Modern Technologies for Diagnosis and Prognosis of Salt-affected Soils and Poor-quality Waters

4

A. K. Mandal

Abstract

Soil salinity and brackish groundwater are primary concerns for reduced productivity of 953 million ha in the world. In India, 6.73 M ha of salt-affected soils (SAS) is distributed in 15 states and 13 agroclimatic regions. Salt deposition at low topographic zones, high evaporation in arid zone, salty parent materials and brackish ground use in peninsular plain, and inundation of saline seawater in coastal areas are primary processes controlling genesis and distribution of SAS. Canal irrigation practices have contributed to waterlogging, soil salinization, and losses of soil productivity in poorly drained soils. Remote sensing data with improved spatial and spectral resolutions has facilitated detection and delineation of SAS with limited ground truth and soil studies. Using high-resolution remote sensing data, prognosis of soil salinity was studied to quantify soil salinization processes in canal command areas integrating topography, hydrology, and aquifer characteristics. Spatial variability of sodic and saline soils with salty groundwater was studied at farm scale at experimental farms. Visual and digital analysis of remote sensing data facilitated the identification of strongly salt-affected soils by high spectral reflectance of salt crusts from barren surfaces. High energy absorption in the SWIR band enabled identification of waterlogged soils in canal-irrigated areas with poor natural drainage. Temporal dynamics of salty surfaces, vegetation, and normalized difference vegetation index (NDVI) data during June, March, and October seasons were used for SAS with poor-quality or high RSC groundwater. Mixed spectral signatures for salt crusts, moderate cropping density, and surface wetness in moderately and slightly sodic soils are authenticated by ground truth study. Thermal band was used for salty soils and sand dunes showing close spectral signatures in visible range. Natric horizon formation, clay illuviation, iron and manganese mottles, higher moisture content, and

A. K. Mandal (✉)
ICAR-Central Soil Salinity Research Institute, Karnal, Haryana, India
e-mail: AK.Mandal@icar.gov.in

J. C. Dagar et al. (eds.), *Research Developments in Saline Agriculture*,
https://doi.org/10.1007/978-981-13-5832-6_4

precipitation of subsurface calcareous materials are typical soil-forming processes in sodic soil. Chemical analysis indicated high pH, exchangeable sodium percentage (ESP), and sodium adsorption ratio (SAR) values and the dominance of carbonate and bicarbonates of sodium. High moisture content and salt saturation (commonly saline soils of sodium chloride and sulfate salts) are typical features associated with waterlogged (surface ponding) soils and high water table depth (potential waterlogging). Periodic irrigation with water of high pH, SAR, and RSC (residual sodium carbonate) values favored the formation of salty soil profiles in arid and semiarid regions. High clay contents, smectite clay minerals, critical ESP (5 or more), and salty groundwater are primary constraints of black soil in the peninsular plains. The complex saline-sodic soils of alluvial (A), aeofluvial/arid (B), and others (H) are classed as sodic. Soils of coastal (D), deltaic (C), and mud flats/mangrove swamps (G) were classified as saline. Benchmark salt-affected soils were identified for monitoring in agroclimatic and physiographic regions. The largest areas (67% and 75%) of SAS lie in the arid to semiarid (300–1000 mm rainfall) and strong hyperthermic (25–27.5 °C) temperature zones and in the Pleistocene and Recent (39%) geological formations. Recent IRS data (years 2010–2013) revealed 315,617 ha of SAS lies in 18 districts of Haryana state. Attempts were also made to update similar databases for Uttar Pradesh and Gujarat states.

Keywords
Salt-affected soils · Soil salinity · Sodicity · Waterlogging · Remote sensing · Saline/sodic groundwater · SAR (sodium adsorption ratio) · RSC (residual sodium carbonate) · ESP (exchangeable sodium percentage) · Soil profile · Diagnosis and prognosis

4.1 Introduction

Accumulation of excess soluble salts in soils has led to the formation of salt-affected soils that adversely affect plant growth and crop yield. The main causes of salt accumulation include capillary rise from subsoil salt beds or from shallow brackish groundwater, besides other factors such as the indiscriminate use of irrigation water of variable qualities, weathering of rocks and minerals that brought down salts from the upstream to the plains by rivers and subsequent deposition along with alluvial materials, while the ingress of seawater along the coast, salt-laden sand blown by sea winds, and lack of natural leaching due to impeded topography in arid and semiarid regions also caused soil salinization. Higher proportion of alkaline salts alters soil reaction (pH) and influences the physical and chemical properties and the exchangeable cations content in particular. These salts influence osmotic and ion toxicity causing nutrient imbalances and thus are unfavorable for sustained crop production. The presence of excess neutral salt essentially influences solute transport and availability of selected macro- and micronutrients required for plant growth. Globally, 20% of the irrigated land (450,000 km^2) is salt-affected and about 2000–5000 km^2 land lost production every year as a result of salinity (UNEP 2009). In South Asia, the annual economic loss is estimated to be US$1,500 million due to salinization (UNEP 2009). In the tropical countries, soil salinity is a serious problem affecting crop production, plant growth, and soil and water quality leading to soil and environmental degradation. In Africa, a serious impact on economy has been reflected on average loss on agriculture from 28%–76% as a result of land degradation. In India, the average production loss from such degradation varies from 40% in wheat, 45% in rice, 63% in cotton, and 48% in sugarcane (Joshi and Agnihotri 1984). Based on various studies, the Central Soil Salinity Research Institute (CSSRI) (2000) reported that the alkali land reclamation schemes operated in Haryana, Punjab, and Uttar Pradesh states (Trans-Gangetic plain) brought changes in cropping intensity by 25% in paddy, 10% in wheat, 21% in pulses, and 10% in cotton. The economic benefit accrued from the sodic land reclamation programs showed the improvements of B:C (benefit-cost) ratio to 1.89 and 1.80 for rice and wheat, respectively (Thimmappa et al. 2013). Soil analytical data of reclaimed sodic soils showed prominent changes in soil pH and concurrent increase of organic carbon that showed improvement in fertility status (CSSRI 2000, 2007). The use of flow method of irrigation in poorly drained areas caused the emergence of waterlogging and secondary salinization that caused losses in productivity for rice (42%), wheat (38%), and sugarcane (61%) crops (Samra et al. 2006). Due to the use of salty groundwater (60–70% of TGA) for irrigation, secondary salt enrichment in soil profiles occurred along the Ghaggar and Markanda river plains (Manchanda 1976; Gupta 2010; Phogat et al. 2011). Present status and selected modern technologies for diagnosis and prognosis of salt-affected soils and poor-quality waters have been discussed in this chapter.

4.2 Categories of Salt-affected Soils

Five categories of salt-affected soils were identified based on the nature and composition of salts at global scale (Szabolcs 1989). These are saline enriched by natural salts, alkali with higher Na_2CO_3 and $NaHCO_3$ content that favor alkaline hydrolysis, gypsiferous with excess gypsum ($CaSO_4$,$2H_2O$), calcareous rich in the precipitated calcium carbonate ($CaCO_3$), magnesium with magnesium ($MgCO_3$) and sodium carbonate (Na_2CO_3), acid sulfate saturated with pyrite and jarosite (ferric and aluminum sulfates), and others including strongly degraded subsoil and potential salinity in irrigated region. In Eastern Europe, these soils were known as Solonchak, Solonetz, and Solod. The alkali soils of Europe and erstwhile USSR showed a good A horizon and a *natric* (sodic) subsurface B horizon. In India, these soils are known as *Kallar* or *Thur* in Punjab and Haryana, *Usar* or *Reh* in Uttar Pradesh, *Luni* in Rajasthan, *Khar* or *Kshar* in Gujarat and Maharashtra, *Chhouddu* or *Uppu* in Andhra Pradesh, *Choppan* in Karnataka, etc. The US Soil Salinity Laboratory (Richards 1954) proposed criteria for distinguishing sodic with saline and saline-sodic soils based on the critical limits of electrical conductivity (ECe) of saturation extract, ESP (exchangeable sodium percentage), and soil reaction (pHs) of saturated soil paste. The Soil Science Society of America (1987) used ECe and SAR (sodium adsorption ratio) as criteria for classification of salt-affected soils. The Central Soil Salinity Research Institute (CSSRI) proposed pH 8.2 as critical limit for initiation of soil sodicity and alkalinity following characterization of alkali soils of the Indo-Gangetic alluvial plain (IGP) (Agarwal and Yadav 1956). Later, Abrol et al. (1980) also reported that the adverse effect of soil sodicity on crop growth initiates at pH 8.2. Similarly, Balpande et al. (1996) proposed the critical limit of ECe to be 2 dS m^{-1} and ESP 5 for sodic vertisols showing higher clay content and smectite mineralogy. Australian workers proposed soil physical properties such as low hydraulic conductivity as a critical factor that affects plant growth in sodic soils. Soil characterization revealed that ESP 6 was the limiting value that impaired soil physical properties in a swell shrink soil in Australia (Northkote 1979). In India, broad categories such as saline and sodic were identified for reclamation and management purposes (Abrol and Bhumbla 1978; Abrol et al. 1988). The diagnostic features of these soils are described below.

Saline soils are appearing as salt patches with white encrustation on the soil surface commonly occurring in the lower landscape position. Due to high salt content, high osmotic pressure, and ion toxicity, these soils do not support normal growth of agricultural crops. These are also appearing in the irrigated areas along with waterlogging. The prolonged use of saline groundwater for irrigation also caused in situ soil salinity development in the arid and semiarid regions. These soils also exist along the seacoast as a result of saline seawater inundation, causing high soil salinity at the root zone. The soil chemical analysis data indicated dominance of neutral salts such as chlorides and sulfates of sodium, calcium, and magnesium higher than the prescribed limit. The pH of the saturated paste lies <8.2, and electrical conductivity exceeds 4.0 dS m^{-1} at 25 °C. These soils showed higher (>10) sodium adsorption ratio (SAR) in general.

Field studies of alkali soil showed bleached color, strong structure (blocky/prismatic/columnar), iron and manganese mottles, concretions/nodules of calcium and magnesium, fine-textured silt/clay layer (natric) at subsurface depth, moderate to strong/violent effervescence on application of dilute HCl, and pink color on application of phenolphthalein indicator. Alkaline pH (>8.2) affects plant growth and crop yield, while poor (dispersed) soil physical properties and internal drainage caused the imbalance of nutrient availability. High carbonate and bicarbonate of sodium, calcium, and magnesium and high sodium adsorption ratio (SAR) resulted in high exchangeable sodium percentage (ESP > 15).

4.3 Status of Salt-affected Soils: Global and National Scenarios

According to the FAO/UNESCO soil map of the world, 831 million hectares of land (6.5%) is affected due to soil salinization and alkalization (FAO Soil Map of the World 1974–1980). Later Szabolcs (1989) estimated 953 M ha based on the compilation of salt-affected soils of the world. The worst affected areas include Africa, Asia, Australia, Europe, Latin America, the Near East, and North America (Koohafkan 2012). Survey in Australia reported that 2 M ha (20,000 farms) is affected due to climate changes and 10% of Western Australia is seriously endangered by soil salinity/alkalinity of primary and secondary origin (Australian Bureau of Statistics 2002; McFarlane 2004). Keeping in view the large-scale variability of salt-affected soils and scale of mapping, FAO (2008) again reported harmonized data of salt-affected lands to be 434 M ha to be sodic and 397 M ha saline for planning and management purposes.

Systematic mapping and assessment of salt-affected soils (SAS) in India involves spatial measurements, field and laboratory studies, and reconciliation to arrive at a figure of 6.73 million hectares which is distributed in 15 states and 13 agroclimatic regions (CSSRI 2007; NBSS and LUP 2006; NRSA 1997, 2008). The saline (2.95 M ha) and sodic (3.77 M ha) soils are distributed in seven physiographic regions (Mandal et al. 2010). The occurrence of salt-affected areas is primarily influenced by rainfall, and about 29.4%, 26.2%, and 19.4% SAS exist in the ranges between 500 and 800 mm, 1000 and 1500 mm, and 300 and 500 mm, respectively. These soils are associated with a wide range of parent materials, most importantly, in Pleistocene and Recent origin (38.9%), Archean Schists and Gneisses (9.5%), and Deccan and Rajmahal Traps (7.8%), respectively (Mandal et al. 2011).

The irrigation through groundwater is a common practice for growing arable crops in the arid and semiarid regions. The water quality is of primary concern as on an average 25% poor-quality water is used in these regions for crop production. The distribution figures of saline groundwater in Rajasthan (41.2%), Haryana (25.9%), and Gujarat (12.4%) states warrant necessary inputs for management (Manchanda 1976; HSMITC 2001; Gupta 2010), while the extent of alkaline groundwater areas in Punjab (54%), Rajasthan (35%), Haryana (30%), and Gujarat (28%) states showed necessity for reclamation. The complex saline-alkali water is prevalent in Gujarat (52%), Rajasthan (49%), Haryana (46%), and Punjab (24%) and needs special care for crop production. On the other hand, the expansion of canal irrigation network in arid and semiarid regions caused emergence of salinity and waterlogging problems in un-drained areas.

4.3.1 History of Soil Mapping in India Through Remote Sensing

In India, systematic mapping of soil salinity was originated at the Central Soil Salinity Research Institute at Karnal under the Indian Council of Agricultural Research (ICAR) New Delhi collaborating with the National Bureau of Soil Survey and Land Use Planning (ICAR) Nagpur and National Remote Sensing Centre (DOS) Hyderabad under the Ministry of Defense, Government of India. A methodology for soil salinity mapping on a reconnaissance scale (1:250,000 scale) was developed using remote sensing data in conjunction with ground truth survey and soil and laboratory studies (Sharma and Mandal 2006; NRSA 2008; Mandal and Sharma 2010; Sharma et al. 2011). Regional-scale mapping of soil salinity was carried out for coastal areas of Gujarat state using Landsat TM data supported by ground truth (Joshi and Sahai 1993). Soil sodicity in Uttar Pradesh state was mapped on 1:50,000 scale integrating Indian Remote Sensing data (IRS LISS II) with soil profile studies (Saxena et al., 2004). Attempts were also made for digital image classification of soil degradation features combining field data and laboratory analysis (Mitternicht and Zinck 1997). Singh et al. (2010) suggested reconciliation and harmonization to estimate complex salt-affected soils.

Soil salinity map of Haryana indicated 52% of salt-affected soils are distributed in central Haryana covering Karnal, Kurukshetra, Panipat, and Sonepat districts (Mandal and Sharma 2005). Interpretation of Landsat images showed old levees, relict flood plain, and poorly drained low-lying flats are common topographic zones with salt infestation along the Gangetic alluvial plain (Manchanda and Iyer 1983). Introduction of canal irrigation from Western Yamuna Canal (WYC) in Haryana during the 1950s accentuated upward movement of salt by rising water table (Singh et al. 2010).

4.3.2 Traditional Methods: Field Assessment and Laboratory Characterization of Soils

Metternicht and Zinck (1997) combined digital analysis with field and laboratory analysis data for mapping sodium- and salt-affected soils. They concluded that the main causes of spectral confusions, masking different soil salinity-alkalinity degrees, were the type and abundance of salt-tolerant vegetation cover, topsoil texture, and other field properties. Joshi and Sahai (1993), Verma et al. (1994), and Sharma et al. (2000) used a similar approach combining remote sensing, ground truth, and soil analysis data for mapping coastal salt-affected soils in Saurashtra (Gujarat state) and inland salt-affected soils of Uttar Pradesh state. Such methods are laborious and need concerted efforts for image analysis, ground truth, soil sampling, and laboratory analysis of soil and water to integrate for mapping but produce results and classified outputs of salt-affected soils with higher accuracies. Classification of soils for salinity/alkalinity classes, such as slight, moderate, and strong, is useful for deciding precise soil reclamation and management options.

4.3.3 Modern Tools and Techniques for Diagnosis and Assessment of Salt-affected Soils

Due to spatial variability and dynamic nature, the mapping of salt-affected soils is difficult using traditional methods of surveying, soil sampling, and laboratory estimations. Remote sensing data with adequate spatial and spectral resolutions is widely used in detection, delineation, and monitoring of salt-affected and water-logged soils in a time- and cost-effective manner (Saxena 2003; Rao et al. 1998; Shrestha 2006; Dwivedi 2006; Mandal and Sharma 2013). Initially, the aerial photographs were used for mapping salt-affected soils using visual interpretation approach which is based on the differentiating tone, texture, size, shape, and patterns of image elements. With the advent of digital technology and launching of the first Earth Resources Technology Satellite (ERTS 1) later renamed as Landsat 1, the mapping and monitoring of earth resources such as salt-affected soils become quite reliable and efficient. Subsequently, satellites with improved spatial and spectral resolution in Landsat, IRS, and SPOT series were included to enhance mapping efficiency (Singh et al. 1977, 1983; Venkatratnam 1984; Saxena 2003; Mandal et al. 2016). Mougenot et al. (1993) could easily identify barren salt-affected soils by high reflectance in the visible range, while thermal, infrared, and microwave data were also used to distinguish hygroscopic salts and vegetation-covered soils (Howari 2003). Howari et al. (2002) used spectroradiometry studies in visible and near-infrared range to quantify spectral properties of salt-affected soils with variable salt composition. Srivastava et al. (2016) also reported 1300–2400 nm bands as the optimum range for studying salt-affected soils. Recently, Allbel and Kumar (2013), Wu et al. (2014), Scudiero et al. (2014), and Ali et al. (2015) used high-resolution (MODIS) remote sensing data for quantification of soil salinity/sodicity with limited ground truth (land use), field, and laboratory soil studies. Khan et al. (2005) integrated ratio/brightness/salinity indices and spectral properties for digital classification of hydro-saline land degradation in the Indus basin, Pakistan.

