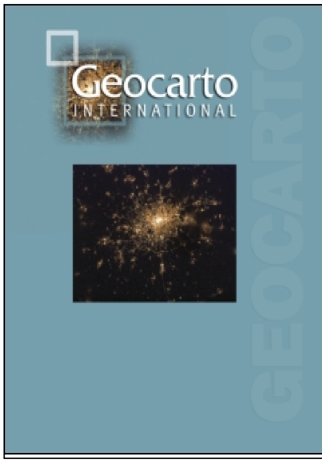

Geocarto International

Publication details, including instructions for authors and subscription information:
http://www-intra.informaworld.com/smpp/title~content=t759156373

Delineation and characterization of waterlogging and salt affected areas in a canal irrigated semiarid region of north west India

A. K. Mandal [a]; R. C. Sharma [a]
[a] Central Soil Salinity Research Institute, Karnal, Haryana, India

First Published: June 2008

To cite this Article: Mandal, A. K. and Sharma, R. C. (2008) 'Delineation and characterization of waterlogging and salt affected areas in a canal irrigated semiarid region of north west India', Geocarto International, 23:3, 181 — 195

To link to this article: DOI: 10.1080/10106040701207449
URL: http://dx.doi.org/10.1080/10106040701207449

Geocarto International
Vol. 23, No. 3, June 2008, 181–195

Delineation and characterization of waterlogging and salt affected areas in a canal irrigated semiarid region of north west India

A. K. MANDAL* and R. C. SHARMA
Central Soil Salinity Research Institute, Zarifa Farm, Kachhwa Road, Karnal, Haryana 132001, India

(*Received 6 January 2007; in final form 10 January 2007*)

Indian Remote Sensing (IRS) Linear Imaging Self Scanning (LISS II) data are interpreted, followed by ground verification facilitated identification of waterlogged areas (ponded water), salt affected soils (salt efflorescence) and high water table zones (potential waterlogging zones) in the Indira Gandhi Nahar Pariyojona (IGNP) command area (India). The false colour composites (bands 4, 3, 2) for February 1996, November 1996 and June 1998 on 1:50 000 scale revealed occurrence and seasonal dynamics of permanent waterlogging in low-lying flats and depressions. The extent of waterlogging was higher in February 1996 due to less evaporation and more agricultural operation during the period. Salt accumulation was higher in November 1996 due to freshly precipitated seasonal salts. Seepage and accumulation of excess irrigation water through coarse sandy mass was primarily responsible for the development of waterlogging in the irrigated zone. The capillary rise of soluble salts with a rising water table and high evaporative demand caused secondary soil salinization. A ground truth study found areas with a high water table (<1.5 m) with patchy crop stands and a potentially sensitive zone with a fluctuating (1.5–6.0 m) water table with poor vegetative growth. The soil characteristics showed moderate to high soil salinity in the control section of soil profiles. These were characterized by medium to coarse texture, weak to moderately strong structure, weak consistency, low organic matter content and the presence of abundant $CaCO_3$ nodules. The composition of saturated soil paste showed a preponderance of chlorides and sulphates of sodium, calcium and magnesium. The presence of fine texture and calcium carbonate layers at a depth below the surface caused the development of a perched water table indicating unsuitability for traditional irrigated agriculture. The quality of pond water was extremely poor and unfit for reuse. The ground water was saline in some areas but normally lies within the prescribed limit. The quality of drainage water was poor in saline depressions and unsuitable for reuse but moderate in other areas suggesting its safe reuse when mixed with good quality water. Suitable soil and water management practices were necessary for sustainable crop production in the command area.

Keywords: Salt affected soils; Remote sensing; Waterlogging; Water quality

*Corresponding author. Email: akmondal@cssri.ernet.in

Geocarto International
ISSN 1010-6049 print/ISSN 1752-0762 online © 2008 Taylor & Francis
http://www.tandf.co.uk/journals
DOI: 10.1080/10106040701207449

1. Introduction

Soil and water are the basic natural resources for agriculture and economic development of the nation. Canal irrigation was introduced in the north west part of Rajasthan State, commissioning Indira Gandhi Nahar Pariyojona (IGNP) to irrigate nearly 2.2 million ha of arid lands. Although irrigation has enhanced considerable food production, it also brought problems, namely waterlogging and secondary salinization. Indiscriminate use of irrigation water, canal seepage, sandy texture and absence of natural surface drainage are considered to be the main reasons for soil degradation (Shankarnarayana and Gupta 1991). Fluctuations of the water table during wet and dry cycles initiated the development of secondary salinization (Sharma and Mathur 1991; Hooja *et al*. 1995). Indian Remote Sensing (IRS) data emerged as a potential tool for monitoring salt affected soils (Mougenot *et al*. 1993, Dwivedi and Sreenivas 1998, 2002, Dwivedi *et al*. 1999, Khan *et al*. 2005). Visual interpretation of the IRS data was used to delineate salt affected and waterlogged soils (Sharma and Bhargava 1988, Sharma *et al*. 2000, Sujatha *et al*. 2000). Spectral classification of salt affected and waterlogged areas was done using computerized analysis of digital data (Chaube 1998, Dwivedi and Sreenivas 1998). Permanently and seasonally waterlogged areas were successfully mapped with remote sensing data (Kaluberme *et al*. 1983, Mandal and Sharma 2001). However, the areas with high water tables are still in the realm of research. An attempt was made to evaluate the waterlogging and soil salinity condition in the IGNP (Stage I) command area integrating remote sensing and a ground survey.

