flow from irrigation. Further, the seasonal change in the area under the crop cover is considered to represent the corresponding change in the groundwater recharge zones.

The leakage from the canals contribute to the groundwater recharge, whenever there is water in the system (Heuperman *et al.*, 2002; IGNB, 2002; Mishra *et al.*, 1995). But the leakage is different in different sections of the canals depending on their discharge capacity, which decreases downstream from channel-head to channel-tail with the decrease in the area to be served. Hence, it is desirable that the leakage is determined in a spatially distributed form for which the spatially varying wetted perimeter of canals is required. Longitudinal-sections of canals obtained from the irrigation authorities provided information on the cross-section parameters; however, these sections were not spatially referenced in the real-world coordinate system. Therefore, satellite imagery have been used to generate the spatially referenced information on the distribution of canals, which is then integrated with the longitudinal-sections in order to spatially quantify the wetted perimeter of the canal network in the area.

Spatio-temporal distribution of irrigated areas contributing groundwater recharge

The ASTER image (Dec. 05), with high resolution of 15m, was used for preparing the preliminary land cover map using supervised image classification technique with maximum likelihood classifier. Training set was prepared on the basis of ground truth collected during the fieldwork (July–August 2006) and the knowledge of the study area for the classes – 'plantation,' 'pasture,' 'sand dune,' 'fallow,' and 'crop'.

The feature space occupied by different land cover classes is shown in Fig. 2b.

The classified 'preliminary land cover' map of Upper Charanwala is shown in Figure 2c, and associated statistics is given in Table 1. The 'crop' and 'fallow' classes were classified separately, but later merged under the class 'agriculture'. The feature vectors of canals with width varying between 2–10 m (apart from the Indira Gandhi Main Canal (IGMC), mixes with the classes 'fallow' and 'pasture,' and could not be classified accurately. Hence, the canal network was extracted by on-screen visual interpretation and was overlaid on the classified land cover map and integrated with it. The accuracy of classification was tested on the basis of ground truth collected during the fieldwork (Table 2). The overall accuracy of the classification was estimated to be about 77%. The class 'plantation' was extracted very accurately; the classification accuracy was estimated 96%) and reliability as 84%). Since the class 'canal' was visually extracted, it was not tested for accuracy assessment.

The classes 'agriculture' and 'pasture' were misclassified into each other; their producer's accuracy was 0.71 and 0.66, while the user's accuracy or reliability was 0.71 and 0.74, respectively. The low accuracy and reliability can be mainly attributed to inappropriate date of acquisition of ASTER image (i.e. month of December). During this period, as mentioned earlier, either the rabi crop was being sown or was under the initial development phase, which resulted in mixing of the spectral signature of 'fallow' agricultural fields and 'pasture' classes. 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 than 50% of the ground cover fraction in the month of December belongs to this class.

In short, though the high-resolution ASTER image allowed extraction of 'plantation' areas with high accuracy, the classification accuracy was low for the 'agriculture' and 'pasture' classes. For improving the classification accuracy of these two classes, and to map the seasonal changes in the irrigated crop cover, multi-temporal satellite imagery obtained from IRS LISS–III (spatial resolution 23.5 m) acquired during three seasons – summer (12th May 1999), monsoon (14th September 1999) and winter (11th February 2000) – in an agricultural year have been used. The agricultural statistics of the Charanwala area for 'kharif' (monsoon) as well as 'rabi' (winter) seasons for the agricultural years 1999–2000 and 2000–2001 obtained from CADA (Table 3) were used as ancillary data. These statistics provided consolidated information for the entire Charanwala irrigation system falling in two different revenue tehsils; therefore, it was not possible to disaggregate the statistics based on CCA of canals (comprising of branch, distributary, minor, and sub-minor) covered in the study area. According to CADA authorities the total area under crops in the upper Charanwala area (study area) can be assumed to be about 25 to 30% of the total area under crops in the entire Charanwala irrigation system.

The LISS–III images were registered with the ASTER image; the RMS error of registration was 0.21 for the May image, 0.25 for the September image, and 0.24 for the February image. Normalized Difference Vegetation Index (NDVI)

Table 1: Area statistics of different land cover classes derived from ASTER image of 14th December 2005.

		Area	
Land Cover	No. of pixels*	Hectares	% of Total Area
Agriculture**	280158	6303.6	19.0
Pasture	498490	1216.0	33.8
Plantation	66777	1502.5	4.5
Sand dune	623113	14020.0	42.3

**of 15 m x 15 m; **including crop land and fallow land*

Table 2: Confusion matrix of preliminary land cover map prepared based on supervised classification of ASTER image of 14th December 2005.

	Agriculture	Pasture	Plantation	Sand dune	Accuracy
Agriculture	51	11	7	3	0.71
Pasture	18	50	2	6	0.66
Plantation	1	0	46	1	0.96
Sand dune	2	7	0	49	0.84
Reliability	0.71	0.74	0.84	0.83	

Table 3: Crop area statistics of entire Charanwala irrigation system for agricultural years 1999-2000.