4.4 Spectral Characteristics of Salt-affected Soils

The salt-affected soils are typically characterized by either high pH or high ECe or both. Prominent reflectance of salt-covered areas was shown in the visible part of the spectrum (Mougenot et al. 1993). The False Color Composites (FCC) prepared from red, green, and blue bands showed that these soils appeared as bright white to dull white patches associated with the brown/reddish color representing green vegetation. Bands in the middle-infrared range provide information on soil moisture often associated with salts, and the reflectance differs on the type of salt. Limited studies have been reported on the spectral behavior of salt-affected soils. Well-developed saline efflorescence and crusts are associated with high reflectance in visible and near-infrared bands and high DN (digital number) values in the digital data with a high value of brightness index (Berenger 1985; Rao et al. 1995). Halite occurrence of salt-affected soils was indicated by white gray tones in satellite data (Sharma and Bhargava 1987). Middle-infrared bands with water and OH- absorption band allow differentiation of chloride (as halite) and sulfates (as gypsum) soil surfaces if both are dry (Mulders 1987; Saha et al. 1990). The thermal infrared band is commonly used to estimate moisture and salinity. It also recognizes features of sulfates, phosphates, and chlorides showing high energy absorption (Mulders 1987). Mandal and Sharma (2011a) reported variable reflectance of salty, waterlogged, and sandy soils in IRS LISS II data representing irrigated areas of IGNP (Indira Gandhi Nahar Pariyojana). Mandal et al. (2016) identified reflectance in IRS LISS III data representing irrigated sodic soils with good and sodic groundwater in Kurukshetra district of Haryana.

4.4.1 Role of Vegetation in Detection of Soil Salinity

Contrasted association of vegetation and bare soils is useful for salinity detection in agriculture (Richardson et al. 1976; Everitt et al. 1977). An inverse relationship was reported between spectral reflectance and soil salinity of salt-affected soils. Since salt content induces less plant cover, decreased density, low LAI (Leaf Area Index) and plant height, the salin stressed vegetation showed a reddish or dark red shift on standard color composite data (Everitt et al. 1977; Colwell 1983). An infrared vegetation index (IR−NIR/IR+NIR) was proposed to detect canopy moisture influenced by salinity which is considered as superior to normalized difference vegetation index (NDVI) = NIR−IR/NIR+IR (Hardinsky et al. 1983). Besides, salinity index [$SI = (G \times R)^{1/2}$], normalized difference salinity index ($NDSI = (R-NIR)/(R+NIR)$), and brightness index ($BI = (R^2+NIR^2)^{1/2}$) are also used for differentiating spectral nature of salty soils. Kalra and Joshi (1994) reported spectral reflectance characteristics of salt-affected soils in arid sandy region of Rajasthan (under *Thar* desert) and found highest reflectance from natural salt-affected soils showing surface salt encrustation followed by sodic soils formed due to the application of high residual sodium carbonate/bicarbonate containing irrigation water, natural saline soils, and saline soils developed from irrigation with saline groundwater. Soil texture, pH, $CaCO_3$, and organic matter percentage together accounted for 29.6% variation in the maximum reflectance percentage value, out of which pH accounted for more than half (14.2% variation).

4.4.2 Landscape Characteristics

Good correlation was observed between soil distribution and geomorphological shapes (Rafiq 1976; Manchanda and Iyer 1983; Manchanda 1984). Relative elevation is one of the most evident landscape features in relationship with salinity and moisture provided by saline and shallow groundwater table. Salt efflorescence occurs with more rapid evaporation on the margin than in the center of depressions with vertical and lateral salt variations (Menenti 1984).

4.4.3 Type and Degree of Soil Salinity

Strong and medium salinity was detected in salt-affected soils of the Indo-Gangetic Plain (Singh et al. 1983). High spatial variability of salt quantity was found characteristic of most salt-affected soils (Mougenot et al. 1993). Satellite data facilitate detection and mapping of salts and high sodicity (high pH and SAR) due to high reflectance (Colwell 1983). Standard False Color Composites (FCC) with combination of red (band 3), green (band 2), and blue (band 1) indicated bright white patches with smooth image texture representing strongly sodic soils and dull white to strong brown for moderately sodic soils (Rao et al. 1995). Combination of Landsat TM bands (1, 2, 4, 5, 6, and 7) was used for differentiating salt- and sodium-affected soils with limited field observation and laboratory determination of soils (Metternicht and Zinck 1997). Howari (2003) reported distinctive reflectance patterns of salts using Landsat Enhanced Thematic Mapper (ETM^+), airborne visible/infrared imaging spectrometer (AVIRIS), color-infrared (CIR) aerial photo, and high-resolution field spectroradiometer (GER3700).

4.4.4 Remote Sensing for Monitoring Salt-affected Soil

The satellite data due to its repetitive coverage provides temporal information of salt-affected soils by acquiring data at suitable time and scale. It also provides information regarding the dynamics of salt-affected soils over a period of time. A team of experts from the National Remote Sensing Agency (NRSA), Hyderabad, studied 130 km^2 of the Sangrur district of Punjab state during 1975 and 1981 and found that an area of 4.33 km^2 of salt-affected soils was reduced due to the intensive reclamation practices. Using aerial photographs and Salyut 7 data, Rao and Venkatratnam (1987) monitored salt-affected soils in the Ukai Kakrapar command area covering 21,203 ha in Bharuch district. Aerial photograph of December 1977 showed 36% of the area was occupied by various categories of salt-affected soils, while Salyut data of April 1984 showed 79% of the area under salt-affected soils indicating twofold increases of salty area. Landsat MSS and TM data for 1975 and 1986 revealed significant reduction of salt-affected areas in Karnal and Jind districts of Haryana (Dwivedi et al. 1987), while remote sensing technique showed an increase in 15% over a period of 28 years in Aligarh district of Uttar Pradesh (Saha et al. 1990). NRSA (1995) reported a significant shrinkage of salt-affected soils over a period of 18 years in Sharda Sahayak command area in Uttar Pradesh.

4.4.5 Visual vs. Digital Methodology for Image Interpretation and Analysis

Two methods, viz., visual interpretation and digital analysis, of remote sensing data are commonly used to derive information on salt-affected and waterlogged soils. Visual interpretation of these soils involves satellite image interpretation using variable tone, texture, shape, size, and pattern of the image elements, while digital analysis involves generation of spectral signature of training areas, separation analysis generating scatter plots and classification of digital data registering training sets using suitable algorithms, and finally assessing accuracy of estimate. The imageries were initially analyzed with the help of topographical maps, published reports, and other ancillary information to delineate broad categories of salty lands. Again, each unit is subdivided into subunits based on the drainage density, vegetation cover, or land use or land cover. These units were transferred onto the base map prepared from the Survey of India topographical maps at suitable scale. Representative areas were selected for ground truth collection, and field visits were conducted to collect data on the soil topography and other site characteristics, and soil samples were collected from soil profile studies for laboratory analysis. The preliminary interpreted maps were modified in the light of field data and soil chemical analysis data to prepare final map of appropriate legend. Mapping of salt-affected soils was carried out in Haryana state at 1:250,000 scale using visual interpretation of photographic prints (black and white, color composites) and correlated with field studies (Sharma and Bhargava 1987). False Color Composites (FCC) of IRS LISS II data was used to delineate waterlogging and soil salinity in irrigated region of IGNP, Rajasthan state, India (Mandal and Sharma 2001).

Visual interpretation of Landsat TM imagery was integrated with field studies and soil physicochemical characteristics, to map the salty soils at 1:250,000 scale for 15 states. To accomplish the task, the National Remote Sensing Agency (NRSA), Hyderabad, collaborated with the National Bureau of Soil Survey and Land Use Planning (ICAR), Nagpur; the Central Soil Salinity Research Institute, Karnal (ICAR); and other central and state government organizations. The physiography, nature (saline/sodic/saline-sodic), magnitude (slight/moderate/strong), and extent (<1/3, 1/3–2/3, and >2/3) were used as map units for characterization of salt-affected soils.

The digital data were analyzed and interpreted using special image processing software. These data were processed at various stages for geometric correction, radiometric normalization, and image enhancement using different techniques. Computer-aided delineation of salt-affected soils using remote sensing data has been demonstrated by various workers (Venkatratnam and Rao 1977; Singh and Dwivedi 1980; Singh 1982; Saha et al. 1990). Maximum likelihood classifier was used for supervised image classification of Landsat TM data while mapping wastelands in Aligarh district of Uttar Pradesh (Saha et al. 1990). Landsat bands 3, 4, 5, and 7 highlighted successful separations of salt-affected and surface-waterlogged soils on the basis of spectral response and training statistics.

4.5 Case Studies for Assessment of Soil Salinity Using Traditional and Space Technology

4.5.1 Waterlogged Saline Soils in IGNP (Phase I) Rajasthan

IRS (Indian Remote Sensing) LISS II data are interpreted for the identification of waterlogged areas (ponded water), salt-affected soils (salt efflorescence), and high water table zones (potential waterlogging zones) in the Indira Gandhi Nahar Pariyojana (IGNP) command area followed by ground verification. False Color Composites (FCC) of bands 432 for February 1996, November 1996, and June 1998 on 1:50,000 revealed occurrence and seasonal dynamics of permanent waterlogging in low-lying flats and depressions. Due to less evaporation and more agricultural operation, waterlogging was higher during February. Prominent salt accumulation in November may be ascribed due to freshly precipitated salts. Seepage and accumulation of excess irrigation water through coarse sandy soils appeared to be primarily the reason behind waterlogging (ponded water). The secondary soil salinization occurred due to the capillary action of salts and high water table with high evaporative demand. Ground truth study also revealed the patchy crop stands with high water table (<1.5 m) depth and poor vegetative growth with fluctuating (1.5–6.0 m) water table depth indicating potentially sensitive areas for waterlogging. The soil properties showed moderate to high soil salinity in the control section of soil profiles. Field soil study data indicated medium to coarse texture, weak to moderately strong structure, weak consistency, low organic matter content, and abundant $CaCO_3$ nodules. Saturated soil paste indicated dominance of chloride and sulfate of sodium, calcium, and magnesium. Field studies also indicated the perched water table at shallow depth in fine-textured soils and a $CaCO_3$ layer at subsurface depth of soil profile and also question its suitability for traditional irrigated agricultural practices. The quality of pond water was extremely poor and unfit for reuse. The groundwater was saline in some areas but normally lies within the prescribed limit. The quality of drainage water was poor in highly salinized soils at depression areas and unsuitable for reuse. Moderate salinity in other drainage sites suggested its safe reuse if applied mixing with good-quality water. Suitable soil and water management practices were necessary for sustainable crop production in the command area (Mandal and Sharma 2011a).

4.5.2 Waterlogged Saline Soils in Lunkaransar Canal Areas of IGNP (Phase II) Rajasthan

Indian Remote Sensing (IRS LISS II) data on 1:50,000 scale showed prominent waterlogging as surface ponding in sandy flats and depressions along the Lunkaransar lift canal under the IGNP. The seasonal data revealed higher extent of waterlogging in February (1996) and mixed spectral signatures of high moisture content with poor crop stand in November (1996) and permanent waterlogging (close to the lift canal) in June (1998) data. Ground truth survey revealed the presence of shallow aquifer (water table depth <1.5 m) condition, patchy crop stand, moist soil profile, and soil salinization. The occurrence of fluctuating (1.5–6.0 m) water table depth during dry and wet cycles and poor cop stand in irrigated areas showed the presence of potential waterlogging zones. Moderate to high soil salinity was found at surface soil located in low-lying flats and higher salinity at subsurface depth (control section, 0.2–0.8 m) of soil profiles indicating initiation of secondary salinization. The layer of calcium carbonate was present at a depth below the surface. The chlorides and sulfates of sodium, calcium, and magnesium were dominant salts in the study area. The water quality of drainage effluents was extremely poor and may be used with good quality of water either in cyclic or mixing mode. The ponded and subsurface water quality is moderate and is fit for reuse (Mandal and Sharma 2013, 2014)

4.5.3 Waterlogged Saline Soils in Central Haryana

Salt-affected soils of Western Yamuna Canal (WYC) irrigation command were mapped using digital analysis and GIS. Sample strips were used to assign training sets while conducting supervised classification of Landsat TM data using ILWIS software. Five salinity classes were identified that showed an overall accuracy of 85.6%. Moderately and highly saline areas were easier to identify than the slightly saline areas. Combination of red and infrared bands was used for separating saline and sodic soils. A GIS overlay of thematic layers from the Survey of India maps on 1:50,000 was developed to generate a base map. The nonspatial data for soil physicochemical and salt composition were included as attribute table and were linked with the spatial data though a common geo-reference to prepare a relational database. Digitized spatial and attribute datasets were used as inputs to prepare the classified output as raster map. Thus, relating salinity classes with topology and soil attributes favors salinity management of irrigated areas (Sharma and Mandal 2006).

4.5.4 Salt-affected Soils in Upper Krishna Project, Karnataka

The Upper Krishna project in Karnataka aimed at providing canal irrigation to the chronically drought-prone areas of Gulbarga, Bijapur, and Raichur districts. The project irrigated 843,000 ha in two stages: 425,000 ha in stage I and 410,000 ha in stage II. Preliminary survey indicated that 27.6,000 ha area was salt-affected. Through visual interpretation, salty soils could be identified and classified in three classes, viz., moderate (<40% salt-affected), severe to moderate (40–75% affected), and severe (>75% affected). The severely salty lands were appearing as while salt crust on the IRS LISS III 1997 data, while mixed blue/green and white impressions and red mottles for crop covers were found in moderate salty soils. The total salt-affected areas were 21,906 ha in phase I. The spectral reflectance studies revealed correlation with ground soil salinity measurements limited to severely salt-affected soils. Attempts were made to classify image characteristics using brightness index, NDVI, and physiography data for mapping these soils with higher accuracy (IDNP 2002).

4.5.5 Waterlogging and Soil Salinity for Drainage Project, Gohana (Sonepat), Haryana

Satellite imageries (IRS IC, IB, SPOT, and Landsat-5 TM) for October 1988; January 1989; November 1994, 1995, and 1996; February 1996; and April and June 1996 were used to get insight in the dynamics of salinity and waterlogging under a subsurface drainage project site covering 5000 ha along the JLN feeder and Bhalaut branch of WYC (Western Yamuna Canal) in Sonepat district of Haryana state. Dynamics of salinization and waterlogging was established by digital classified satellite imageries at different crop seasons. Spatial interpolation was used for assessing spatial variability of soil salinity. The data on water table depth during June and October, elevation, soil pH, and ECe (dS m^{-1}) were used for assessing evolution of waterlogging and soil salinity (IDNP 2002).

4.5.6 Soil Salinity in Ukai Kakrapar Canal Command (Gujarat)

The Kakrapar canal was introduced in 1957 to irrigate 200,000 ha covering 12 *talukas* of Surat, Navsari, and Valsad districts of Gujarat (IDNP 2002). The area is broadly divided into seven river basin zones, and the extents of *Khar* (salt-affected) and unproductive lands covered 64,450 ha and 15,860 ha, respectively. In the coastal zones, the climate is subhumid to semiarid, and the soils are deep and clayey (40–60%) and showed low permeability. IRS LISS III-PAN merged data were used to study soil salinity along with the cadastral maps and soil physicochemical data such as pH, ECe, and ESP. About 37% areas suffer from soil salinity or sodicity or both (5%), and greenish/dirty whitish tones on the satellite data indicated salt-affected soils, of sodic or saline nature. The ESP of the highly sodic soils in Vertic Ustochrepts of south Gujarat showed positive correlation (R^2 = 0.46–0.47) with spectral radiance values of band 2 (green, 0.52–0.59 μm) and band 3 (red, 0.62–0.68 μm).

4.5.7 Soil Salinity and Waterlogging in Nagarjuna Sagar Project

LISS III April 2000 data was used to identify and map salty soils and waterlogged areas on 1:50,000 scale in 74,000 ha areas of Nagarjuna Sagar Project. The salt-affected soils usually appear in different tones of bright white to dull white with medium to coarse texture on FCC print in the background of normal soils due to the presence of salts. The waterlogged ponded areas appear on FCC image in various shades of dark blue to black tones with smooth texture. The salty soils are encountered at the lower slopes of the terrain and occupied 4% of the total study area. These are classified as saline-sodic classes and exhibited higher spectral reflectance value in band 3. "Moderately saline and moderately sodic" category of soils showed highest spectral reflectance values in IRS IC bands followed by "slightly saline and moderately sodic" and "slightly saline and slightly sodic," respectively (IDNP 2002).