2. Site characteristics

The area lies between 29°00′N and 29°35′N latitude and 74°00′E and 74°40′E longitude (figure 1) irrigated by the IGNP main canal (Indira Gandhi Mukhya Nahar) and its branches. Pearl millet, sorghum, cluster bean and sesamum are mainly grown in the summer (*kharif*) season, wheat and gram in the winter (*rabi*) season. Paddy, sugarcane, cotton, mustard are also cultivated. The climatic parameters categorize the soils in Ustic and Hyperthermic soil moisture and temperature regimes (figure 2). The soils are subject to wind erosion of moderate to severe intensity and are situated above 180–200 m above mean sea level (msl). Sandy plains, sand dunes, flood plains, depressions, interdunal flats are the common landforms of the area (Singh and Kar 1991). According to a FAO/UNDP (1971) survey report, out of 2.2 m ha, 59% of the land is non-irrigable and about 80% of the irrigable land is sandy in nature. The water table depth is reported to be rising by 1–2 m per year (Hooja *et al*. 1995, Government of Rajasthan 1999). Flood irrigation practice, canal seepage, sandy soil texture and absence of natural surface drainage are some of the major limitations for sustained irrigated agriculture.

3. Material and methods

3.1 *Data and software used*

Preprocessed (atmospheric and radiometric corrections) IRS LISS II geocoded imageries (FCC, bands 432) for February 1996, November 1996 and June 1998 on 1:50 000 scale, the Survey of India topomaps and other ancillary information were

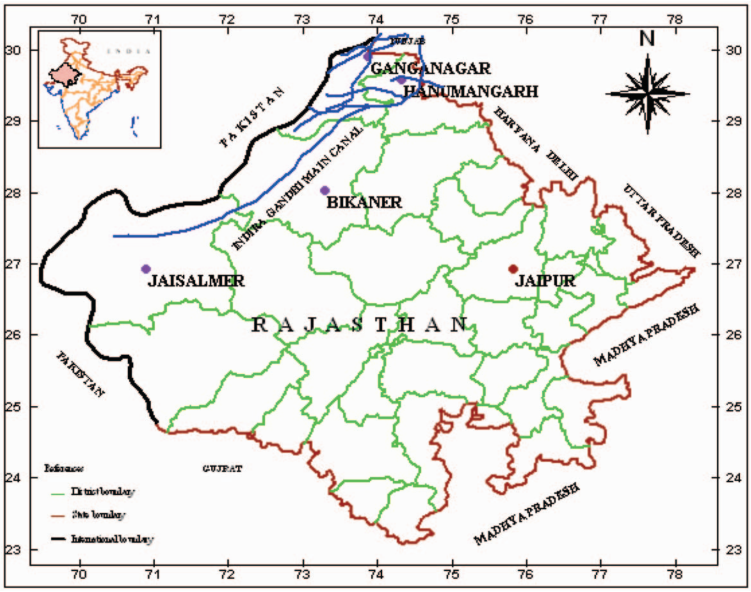

Figure 1. Location of Indira Gandhi Canal Command, Rajasthan, India.

used for the identification of waterlogged and salt affected areas (table 1). The digital data for February 1996 were used for detailed analysis and classification. The software Integrated Land and Water Information System, version 3.3 (ILWIS) was used for image processing, digitization, map calculations and overlaying multiple data layers for image interpretation and output generation.

3.2 *Georeferencing, image processing and basemap preparation*

The Survey of India topomaps on 1:50 000 scale were georeferenced and digitized to generate thematic layers of administrative and political boundaries (State/district); irrigation and drainage; infrastructure (roads, railways) and settlements (State/district HQs) then overlaid to prepare a base map of the study area. IRS (digital) imageries were georeferenced using the Survey of India topomaps and resampled for geocoding using ILWIS software. The false colour composites were used for visual interpretation and seasonal dynamics of waterlogged areas and salt affected soils (figures 3–6). The interpreted units were digitized and polygonized using ILWIS software (figure 7). A flow-chart describing the methodology for identification and delineation of waterlogging and salt affected soils was prepared (figure 8).

3.3 *Field survey and characterization of soil samples*

A field check was carried out during the post-monsoon season for spot identification and image correlation. The interpreted units were verified in the field for waterlogging and soil salinity conditions and other land uses (table 2). The sampling sites for soil profiles (excavated pit to a depth of 1.5 m) were selected and studied for

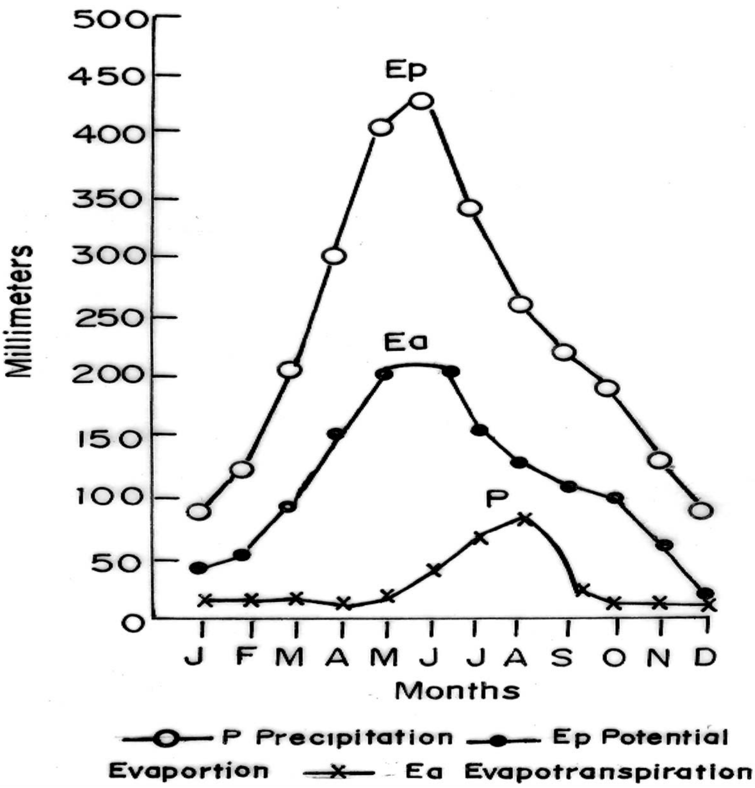

Figure 2. Mean monthly precipitation, potential evaporation and evapotranspiration in Indira Gandhi Nahar Pariyojona (IGNP).