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

(Source: Mr. M.L. Godara, Assistant Director, Agricultural Extension Wing, CADA, personal communication, 10th September 2006).

images were generated for the above three LISS–III images. These NDVI images were thresholded to map the vegetated cover, i.e. the pixels with NDVI value equal to or above the threshold level were assumed to represent the vegetated cover. The thresholds were arrived at by trial and error method, considering the plantation area mapped using ASTER image and the cropped area statistics (obtained from CADA) as guide. For classifying the vegetation from the LISS–III images of summer (May 1999), kharif (September 1999), and rabi (February 2000) periods, NDVI thresholds were used respectively.

From the pixels representing the ground covered by vegetation, the area under the class 'plantation' as determined by the preliminary land cover map prepared using ASTER image was masked out; the remaining vegetated areas represented the irrigated cropped area during kharif, rabi, or summer seasons. These irrigated cropped areas in turn represent the spatial distribution of ground water recharge zones (Figure 3).

To validate the results obtained using NDVI thresholding technique discussed above, an image captured on February 20, 2001 representing the area under the rabi crop in the successive agriculture year of 2000-2001 was acquired and analysed. The same NDVI threshold of '0 and above' was applied to this image (Figure 3d) as was used upon the February 2000 image for classifying the area under crop cover, so that the satellite based results (cropped area statistics) could be compared with the information available from the irrigation authorities for two consecutive agriculture years. Table 4 provides the comparison of the cropped area statistics derived from multi-temporal satellite images and that available from the irrigation authorities. It is observed from Table 4 that the satellite based results match well with the ground based information. It is mentioned again that the crop area is assumed to be ranging between 25 and 30% of the entire Charanwala irrigation system. The area under crop cover was much lower in the rabi season of the agriculture year of 2000–2001 as compared to that in the previous year due to substantial decline in the irrigation inflows (WCCR, 2002). The crop area returned by the NDVI threshold of '0 and above' for the LISS-III imagery of the corresponding period also shows the similar decline. Therefore, the spatial distribution of the seasonal crop cover mapped through satellite images can be considered to be quite close to the actual ground conditions, thereby also indicating the efficacy of the approach of using NDVI thresholds for classifying the crop cover.

As mentioned earlier, the area contributing to ground water recharge as a result of return flow from irrigation varies intra- and inter-annually depending on the spatial distribution and areal extent of irrigated crops, which in turn depend on the canal inflows. The irrigated crop cover maps prepared from the satellite images pertaining to different cropping seasons within an agriculture year can be integrated in GIS to prepare a single map depicting spatio-temporal variations in the ground water recharge zones in the irrigated landscape. Such a map is presented in Figure 4a, wherein irrigated crop maps of kharif (September 1999) and rabi (February 2000) seasons were combined using the 'cross' operation in ILWIS software. This

Table 4: Comparison of cropped area statistics extracted from the IRS LISS-III images and that available from CADA.

		Crop Area as per CADA (ha)		
Agricultural Year (Season)	Crop Area from LISS-III Images (ha) for Study Area	Total Area in Charanwala Irrigation System	30% Share of entire Charanwala System for Study Area	25% Share of entire Charanwala System for Study Area
1999-2000 (Kharif)	5243	17300	5190	4325
1999-2000 (Rabi)	5806	20567	6170	5142
2000-2001 (Rabi)	2412	8835	2651	2209

Table 5: Area statistics of groundwater recharge zones causing return flow from irrigation to ground water system in the study area (Upper Charanwala irrigation system) as extracted from multi-temporal IRS LISS–III images.

Period	Type of Area	No of pixels*	Area (ha)
May 1999	Area Contributing GW Recharge from Irrigation	6522	360
	Background Area	594032	32805
September 1999	Area Contributing GW Recharge from Irrigation	94942	5243
	Background Area	505612	27922
February 2000	Area Contributing GW Recharge from Irrigation	108437	5988
	Background Area	492117	27177
February 2001	Area Contributing GW Recharge from Irrigation	46548	2570
	Background Area	554006	30594

**of 23.5 m x 23.5 m; GW–Groundwater*

map depicts the agricultural parcels leading to groundwater recharge due to return flow from irrigation in either the rabi or kharif or during both the seasons. The area statistics of such ground water recharge zones as mapped from the LISS–III images of 1999, 2000 and 2001 are given in Table 5. During the summer period, represented by May image, very little area (only about 6–7% of that during kharif and rabi periods) is under crop cover as little water is available in the irrigation system at this time. Due to limited irrigation availability, only in few farms located in close vicinity to the irrigation channels, some fodder crop could be grown. This crop continues to grow through the kharif season. This is also the time for the preparation of fields or sowing of long duration kharif crops like cotton. Since these crops are represented in the kharif crop map as well, they are not represented as separate summer crop category in Figure 4a along with that of kharif and rabi periods.

Table 6: Area statistics of different land cover classes derived from integration of ASTER and multi-temporal LISS-III images.