4.5.8 Salt-affected Soils in the Sarda Sahayak Canal Command Areas Uttar Pradesh

Waterlogging and soil sodicity in Sarda Sahayak canal command areas in Uttar Pradesh state were studied using Landsat TM (1986) and IRS LISS II (1996) data on 1:250,000 and 1:50,000 scales, respectively. Depth-wise profile soil samples were collected from 19 Pedon in 12 blocks of Kanpur district. The soils of the district are derived from the alluvium deposited by rivers and are generally medium textured and poorly drained. The analytical data indicated that the pedons were alkali in nature with hard epipedon. The increase in the clay content of the subsurface layers is indicative of the processes of alleviation and an argillic horizon. The soils are slightly calcareous, the intensity of which increases at lower depths. The pH of the pedons was between 8.2 and 10.5. The ECe was as high as 16.7 dS m^{-1}. The SAR and ESP values indicated the level of sodification, and the major cations and anions are sodium, calcium, magnesium, carbonates, bicarbonate, and chloride. The CEC values increased with increase in clay content and ranged between 5.2 and 17.0 c mol. p^{+} kg^{-1}. The physicochemical properties indicate the presence of an argillic and natric horizon with high value of chroma >2, due to reduced conditions in the mottled horizon, coupled with Ustic moisture regime and calcic horizon in lower depth. Over the district, alkali lands are widespread, and very severe alkalinity (pH > 10.2) covers 560 km^2 area while severe (pH 9.6–10.1) covers 330.6 km^2 and moderate (pH 9.1–9.5) 156.2 km^2, and marginal lands (pH 8.6–9.1) are present in 193.2 km^2; a total of 736 km^2 were affected by soil sodicity (11.9%) of the TGA (6177 km^2) (CSSRI 1992–1996).

4.5.9 Salt and Water Regimes in Benchmark Salt-affected Soils in India

Benchmark salt-affected soils were studied in 14 irrigation commands including coastal soils of Ramanathapuram and Andaman and Nicobar Islands (A&N) of India. Thirty benchmark soil profiles were studied to know and understand seasonal salt dynamics and composition in varied agro-eco-regions of the country. Based on the profile characteristics of salt-affected soils, GPS-assisted benchmark sites were marked in 11 irrigation commands, such as the Western Yamuna, Bhakra and Jawaharlal Nehru canal commands in Haryana, Agra, Sharda Sahayak and Upper-Ganga canal in Uttar Pradesh, saline vertisols in Narmada Sagar (MP), secondary salinity in IGNP (Rajasthan), Krishna Western and Cauvery (Undi) deltas, Nagarjuna Sagar in AP, Tungabhadra (Gangawati) in Karnataka and coastal saline soil of Ramanathapuram and A&N Islands. (CSSRI 2002–2005) (Murthy et al. 1980)

4.5.10 Waterlogged Sodic Soils in Gandak Command (Bihar)

The interpretation of IRS ID LISS III imageries with ground truth and soil study data indicated small white spots of alkali soils in cropped and waterlogged areas of Gandak command covering Gopalganj and Siwan districts of Bihar. The alkali soils were noticed in abandoned land, old mango orchards, and small patches in arable areas. The calcite and dolomite in soil produced CO_3^{2-} and HCO_3^- ions and accumulate in poorly drained areas. The high sodium ions favored developing high SAR, soil alkalinity, and pH. The alkali soils were characterized as very deep with pale brown to light yellowish brown soil matrix and few to common yellowish brown mottles in the subsurface horizons. These soils can be reclaimed with low (4 t ha^{-1}) doses of gypsum or pyrites and better management practices (Sharma et al. 2011).

4.5.11 Sodic Soils in the Gangetic Alluvial Plain of Etah District, Uttar Pradesh

Sodic soils are widespread in the alluvial plain of Ganges basin located in Uttar Pradesh. The integrated approach of IRS LISS II data with soil survey revealed sodic soils (43,040 ha, 9.7%) in the old, recent (7594 ha, 1.7%) and active alluvial plains (2102 ha, 0.5%) of Etah district. High pH and ESP values in sodic soils of alluvial plains indicated Na^+ ion saturation of soil exchange complex and favorable conditions for the formation of natric horizon, platy soil structure, and precipitation of $CaCO_3$ as nodules and concretions. In the recent alluvial plain, sodic soils were characterized by moderate pH and ESP values and salt contents for Na^+, CO_3^{2-} + HCO_3^-, and $CaCO_3$ in subsoil layers and blocky soil structure. In active alluvial plain, sodic soils were characterized by low to medium pH (8.8–9.6), ESP (23), Cl^-, CO_3^{2-}, and nodular lime contents. The typical characteristics of sodic soils located in varied geomorphic location are useful information for reclamation strategies in Etah district of Uttar Pradesh (Saxena et al. 2004).

4.5.12 Sodic Soils of the Shivari Experimental Farm, Lucknow, Uttar Pradesh, India

CSSRI experimental farm Shivari was surveyed for characterization and classification of sodic soils. Moderately to severely sodic soils were identified in three farm terraces, viz., >120.6 m, 120.6–119.8 m, and <119.8 m MSL. Typical characteristics of sodic soils are light color, sandy loam to clay loam texture, strong subangular to angular blocky structure, and imperfect drainage leading to restricted air and water movement in B and C horizons, respectively. The clay content in B is 1.3–1.6 times higher than the upper layers, thus indicating illuviation. pH is strongly alkaline (9.4–10.9) and increases with depth. ECe is high 10.6–15.2 dS m^{-1} at surface and decreases with depth. CO_3 and HCO_3 of Na are the dominant salt in the saturated paste. High SAR caused low infiltration rate, and ESP values <20 at surface soil indicated its status after reclamation. These soils showed variable ESP (47–91), pH, and significant lime nodules (250–500 g kg^{-1}) at a depth below the surface. Organic matter content is low (0.16–0.62%) in general. The soil properties showed overall poor productivity and also indicate application of suitable dosages of gypsum and proper soil management for potential use in arable crops and horticulture and forestry purposes. Illite, chlorite, kaolinite, mixed layers, and smectite are dominant minerals along with quartz, feldspar, mica, and amphibole. These soils are classified as associations of fine-loamy, mixed, hyperthermic, Natrustalfs, and Haplustepts (Sharma et al. 2011).

4.5.13 Soil Salinity and Groundwater Quality in Nain Farm, District Panipat, Haryana State

Salt-affected soils of experimental farm at Nain village (Panipat district and Haryana state) were surveyed, characterized, and classified for reclamation and management. Historically, the farm area (10.8 ha) was a barren, flat scrub land showing thick salt efflorescence/crust with high soil salinity at surface and saline groundwater. Located at the Indo-Gangetic alluvial plain under semiarid climate, the salty soils are highly variable and complex saline and sodic in nature. The presence of calcium carbonate as *calcretes* and iron oxides nodules as *ferricretes* indicated an irreversible precipitation of calcium, iron, and manganese in sodic soils under poor drainage condition. These soils are characterized by variable soil texture, the absence of distinct horizon development and *Ustic* soil moisture regime and are classified as Haplustepts under the USDA Soil Taxonomy. Highly saline soils are classified at phase level. Sodic character is shown at the subgroup level following modified classification by Verma et al. (2007). The non-availability of good-quality water (canal/tube well) restricted its use for arable cropping. Seepage and accumulation of salty parent materials caused high soil salinization in soil profiles at lower topographic zone. Using grid sampling method, the spatial variability was studied to assess variability soil salinity/alkalinity and soluble ions. The dominance of chloride and sulfates of sodium, calcium, and magnesium in saline soils and the presence of carbonates and bicarbonates in sodic soils showed necessity for salt leaching and gypsum treatment for reclamation. Soils with low to moderate salinity are suitable for growing salt-tolerant varieties with necessary soil and water management practices. Highly saline and sodic soils may be used for fishery development or forestry purposes. The quality of groundwater at shallow depth (~24 m) is saline and unfit for irrigation. It may be used in cyclic or mixed mode with good-quality water. The quality of drain water is good but is available in monsoon season only. These soils are also used for brick kilns and industrial development purposes such as thermal power generation, fertilizer manufacturing (NFL), and oil refinery (IOC) plants in nearby areas. In areas where good-quality irrigation water is available, these lands were used for growing rice and wheat (Mandal et al. 2013).

4.5.14 Prognosis and Characteristics of Salty Soils of South-West Punjab, India

The evidence of secondary salinization in south-west Punjab was studied using IRS LISS III March 2000 data on 1:50,000 scale. The study area covered Bhatinda, Giddarbaha, Malaut Mandi, Lambi, Dabwali, Muktsar, and Faridkot areas. The salty soils appear in white to white blue tones on the images and were found mostly along the Sirhind main canal. Waterlogged soils were mapped by their dark and uneven appearance on the imagery. Seepage from Sirhind and Rajasthan Feeder canals and overuse of irrigation water for crops have brought about the rise of water table and eventually waterlogging and secondary salinization. The depth to water table in the study area was 11 m in 1981 and is close to the surface. It has forced the farmers to give up the cultivation of cotton and grow rice instead. Three categories of risks were identified, these were high water-table areas with onset of salinity and waterlogging, high water table areas with predicted soil salinity and waterlogging in the alluvial plain, Paleochannels, dune and inter-dune areas. The average increase in the areas under risks was 42% between 1997 and 2001. The physicochemical characteristics of salt-affected soils of south-west and central Punjab showed complex saline and sodic nature. Coarse texture soils under canal irrigation showed development of waterlogging and soil salinity. The presence of concretionary calcium carbonate at subsurface depths caused poor internal drainage and favored waterlogging. Suitable management options for growing salt resistant crops, proper water management practices and alternate land uses, such as horticulture and forestry plantations are suggested. The quality of surface water samples was also poor (Mandal 2014).

4.5.15 Extent, Nature and Management of Salt-affected Soils in Gujarat State

The state of Gujarat, located on the western edge of the Indian subcontinent, has a large part of its land surface under salinity/sodicity. To assess extent, nature, and characteristics of these soils, surveys were conducted and remotely sensed data collated. Soil profiles (419 Nos.) were examined from nine soil survey units viz, South Gujarat and the Panchmahals, Mahi command, Bhal, Khara Pat, coastal areas of Jamnagar, Rajkot, Amreli and Junagadh, area under the Nal Sarovar, south Gujarat, areas adjoing the Rann and Katchh. Based on the field and laboratory analytical data, 27 representative profiles have been classified into subgroup level under the Soil Taxonomy. The primary soil units were classified under the Aridisols, Inceptisols, Vertisols, and Entisols orders. Based on the prominent soil morphology, these soils were further classified as Natrargids, Camborthids, Salorthids, Calciorthids, Halaquepts, and Ustochrepts at the subgroup level. A sizeable area of 16, 89, 860 ha (8.62% of TGA) in Gujarat is affected by salinity and sodicity. Salinity is major problem in Kachchh, Mahi command, Rann, and Panchmahal as a result of tidal ingress and secondary origin. Sporadic occurrence of alkalinity is found in Mahi command, Nal Sarovar, North and South Gujarat, Bhal, and the Panchmahals. Factors responsible for soil salinization include climate, irrigation system, irrigation practices, imperfect drainage, tidal ingress, and parent materials (Dubey et al. 1995).

4.5.16 Description and Characterization of Typical Soil Monoliths from Salt-affected Areas in Rajasthan

The study was undertaken to describe methodology for collection, preparation, and characterization of two soil monoliths, an alkali soil of Borai village Bharatpur district and an irrigated saline soil from Lunkaransar area Bikaner district, of

Rajasthan state for display and demonstration to users. Soil monoliths were collected from a profile pit measuring 1.8 m × 1.8 m × 1.5 m dimension using a wooden box of 1.2 m × 0.25 m × 0.1 m and 1.5 m × 0.25 m × 0.1 m dimensions at Lunkaransar and Bharatpur, respectively. The soil surface and the base of the box were repeated sprayed with adhesive containing acetone and cellulose. After clamping the box on the prepared column of the soil, it was detached from the soil mass by careful scrapping. The freshly separated side of the monolith was carefully brought to its natural state by exposing structural Peds color differentiation and concretions. The front side of the monolith was sprayed with a clear transparent adhesive for better preservation and display. The important features of the monoliths were annotated for display and presentation (Mandal and Sharma 2012).

4.6 Development of Computerized Database on Salt-affected Soils Using GIS

4.6.1 Digital Database of Salt-affected Soils in India on a Reconnaissance Scale

Salt-affected soils were mapped on 1:250,000 scale based on the interpretation of remote sensing data, ground truth studies, and laboratory analysis of soil samples for pH, ECe, and ESP. These soils covered 15 states (printed on 125 paper sheets) and contained voluminous data on spatial coverage, physiography, and categories of salt-affected soils. In the analog form, such data is difficult to handle by users of varied background and interest. For easy access, quick retrieval, and spatial analysis in multiple thematic layers, the analog maps were geo-referenced and digitized to develop theme layers of salty soils and a base map overlaying infrastructure (roads/railways), irrigation/drainage (canal/river), settlements (state/district capitals), and political/administrative boundaries. Soil salinity maps of 15 states were compiled in GIS to develop a composite map of India. An estimated area of 6.73 M ha was salt-affected soils; saline and sodic soil covered 2.9 and 3.7 M ha, respectively (Mandal et al. 2010).

4.6.2 Regional Databases for Western and Central India

Salt-affected soils occupy significant areas in western and central India manifested by the arid and semiarid climate, sandy/clayey soil texture, absence of natural drainage, and inadequate infrastructure and irrigation development. These soils are also potentially productive following reclamation and appropriate management. Based on the salt-affected soil maps of Rajasthan, Gujarat, Madhya Pradesh, and Maharashtra states, a composite (master) database showing the extent and distribution of salt-affected soils in western and central India was prepared (Mandal and

Sharma 2011b). Spatial data such as agroclimatic zones, physiography, climate, geology, and agro-eco-subregion was overlaid to show spatial relation with salt-affected soils. The saline soils were dominant in the arid (B), alluvial (A), and coastal (D) plains of Rajasthan and Gujarat, and sodic soils are located the peninsular plain (F) of Maharashtra and Madhya Pradesh. It occupied 2,596,942 ha (78%) in Rajasthan and Gujarat and 733,608 ha (22%) in Madhya Pradesh and Maharashtra and covered 3.3 million ha in the western and central region accounting 50% of the total salt-affected soils in India. The saline and sodic soils covered 2,069,285 ha (62%) and 1,261,266 ha (38%), respectively.

4.6.3 Peninsular Plain

State maps of salt-affected soils for Andhra Pradesh, Karnataka, Tamil Nadu, Kerala, and Orissa were integrated to prepare a composite database for peninsular plain using GIS (Mandal and Sharma 2009). Sodic soils (73%) are distributed in the peninsular (F) and alluvial plains (A) of Andhra Pradesh (20%), Tamil Nadu (37%), and Karnataka (15%). Saline soils (27%) were located in coastal (D), deltaic (C), and mangrove (G) regions of Orissa (15%) and Kerala (2%). Significant areas (69%) were distributed in three agroclimatic zones such as West Coast Plain and Ghat Region (ACR XI), Southern Plateau and Hills Region (ACR X, 26%), and East Coast Plains and Hills Region (ACR XII, 4.5%).

4.6.4 The Indo-Gangetic Plain

Indo-Gangetic Plain (IGP) of India has stretched from the Punjab to West Bengal state and is known for fertile soil and favorable climate for rice-wheat production. Soil salinization in IGP is a major concern due to loss of productivity. State maps of salt-affected soils for Haryana, Punjab, Uttar Pradesh, Bihar, and West Bengal were integrated in GIS to prepare composite database of IGP. The boundaries of 4 agroclimatic regions (ACRs) and 17 agroclimatic zones (ACZs) were used for regional planning and development of salt-affected soils using ILWIS-GIS. Soils were saline at the Lower and Middle Gangetic Plains and complex saline-sodic in the Upper and Trans-Gangetic Plains. The largest areas of salt-affected soils were recorded in the Upper Gangetic Plain (ACR V) of Uttar Pradesh followed by the Middle Gangetic Plain (ACR IV) of UP and Bihar, the Lower Gangetic Plain (ACR III) in West Bengal, and the Trans-Gangetic Plain (ACR VI) of Haryana and Punjab (Mandal and Sharma 2006).

4.6.5 Coastal Plains

Salt-affected soil maps for eight states (49 districts) were compiled to prepare a composite database for coastal region using GIS (Mandal et al. 2018). Saline

(1,828,361 ha, 73%) and sodic (673,008 ha, 27%) soils were distributed in D (38.8%), F (13.9%), G (13.4%), C (9.6%), B (6.5%), A (3.5%), and H (14%). Significant areas are distributed in Gujarat (50%), West Bengal (17.6%), Tamil Nadu (12.7%), Andhra Pradesh (7.6%), Orissa (5.8%), Andaman and Nicobar Islands (3.0%), Maharashtra (2.0%), and Kerala (0.8%) states.