Table 1. Particulars of satellite imageries.

Sensor	Spectral resolution	Spatial resolution	Image/SOI topomap no. and scale	Period
IRS- IB LISS II	B1 0.45–0.52 (Blue) B2 0.52–0.59 (Green) B3 0.62–0.68 (Red) B4 0.77–0.86 (NIR)	36.25 m Swath 148 km No. of pixel/ha 7.61	44 K03, K07, K10, K11, K12, G15, G16 Scale 1: 50 000 scale	FCC: February 1996 November 1996 June 1998 Digital data: February 1996

morphological characteristics (Soil Survey Staff 1995). The soil samples were collected from the master horizons of the soil profile for laboratory determination of physico-chemical characteristics of soils. The water samples were collected from the accumulated seepage lakes (*Tal*), auger bore and profile pits. The water table depths were recorded at some selected locations during the auger bore and profile studies. Standard methods were followed for determining mechanical composition, calcium carbonate, cation exchange capacity (CEC), and exchangeable sodium percentage (ESP) (Jackson 1967). Saturation extracts of soils samples were prepared and

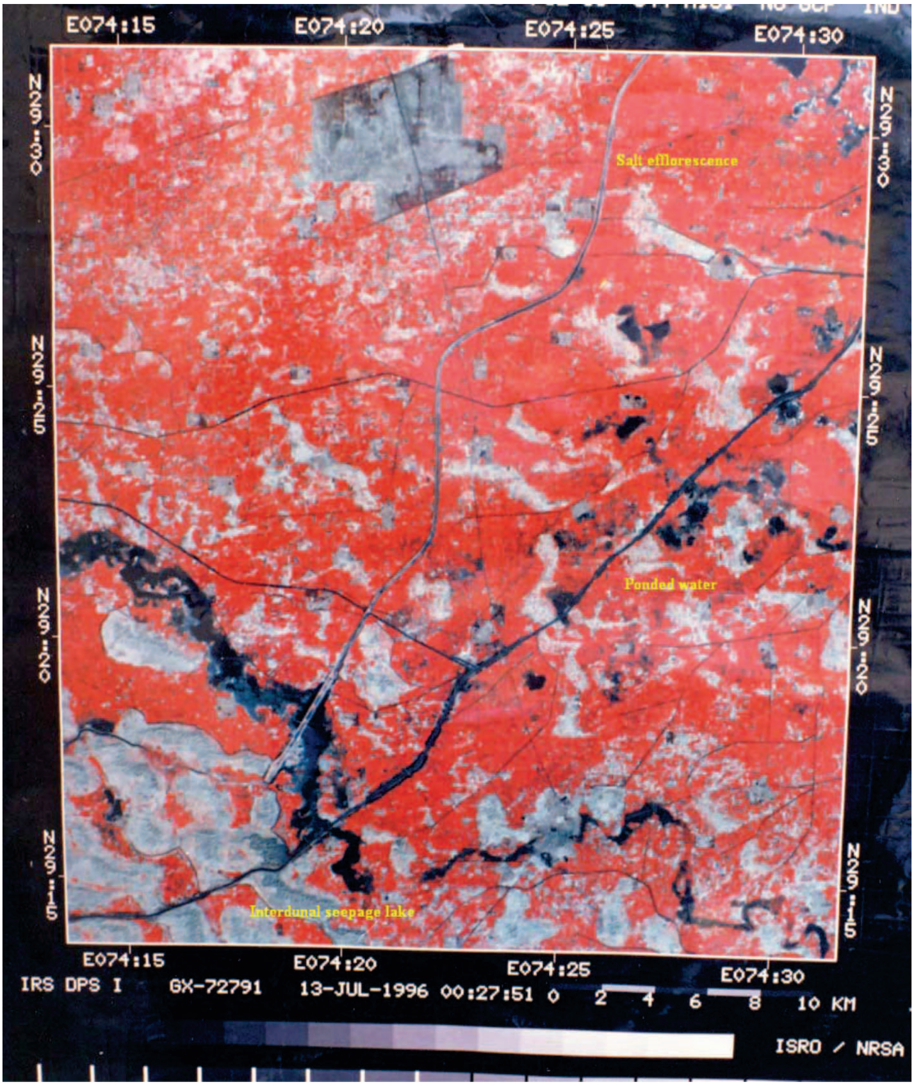

Figure 3. Imagery showing waterlogged and salt affected areas in February 1996.

analysed for pHs, electrical conductance of saturation extract (ECe), soluble cations and anions (Richards 1954). Water samples were analysed for pH, EC_{iw}, Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}, CO_3^{2-}, HCO_3^-, and SAR [Sodium Adsorption Ratio $= Na^+/(Ca^{2+} + Mg^{2+}/2)^{1/2}$] for quality appraisal (table 4) using standard methodology (Richards 1954).

4. Results and discussion

4.1 *Image interpretation and ground truth*

The interpretation of IRS data revealed prominent waterlogging as a dark blue to black tone for surface ponding (pond water) in low-lying flats and depressions.

Figure 4. Imagery showing waterlogged and salt affected areas in June 1998.