		Area	
Land Cover	No. of pixels*	Hectares	% of Total Area
Agriculture**	127603	7047	21.5
Pasture	209166	11551	34.9
Plantation	27241	1504	4.3
Sand dune	233991	12922	38.9

**of 23.5 m x 23.5 m; **including crop land and fallow land*

Table 7: Confusion matrix of final land cover map prepared from integration of ASTER and multi-temporal LISS-III images.

	Agriculture	Pasture	Plantation	Sand dune	Accuracy
Agriculture	64	3	6	0	0.88
Pasture	10	58	2	6	0.76
Plantation	3	0	44	1	0.92
Sand dune	2	8	0	48	0.83
Reliability	0.81	0.84	0.85	0.87	

It is important to note that the actual irrigated area during kharif and rabi seasons of agriculture year of 1999–2000 is only 28–31% of the designed CCA. The quantum of groundwater recharge and evapotranspiration depends not only on the quantum of water applied but also on the area of application of irrigation water. The evapotranspiration would be lower and recharge would be higher if a given quantum of irrigation water is applied over a smaller area; whereas, vice versa would happen if the same quantum of water is applied to a larger area. It, therefore, implies that considering the entire CCA as the groundwater recharge zone would have led to erroneous results on water balance components and simulated scenarios of groundwater table. The recharge zone map as presented in Figure 4a can be used to spatially allocate the water applied for irrigation based on the data of canal inflows and supply to prepare reliable inputs for distributed hydrologic models.

The maps showing irrigated crop areas, prepared using multi-temporal LISS–III images, have been integrated with the preliminary land cover map prepared using ASTER image to derive the 'final land cover' map (Figure 4b). This map retains the classes 'plantation' and 'canal' extracted from the ASTER image, and the class 'agriculture' extracted from LISS–III images. As a consequence of this integration, the area under the land cover classes 'pasture' and 'sand dune' also underwent small changes. The statistics of area under different land cover categories is provided in Table 6. The accuracy of this map was checked using the ground-truth collected in the field (Table 7). The overall classification accuracy of this map improved to 81.5%, and the overall reliability improved to 84.6%. More importantly, the reliability of the classes 'agriculture,' 'pasture' and 'sand dune' improved to 81%, 84% and 87%, respectively (Table 7). The 'agriculture' class of this map delimits the overall distribution of groundwater recharge zones in the area where applied irrigation water can percolate downward to reach the groundwater system. It is also shown that the multi-sensor and multi-temporal datasets could be used to derive complementary information, which when integrated helped improve the overall accuracy of the land cover map prepared using a single dataset.

Estimation of wetted perimeter of canals

To calculate the gradually declining wetted perimeter of canals from their head to tail, the longitudinal-sections of the canals in study area were procured from the irrigation authorities. To geo-reference this information, the irrigation canals – Indira Gandhi Main Canal (IGMC), Charanwala Branch, Phulasar Distributary, Khara Distributary, Godu Minor, and Naryansar Minor (Figure 1) – interpreted from ASTER image were stored as segment maps using ILWIS software. ASTER image was used for interpretation of canals because of its better spatial resolution (15 m) as compared to that of LISS–III image (23.5 m). Each segment map was converted to a point map, with one point recorded for every successive 5 m sub-section of canal length. These maps were opened as tables, and distance downstream from the off-take, i.e. from the head to the tail, were read for each point coordinate using the following operator:

Distance = (%R-1) * 5,

where, %R is a predefined variable in ILWIS, and refers to the record indexes of the coordinates of point map (ILWIS, 2001). The formula results in distances in meters from the canal off-take. The wetted perimeters of the canals were calculated from canal cross-section parameters, i.e. bed width, side slope, and full supply depth, extracted from the longitudinal-sections of the canals. The wetted perimeter information was added as an attribute to each of the record index in the table, and point maps were created using the wetted perimeter attribute. These point maps were rasterized and resampled to the model grid's spatial resolution; and finally, glued together into one map showing canals with their wetted perimeters (Figure 5). This map can be linked with the daily irrigation inflow time series for determining the spatio-temporally varying leakage from canals.

Conclusions

This study demonstrates the role of remote sensing data in generating the spatio-temporally distributed information on the actual area contributing to groundwater recharge due to return flow from irrigation, and in estimating the spatially varying wetted perimeter of canals in an irrigated desert landscape. The information generated has been used to spatially and temporally allocate the quantum of applied irrigation water as input to surface-water and groundwater modelling study initiated in the area for simulating the risk of waterlogging in response to applied surface water irrigation. The study also underscores the potential of remote sensing data for disaggregating the official revenue statistics on the cropped area, which are rather easily available but do not have much value for distributed environmental modelling. The methodology adopted also has implications for the highly desirable change detection studies, for example periodic evaluation of irrigation project performance.

Acknowledgements

This study forms a part of the research carried out by the first author (RB) under the joint Geohazards research and education program between the Indian Institute of Remote Sensing (IIRS) and International Institute for Geo-information Science and Earth Observation (ITC). University Grants Commission, India provided valuable financial support. RB and SKS are grateful to Prof. R.C. Lakhera, Head, Geosciences Division, and Dr. V.K. Dadhwal, Dean, Indian Institute of Remote Sensing, Dehradun for their support and encouragement. We also thank the Mr. Birdichand, Assistant Chief Engineer, Indira Gandhi Nahar Project (IGNP) and Mr. M.L. Godara, Assistant Director, Agriculture Extension Wing, Command Area Development Authority, Bikaner for providing relevant data required for the present study.