4.7 Updating of Salt-affected Soils Database for Haryana State at Post-reclamation Stage

4.7.1 Significance of the Study

The first survey of salt-affected soils was initiated by identifying soil alkalinity and salinity problems in the Gangetic alluvium located at Etah district in Uttar Pradesh (Leather 1914). Patches of salt-affected soils were detected in the lower Ganges canal areas of Uttar Pradesh (Agarwal et al. 1957). Investigations revealed that salts are drained from the Himalayas and Siwalik through rivers/streams and are accumulated at the alluvial plains (Sidhu et al. 1995; Bhargava et al. 1980). The lack of adequate internal drainage in lower topographic regions prompted soil salinization (Bhargava et al. 1980). High evaporation during the dry season and lack of good-quality water for leaching caused salt accumulation in soil profiles. The coexistence of salt-affected soils and poor-quality groundwater in central Haryana is a primary constraint for agriculture (Yadav 2003). The use of poor-quality groundwater for irrigation increased salt buildup in soil profiles, which caused reduced productivity. Canal irrigation in un-drained areas has also accentuated waterlogging, formation of high water table, and secondary salinization in soils. The erratic rainfall and temperature patterns not only threaten agriculture but cause redistribution of salinity-affected areas. In the dry regions of central Haryana, the primary dependence on groundwater for irrigation has degraded soils through the deteriorating physical and chemical properties of soils coupled with fine-textured Ghaggar alluvium that caused a congenial environment (waterlogging) unfavorable for sustainable agriculture. A thorough investigation of soil and water and spatial distribution of salt-affected soils using remote sensing data are required for precise assessment. The variable extents of salty soils (454–232,000 ha) in Haryana (Abrol and Bhumbla 1971; NRSA 2008) and the complex nature for salts, soil physical properties, and drainage (Sharma et al. 2011; Chinchmalatpure et al. 2016) have been reported periodically. The complex pedogenic processes due to the anthropogenic activities using poor-quality groundwater for irrigation were also reported in arid and semiarid areas (Jain and Kumar 2007; Bhalla et al. 2011). For accurate assessment of reclamation and management, precise diagnosis, quantitative analysis for physico-chemical characteristics, and quality appraisal of irrigation water are of primary importance. This chapter addresses role of remote sensing for developing methodology for mapping and chemical characterization of salt-affected soils and quality appraisal of groundwater in Haryana, India, for reclamation and management.

4.7.2 Study Area

The Haryana state (4410 sq.km) lies between 27°39′N 74°27′E and 30°55′N 77°36′E, under the alluvial and aeolian plains, Siwalik and Aravalli hills, that covered 4 agro-eco-regions, 4 subregions, 8 agro-ecological zones and 22 administrative districts. The climate varies from arid to semiarid and subhumid. The average rainfall of the state is 500–600 mm which ranges between 300 and 500 (hot arid region), 50 and 750 mm (hot semiarid region), and 75 and 1050 mm (hot subhumid region). The cultivable area covers 85% of TGA, the area under forest is 168,000 ha (3.8%), and barren and uncultivable land covers 104,000 ha (2.4%). The net irrigated area is 2,532,000 ha (71%) mainly by canals (49%) and groundwater (50%). The primary source of irrigation is Western Yamuna and Bhakra canals. The primary crops include paddy in summer (*Kharif*) and wheat in winter (*Rabi*) seasons, while cotton, pearl millet, sugarcane, sunflower, and pulses (moong) are also practiced. Growing Dhaincha (*Sesbania aculeata*) is common practice in areas under salt-affected (alkaline) soils and water to reduce salt injuries and improve soil health (physical properties). The primary landform is alluvial (Ghaggar and Yamuna alluvium) in general.

4.7.3 Satellite and Related Data Used

Indian Remote Sensing (IRS) (Resource SAT) LISS III data with spatial resolution of 23.5 m and spectral resolution (green, 0.52–0.59 μm; red, 0.62–0.68 μm; near infrared, 0.77–0.86 μm; and short-wave infrared, 1.55–1.70 μm) for March, May, and October 2009–2012 was used in the study (Table 4.1).

The Survey of India topographical maps on 1:50,000 scales were used for preparing the base map comprising of administrative and political boundaries, irrigation/drainage, infrastructure, and settlement. Software ERDAS IMAGINE and ILWIS (*ver 3.3*) were used for digital and spatial data analysis. The software Arc GIS (ver 9.3) was used for generation of thematic layers. A Cal Comp (A_0) digitizer, a scanner, and a printer attached to a Pentium (PIV) computer equipped with Microsoft Windows XP and Office (2000) were used for entry, editing, and

Table 4.1 Particulars of satellite imageries

Sensor	Spectral resolution (μm)	Spatial resolution	Period
IRS- P6 LISS III Resource SAT I	B1 0.52–0.59 (green)	23.5 m	February–March 2009–2010
	B2 0.62–0.68 (red)	Swath 140 km	May–June, 2010–2012
	B3 0.77–0.86 (NIR)		October–November, 2010–2011
	B4 1.55–1.70 (SWIR)		

analysis of map and attribute data. The ancillary data (State Department of Agriculture Haryana and NBSS&LUP, RC Delhi), water quality data (Gupta 2010; Manchanda 1976; HSMITC 2001), crops, and associated land characteristics (District Gazettes Haryana) were also collected for the study area. The salt-affected soil map of Haryana (NRSA 1997) on 1:250,000 was also used as legacy data. Soil sampling tools, like color chart, auger, spade and knife, etc., also were used. Global Positioning System (GPS) was used for collecting data related to the location of field data.

4.7.4 Methodology

4.7.4.1 Geo-Referencing and Digitization for Base Map Preparation Using GIS

The Survey of India (Government of India) topographical maps on 1:50,000 scale were used for geo-referencing and related with real-world coordinates using Universal Transverse Mercator (UTM) projection with projection (ellipsoid WGS 84) and datum (WGS 1984) information. The spatial features for state, district boundaries, roads and railways, canal and river and state, district HQ, and villages were digitized, and the thematic layers were overlaid to develop a base map of the study area.

4.7.4.2 Image Processing and Interpretation of IRS Data

The IRS imageries were processed for radiometric and geometric corrections and were geo-referenced. The False Color Composites (FCC) were prepared using combination of bands such as NIR, R, and G (B321) and SWIR, NIR, and R (B432). The seasonal data were also analyzed to study the dynamics of soil salinity and waterlogging. Visual analysis was done, and interpreted units were digitized following standard guidelines (Colwell 1996). The principal component analysis was done to segregate homogenous data for visual analysis, and filters were used to improve sharpness of the images for visual analysis. The spectral response patterns were analyzed for spatial properties of salt-affected, waterlogged, vegetation, crop, and sandy soils. Spectral reflectance was calculated based on the mean reflectance in bands B2, B3, and B4. NDVI [(B3−B2/(B3+B2)] and VI (B3/B2) were used to distinguish normal and stressed crops. Principal component analysis was performed to homogenize digital data and achieve higher accuracy in image classification. An average (AVG 3 $\times$ 3) filter was used to enhance image sharpness for visual analysis and reduce noises prior to multiband image classification. The nearest nine pixels were used to assign the values for central pixel to reduce noises and enhanced interpretation of the images. Digital classification was performed using a supervised classification approach based on maximum likelihood classifier. Ground truth, laboratory analysis, and land use data such as field crop, forestry, urban settlement, roads, and natural water for pond, river, and canal were included as training sets for digital classification. Legacy data such as digitized maps of salt-affected soils, water table depth and quality, and the Survey of India maps were used as supporting data (Saxena 2003; Verma et al. 2004). Average reflectance of a cluster of homogenous

Table 4.2 Keys to the degree of salinity/sodicity in salt-affected soils (Richards 1954)

	Saline soil	Sodic soil	
Degree	ECe (dS m^{-1})	pHs	ESP
Slight	4.0–8.0	8.5–9.0	<15
Moderate	8.1–30.0	9.1–9.8	15–40
Strong	>30	>9.8	>40

pixels in B1 to B4 of March season was assigned a class name, and the sample statistics (feature space) of the training set was generated to separate pixel classes assigned as training set and a scatter plot of two bands.

4.7.4.3 Field Survey for Soil Profile and Related Ground Truth Studies

Ground truth studies were conducted to verify and authenticate interpreted units and establish relationship between image interpretation and field conditions. During field survey important properties such as surface salinity and waterlogging status, seasonal behavior, topography, irrigation/drainage, and crops/cropping practices were studied. GPS (Global Positioning System) was used to locate sites for ground truth observations, soil profiles, and soil and water sampling. The groundwater samples were collected from tube wells (used for irrigation in agriculture). The soil profiles (10 Nos.) were studied to a depth of 1.5 m at representative locations, and depth-wise soil samples were collected for laboratory analysis for soil physicochemical properties (Soil Survey Staff 1998). These were classified using taxonomic system of soil classification (Soil Survey Division Staff 2004). The soil samples were also characterized (Richards 1954) for salinity/alkalinity appraisal (Table 4.2).

4.7.4.4 Laboratory Studies for Soil Characterization, Classification, and Water Quality

Soil samples were analyzed for physicochemical properties, viz., pHs; ECe (dS m^{-1}); soluble ions (me L^{-1}) such as Na^+, K^+, Ca^{2+}, Mg^{2+}, CO_3^{2-}, HCO_3^-, and Cl^- (me L^{-1}); $CaCO_3$ (<2 mm size, %) and organic matter (OM%); CEC (cation exchange capacity as c mol (p^+) kg^{-1}) and ESP (exchangeable sodium percentage); sand (%), silt (%), and clay (%); soil texture; and available (AV.) N (nitrogen, kg ha^{-1}), P (phosphorus, kg ha^{-1}), and K (potassium, kg ha^{-1}) (Jackson 1996; Singh et al. 1999). Soils are classified as saline, sodic, and saline-sodic and the degrees of classes as slight, moderate, and strong (Richards 1954). The waterlogged areas were classified as permanent waterlogged (surface ponding) and subsurface waterlogging (water table depth <1.5 m) based on NRSC (2007). Groundwater (GW) samples were collected from tube wells/open dug wells to study the water quality for agricultural applications. These were analyzed for pH_{iw}; EC_{iw} (dS m^{-1}); soluble ions (me L^{-1}) such as Na^+, K^+, Ca^{2+}, Mg^{2+}, CO_3^{2-}, HCO_3^-, and Cl^-; SAR (sodium adsorption ratio) $= [Na^+/\{(Ca^{2+} + Mg^{2+})/2\}^{1/2}]$, and RSC (residual sodium carbonate) $= [(CO_3^{2-} + HCO_3^-)-(Ca^{2+} + Mg^{2+})]$.

4.7.5 Mapping of Salt-affected and Degraded Soils Using GIS

An integrated approach of image interpretation, ground truth survey, and laboratory analysis data for soil physicochemical properties was used for mapping salt-affected and waterlogged soils (NRSA 2007; Mandal and Sharma 2012, 2013; Dwivedi 2001). Overlaying thematic layers of base map and ancillary data, the interpreted units were delineated using on-screen digitization technique. The thematic map of salt-affected soils for Haryana state was prepared. The area statistics of salt-affected and waterlogged soils were generated (Mandal and Sharma 2011a). The thematic layers of salt-affected soils were linked with the physicochemical properties of soils to develop a relational database (Mandal and Sharma 2011b). Supervised classification was carried out using a nearest neighborhood operator. An interactive database was prepared integrating maps prepared from digital and visual analysis, and a confusion (error) matrix was generated for accuracy assessment.

4.8 Visual Interpretation of IRS Data for Degraded Soils

Strongly sodic soils (white to yellowish white tone in B321, irregular shape), normal crops (bright red tone, continuous), and waterlogged soil (surface ponding, dark blue to black tone, irregular shape) were easily detected based on their strong signatures from the visible and infrared bands in the IRS data. Image interpretation identified salt-affected soils as white to yellowish white patches in the old alluvial plains of Ghaggar and Saraswati (Fig. 4.1). Dark blue to black patches and red to dark red tone indicated the association of waterlogging, soil salinity, and patchy cropped areas. FCC of bands B432 (SWIR, NIR, and R) showed higher contrast and clear boundaries of waterlogged areas than the FCC of bands B321 (NIR, R, and G). Prominent waterlogging and salt infestation were also located in the old paleochannels of Saraswati in Kaithal district. The ground truth data indicated that prolonged irrigation with salty groundwater caused low permeability, infiltration, and poor drainage in moderate- to fine-textured soils at subsurface depths in Ghaggar plain. Barren patches interspersed with cropped areas showed the existence of waterlogged soils and poor vegetative growth in Siwan block. The ground truth data confirmed the presence of sodic soil and the practice of poor-quality groundwater for irrigation in wheat and rice crops. IRS imagery also indicated prominent waterlogging, severely salt-affected soils, and the absence of natural drainage. Ground truth studies indicated the presence of fine-textured layers at subsurface depth inhibiting percolation of salts, water, nutrient, and restricted root growth. At places, salt crusts and sodic groundwater were detected in the forest-covered areas near Pehowa in Saraswati forest range of Kurukshetra district. The spatial distribution of salt-affected soils indicated common occurrence in the Markanda and Ghaggar plains in Ambala district. IRS LISS III March data showed temporary waterlogging and alkali soil formation in the patchy cropped areas. White salt crust along the Bhakra canal command indicated soil salinization.

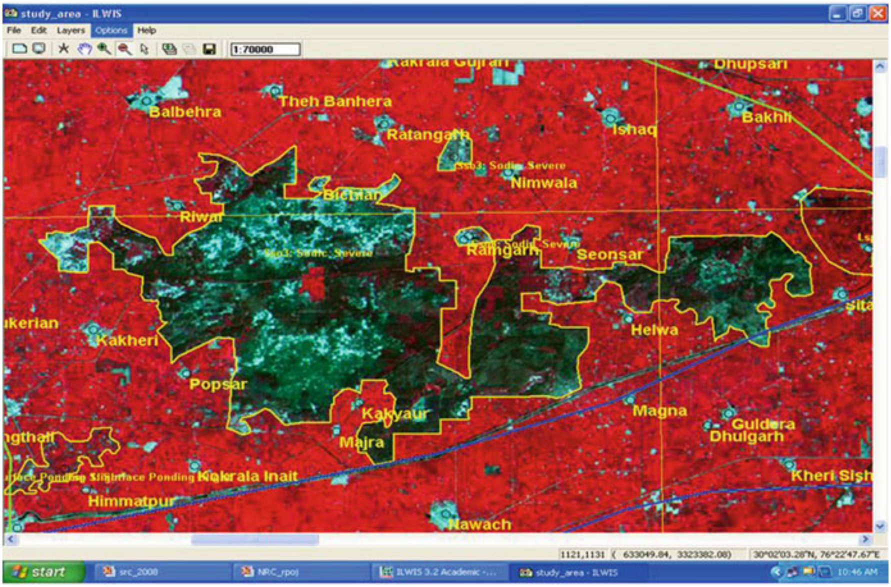


Fig. 4.1 Salt-affected soils viewed in IRS LISS III data

In the irrigated areas, waterlogging and soil salinization were identified in the low-lying flats/depressions with imperfect internal drainage in central Haryana (Fig. 4.2). Continuous irrigation in poorly drained areas caused rise of water table. The salt concentration was higher in post-monsoon season due to salt transport with rising water table. Repeated wet and dry cycles favored salt precipitation and enriched salt concentration during the dry period. Critical areas include the canal commands of WJC and Bhakra that covered Hisar, Jind, Bhiwani, and Sirsa districts. Prominent areas of waterlogging and soil salinization were also identified along the Bhakra canal command in Narnaud, Hansi, Hisar, Barwala, and Uklana blocks, Hisar district.