Permanent waterlogging was found in the buried paleochannel of river Saraswati (interdunal seepage lake) and natural depressions (Ghaggar depression) due to seepage and accumulation of irrigation water and diversion of flood water from the river Ghaggar (figures 3–5). Salt efflorescence was identified as a grey to yellowish white tone in (Kalra and Joshi 1996) irregular patches around the waterlogged areas (figure 5). The areas appearing in variable tones and textures (light grey to dark grey and red mottling) indicated the presence of a high water table or a potential waterlogging zone. The ground survey also identified critical areas with shallow water table depth (0–1.5 m) and a potentially sensitive zone with a fluctuating water table depth (1.5–6.0 m). Due to a close spectral signature and spatial association, these two categories were merged in the final classification (Mandal and Sharma 2001). The data from pre-monsoon (February 1996), post-monsoon (November

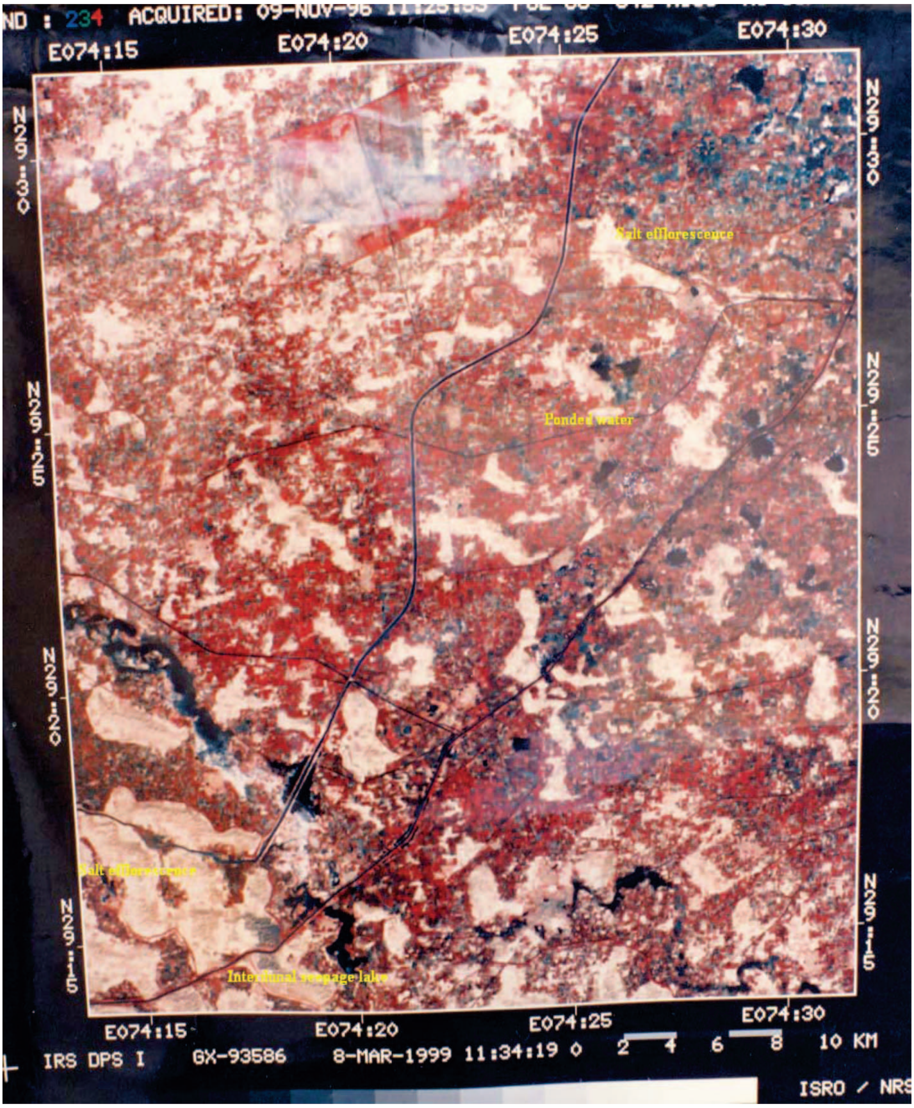

Figure 5. Imagery showing waterlogged and salt affected areas in November 1996.

1996) and summer (June 1998) seasons revealed seasonal dynamics of waterlogging in irrigated areas, interdunal flats and depressions areas (figure 6). Due to close spectral signatures, higher atmospheric influences over the incident and reflected radiations, and strong aeolian activity, the intermixture of sand and salt was difficult to separate during visual interpretation (Mandal and Sharma 2001). Surface salinization was higher in November due to freshly precipitated salts and higher evapotranspiration (Mandal and Sharma 1997). The aerial extent of waterlogging was higher during February, probably due to less evaporation and higher irrigation frequencies for agricultural operations during the period. The area statistics showed that the waterlogged areas significantly occupied 22 268 ha (5.4%) while salt efflorescence and the potential waterlogging zone covered 3342 ha (0.82%) and

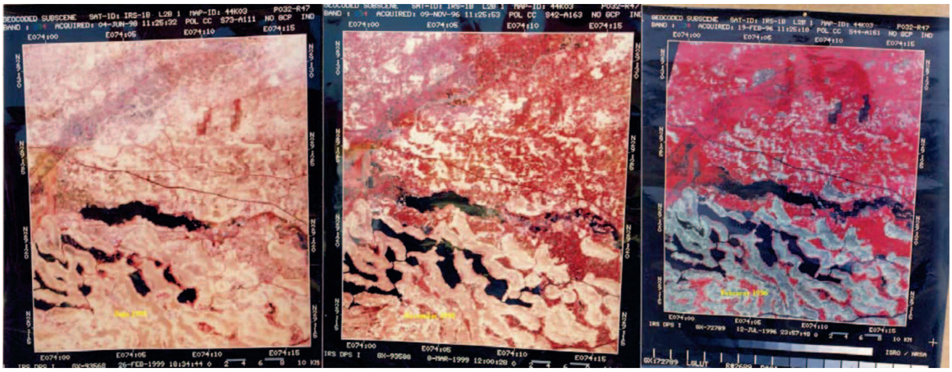

Figure 6. Seasonal dynamics of waterlogging in depression areas.