References

Attwood, D.W., 2007. *Small is deadly, big is wasteful: the impact of large scale industrial systems in India.* In: A. Bavisksr (Editor), *Waterscapes.* Permanent Black, Ranikhet, Uttranchal, pp. 11-39.

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.

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

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.

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.

Dwivedi, R.S. and Sreeniwas, 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.* M.Sc. Thesis, ITC, Enschede.

Gieske, A. and Miranzadeh, M., 2002. *Groundwater Modelling of the Lenjeanat Aquifer System.* 15. IAERI, EARC, IWMI.

Goyal, R. and Arora, A.N., 2003. Use of Remote Sensing in Groundwater Modelling. *G.I.S. Development.*

Hellden, U., 1991. Desertification: time for an assessment. *Ambio,* 20: 372–383.

Heuperman, A.F., Kapoor, A.S. and Denecke, H.W., 2002. *Biodrainage: Principles, Experiences and Applications.* IPTRID, Rome, 79 pp.

IGNB, 2002. *History of Indira Gandhi Nahar: A Venture to Turn Desert of Rajasthan into Granary*, Indira Gandhi Nahar Board, Bikaner.

ILWIS, D., 2001. *Chapter10: Digital Elevation Models, ILWIS 3.0 Academic*, User's Guide. ITC, Enschede, pp. 387-415.

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

Kar, A., 2005. *Sand Dunes of the Thar Desert: Relevance of Process and Morphology in Sand Control Measures.* In: S.C. Kalwar, M.L. Sharma, R.D. Gurjar and S.K. Wadhawan (Editors), *Geomorphoogy and Environmental Sustainability.* Concept Publishing Company, New Delhi, pp. 3-19.

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, pp. 17-49.

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., King, P., Wang, B., Best, L. and Short, L., 2004. Role of GIS, Remote Sensing and Hydrology in the Environmental Management of Rice Growing Areas, Australia.

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

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.

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.

NIH, 1996. *Drainage Manual. Report*, National Institute of Hydrology, Roorkee, India.

Okin, G.S., Murray, B. and Schlesinger, W.H., 2001. Degradation of sandy arid shrub-land environments: observations, process modelling, and management implications. *Journal of Arid Environments,* 47(2): 123-144.

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

Prince, S.D., Brown de Colstoun, E. and Kravitz, L.L., 1998. Evidence from rain-use efficiencies does not indicate extensive Sahelian desertification. *Global Change Biology*, 4: 359–374.

Singh, R., Jhorar, R.K., van Dam, J.C. and Feddes, R.A., 2006. Distributed ecohydrological modelling to evaluate irrigation system performance in Sirsa district, India II: Impact of viable water management scenarios. *Journal of Hydrology*, 329(3-4): 714-723.

Strahler, A. and Strahler, A., 2002. *Physical Geography: Science and Systems of the Human Environment.* John Wiley and Sons Inc, Singapore, 750 pp.

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

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

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

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

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

Rajesh Bhakar*
Govt. Dungar College,
Bikaner, India
**Corresponding Author*
e-mail: rajeshxbhakar@gmail.com

H.S. Sharma
University of Rajasthan,
Jaipur,India

S.K. Srivastav
Indian Institute of Remote
Sensing, Dehradun,
India

Victor Jetten
International Institute
for Geo-information
Science and Earth Observation,
The Netherlands