The periodic use of the saline groundwater for agriculture increased salt concentration in soil profile that deteriorated soil physical properties and favored waterlogging at the low-lying areas. IRS data (2009) showed mixed spectral signatures of dry salts and dark tones of residual moisture at the soil surface that indicated signatures of sodic soils and temporary waterlogging along the paleochannel of river Chautang. In dry areas, the use of sodic groundwater for irrigation favored developing strongly sodic soils appearing as white patches of barren salt crust in Chika block. The moderately sodic soils were appearing as tiny white patches in irrigated areas with good-quality groundwater interspersed with red to dark red tones of crops (Mandal and Sharma 2011a). Partially reclaimed sodic soils showed moderate crop cover and intermittent salt patches in low-lying flats and depressions of Panipat, Karnal, and Kurukshetra districts (Mandal 2012). Slightly sodic soils showed good to very good crop and vegetative covers (Howari 2003),

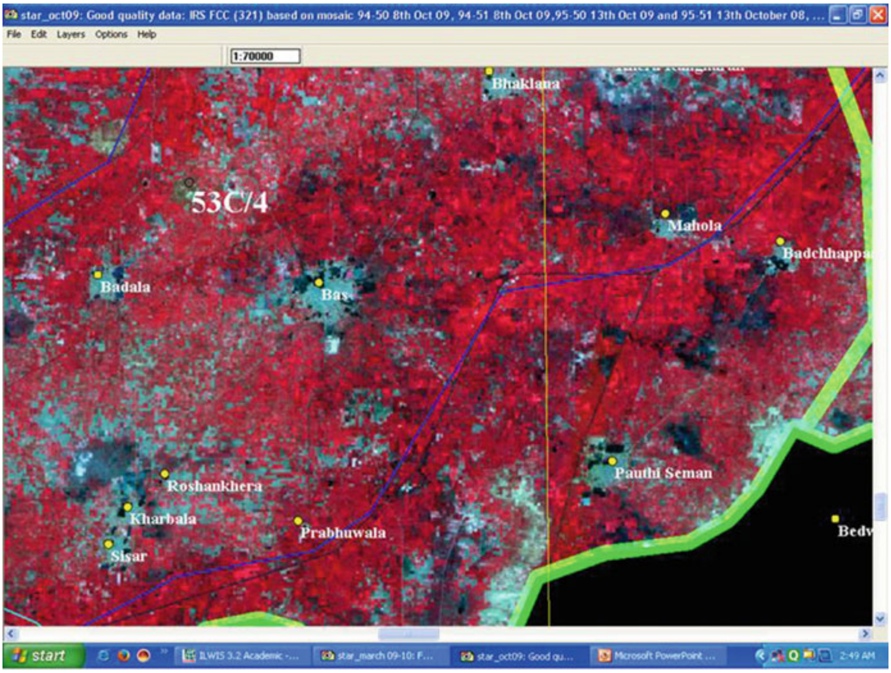
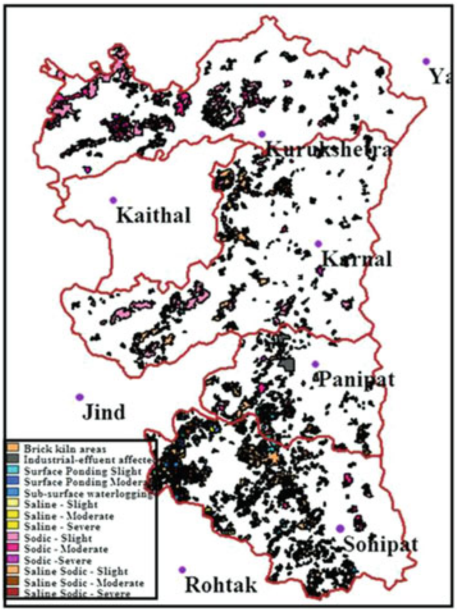


Fig. 4.2 Waterlogging in the irrigated areas of Hisar district

though the field study reported low productivity due to crop damages in the maturity stage. The similarity of spectral signatures for village settlements (muddy roof top) and barren salt-affected soils caused spectral confusion during digital analysis. Visual analysis revealed definite shape and sizes of rural settlements that differ from irregular pattern in salt-affected soils (Khan et al. 2005). Mixed gray to reddish gray and mottled red tones indicated waterlogging in cropped areas (Mandal and Sharma 2013), which was authenticated during field studies. The linear shape of canals and typical curvilinear meandering rivers differs from stagnant water bodies (waterlogged surface) though these elements showed similar spectral reflectance.

Visual analysis of IRS LISS III data (2005–2006) revealed the distribution of salt-affected soils (saline, Ssa; sodic, Sso; and saline-sodic, Sss), subsurface waterlogging (Lsw), surface ponding (slight, Lsp1, and moderate, Lsp2), brick kiln (Hbk), industrial effluent affected area (Hie), partially stabilized dune (Edp2), riverine sand (Tms), and sand mining (Hmd) in Karnal, Kurukshetra, Panipat, and Sonepat of central Haryana. The salt-affected areas were identified as with high surface reflectance of dry salts during summer season and as small patches amidst the cropped areas with poor crop stand and vegetative growth. In the forest areas, these soils were identified in February–March season due to lesser vegetative coverage following litter fall. Ground truth studies revealed localized patches of moderately to severely salt-affected soils with variable extent in Panipat and Kurukshetra districts. Prominent waterlogging was found in irrigation command



Categories of degradation	Area (ha)
Partially stabilized dunes (Edp2)	314
Brick kiln areas (Hbk)	891
Industrial effluent affected areas (Hie)	1934
Mining (Hmd)	331
Surface ponding slight (Lsp1)	6529
Surface ponding moderate (Lsp2)	19
Sub-surface waterlogging (Lsw)	6859
Saline slight (Ssa1)	4405
Saline moderate (Ssa2)	1431
Saline severe (Ssa3)	596
Sodic slight (Sso1)	32201
Sodic moderate (Sso2)	18347
Sodic severe (Sso3)	5081
Saline-sodic slight (Ss1)	31641
Saline sodic moderate (Ss2)	15906
Saline sodic severe (Ss3)	399
Riverine sand (Trns)	210
Total	127094

Fig. 4.3 Mapping and assessment of land degradations in Central Haryana

areas of Sonepat district. High water table (<1.5 m) depth has favored salt accumulation at surface during the dry seasons. Prominent waterlogged soils were identified in the irrigated areas of Gohana block in Sonepat district (Fig. 4.3).

Soil profile studies revealed the distribution of salt-affected soils in the Ghaggar flood plain of Kurukshetra district. Satellite imageries also showed waterlogging due to the irrigation with poor-quality groundwater. Severely salt-affected soils were identified in Saraswati forest range under Pehwa block and Seonti forest area under Ladwa block of Kurukshetra district. The chemical analysis data of soil profiles showed sodicity to the extent of pH 11 at surface in Saraswati and pH 10.2 below the surface in Seonti RF. Salt-affected soils were identified in the Markanda flood plain with moderate crop stand (Fig. 4.4).

The satellite imageries showed soil salinization in the paleo-channels of river Chautang affecting large areas of rice-wheat crops. Chemical analysis of soil and groundwater quality showed high salt load in water samples and slight to moderate alkalinity and fine-textured strata in soil profiles. Patchy salt-affected soils were found in Rajaund and sporadic sodic soils in the Nilokheri and Indri blocks, and slightly to moderately sodic soils were located near the Chautang escape that drained alkaline salts from the Siwalik regions.

Salinity and sodicity were located in Israna block of Panipat district, where significant areas (23,030 ha) of salt-affected soils (Fig. 4.5) were reclaimed and further used for rice-wheat production. Severely sodic soils were used for thermal power and fertilizer production and oil refinery projects. Following successful

Fig. 4.4 Strongly sodic soils in Saraswati forest range of Kurukshetra district

Fig. 4.5 A barren sodic soil (pHs > 10) in Village Naultha District Panipat

Fig. 4.6 Prosopis – a common vegetation in barren salt-affected soil

reclamation, moderately to highly sodic soils were used for crop production and at places used for grazing purposes (Fig. 4.6).

Prominent areas of saline and sodic soils were located Gohana and Kharkhauda blocks of Sonepat district along the Western Yamuna canal command. Large-scale waterlogging and soil salinization rendered vast irrigated areas out of cultivation (Figs. 4.7 and 4.8). Soil profile studies identified fine-textured clayey layer, profuse accumulation of calcium carbonate nodules at the surface horizon, and thick impermeable layer of calcium carbonate concretions that restricted water movement and leaching of salts beyond the root zone (Sharma and Mandal 2006).

4.9 Digital Analyses of Remote Sensing Data for Spectral Properties of Degraded Soils

Spectral analysis of IRS data identified prominent energy absorption for waterlogged area (surface ponding, SP_S) during October (B3 > B4 > B2) and March (B3 > B4 > B2) (Mandal and Sharma 2001). Sodic soils showed higher reflectance (B2 > B3 > B4) in green band (0.55 nm) during June, apparently due to dry and bare soil cover and less vegetation. The reflectance of strongly sodic soils was ~40% higher than the moderately sodic soil (Sehti et al. 2012). The lower reflectance values

Fig. 4.7 Soil salinity affecting productivity in irrigated areas of Gohana, Sonepat district

Fig. 4.8 Surface ponding from canal seepage and poor natural drainage in Sonepat district

of moderately sodic soils in red (650 nm) and SWIR (1625 nm) bands appeared to be due to higher vegetative cover. The reflectance of moderately sodic soil irrigated with good-quality groundwater was ~20% higher than soils irrigated with sodic groundwater during March season (Mandal et al. 2016). The reflectance of strongly sodic soils increased ~40% for irrigating with normal groundwater during October (rice season) and decreased ~60% due to less salt load and low cropping density during June and unchanged with wheat crop that requires low frequency of irrigation water during March (Mandal et al. 2016). The slightly sodic soils with normal groundwater followed an order of B3 > B4 > B2 possibly due to higher canopy cover. The reflectance of surface ponding (SP_S) was low due to higher energy absorption during March (less irrigation) and October (rice crop) seasons and minimum during June (dry season). The reflectance of subsurface waterlogged soils (SSW) is ~80% higher in B3 (NIR) than B4 (SWIR) and B2 (green) as a result of higher crop canopy cover and low due to submergence of water during October (rice crop). The reflectance in NIR band was higher in normal crop due to healthy vegetation. Matured winter crops showed higher reflectance of B3 during March (B3 > B4 > B2), while crops with moist soil surface showed higher values of B4 during October. The spectral reflectance of riverine sand was high (60–100) due to bare surface. The low reflectance values of irrigated sodic soils in March data (40–60) appeared to be due to surface moisture. Similar results were reported for carbonate-rich salts in visible (0.55–0.77 μm) and infrared (0.9–1.3 μm) ranges (Csillag et al. 1993; Rao et al. 1995; Khan et al. 2005).

The NDVI values were low (0.1–0.3) in soils with less vegetative cover (Mandal and Sharma 2011a). Waterlogged soils showed low NDVI values (0.24–0.34) and indicate stressed vegetation (Joshi et al. 2002). Crop irrigated with poor-quality groundwater showed low NDVI values (0.18–0.52), and it increased (0.48–0.52) in areas with normal groundwater. Low NDVI values (−0.04 to 0.04) of riverine sand indicated the scanty vegetative cover. The higher NDVI values of moderately sodic soils (0.29–0.52) may be ascribed to higher vegetative cover and also management interventions at selected locations (Mandal and Sharma 2011a; Raghuwanshi et al. 2010).

The principal component coefficients (PC) showed significant relationship between B1 and PC1 (0.524); B2 and PC4 (0.831); B3 and PC1 (0.707) and PC2 (0.683); and B4 and PC3 (0.670). PC1 showed 93.5% variance, while PC2, 3, and 4 showed 5.91, 0.30, and 0.09%, respectively. The feature spaces for B1 and B2, B1 and B4, and B2 and B4 indicated positive relation and null or partial relation between B1 and B3, B2 and B3, and B3 and B4. An interactive (cross) database was prepared using maps prepared from visual analysis and digital classification. A confusion (error) matrix was prepared to assess the accuracy of digital classification. The data showed an overall accuracy 25.4%, average accuracy 18.0%, and reliability 10.5%, respectively. The slightly sodic soil showed highest accuracy (34%, reliability 65%) followed by subsurface waterlogging (27%, reliability 3%), riverine sand (27%, reliability 21%), and moderately sodic soil (11%, reliability 35%), respectively.

4.10 Soil Physicochemical Properties and Suggested Management Practices

4.10.1 Kaithal District

The physicochemical properties of soils from Kaithal district are presented in Table 4.3. Pedon 1 (P1) showed salt accumulation; sodic condition; moist soil strata; deep, fine soil texture; massive to moderate, fine to medium, angular to subangular blocky structure; and the significant presence of iron and manganese mottles (1–2 mm, 10–20%) at 24–105 cm depth and calcium carbonate concretions (2–4 cm, 20–40%) at 70–135 cm depth, respectively. Based on the data of physicochemical properties (pHs 10.3–10.4 and ESP 75.4–83.2), the Pedon is classified as strongly sodic (Richards 1954). The higher contents of CO_3^{2-} + HCO_3^{-} (14.5–16.9 me L^{-1}), Na^{+} (15.6–44.9 me L^{-1}), Cl^{-} (8.0–14.0 me L^{-1}), and SO_4^{2-} (2.8–7.0 me L^{-1}) ions were noted. The soil texture ranges from silty clay loam to loam showing higher clay content (12.2–36.6%). CEC varies from 28.7 (at surface) to 13.6 (at 187 cm) c mol (p^{+}) kg^{-1}. The *calcrete*s ($CaCO_3$) are present (10.2–11.4%) at 1m depth. The organic carbon, available nitrogen, and phosphorus contents are low throughout. These soils can be used for rice-wheat cropping following reclamation with gypsum (4–6 Mg ha^{-1}).

Located at the old alluvial plain of Ghaggar (Sachdev et al. 1995; Mandal 2014) and irrigated by salty groundwater (Kaithal block), Pedon 2 (P2) showed water stagnation and patchy crop stand in March and November satellite data. The soil is characterized by deep, massive to medium, subangular blocky structure, clayey texture, and pale yellow to dark yellowish brown color. The moist to wet subsurface layers and the presence of iron and manganese nodules showed anaerobic condition in soil profile. The physicochemical analysis data indicated both sodic (pH 8.7) and saline (ECe 6.5–8.6 dS m^{-1}) conditions at subsurface depths. The Na^{+} (1.5–63.5 me L^{-1}), Ca^{2+}+Mg^{2+} (4–38 me L^{-1}), Cl^{-} (128–725 me L^{-1}), and SO_4^{2-} (5.9–54.0 me L^{-1}) ions are prevalent. The higher CEC values (42.6–44.1 cmol (p^{+}) kg^{-1}) arise from high clay content (53–57%) which is also causing poor internal drainage (Mandal 2014; Mandal and Sharma 1997). The soil is low in organic carbon (0.2–0.3%), available nitrogen (11–78 kg ha^{-1}), and phosphorus (16–53 kg ha^{-1}) contents and showed moderate to high available potassium (466–509 kg ha^{-1}). The treatment with FYM or compost is required to improve soil physical properties and internal drainage. The alkali groundwater may be treated suitably with gypsum, while the saline groundwater may be used in mixing or cyclic mode for irrigation purpose (Gupta 2010; Singh 2009).

The subangular blocky structure, silty loam texture, and pale yellow to yellowish red color and sodic groundwater were characteristic features of Pedon 3 (P3) (Jain and Kumar 2007). The scattered crop and higher water absorption (dark gray tone) for waterlogging are typical surface features in the satellite imageries. The pH (8.6–9.3) and ESP (44.6–54.4) values indicated slight to moderate sodicity and are used for rice-wheat cropping following reclamation (0–30 cm). Prominent waterlogging appeared due to fine soil texture (silt loam) and stratification caused

Table 4.3 Physicochemical properties of selected soil profiles from Kaithal district