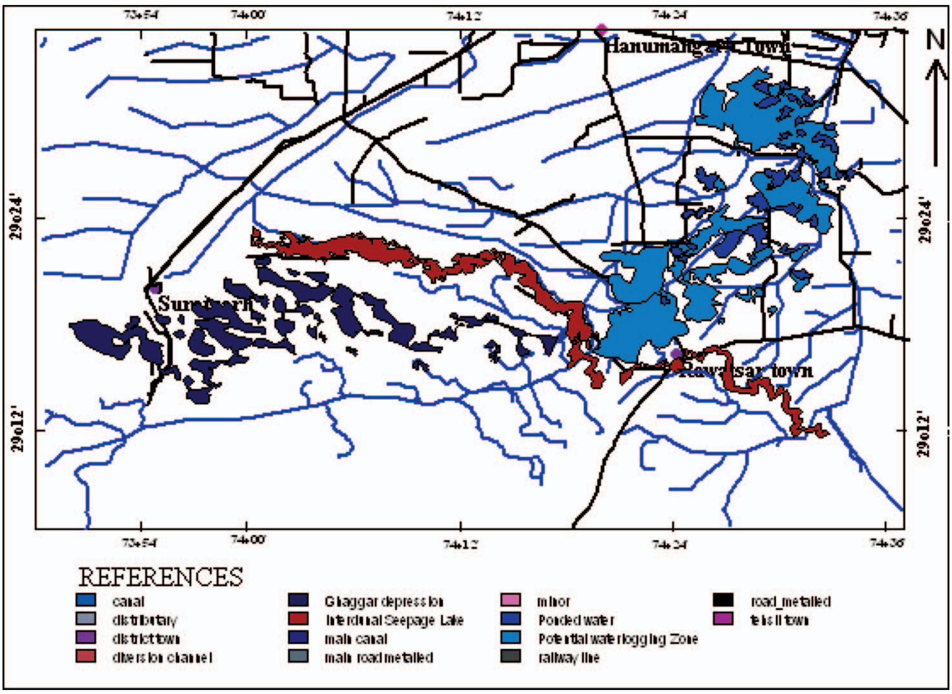

Figure 7. Distribution of waterlogged areas in Indira Gandhi Nahar Pariyojona (IGNP).

18 029 ha (4.41%), respectively (table 3). Features appearing as dark reddish and whitish grey tones were identified as normal cropped and sand dunes.

4.2 *Soil characteristics*

The salient characteristics of five representative pedons were presented to show salt composition and related characteristics (table 4). Morphological characteristics showed variable texture, weak to moderately strong structure, weak consistence and few to abundant $CaCO_3$ nodules. A few iron and manganese mottling/concretions

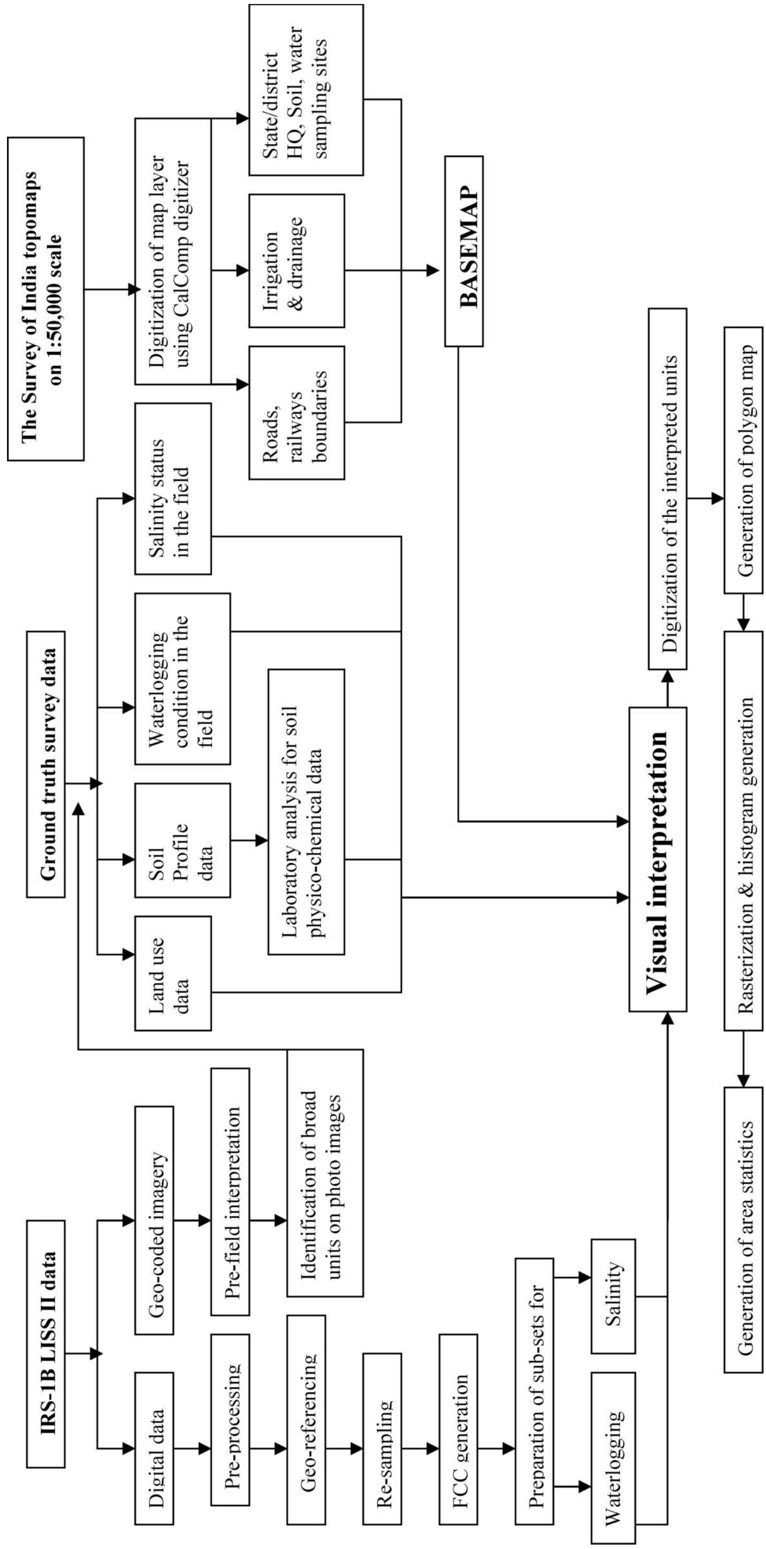

Figure 8. Methodology for delineating waterlogging and soil salinity in Indira Gandhi Nahar Pariyojona (IGNP).