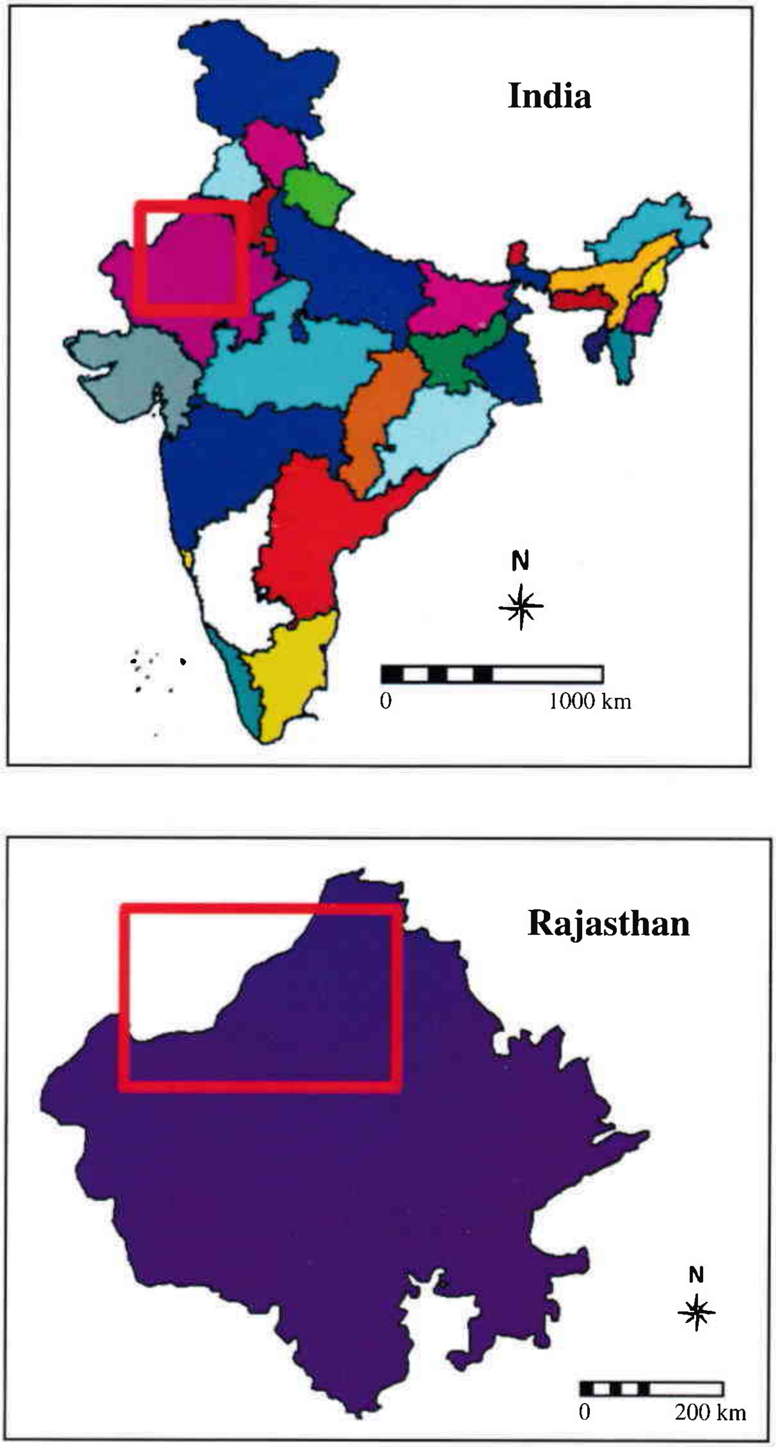
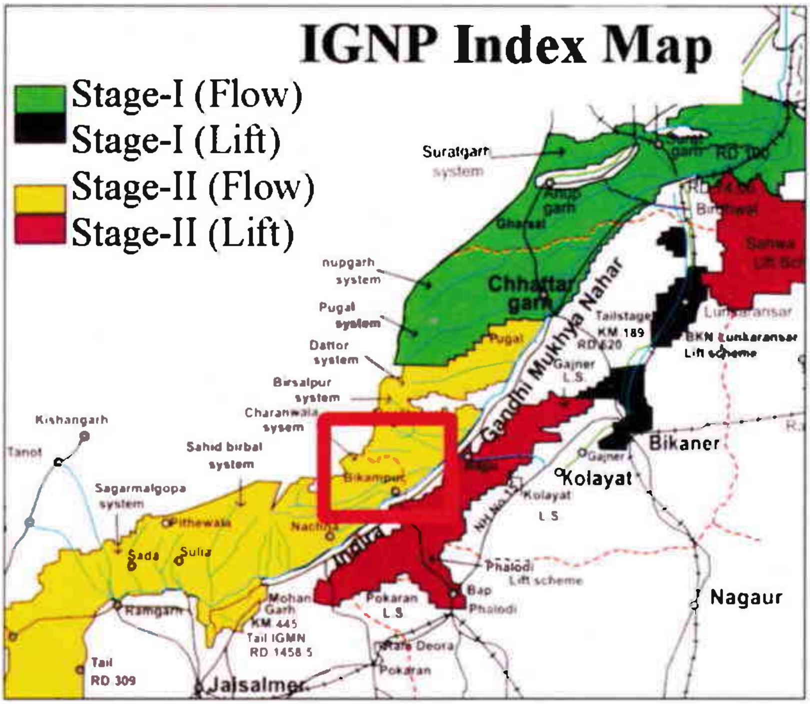