Horizon	Depth (m)	pHs	ECe (dS m^{-1})	Na^+ (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})	OC (%)	ESP	$CaCO_3$ (%)	CEC (c mol (p^+) kg^{-1})	Texture	Clay (%)	Silt (%)	Sand (%)	N (kg ha^{-1})	P (kg ha^{-1})	K (kg ha^{-1})
P1:29°47′38.9″N to 76°39′52.3″E Fine-Loamy Sodic Haplustepts, sodic soil in paleo-channel of the river Chautang, calcareous parent material																			
A1	0.0–0.2	10.3	1.6	15.6	4	15.6	8.0	2.8	0.2	76.6	1.9	24.6	sicl	36.6	38.9	24.4	31	17	208
Bw1	0.2–0.4	10.4	2.6	27.4	4	15.1	10.0	5.4	0.2	75.4	1.9	28.7	sicl	34.6	37.4	27.9	27	14	208
Bw2	0.4–0.7	10.3	2.3	22.9	4	14.5	10.0	4.2	0.2	83.2	1.2	25.4	sicl	28.0	32.1	39.8	23	10	188
B21k	0.7–1.0	10.4	3.4	28.7	4	16.7	14.0	5.7	0.2	74.8	2.3	21.1	l	18.3	24.1	57.5	23	10	151
B22k	1.0–1.3	10.4	4.0	44.9	4	16.9	13.0	7.0	0.1	80.1	11.4	14.6	l	12.3	17.6	70.0	19	10	88
BC k	1.3–1.9	10.4	3.6	39.4	4	15.2	14.0	6.4	0.1	82.4	10.2	13.6	l	12.2	16.8	71.0	19	10	93
P2: 29°46′38.9″N to 76°29′–34.9″E Fine Typic Ustochrepts, waterlogged soil, rice basmati (CSR 30) irrigated by sodic water produce moderate yield																			
Ap	0.0–0.2	8.7	1.0	1.5	4	4.0	6.0	5.9	0.3	22.5	1.3	42.6	c	53.2	21.5	25.2	11	21	509
Bw1	0.2–0.6	8.0	6.5	49.5	20	4.5	9.0	41.8	0.3	27.2	0.7	44.1	c	55.6	23.2	21.1	78	16	488
Bw2	0.6–0.9	8.0	8.6	63.5	38	3.5	12.0	54.0	0.2	31.3	1.2	44.1	c	57.3	22.3	20.4	74	53	477
Bw3	0.9–1.2	7.9	8.0	44.2	24	4.5	19.0	44.2	0.2	21.8	1.3	42.6	c	57.6	23.6	18.8	70	39	466
P3: 29°46′46.4″N to 76°30′1.9″E Fine-Loamy Typic Ustochrepts, sodic soil and sodic GW, calcareous parent material, rice CSR 30 grown, low yield																			
Ap	0.0–0.2	8.6	2.5	22.3	6	4.5	10.0	13.6	0.3	44.6	3.2	13.2	sil	21.4	28.0	50.5	10	38	456
Bw1	0.2–0.6	9.2	1.2	12.4	6	4.0	8.0	5.9	0.1	52.3	3.8	19.7	sil	24.8	32.7	42.3	51	34	429
Bw2	0.6–0.9	9.2	1.7	19.4	4	4.5	8.0	8.8	0.1	45.8	1.5	22.6	sil	23.6	38.1	38.2	43	23	413
Ck	0.9–1.2	9.3	1.9	21.2	6	4.5	8.0	10.9	0.1	54.4	9.9	26.9	sil	19.6	29.3	51.0	31	13	360
P4: 29°49′6.7″N to 76°28′10.6″E Fine Typic Ustochrepts, sodic soil and sodic GW in the old Ghaggar plain, severely waterlogged and partially barren																			
A1	0.0–0.2	8.3	2.3	18.8	8	1.5	10.0	13.7	0.4	32.3	2.3	21.5	c	40.0	24.1	35.8	10	33	392
Bw1	0.2–0.6	8.6	2.4	17.7	8	3.0	6.0	11.9	0.2	40.1	1.4	26.8	c	47.0	24.2	28.7	70	22	356
Bw2	0.6–0.9	8.4	2.5	19.9	8	4.0	8.0	16.5	0.2	37.3	1.7	31.8	c	49.8	25.4	24.7	70	12	339
Bw3	0.9–1.3	8.0	4.1	35.5	10	5.0	10.0	28.3	0.1	29.7	2.1	36.0	c	54.1	25.6	20.3	51	14	332
P5: 30°3′39″N to 76°18′33.9″E, Loamy Sodic Haplustepts, severely sodic soil and GW in the recent Ghaggar plain, barren with sparse vegetation																			
A1	0.0–0.2	9.9	6.1	64.5	1.5	6.5	23.0	33.9	0.2	56.0	2.1	16.4	l	14	17.8	68.6	88	28	377
B1	0.2–0.6	10.4	8.9	108	1.5	9.0	29.0	52.8	0.2	61.0	1.8	19.5	l	14	22.0	65.8	19	28	470
B2	0.6–0.8	10.6	5.8	56.7	1.5	8.5	16.0	38.4	0.1	60.0	3.0	20.0	l	18	22.1	59.3	15	19	203
Ck	0.8–1.2	10.7	5.0	42.3	2.0	17.5	14.0	16.5	0.1	64.0	2.9	19.5	l	21	19.6	59.1	15	25	203
P6: 30°8′56.3″N to 76°24′37.2″E, Fine-Loamy Typic Natrustalf, reclaimed sodic soil, calcareous, rice-wheat grown, and produce moderate yield																			
A1	0.0–0.2	9.1	1.2	13.3	2	5.0	5.0	4.4	0.6	53.1	4.4	19.2	sil	25	28.1	47.1	86	14	321
Bt1	0.2–0.5	9.6	1.4	15.7	1	6.0	4.0	9.6	0.2	66.7	8.1	16.8	sicl	37	24.8	38.5	27	24	349
Bt2	0.5–0.9	9.7	1.6	18.5	1	7.0	4.5	9.2	0.1	69.0	5.2	20.0	sicl	29	33.3	38.0	14	27	488
Ck	0.9–1.2	9.6	1.7	19.5	3	6.0	3.0	8.4	0.2	58.5	9.5	21.2	sil	25	39.7	35.9	14	26	396

(continued)

Table 4.3 (continued)

Horizon	Depth (m)	pHs	ECe ($dS\ m^{-1}$)	Na^+ ($me\ L^{-1}$)	$Ca^{2+} + Mg^{2+}$ ($me\ L^{-1}$)	$CO_3^{2-} + HCO_3^-$ ($me\ L^{-1}$)	Cl^- ($me\ L^{-1}$)	SO_4^{2-} ($me\ L^{-1}$)	OC (%)	ESP	$CaCO_3$ (%)	CEC (c mol (p^+) kg^{-1})	Texture	Clay (%)	Silt (%)	Sand (%)	N ($kg\ ha^{-1}$)	P ($kg\ ha^{-1}$)	K ($kg\ ha^{-1}$)
P7: 30°2′36.3″N to 76°14′49.5″E Loamy Typic Ustochrepts, sodic soil in recent alluvial plain, calcareous, rice-wheat crops showed moderate yield																			
Ap	0.0–0.2	8.9	4.4	39.2	4	5.3	12.5	22.4	0.4	40.0	2.3	24.5	l	23	21.6	55.0	82	10	243
Bw1	0.2–0.6	9.0	4.8	42.3	2	4.0	17.5	28.4	0.2	38.1	2.6	21.1	l	15	17.4	67.4	23	9	286
Bw2	0.6–0.9	9.1	3.6	34.1	4	4.8	15.0	17.9	0.2	46.6	2.3	16.3	l	15	18.1	66.6	20	14	340
Bw3	0.9–1.2	9.4	2.4	19.2	2	3.5	10.0	8.8	0.1	44.2	4.1	19.0	sil	19	31.6	49.9	16	18	303
P8: 29°59′54.3″N to 76°25′41.3″E Fine-Loamy Typic Natrustalf, strongly sodic soil in old alluvial plain, natural vegetation and forestry plantations																			
A1	0.0–0.2	10.6	7.4	98.7	4	15.0	31.0	10.9	0.1	99.5	2.4	14.3	l	15.2	14.7	69.9	79	56	543
Bt1	0.2–0.6	11.0	5.5	80.0	4	15.0	18.0	12.8	0.1	91.8	2.4	20.6	cl	24.9	19.4	55.5	73	43	490
Bt2	0.6–0.9	11.1	4.6	70.4	3	20.0	15.0	9.1	0.1	96.9	0.9	25.7	cl	25.8	18.8	55.2	67	24	463
BC	0.9–1.2	11.2	5.3	83.9	3	27.0	12.0	6.2	0.1	94.1	1.4	24.6	cl	23.3	18.5	58.1	56	15	390
P9: 29°40′35.9″N to 76°13′8.5″E Coarse-Loamy Typic Ustochrepts (Saline phase), waterlogged (WT <0.5m) soil under canal irrigation, cotton crop																			
A1	0.0–0.2	7.9	21.7	168	78	3.0	112	131	0.3	51.5	0.6	14.6	sl	14.7	16.5	68.6	121	25	437
Bw1	0.2–0.5	7.8	19.3	144	74	3.5	104	111	0.2	32.6	0.2	13.6	sl	15.8	15.6	68.5	109	15	389
Bw2	0.5–0.9	7.9	16.7	123	60	3.0	90	90	0.1	43.8	0.5	17.1	sl	19.1	18.7	62.0	90	13	320
B k	0.9–1.3	7.9	12.5	88	48	2.5	80	53	0.1	37.3	10.0	14.1	sl	11.8	23.3	64.8	82	10	277
P10: 29°52′25.3″N to 76°19′49.9″E Loamy Sodic Haplustepts, reclaimed sodic soil in the old alluvial plain, medicinal and aromatic plants growing																			
A1	0.0–0.3	9.6	9.2	117	4.0	20.0	33.0	0.6	0.1	75.9	0.1	13.6	l	13.8	21.8	64.7	115	10	425
B1k	0.3–0.6	10.4	13.7	193	4.0	44.5	32.0	4.6	0.1	91.2	0.6	14.3	l	14.1	24.7	61.1	105	6	358
B2k	0.6–0.9	10.8	13.4	193	3.0	33.0	35.0	8.1	0.1	92.3	0.7	16.6	sil	12.2	26.5	61.2	25	7	268
B3k	0.9–1.3	10.8	11.5	151	3.0	30.0	31.0	7.1	0.1	96.7	0.8	15.0	sil	11.7	25.1	63.1	20	15	186

l loam, *sl* sandy loam, *cl* clay loam, *sil* silt loam, *sicl* silty clay loam, *scl* sandy clay loam due to irrigation by poor-quality groundwater. The Na^+ (12.4–22.3 me L^{-1}), CO_3^{2-}, and HCO_3^- (4.0–4.5 me L^{-1}) ions are dominating and favored sodicity development. The presence of Cl^- (8.0–10.0 me L^{-1}) and SO_4^{2-} (5.9–13.6 me L^{-1}) ions showed the presence of mixed parent materials (Sachdev et al. 1995). The $CaCO_3$ content (1.5–9.9%) indicated calcareous parent materials. The high CEC values (13.2–26.9 c.mol (p^+) kg^{-1}) appeared due to higher clay contents (19.6–24.8%). The organic carbon (0.1–0.3%), available nitrogen (10–51 kg ha^{-1}), and phosphorus (13–38 kg ha^{-1}) contents are low. The gypsum and FYM application is suggested prior to arable cropping.

The pH (8.0–8.6) and ESP values (29.7–40.1) of Pedon 4 (P4) indicated the initiation of sodicity development. The $CaCO_3$ (<2 mm) is evenly distributed (1.4–2.3%) in the soil profile, and higher values may be attributed to the carbonate containing irrigation water. The increase of ECe values (2.3–4.1 dS m^{-1}) at subsurface depths indicated the presence of salty groundwater. The Na^+ (17.7–35.5 me L^{-1}), Ca^{2+} + Mg^{2+} (8.0–10.0 me L^{-1}), CO_3^{2-} + HCO_3^- (1.5–5.0 me L^{-1}), Cl^- (6.0–10.0 me L^{-1}), and SO_4^{2-} (11.9–28.3 me L^{-1}) ions indicated dominance of alkaline parent materials. The higher CEC values (21.5–36.0 c mol (p^+) kg^{-1}) are attributed to high clay content (40.0–54.1%). The increasing ESP values (29.7–40.1) indicated the influence of alkali water for irrigation. The sprinkler and drip methods of irrigation are suggested for irrigation with salty groundwater. The soil is suitable for growing low water-requiring crops, fruits (horticulture), and forestry plantations to sustain in waterlogged soil-affected soils and poor-quality waters.

The pH values (9.9–10.6) of Pedon 5 (P5) indicated strongly sodic soil characterized by sparse vegetation in the Ghaggar plain (Guhla block). The ECe values (8.9–5.0 dS m^{-1}) indicated salt accumulation due to irrigation with salty groundwater (Qureshi et al. 1996). High Na^+ (42.3–108.0 me L^{-1}) and CO_3^{2-} and HCO_3^- (6.5–17.5 me L^{-1}) contents increased soil pHs, and low contents of Ca^{2+} + Mg^{2+} (1.5–2.0 me L^{-1}), Cl^- (14.0–29.0 me L^{-1}), and SO_4^{2-} (16.5–52.8 me L^{-1}) resulted in high SAR. The higher ESP values (56.0–64.0) appeared due to the saturation with Na^+ ions. The low organic carbon (0.1–0.2%), available nitrogen (15–88 kg ha^{-1}), and phosphorous (19–28 kg ha^{-1}) contents indicated low fertility status. For reclamation, gypsum (@ 8–10 Mg ha^{-1}) application is necessary prior to growing arable crop such as rice and wheat.

The Pedon 6 (P6) soil is characterized by silt loam to silty clay loam texture, moderate medium to massive subangular blocky structure, fine consistency, and yellowish brown color. Poor to imperfect drainage and the presence of lime, iron, and manganese nodules and concretions of $CaCO_3$ (calcareous layer) were found at a depth below the surface. The silty clay loam soil texture at subsurface depth with clay content ranging from 29 to 37% and ESP (66.7–69.0%) favored the formation of natric horizon. The pH (9.1–9.7) and ECe (1.2–1.7 dS m^{-1}) values indicated strong sodicity except the surface soil which is reclaimed. Higher contents of Na^+ (13.3–19.5 me L^{-1}), CO_3^{2-}, and HCO_3^- (5.0–7.0 me L^{-1}), as compared to Ca^{2+} + Mg^{2+} (1.0–3.0 me L^{-1}), Cl^- (3.0–5.0 me L^{-1}), and SO_4^{2-} (4.4–9.6 me L^{-1}) indicated strong alkaline ions causing sodicity development. The higher ESP values (53.1–69.0) supplemented soil alkalization. The $CaCO_3$ (<2 mm) content (4.4–9.5%) showed precipitated calcareous parent materials at higher soil pHs and ESP. The Pedon can be used for arable crops following reclamation using gypsum (@ 6–8 Mg ha^{-1}). Due to the presence of *natric* horizon and poor-quality groundwater, plantations of forestry, medicinal, and aromatic plants and low water-requiring food crops are more suitable.

The range of pH and ESP values (8.9–9.4 and 38.1–44.2) of Pedon 7 (P7) indicated moderately sodic soil and higher salt concentration (2.4–4.8 dS m^{-1}) at surface resulting from the irrigation with salty groundwater. The dominance of Na^+ (19.2–42.3 me L^{-1}) and CO_3^{2-}+HCO_3^- (3.5–5.3 me L^{-1}) increased soil pHs. The CEC values (16.3–24.5 c mol (p^+) kg^{-1}) are related to clay content (15–23%). The $CaCO_3$ content is increased with depth (2.3–4.1%). The available nitrogen (16–83 kg ha^{-1}) and phosphorus (9–18 kg ha^{-1}) contents are low. The use of salt-resistant varieties of rice and wheat is suggested to improve productivity.

In the old alluvial plain of Ghaggar (Siwan block), the soil (P8) showed finer soil texture (loam to clay loam), massive to moderate medium subangular to angular blocky structure, yellowish brown to pale yellow color, and poor to imperfect drainage. The pH values (10.6–11.2) showed strongly sodic soil. The high ESP values indicated saturation with sodium favoring hydrolysis and soil alkalinity. The Na^+ (70.4–98.7 me L^{-1}) and CO_3^{2-}+HCO_3^- (15.0–27.0 me L^{-1}) ions are dominating and favored sodicity development (Sharma et al. 2011). The CEC values (14.3–25.7 c mol (p^+) kg^{-1}) showed dominance of mixed mica-type clay minerals. The increasing clay content (24.9–25.8%) and higher ESP (91.8–96.9) showed *natric* horizon formation. The gypsum application @ 8–10 t ha^{-1} is required for reclamation, and the soil can be used for arable (rice-wheat) cropping.

Located in the arid sandy alluvial plain of Ghaggar (Kalayat block) and irrigated with Narwana branch of Western Yamuna canal, Pedon 9 (P9) showed waterlogging (water table depth 0.5m) and poor productivity. A thick layer of $CaCO_3$ concretions (2–5 mm, 50–60%) is found at a depth (120 cm) below the surface. The neutral soil pHs (7.8–7.9) and higher salinity (12.5–21.7 dS m^{-1}) are found throughout the soil profile. The higher contents of Na^+ (88–168.0 me L^{-1}), Ca^{2+} + Mg^{2+} (48–78 me L^{-1}), Cl^- (80–112 me L^{-1}), and SO_4^{2-} (53–131 me L^{-1}) are noted. The $CaCO_3$ (<2 mm) content increased from 0.6 at surface to 10.0% below. The CEC values are low (13.6–17.1 c mol (p^+) kg^{-1}) due to coarse soil texture (sand 62.0–68.8%). The ESP values and the presence of carbonate and bicarbonate salts showed complex saline-alkaline nature. The soil needs installation of subsurface drainage (SSD) to lower the water table depth below the root zone and reduce soil salinity. Alternately it can also be used for aquaculture.

Strongly sodic soil (P10) is located at the old alluvial plain of Ghaggar in central Haryana (Siwan block) and is currently used for forestry, medicinal, and aromatic plantations. The soil texture varies from loam to silty loam, while strong to medium soil structure and pale yellow to dark yellowish brown color at surface and subsurface depths resulted due to high soil sodicity and impaired drainage. The pH and ESP values range from 9.6 to 10.8 and 75.9 to 96.7 at surface and subsurface depths, respectively. The high Na^+ (117.0–193.0 me L^{-1}) and CO_3^{2-}+HCO_3^-

(20.0–44.5 me L^{-1}) contents favored strong sodicity development. The higher soil salinity (9.2–13.7 dS m^{-1}) has resulted from irrigation of salty (high RSC) groundwater. The CEC values are low due to loamy soil texture (sand 61.1–64.7%). The soil needs suitable dosage @10–12 Mg ha^{-1} of gypsum application to neutralize CO_3^{2-}+HCO_3^{-} and reduce ESP. The arable cropping (rice-wheat) is suggested after reclamation.

4.10.2 Kurukshetra District

Field morphological characteristics of four soil profiles from Kurukshetra district range from deep to very deep, pale brown to dark yellowish brown, sandy loam to sandy clay loam/clay loam texture; medium to strong, coarse to fine angular/subangular blocky structure; sticky, plastic to very sticky, very plastic consistence; presence of few to abundant $CaCO_3$ nodules; and moist to wet subsurface horizons. A few iron and manganese mottles were also found in subsurface (50 cm) layers of P13 (Markanda plain) and P14 (Ghaggar plain), due to prolonged saturation with water. $CaCO_3$ concretions (2–5 cm, 10–30%) were found at 1 m depth in P2 and P4. The textural changes occurred from sandy loam to sandy clay loam and sandy clay loam to clay loam at P11, P12, and P14 apparently due to clay illuviation. The silt and clay contents were higher than sand content in P13 and P14 possibly due to lower topographic position (Table 4.4).