Table 2. Spatial characteristics of interpreted units in Indira Gandhi Nahar Pariyojona (IGNP) area.

				Range of soil properties		
SI no.	Interpreted units	Landuse/land cover	Image tone	pHs	ECe dS m^{-1}	Depth of water table (m)
1.	Waterlogged area (surface ponding)	Stagnant water and scattered growth of aquatic grasses	Dark blue/blue-black	8.4–8.9	22–45	Surface water
2.	Waterlogged area with high water table	Partially cropped with low vegetative growth	Dark greyish red	7.8–8.2	15–25	<1.5 m
3.	Potential waterlogging zone	Moderately dense crop	Reddish grey	7.5–8.4	5–10	1.5–6.0 m
4.	Saline soil with 2–3 cm salt crust	Barren, presence of salt grass, bushes, shrubs	Greyish white/yellowish white	8.5–9.2	30–45	<1.0 m
5.	Saline soil without salt efflorescence	Sparse vegetation	Greyish red	7.5–8.0	5–15	<3.0 m
6.	Irrigated crop	Normal vegetation	Red to dark red	7.0–7.5	2–5	>3.0
7.	Sand dune	Barren with grasses, shrubs, bushes	Yellowish white/white	6.5–7.5	2–4	>6.0 m

Table 3. Extent of area for waterlogged and salt affected soils in Indira Gandhi Nahar Pariyojona (IGNP).

Land use classes	Area (ha)	% geographical area
Ponded water	3 866	0.94
Potential waterlogging zone	18 029	4.41
Salt efflorescence	3 342	0.82
Interdunal seepage lake	7 702	1.88
Ghaggar depression	10 700	2.61
Total	43 639	10.68

were found around the micro-pores in the subsoil horizons. The presence of a kankar layer was observed at places below the surface horizon. The soil profile was generally moist at the surface and wet within the control section. Poor horizon development and mixing of soil particles showed the presence of alluvial parent material. The accumulation of finer soil particles below the surface layer caused restricted permeability. The physico-chemical characteristics data showed that pH values ranged between nearly neutral to slight alkalinity (7.9 to 8.8). The ECe values ranged from moderate (9.3 dS m^{-1}) to very high/severe (40.3 dS m^{-1}). The composition of saturation extract showed a dominance of chlorides (15453 me l^{-1}) and sulphates (10 to 44 me l^{-1}) of sodium (25 to 454 me l^{-1}) and calcium and magnesium (8–to 62 me l^{-1}). A significant amount of calcium carbonate was found in Pedons 1 and 2, located on the old alluvial plains, while lower values in other pedons were due to their recent origin. The particle size analysis data showed silty clay loam and sandy clay loam texture in Pedons 1 and 2, while other pedons showed a loamy sand to sandy loam texture. The organic matter content was generally low. The CEC values were low, possibly due to coarse textures and the presence of non-expanding minerals or mixed mineralogy. The ESP values ranged from 3 to 19, related to pH values (Khan *et al.* 1999; Mathur *et al.* 1996). Based on the physico-chemical characteristics data, Pedon 1, characterized as highly saline with a fine loamy texture, could be treated for salt leaching and installation of subsurface drainage before use for agricultural purposes. Pedons 2, 4 and 5, characterized as moderately saline with a sandy loam texture and increasing clay content in the subsoil layers, could be used for growing salt tolerant varieties following salt leaching. Pedon 3, with a loamy sand texture, could be used for arable cropping with proper soil and water management practices.

4.3 *Water quality*

As a result of surface irrigation, a considerable amount of seepage occurred in the irrigated areas, which brought about the formation of lakes (*Tal*) inundating good agricultural lands. The chemical characteristics of water samples collected from various sources were presented to show the salt content and composition for quality appraisal (table 5). A wide range of EC_{iw} values were found in the water samples collected from different sources (table 5). High to very high EC_{iw} values (93.4–102.6 dS m^{-1}) were found in severely affected areas of Masitanwali and Bhairusari villages, apparently due to prolonged salt accumulation. The ECe of water samples collected from profile pits and the auger bore ranged from 1.7 to 22.0, suggesting its safe reuse. The higher ECe of water samples (22.2 dS m^{-1}) from the profile pit in

Table 4. Physico-chemical properties of representative soil profiles.