Fig. 1(a): Location map of the study area



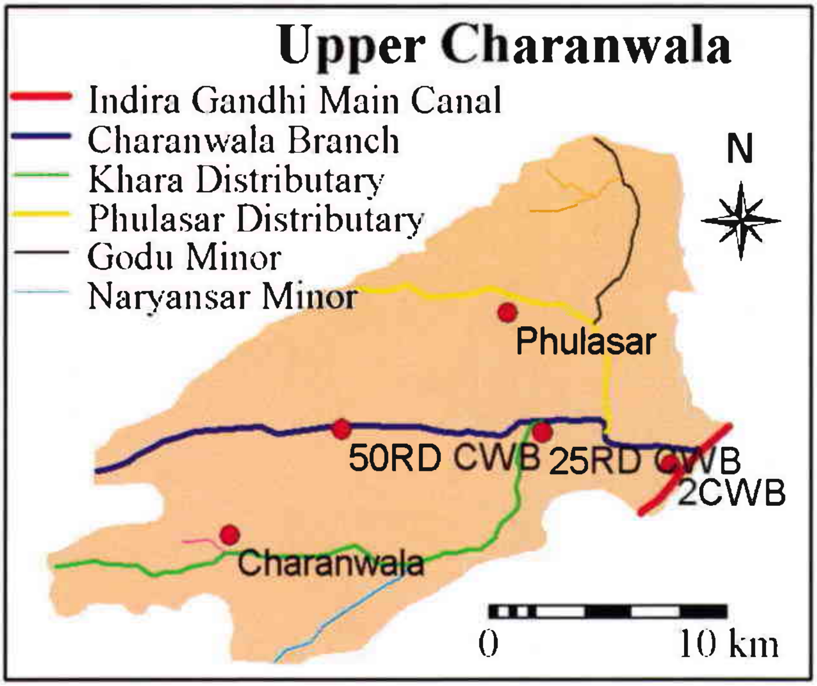


Fig. 1(b): Location of IGNP and Upper Charanwala

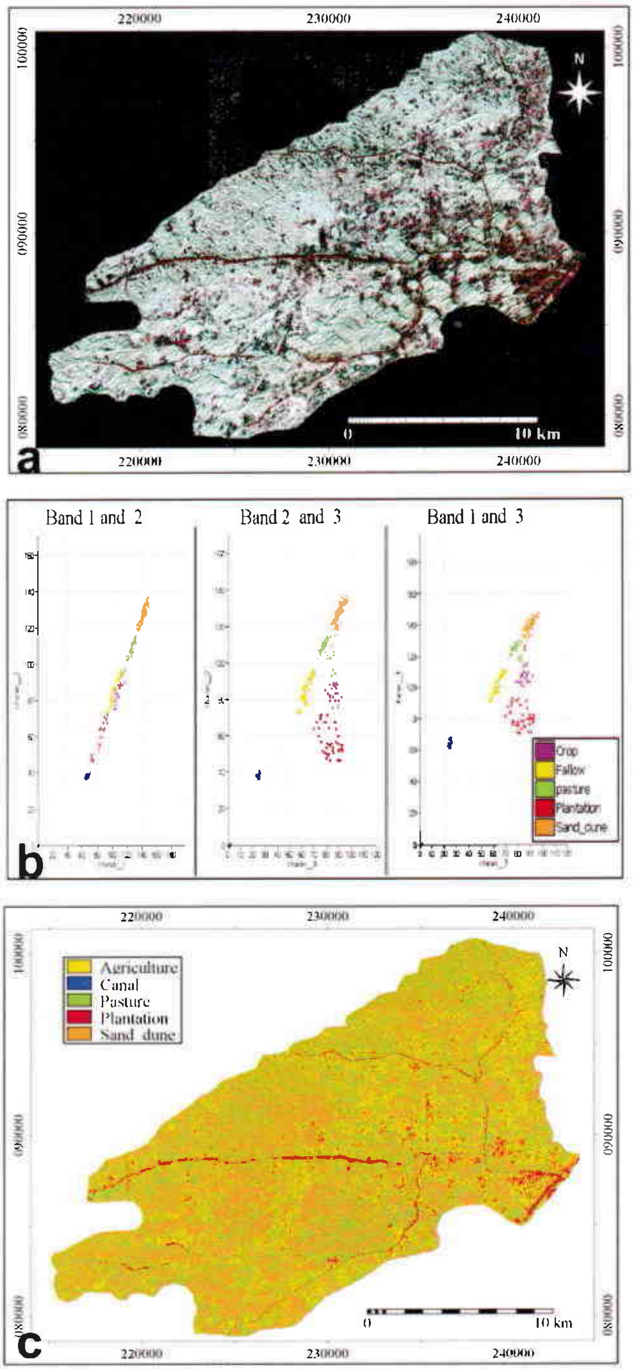


Fig. 2 : (a) ASTER image of the study area captured on 14th December 2005; (b) Feature space occupied by different land cover classes; and (c) Preliminary land cover map of the study area prepared from ASTER image