The pH value ranges from 9.1 to 10.7 indicating alkaline reaction. The distribution of ECe values of P11 (4.5–7.4 dS m^{-1}) and P13 (2.4–6.6 dS m^{-1}) indicated moderate soil salinity, while P12 (1.2–8.5 dS m^{-1}) showed higher salinity at subsurface depth, and soil salinity in P14 (1.2–1.8 dS m^{-1}) is low in general. The carbonate plus bicarbonate content is high in P11 (17.0–28.5 me L^{-1}) and P12 (15.7–35.5 me L^{-1}) and low in P13 (5.0–15.5 me L^{-1}) and P14 (5.0–10.0 me L^{-1}). A significant content of $CaCO_3$ (calcretes) was noted at 99 cm and 105 cm depths in P2 (1.3–4.9%) and P4 (4.4–14.5%) which caused restricted drainage and caused low permeability. CEC values were low in P1 (8.8–13.1 c mol (p^+) kg^{-1}) and P13 (13.2–18.4 c mol (p^+) kg^{-1}) due to coarse texture. The higher ESP values in P11 (49.6–76.9), P13 (50.0–94.6), P2 (46.8–56.5), and P14 (53.1–69.0) favored high alkalinity. The higher soil pHs (P3) at 40 cm depth indicated unfavorable soil physical properties and development of waterlogging. The high soil pH of P11 (9.6–10.2) and P12 (9.8–10.7) at surface depth also limits use for arable cropping. The dominance of CO_3^{2-} + HCO_3^{-} anions and high Na^+ content in P11, P13, P12, and P14 indicated the sodium carbonate and bicarbonate parent materials that favored sodicity development in soils (Bhargava et al. 1980; Sharma et al. 2011). The low contents of Ca^{2+}+Mg^{2+} are due to precipitation of calcium carbonates in an alkaline medium (Bhargava and Bhattacharjee 1982). The texture analysis of P14, P13, P11, and P12 indicated higher clay contents in subsurface layers that caused restricted drainage and favored waterlogging. Higher CEC values in P12 and P14 are attributed due to higher clay content. The high ESP values showed significant saturation with exchangeable Na^+ that favored alkali soil formation. The high

Table 4.4 Physicochemical characteristics of selected soil profiles from Kurukshetra district

Horizon	Depth (m)	pHs	ECe (dS m^{-1})	Na^+ (me L^{-1})	K^+ (kg ha^{-1})	Ca^{2+} + Mg^{2+} (me L^{-1})	CO_3^- + HCO_3^- (me L^{-1})	Cl^- (me L^{-1})	SAR	OM	$CaCO_3$ (%)	ESP	CEC (c mol (p^+) kg^{-1})	Sand (%)	Silt (%)	Clay (%)	Texture
P11 29°59′54.3″N 76°25′41.3″E Strongly sodic soil (Sodic Haplustept) and sodic GW, Ghaggar plain, Kikar, *Prosopis juliflora* plantation																	
A1	0.0–0.1	9.6	7.4	98.7	0.9	4.0	17.0	31.0	49.3	0.08	2.45	49.6	13.1	71.2	14.9	13.7	sl
AB	0.1–0.4	10.0	5.5	80.0	0.2	4.0	21.0	18.0	40.0	0.06	2.45	51.8	8.8	61.9	21.6	16.3	sl
B21t	0.4–0.8	10.1	4.6	70.4	0.1	3.0	28.5	15.0	40.6	0.03	0.98	76.9	11.1	58.8	20.0	21.0	scl
B22t	0.8–1.1	10.2	5.3	83.9	0.1	3.0	27.5	12.0	48.4	0.02	1.47	54.1	13.9	58.6	18.6	22.6	scl
C	1.1–1.4	9.8	4.5	75.8	0.1	3.0	18.5	11.5	43.8	0.02	2.85	43.2	9.5	63.2	20.1	16.7	sl
P12 29°59′02.7″N 76°59′37.6″E Strongly sodic soil, (Sodic Haplustept), good-quality (normal) GW, Yamuna plain, forestry plantations																	
A1	0.0–0.1	9.8	1.2	11.5	0.1	1.0	15.7	3.5	11.5	0.17	1.3	46.8	21.6	59.0	23.0	18.0	sl
B21t	0.1–0.3	10.7	5.3	54.0	0.1	1.5	30.2	12.5	44.1	0.11	1.0	56.5	26.3	53.0	22.0	25.0	scl
B22t	0.3–0.6	10.6	6.2	60.6	0.1	1.0	27.5	10.5	60.6	0.17	2.0	51.8	22.0	52.0	24.0	24.0	scl
B23t	0.6–1.0	10.7	7.6	67.1	0.1	1.0	31.5	12.0	67.1	0.11	3.3	50.0	21.2	52.0	27.0	21.0	scl
Ck	1.0–1.4	10.5	8.5	75.4	0.1	1.0	35.5	12.5	75.4	0.11	4.9	55.0	21.0	53.0	28.5	18.5	sl
P13 30°02′33.6″N 76°51′40.7″E Moderately sodic soil (Sodic Haplustept), cropped (rice), good-quality (normal) GW, Markanda plain																	
Ap	0.0–0.1	9.3	2.4	28.6	0.2	3.0	5.0	25.0	16.5	0.18	5.3	50.0	13.2	51.3	25.1	23.4	scl
AB	0.1–0.4	9.7	2.6	33.0	0.1	2.0	4.0	20.0	23.3	0.08	1.7	94.6	15.5	43.9	31.1	24.8	l
Bw1	0.4–0.8	10.1	4.0	53.9	0.1	2.0	10.0	25.0	38.1	0.08	1.3	94.2	15.9	47.3	26.8	25.8	scl
Bw2	0.8–1.0	10.2	5.9	96.7	0.2	2.0	12.5	30.0	68.3	0.08	1.7	83.1	18.4	48.1	24.7	27.0	scl
Bw3	1.0–1.5	10.0	6.6	99.5	0.2	2.0	15.5	32.0	70.3	0.05	1.9	89.7	16.8	46.2	25.8	28.0	scl
P14 30°08′56.3″N 76°25′37.2″E Strongly sodic soil (Typic Natrustalf), reclaimed at surface, partially cropped, sodic GW, Ghaggar plain																	
Ap	0.0–0.2	9.1	1.2	13.3	0.1	1.5	5.0	5.0	10.8	0.6	4.4	53.1	19.2	47.1	28.1	24.8	scl
AB	0.2–0.4	9.6	1.4	15.7	0.1	1.0	6.0	4.0	15.7	0.2	8.1	66.7	16.8	48.5	24.8	26.7	scl
B21t	0.4–0.7	9.7	1.6	18.5	0.1	1.0	7.0	4.5	18.5	0.1	5.2	69.0	20.0	38.0	23.3	38.8	cl
B22t	0.7–0.15	9.6	1.7	19.5	0.1	2.5	6.0	3.0	12.3	0.2	9.5	58.5	21.2	35.9	29.7	34.5	cl
B23k	1.0–1.6	9.8	1.8	22.0	0.1	4.5	10.0	8.5	10.3	0.1	14.5	65.8	22.0	36.8	35.5	27.7	l

l loam, *sl* sandy loam, *cl* clay loam, *sil* silt loam, *sicl* silty clay loam, *scl* sandy clay loam

Fig. 4.9 Auger-hole technique used for forestry plantation in a sodic soil

$CaCO_3$ contents caused drainage congestion. The soil physical and chemical properties indicated variable alkalinity dominated by alkaline earth metals, and poor drainage caused low permeability (Raghuwanshi et al. 2010). Auger-hole technique devised by CSSRI was successfully used for reclamation of severely sodic soils in Pehowa forest range that support young saplings with adequate amendment and nutrients (Fig. 4.9).

4.10.3 Ambala District

Ground truth studies in Ambala district indicated the presence of sodic soil and concretionary layer of calcium carbonates at subsurface depths that inhibits movement of water. Saline soil was also found along the irrigated areas of Bhakra canal. Significant areas of wastelands were found in the hummocky plain of Naraingarh block. Common source of irrigation is good quality of groundwater. Rice-wheat and oilseed crops are common, and forestry plantation is also practiced along the river course. The results of four representative soil profiles were presented in Table 4.5.

Profiles P15 and P16 were collected from Dangri river plain, and P17 and P18 were located in the Markanda plain. The ranges of pH values (7.9–9.4 in P15, 8.5–9.6 in P16, 9.1–9.5 in P17, and 9.3–9.8 in P18) indicated moderately to strongly

Table 4.5 Physicochemical properties of selected soil profiles from Ambala district in Haryana

Depth (m)	pHs	EC_e ($dS\ m^{-1}$)	Na^+ ($me\ L^{-1}$)	K^+ ($kg\ ha^{-1}$)	Ca^{2+} + Mg^{2+} ($me\ L^{-1}$)	CO_3^{2-} + HCO_3^- ($me\ L^{-1}$)	Cl^- ($me\ L^{-1}$)	SO_4^{2-} ($me\ L^{-1}$)	OM	$CaCO_3$ (%)	ESP	CEC (c mol (p^+) kg^{-1})	Texture
P15: Vil. 30°19′56.5″N, 76°57′08.8″E partially cropped													
0.0–0.3	7.9	1.6	12.4	0.05	5	9	12	18	0.33	0.5	24	16	l
0.3–0.6	8.5	1.4	12.9	0.05	7	8	11	20	0.23	1.3	34	21	l
0.6–0.9	9.0	1.4	12.5	0.04	6	10	10	19	0.2	1.1	49	18	l
0.9–0.12	9.4	1.2	11.3	0.04	7	12	10	11	0.21	0.7	60	16	l
P16: Vil. 30°20′43.1″N, 76°57′16.4″E poor crop stand													
0.0–0.3	8.5	1.3	13.0	0.04	8	12	12	14	0.2	1.1	25	11	sl
0.3–0.6	9.2	1.1	10.0	0.03	6	10	13	7	0.2	0.7	54	13	l
0.6–0.9	9.5	1.1	10.0	0.02	7	6	10	7	0.2	0.6	74	14	l
0.9–0.12	9.4	1.1	11.0	0.02	5	4	12	15	0.1	1.8	57	18	cl
P17: Vil. 30°23′10.4″N, 77°02′47.2″E poor crop stand													
0.0–0.3	9.1	1.0	10.0	0.02	7	12	10	5	0.2	1.3	23	15	sl
0.3–0.6	9.2	1.6	15.0	0.04	6	10	9	14	0.2	1.4	28	15	sl
0.6–0.9	9.1	0.9	10.0	0.02	5	10	10	10	0.2	1.5	27	13	sl
0.9–0.12	9.5	0.6	6.0	0.03	4	11	9	–	0.2	1.2	40	14	sl
P18: 30°15′46.0″N, 76°56′01.7″E barren soil													
0.0–0.3	9.8	1.4	14.0	0.12	7	10	10	8	0.1	1.4	39	13	l
0.3–0.6	9.9	1.5	15.0	0.19	6	10	7	4	0.2	1.3	42	14	l
0.6–0.9	9.5	1.8	15.0	0.52	5	8	9	5	0.1	1.2	35	16	l
0.9–0.12	9.4	1.6	14.0	1.74	5	8	8	7	0.2	1.2	22	19	l

sodic soils. Low pHs at the surface layers in P15 and P16 indicated reclamation. pH values increased at the lower depths of P15, P16, and P17 and were consistent at all depths of P18. The dominance of Na^+, Ca^{2+}, Mg^{2+}, CO_3^{2-}, and HCO_3^- salts indicated the presence of alkaline parent materials. $CaCO_3$ content indicated calcareous nature at subsurface depths and imperfect drainage. Low to moderate CEC values are related to coarse to medium soil texture. Particle size analysis data showed loam in P15, loam to clay loam in P16, sandy loam in P17, and loam in P18. P15 showed increasing pHs and ESP (24–60) at subsurface depths and needs careful soil/water management after gypsum application. The pH and ESP (25–75) values of P16 showed sodicity at lower depths. The presence of calcareous layer and higher clay content (13–29%) apparently caused poor drainage and waterlogging. Proper soil and water management is crucial in managing soils after careful reclamation on GR basis. P17 showed higher Na^+, CO_3^{2-}, and HCO_3^- contents that indicated residual sodicity and needs low dosage of gypsum application and is also suitable for growing salt-resistant crops. P18 is a strongly sodic soil located in the Markanda plain, showing high pHs and ESP and loamy soil texture. It needs gypsum application @ 6–8 t ha^{-1} for reclamation followed by salt leaching for arable cropping.

4.10.4 Hisar District

Ground truth studies of Hisar district revealed high water table depth (<1.5 m) causing waterlogging, secondary salinization, and crop damage (Table 4.6). P19 and P20 are irrigated by the Fatehabad branch of Bhakra canal and showed the incidences of waterlogging and high water table depth at 1.5 m depth. It was associated with high soil salinity ranging from 9.8–16.9 dS m^{-1} for P1 and 2.44–12.7 dS m^{-1} for P20. The soil reaction is neutral in P19 (6.4–7.8) and ranges from slightly to moderately alkaline (8.1–9.2) in P20.

Due to high soil salinity, Ca^{2+} and Mg^{2+} contents of P19 (82–127 me L^{-1}) and P20 (7–70 me L^{-1}) exceeded that of Na^+ contents (45.5–103.0 me L^{-1}, 12.52–41.63 me L^{-1}). High Cl^- (70–100 me L^{-1}) and SO_4^{2-} (67.1–86.2 me L^{-1}) contents indicated the presence of neutral salts in P19. The high Na^+ content in P20 was found at higher pH level, and a concomitant decrease of Ca^{2+} and Mg^{2+} contents indicated possibility of precipitation. High SO_4^{2-} contents (141.1–156.9 me L^{-1}) at surface of P20 may be ascribed due to the reclamation with gypsum. The soil pH varies from 8.8 to 9.0 in P21 and 8.7–10.1 in P22 that indicated slight to strong sodicity. The $CaCO_3$ contents increased from 1.4 to 3.6% (P20), 0.3–2.7% (P22), 0.4%–8.96% (P19), and 0.4–24.0% (P21) indicating calcareous nature, indurations, low permeability, and susceptibility to waterlogging. The low CEC values resulted due to coarse to medium soil texture and the presence of non-expanding clay minerals. The ESP values were higher in P20, P21, and P22 due to sodicity. The textural composition showed fine-textured strata in P19 (sandy clay loam) and P20 (loam). The textural changes in P21 (sandy loam to sandy clay loam) and P22 (silty clay loam to clay loam) occurred due to clay illuviation (14–27% in P3, 15–28% in P4).