Depth	pH value	ECe (dS m^{-1})	Na^+ (me l^{-1})	$Ca^{2+} + Mg^{2+}$ (me l^{-1})	Cl^- (me l^{-1})	SO_4^{2-} (me l^{-1})	HCO_3 (me l^{-1})	$CaCO_3$ (%)	Organic matter (%)	ESP (%)	Sand (%)	Silt (%)	Clay (%)	CEC (c mol.kg^{-1})
Pedon 1: Village Manaktheri (29°22′18.44″N, 74° 01′54.40″E), severely saline														
0–22	8.4	40.3	454	62	453	44	0.5	12.2	0.16	19	18	54	28	6
22–136	8.4	25.9	333	44	351	32	1.0	10.2	0.13	15	4	55	41	13
136–159	8.6	18.6	293	35	315	29	1.5	9.88	0.09	13	17	44	39	12
159–191	8.8	14.1	225	27	244	26	1.5	9.53	0.06	10	25	40	35	11
Pedon 2: Village Lahuwali (29°20′22.22″N, 74° 22′44.57″E) waterlogged, highly saline														
0–22	8.7	32.3	416	79	435	29	2.5	9.6	0.29	19	76	16	8	5.6
22–55	8.6	18.6	233	66	249	24	2.5	10.5	0.26	17	74	11	15	7.4
55–106	8.5	14.0	165	45	183	22	1.5	12.7	0.16	15	74	10	16	7.0
106–171	8.6	12.3	105	32	132	12	1.5	18.1	0.13	12	70	18	12	6.6
Pedon 3: Village Dabli Khurd (29°28′57.58″N, 74°31′31.46″E) waterlogged moderately saline														
0–20	8.2	20.4	164	65	210	20	0.5	2.6	0.06	16	78	14	8	8
20–48	8.4	17.3	147	60	191	22	1.0	2.9	0.05	18	82	11	7	6
48–101	8.4	17.5	143	50	179	14	1.0	3.1	0.04	12	86	8	6	5
101–151+	8.4	15.6	127	42	164	10	1.0	4.3	0.02	10	86	9	5	5
Pedon 4: Village Dabli Kalan (29°22′51.79″N, 74° 27′11.94″E) waterlogged saline														
0–19	7.9	9.3	99	15	88	19	2.0	2.4	0.81	3.	89	3	8	8.24
19–50	8.2	3.4	40	9	34	14	1.5	2.0	0.62	4	88	6	6	6.08
50–70	8.1	2.6	37	10	19	12	1.5	2.4	0.62	5	80	10	10	10.4
70–91+	8.0	1.8	25	8	15	10	1.5	3.7	0.36	7	76	11	13	13.1
Pedon 5: Village Silwala (29°25′20.66″N 74° 29′11.21″E) waterlogged moderately saline														
0–15	8.36	18.5	225	81	174	25	2.0	0.37	0.14	12	87	2	11	8.78
15–36	8.42	18.0	220	74	164	15	2.0	0.23	0.12	11	83	6	11	7.38
36–82	8.43	22.1	300	90	228	20	2.5	0.37	0.22	10	76	9	15	9.0
82–151+	8.37	23.8	333	82	256	25	2.5	0.37	0.12	9	69	14	17	15.46

Table 5. Water quality in Indira Gandhi Nahar Pariyojona (IGNP) command area.

EC_{iw} (dS m^{-1})	pH	Na^+ (me l^{-1})	K^+ (me l^{-1})	$Ca^{2+} + Mg^{2+}$ (me l^{-1})	$CO_3^{2-} + HCO_3^-$ (me l^{-1})	Cl^- (me l^{-1})	SO_4^{2-} (me l^{-1})	SAR
(a) Ponded water (in irrigated area)								
Village: Masitanwali (29°26′16.57″N 7°30′21.57″E) severely saline								
102.6	7.9	1935	49.5	370	15.0	2110	450	142.3
Village: Mohanmagaria (29°24′55.03″N 74°25′46.53″E) slightly saline								
7.91	7.55	67	0.5	6.0	4.0	54.0	20.0	38.68
(b) Ponded water (Inter-dunal seepage lake)								
Village: Bahirusari (29°18′47.60″N 74°16′31.21″E) severely saline								
93.4	8.13	1217	7.7	154	6.0	1270	80	138.7
Chak: 4 B P S M (Jiwannagar) (29°16′53.00″N 74° 26.2′31.53″E) slightly saline								
4.21	8.44	21.74	0.43	22.0	13.0	42.60	11.74	6.55
(c) Drainage water								
Village: ARS Loonkaransar (28° 29′40.05″N 7°45′17.83″E) highly saline								
30.66	8.5	285.2	0.52	20.0	11.0	286.2	–	90.2
Village: Lakhuwali (29° 20′22.22″N 74°22′44.57″E) slightly saline								
3.20	7.86	28	2.1	2.0	8.0	19.0	6.0	28.00
Tube well water: Village Dabli Kalan (29° 22′45.60″N 74°27′11.97″ E) slightly saline								
5.09	8.33	19.02	3.09	27.0	4.5	38.0	14.0	5.17
(d) Auger bore water (1.5 m)								
Village: Dabli Kalan (29°23′04.39″N 74°28′08.35″ E) moderately to highly saline								
22.2	7.9	233.5	6.7	43.0	–	230.0	13.0	50.2
Village: Jakhranwali (2°21′14.62″N 74°12′30.21″ E) slightly saline								
4.1	7.5	27.2	0.11	20.0	–	20.0	16.0	8.6
(e) Profile pit (1.5 m) water								
Village: Lakhuwali (29°20′09.82″N 74°22′37.59″ E) normal								
1.7	8.6	8.2	0.18	10.0	2.5	19.0	5.0	3.67
Village: Silwala (29°28′51.43″N 74°31′45.62″ E) slightly saline								
7.07	9.25	90.1	0.19	6.0	28.5	24	16.0	52.1

Dabli Kalan village was due to the presence of a highly saline (46.3 dS m^{-1}) *Tal* close to the profile pit. The ECe of drainage water varies widely from 3.2 dS m^{-1} to 30.6 dS m^{-1} in alluvial plains and saline depressions and may be used for agricultural purposes when mixed with good quality of water. The ionic composition of water samples showed a significant contribution of sodium (8.2–1935 me l^{-1}), calcium and magnesium (2.0–370 me l^{-1}) for the development of high to very high salinity. Among the anions a significant presence of chloride (20.0–2110 me l^{-1}) and sulphate (5–450 me l^{-1}) and moderate quantities of carbonate and bicarbonate (2.5–28.5 me l^{-1}) were observed (table 4). The transportation of salts from a higher to a lower elevation through the coarse sandy mass facilitate the development of poor water quality in *Tal*s and interdunal seepage lakes.

5. Conclusion

The visual interpretation of Indian Remote Sensing data on a 1:50 000 scale, authenticated by ground truthing, was used for the identification of waterlogging and salt infestation in IGNP command, India. The pre-monsoon (February 1996), post-monsoon (November 1996) and summer (June 1998) data revealed the dynamics of waterlogging. The extent of waterlogging was higher during February and lower in June. Soil salinization, commonly found around the irrigated areas, was higher in November (post-monsoon) due to freshly precipitated salts at the surface. The ground survey identified the presence of a high water table, secondary salinization and potential waterlogging zones. Soils were moderate to very highly saline, dominated by neutral salts of sodium, calcium and magnesium. These were variable in texture, weak to moderately strong in structure and lacking adequate natural surface drainage. The presence of high to very high quantities of soluble salts in water samples from the seepage lakes (*Tals*) restricted its reuse.