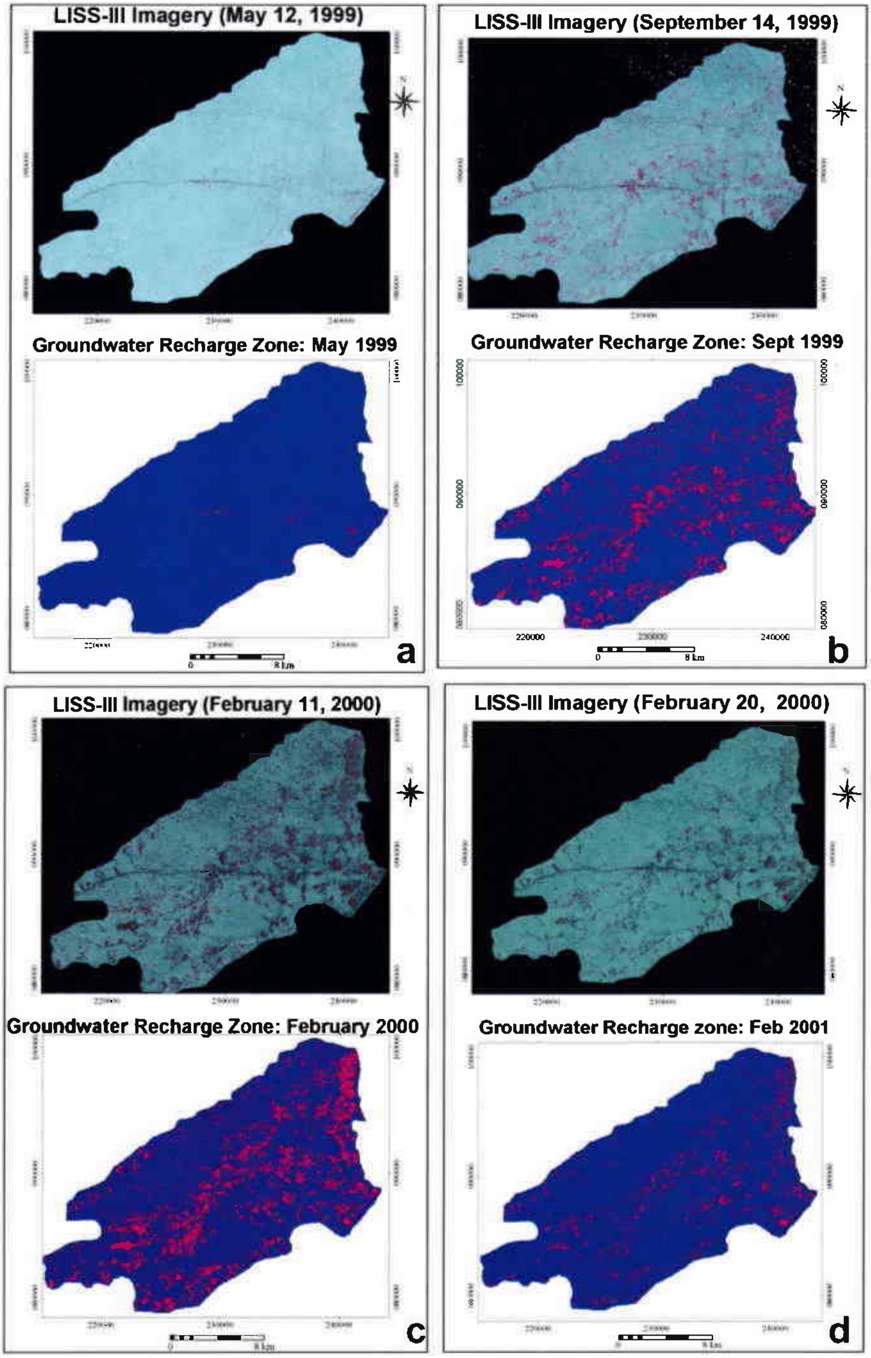


Fig. 3: Spatial distribution of areas contributing groundwater recharge due to return flow from irrigation, extracted from multi-date IRS LISS–III images: (a) 12th May 1999; (b) 14th September 1999; (c) 11th February 2000; and (d) 11th February 2001.