Acknowledgements

We are thankful to the Head, Soils and Crop Management and Director, CSSRI, Karnal (India) for necessary encouragement and financial help. Sincere thanks are due to A.M. van Lieshout, consultant, ITC, the Netherlands, under the Indo-Dutch ORP Network for his guidance in carrying out this work.

References

CHAUBE, V.K., 1998, Assessment of waterlogging in Sriram Sagar command area, India, by remote sensing. *Water Resource Management*, **12**, pp. 343–357.

DWIVEDI, R.S. and SREENIVAS, K., 1998, Delineation of salt affected soils and waterlogged areas in the Indo-Gangetic Plains using IRS-1C LISS III data. *International Journal of Remote Sensing*, **19**, pp. 2739–2751.

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*, **23**, pp. 2729–2740.

DWIVEDI, R.S., SREENIVAS, K. and RAMANA, K.V., 1999, Inventory of salt affected soils and waterlogged areas: a remote sensing approach. *International Journal of Remote Sensing*, **20**, pp. 1589–1599.

FAO/UNDP, 1971, Soil Survey and Soil and Water Management Research and Demonstration in the Rajasthan Canal Area, India. AGL: SF/IND 24, Technical Report 1.4.

GOVERNMENT OF RAJASTHAN, INDIA, 1999, IGNP Studies for the State of Rajasthan. Final Report (Supporting Report 1: Remote Sensing Application Studies).

HOOJA, R., SREENIVAS, V. and SHARMA, G., 1995, Water and Salinity Problems in IGNP, Rajasthan. *Proceedings of the National Seminar on Reclamation and Management of Waterlogged Saline Soils*, K. V. G. K. Rao, M. C. Agarwal, O.P. Singh and R. J. Oosterbaan (Eds), CSSRI, Karnal, pp. 141–159.

JACKSON, M.L., 1967, *Soil Chemical Analysis* (New Delhi: Prentice Hall).

KALRA, N.K. and JOSHI, D.C., 1996, Potentiality of Landsat, SPOT, and IRS satellite imagery for recognition of salt affected soils in Indian Arid Zone. *International Journal of Remote Sensing*, **17**, 3001–3014.

KALUBERME, M.H., SAHAI, B. and BAPAT, M.V., 1983, Remote sensing of waterlogged and salt affected soils in the Mahi command area. In *Proceedings of the National Symposium on Remote Sensing in Development and Management of Water Resources*, Ahmedabad, pp. 182–190.

KHAN, M.A., VANGANI, N.S., SINGH, N. and SINGH, S., 1999, Environmental impact of Indira Gandhi Canal Project in Rawatsar Tehsil of Hanumangarh District, Rajasthan. *Annals of Arid Zone*, **38**, pp. 137–144.

KHAN, N.M., RASTOSKUEV, V.V., SATO, Y. and SHIOZAWA, S., 2005, Assessment of hydrosaline land degradation by using a simple approach of remote sensing indicators. *Agricultural Water Management*, **77**, pp. 96–109.

MANDAL, A.K. and SHARMA, R.C., 1997, Characterization of salt affected soils of the Indira Gandhi Nahar Pariyojona command area, Rajasthan. *Agropedology*, **7**, pp. 84–89.

MANDAL, A.K. and SHARMA, R.C., 2001, Mapping waterlogged areas and salt affected soils in the IGNP command area. *Journal of the Indian Society of Remote Sensing*, **29**, pp. 229–235.

MATHUR, S.K., RAM, M. and SEKHAWAT, K.S., 1996, Soil salinity evaluation in waterlogged areas of Indira Gandhi canal. In *Proceedings of the Workshop on Waterlogging and Soil Salinity in Irrigated Agriculture*. C. V. J. Varma (Ed.), CSSRI, Karnal, pp. 38–46.

MOUGENOT, B., POUGET, T.M. and EPEMA, G.F., 1993, Remote sensing of salt affected soils. *Remote Sensing Reviews*, **7**, 241–259.

RICHARDS, I.A. (Ed.), 1954, *Diagnosis and Improvement of Saline and Alkali Soils*. USDA Agriculture Handbook No. 60 (Washington, DC: US Government Printing Office).

SHANKARNARAYANA, H.S. and GUPTA, V.K., 1991, Soils of the region. In *Prospect of Indira Gandhi Canal Project*, J. Venkateswarulu and I. P. Abrol (Eds), pp. 19–35 (New Delhi: ICAR).

SHARMA, G. and MATHUR, G.P., 1991, Water table in Indira Gandhi Nahar Pariyojona command:problems and solution. In *Prospect of Indira Gandhi Canal Project*, J. Venkateswarulu and I. P. Abrol (Eds), pp. 55–64 (New Delhi: ICAR).

SHARMA, R.C. and BHARGAVA, G.P., 1988, Landsat imagery for mapping saline soils and wet lands in north-west India. *International Journal of Remote Sensing*, **9**, pp. 39–44.

SHARMA, R.C., SAXENA, R.C. and VERMA, K.S., 2000, Reconnaissance mapping and management of salt affected soils using satellite images. *International Journal of Remote Sensing*, **21**, pp. 3209–3218.

SINGH, S. and KAR, A., 1991, Morphological characteristics of landforms and associated problems. In *Prospect of Indira Gandhi Canal Project*, J. Venkateswarulu and I. P. Abrol (Eds), pp. 11–18 (New Delhi: ICAR).

SOIL SURVEY STAFF, 1995, *Soil Survey Manual*. USDA Handbook No. 18 (New Delhi: Oxford & IBH).

SUJATHA, G., DWIVEDI, R.S., SREENIVAS, K. and VENKATRATNAM, L., 2000, Mapping and monitoring of degraded lands in part of Jaunpur district of Uttar Pradesh using temporal spaceborne multispectral data. *International Journal of Remote Sensing*, **21**, pp. 519–531.