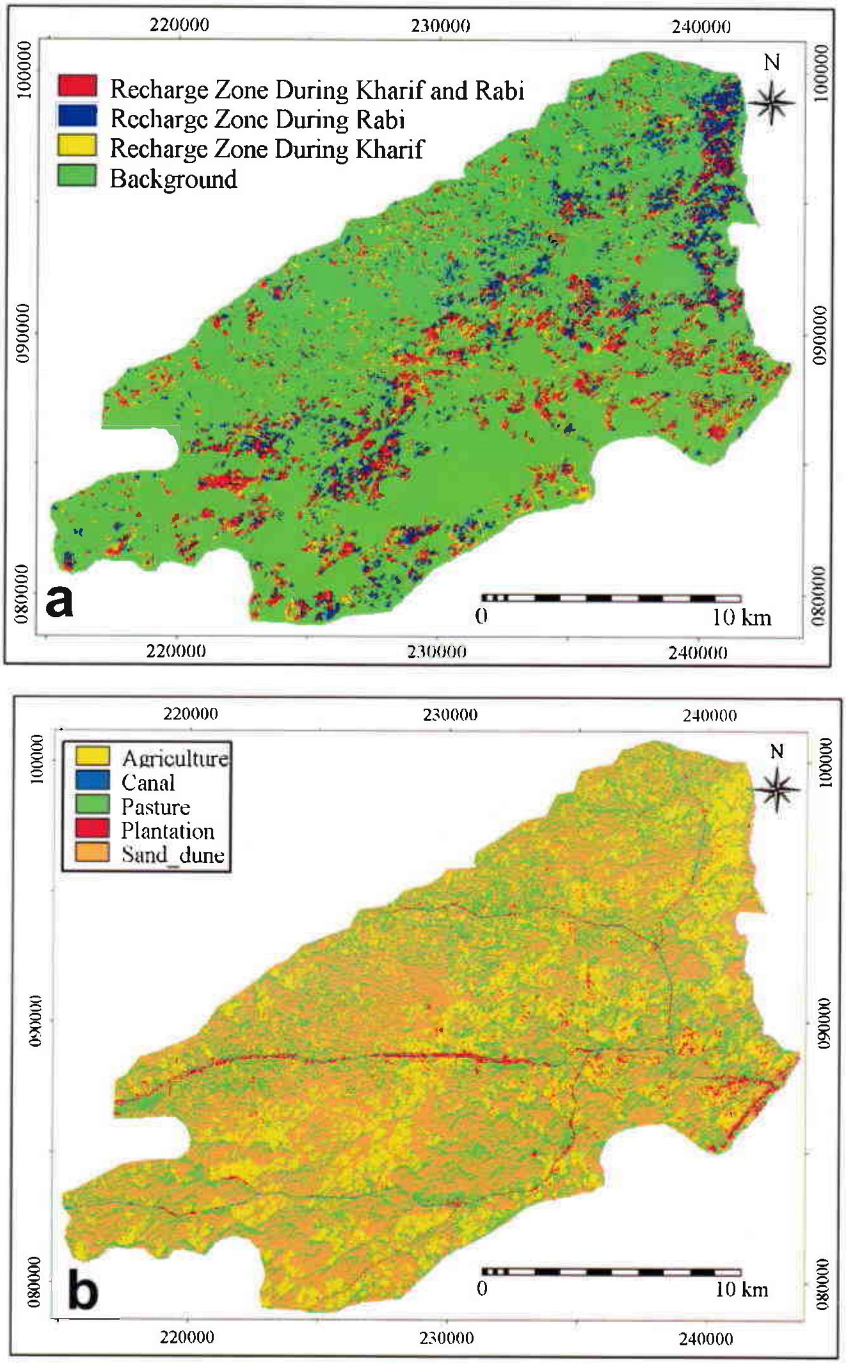


Fig. 4: (a) Spatio-temporal distribution of areas contributing groundwater recharge due to return flow from irrigation, extracted from IRS LISS–III images of kharif and rabi seasons; (b) final Land Cover map prepared using multi-date ASTER and LISS–III images.

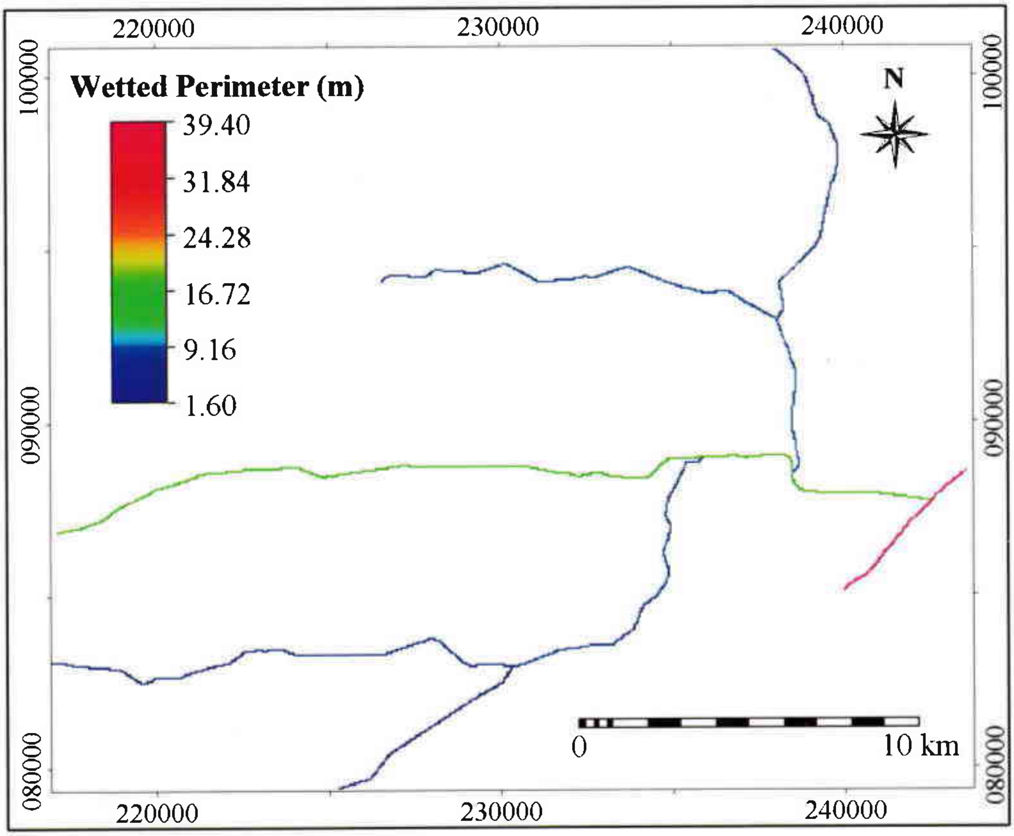


Fig. 5: Map showing wetted perimeter of canals