Table 4.6 Physicochemical properties of soils from Hisar district in Haryana

Depth (m)	pHs	ECe (dS m^{-1})	Na^+ (me L^{-1})	K^+ (kg ha^{-1})	Ca^{2+} + Mg^{2+} (me L^{-1})	Cl^- (me L^{-1})	SO_4^{2-} (me L^{-1})	OM	$CaCO_3$ (%)	ESP	CEC (c mol (p^+) kg^{-1})
P19: 29°10′20.5″N 76°22′28.1″E Barren, waterlogged (WTD 1.5 m), irrigated											
0.0–0.3	7.8	16.9	103.0	0.14	127	200	74.3	0.3	0.4	15.8	15.5
0.3–0.6	6.4	9.8	47.6	0.13	82	80	86.2	0.2	0.3	10.5	16.2
0.6–0.9	6.5	9.8	45.5	0.09	96	70	67.1	0.2	0.7	12.8	13.5
0.9–0.12	7.1	10.8	49.1	0.05	98	100	80.5	0.2	8.96	12.1	9.9
P20: 29°06′58.8″N 76°17′55.0″E waterlogged (1.5 m), crop damaged, irrigated											
0.0–0.3	8.1	12.7	15.9	0.45	70	62	141.1	0.65	2.2	52.8	7.3
0.3–0.6	8.2	11.6	12.5	0.25	60	55	156.9	0.09	1.4	44.1	9.5
0.6–0.9	8.8	4.19	41.6	0.05	12	16	83.9	0.52	3.6	30.9	10.4
0.9–0.12	9.2	2.44	31.1	0.02	7	10	32.5	0.14	3.3	29.7	12.4
P21: 29°03′32.92″N 76°14′32.6″E waterlogged, crop damage, $CaCO_3$ (1.2 m)											
0.0–0.3	8.8	5.5	27.8	tr	8	33	84.9	0.26	0.4	49.7	10.5
0.3–0.6	9.2	2.7	29.4	tr	5	13	28.9	0.22	1.9	54.8	8.3
0.6–0.9	9.1	1.7	20.0	tr	5	11	31.2	0.26	18.8	31.3	6.9
0.9–0.12	9.0	1.9	19.4	tr	6	10	19.3	0.22	24.0	38.5	9.1
P22: 29°03′43.9″N 76°14′15.1″E Barren, thick $CaCO_3$ (1.2 m)											
0.0–0.3	8.7	25.7	303.0	0.9	38	180	123.0	0.28	0.3	29.3	8.7
0.3–0.6	9.5	17.0	251.0	0.1	8	115	49.2	0.21	1.3	57.2	11.3
0.6–0.9	10.1	10.4	156.0	0.0	10	75	76.5	0.22	2.7	51.5	10.4
0.9–0.12	10.1	7.2	91.7	0.0	9	50	66.6	0.27	2.7	58.7	14.7

Table 4.7 Soil physical properties from Hisar district in Haryana (All values are in percentage)

Depth (m)	Sand (%)	Silt (%)	Clay (%)	Texture	Silt + clay (<50μ) MC (%)	WDSS (%)	$CaCO_3$ (<2 mm) in WDSS CS (%)	FS (%)	Silt (%)	Clay (%)
P19: 29°10′20.5″N 76°22′28.1″E Barren, Waterlogged, irrigated										
0.0–0.3	49	28	23	Scl	51	42	0.1	0.1	0.1	tr
0.3–0.6	50	28	22	Scl	50	35	0.1	0.1	0.2	tr
0.6–0.9	51	26	23	Scl	49	41	0.2	0.1	0.3	tr
0.9–0.12	56	29	25	Scl	54	41	2.8	1.7	0.5	tr
P20: 29°06′58.8″N 76°17′55.0″E Waterlogged, Rice crop										
0.0–0.3	28	44	22	L	66	48	0.4	0.3	0.2	tr
0.3–0.6	52	33	14	L	47	56	0.6	0.2	0.2	tr
0.6–0.9	50	32	18	L	50	77	1.7	0.3	0.4	tr
0.9–0.12	36	39	24	L	63	80	1.1	0.3	0.7	tr
P21: 29°3′32.92″N76°14′32.6″E Waterlogged, $CaCO_3$										
0.0–0.3	54	31	14	Sl	45	44	0.7	0.1	0.4	tr
0.3–0.6	57	25	19	Sl	44	49	2.7	0.3	0.5	0.3
0.6–0.9	56	20	24	Scl	44	65	2.6	1.3	2.4	1.7
0.9–0.12	47	27	27	Scl	54	62	1.9	3.2	3.6	1.8
P22: 29°03′43.9″N 76°14′15.1″E Barren, thick $CaCO_3$ layer										
0.0–0.3	49	36	15	L	51	50	0.2	0.1	0.4	0.06
0.3–0.6	45	41	15	L	66	54	0.7	0.4	0.4	0.05
0.6–0.9	34	51	16	Sil	77	73	1.6	0.6	6.4	0.17
0.9–0.12	32	40	28	Cl	68	74	0.8	0.5	5.3	0.03

MC mechanical composition, *WDSS* water-dispersible soil separates, *CS* coarse sand, *FS* fine sand

The water-dispersible un-aggregated silt plus clay particles (<50 μ) and $CaCO_3$ contents were studied to assess nature and distribution of natural aggregates and cementation due to carbonates (Table 4.7). The silt plus clay content varies abruptly (35–42%) in P19 and increased in sodic and calcareous soils (P20, P21, and P22). The $CaCO_3$ content is higher in coarse sand (2.8 and 1.1%), fine sand (1.7 and 0.3%), and silt (0.5 and 0.7%) size particles for neutral to alkaline soils (P19 and P20). Significant contents were noted in silt (0.4–3.6%, 0.4–6.4%), fine sand (0.14–3.2%, 0.1–0.6%), coarse sand (0.7–2.7%, 0.2–1.6%), and clay (0.3–1.8%, 0.03–0.17%) particle in moderately to highly sodic soils (P21 and P22). The study revealed that the silt and clay particles (<50 μ size) and concretionary $CaCO_3$ favored formation of stable structures in sodic soils that restricted water movement and favored waterlogging and soil salinization in irrigated areas.

4.10.5 Fatehabad District

The physicochemical characteristics of soil profiles in Fatehabad district were presented in Table 4.8. P23 is located in the Ghaggar plain and showed moderate

Table 4.8 Physicochemical properties of soils from Fatehabad district Haryana

Depth (cm)	pH_s	ECe ($dS\ m^{-1}$)	Na^+ ($me\ L^{-1}$)	K^+ ($kg\ ha^{-1}$)	$Ca^{2+} + Mg^{2+}$ ($me\ L^{-1}$)	$CO_3^{2} + HCO_3^-$ ($me\ L^{-1}$)	Cl^- ($me\ L^{-1}$)	SO_4^{2-} ($me\ L^{-1}$)	OM	ESP	$CaCO_3$ (%)	CEC (c mol (p^+) kg^{-1})	Texture
P23: 29°32′09.5″N 75°27′51.5″E moderately alkali soil in Ghaggar plain													
0.0–0.3	9.2	2.7	30.1	0.4	4 + 6	3 + 4	10	23.5	0.75	70	2.3	4.5	sl
0.3–0.6	8.9	1.6	28.8	0.1	3 + 5	2 + 9	18	7.9	0.46	62	1.0	4.1	l
0.6–0.9	8.9	1.6	6.01	0.1	5 + 1	4 + 5	20	3.1	0.07	49	2.1	5.9	l
0.9–0.12	9.0	1.1	8.87	0.1	6 + 6	2 + 8	20	0.9	0.07	70	1.2	4.5	l
P24: 29°24′16.7″N 75°18′46.8″E waterlogged (1.5 m), severely saline soil													
0.0–0.3	8.7	46.5	472	8.2	80+120	0 + 20	1210	550	1.36	17	1.1	9.2	ls
0.3–0.6	8.7	11.3	69.7	1.9	40 + 60	0 + 40	510	312	0.64	19	2.4	7.3	sl
0.6–0.9	8.7	11.4	78.4	2.8	40 + 40	0 + 14	268	121	0.52	13	3.0	9.9	sl
0.9–0.12	8.7	10.5	94.0	1.6	42 + 44	0 + 20	900	739	0.87	12	4.9	12.1	sl
P25: 29°38′41.6″N 75°56′03.6″E sodic soil/GW, partial waterlogging, low production													
0.0–0.3	9.0	1.3	18.4	0.09	3 + 3	tr + tr	7	10.0	0.45	28.15	1.8	12.4	scl
0.3–0.6	9.2	1.0	15.8	0.01	3 + 3	2 + tr	4	0.7	0.37	25.48	1.9	16.9	scl
0.6–0.9	9.5	1.6	23.9	0.01	2 + 2	10 + tr	4	0.7	0.18	36.85	0.6	13.8	sl
0.9–0.12	9.4	0.9	13.7	0.02	2 + 2	tr + 2	4	0.5	0.22	20.55	0.5	20.7	sl
P26: 29°38′41.6″N 75°56′03.6″E sodic soil/GW, low productivity, waterlogging													
0.0–0.3	8.8	0.9	13.9	0.04	3 + 7	tr + 5	4	0.6	0.52	13.32	1.9	24.2	sl
0.3–0.6	8.7	0.9	13.3	0.02	tr + 2	tr + 2	3	0.6	0.42	14.81	0.8	26.9	scl
0.6–0.9	8.7	1.6	22.2	0.01	tr + 3	tr + 2	4	2.1	0.27	16.49	0.9	25.8	sl
0.9–0.12	8.8	1.5	21.9	0.02	tr + 5	tr + 2	4	1.2	0.18	14.05	1.4	29.4	scl

alkaline pHs (8.9–9.2). The soluble salt composition showed the dominance of CO_3^{2-}+HCO_3^- (7–11 me L^{-1}) of Na^+ (6.01–30.1 me L^{-1}), and the presence of Ca^{2+}, Mg^{2+}, Cl^-, and SO_4^{2-} was also noted.

The higher ESP values (49–70) indicated saturation with Na^+. The CEC values were low due to the coarse soil texture ranging from sandy loam to loam. P24 is a severely saline soil (ECe 10.5–46.5 dS m^{-1}) irrigated by the Bhakra canal. The salt composition showed the dominance of Na^+ (69.7–472.0 me L^{-1}), Ca^{2+} + Mg^{2+} (80–200 me L^{-1}), Cl^- (268–1210 me L^{-1}), and SO_4^{2-} (121–739 me L^{-1}). The depth-wise $CaCO_3$ content (1.1–4.9%) showed the increasing trend of stratification in soil profile. Soil texture ranges from loamy sand to sandy loam; CEC and ESP values were low to very low. P25 showed alkaline nature (pHs 9.0–9.5) and is irrigated by sodic groundwater showing poor productivity. Na^+ and CO_3^{2-}+HCO_3^- were dominant ions, and the ranges of ESP values (21–37%) indicate slightly to moderately sodic soil. The soil texture is variable ranging from sandy clay loam to sandy loam; higher clay content at surface soil indicated impermeable strata that resulted in temporary waterlogging (shown in the IRS data). P26 showed slightly alkaline nature (pHs 8.7–8.8), and the salt composition is dominated by Na^+ (13.3–22.2 me L^{-1}) and CO_3^{2-}+HCO_3^- (2–10 me L^{-1}). The ESP values were low, and higher CEC values (24–29 c mol (p^+) kg^{-1}) appeared due to fine soil texture, ranging from sandy loam to sandy clay loam. For reclamation and management, P23 needs treatment with gypsum, P2 requires interventions with subsurface drainage, and P25 and P26 should be irrigated with groundwater following treatment by gypsum.

4.11 Water Quality Studies in Haryana

The physicochemical properties of groundwater samples are presented in Tables 4.9, 4.10, and 4.11. The depth of groundwater ranges from 76–83 m in Kaithal, 19–21 m in Kalayat, and 76–91 m in Guhla and Siwan blocks, respectively. The water samples of Kaithal block (PW 1–4) showed neutral to sodic pH_{iw} (7.6–8.3) and dominance of CO_3^{2-}+HCO_3^- (8.5–10.5 me L^{-1}), Na^+ (9.9–17.7 me L^{-1}), and Ca^{2+} + Mg^{2+} (8.0–10.0 me L^{-1}). PW 5 is saline (EC 12.7 dS m^{-1}), showed high SAR (33.6), and showed the dominance of Na^+ (164.8 me L^{-1}), Ca^{2+} + Mg^{2+} (48.0 me L^{-1}), Cl^- (80.0 me L^{-1}), and SO_4^{2-} (54.8 me L^{-1}). PW 6 is sodic (pH 9.3), and high RSC (6.5) resulted due to higher CO_3^{2-} + HCO_3^- (8.5 me L^{-1}) and Na^+ (9.9 me L^{-1}). PW 7–13 showed sodic pH (8.6–9.3), high SAR (5.5–23.4), and at places high RSC (1.0–12.7 me L^{-1}) and is dominated by the Na^+ (6.8–14.1 me L^{-1}) and CO_3^{2-}+HCO_3^- (2.5–15.7 me L^{-1}), Cl^- (1.7–20.0 me L^{-1}), and SO_4^{2-} (0.4–8.8 me L^{-1}) ions. The water samples (PW 7–12) showing low contents of CO_3^{2-}+HCO_3^- and high SAR can be used mixing with good-quality water. PW 6 and 13 should be treated with gypsum for neutralizing residual $NaHCO_3$. PW

Table 4.9 Quality of groundwater samples from Kaithal district

PW	Location and depth (m) of GW	pH_{iw}	EC_{iw} ($dS\ m^{-1}$)	Na^+ ($me\ L^{-1}$)	K^+ ($kg\ ha^{-1}$)	$Ca^{2+} + Mg^{2+}$ ($me\ L^{-1}$)	$CO_3^{2-} + HCO_3^-$ ($me\ L^{-1}$)	Cl^- ($me\ L^{-1}$)	SO_4^{2-} ($me\ L^{-1}$)	RSC	SAR
Water samples from Kaithal subdivision											
1	29°46′38.2″N 76°30′00.0″E, 76	8.3	1.1	10.3	0.06	10.0	9.0	10.0	tr	tr	4.8
2	29°46′41.8″N 76°30′08.3″E, 83	8.3	1.1	10.3	0.05	10.0	9.5	15.0	tr	tr	4.7
3	29°46′41.3″N 76°29′47.3″E, 76	7.6	1.1	9.9	0.08	8.0	10.5	12.0	tr	tr	4.9
4	29°45′34.1″N 76°24′51.5″E, 76	7.2	2.3	17.7	0.01	10.0	8.5	16.0	7.1	tr	7.9
5	29°41′26.7″N 76°14′4.5″E, 21	7.6	12.7	164.8	0.05	48.0	5.0	80.0	54.8	tr	33.6
6.	29°47′48.2″N 76°27′26.4″E, 83	9.3	1.2	9.9	0.07	2.0	8.5	3.0	tr	6.5	9.9
Water samples from Guhla and Siwan blocks											
7	30°2′29.9″N 76°15′41.6″E, 76	8.6	1.3	10.6	0.1	3.0	2.5	10.0	8.8	tr	8.6
8	30°2′13.3″N 76°14′49.5″E, 76	9.1	1.3	12.6	0.1	1.5	2.5	10.0	6.4	1.0	14.5
9	29°59′36.2″N 76°13′55.5″E, 76	9.3	1.4	14.1	0.1	1.0	3.0	6.0	4.7	2.0	19.9
10	29°59′35.2″N 76°13′41.6″E, 91	9.1	1.2	12.1	0.1	2.0	4.0	20.0	2.9	2.0	12.1
11	30°04′57.5″N 76°20′35.8″E, 91	9.1	1.6	16.6	0.1	1.0	3.0	5.0	7.7	2.0	23.4
12	30°07′08.1″N 76°21′33.5″E, 91	8.8	0.8	6.8	0.1	3.0	2.5	3.0	0.4	tr	5.5
13	29°58′52.7″N 76°29′21.5″E, 83	8.8	1.1	13.9	0.1	2.9	15.7	1.7	tr	12.7	11.5

Table 4.10 Quality of groundwater samples in Kurukshetra district

PW	Water sample- Location and latitude-longitude, depth (m)	pH_{iw}	EC_{iw} (dS m^{-1})	Na^+ (me L^{-1})	K^+ (kg ha^{-1})	$Ca^{2+} + Mg^{2+}$ (me L^{-1})	CO_3^{2-} (me L^{-1})	HCO_3^- (me L^{-1})	Cl^- (me L^{-1})	RSC	SAR
14	29°59′8.4″N 76°25′55.1″E, 108	8.8	1.4	13.9	0.1	2.5	2.0	13.2	1.7	12.7	12.4
15	29°59′54.3″N 76°29′41.3″E, 60	8.7	1.1	9.9	0.2	2.5	1.5	10.0	1.7	9.0	8.9
16	29°59′29.9″N 76°29′39.4″E, 108	9.5	1.4	13.3	0.1	2.0	3.0	11.0	1.7	12.0	13.3
17	30°01′19.9″N 76°27′36.6″E, 100	9.1	1.3	12.6	0.1	1.5	Tr.	2.5	10.0	6.4	14.5
18	29°59′36.4″N 76°29′55.5″E 100	9.3	1.4	14.0	0.1	1.0	Tr.	3.0	6.0	2.0	19.7
19	30°04′57.5″N 76°27′35.8″E, 120	9.1	1.6	16.6	0.1	1.0	0.0	3.0	5.0	2.0	23.4

Table 4.11 Quality of water samples from Fatehabad district

PW	Location, source, and depth (m) of GW	pH	EC (dS m^{-1})	Na^+ (me L^{-1})	K^+ (kg ha^{-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})	RSC	SAR
20	29°38′6.1″N 75°53′7.1″E, 78	8.4	0.8	13.0	0.2	10	10 + tr	18	tr	tr	5.8
21	29°38′41.6″N 75°56′3.6″E, 99	9.7	2.5	36.2	0.4	14	10 + tr	16	tr	tr	13.8
22	29°43′01.3″N 75°47′16.8″E, 85	9.0	0.5	7.08	0.1	10	3 + tr	13	tr	tr	3.2
23	29°38′23.0″N 75°56′08.2″E, 95	9.5	1.8	27.7	0.2	8	10 + 2	10	2	4	13.9

5 showing high SAR may be used alternately with good-quality water. PW 1–4 is suitable for irrigation of salt-resistant varieties.

Chemical properties such as pH (8.7–9.5), RSC (9.0–12.7 me L^{-1}), and SAR (12.4–23.4) of six water samples from Kurukshetra district are presented in Table 4.10. Among the anions CO_3^{2-} (1.5–3.0 me L^{-1}) and HCO_3^- (2.5–13.2 me L^{-1}) and cations Na^+ (9.9–16.6 me L^{-1}) and Ca^{2+}+Mg^{2+} (1.0–2.5 me L^{-1}) and Cl^- (1.7–10.0 me L^{-1}) were dominant. RSC values range from 2.0–12.7 me L^{-1} and are critical in 14 (12.7 me L^{-1}), 16 (12.0 me L^{-1}), 15 (9.0 me L^{-1}), and 17 (6.0 me L^{-1}), respectively (Richards 1954). In general, SAR values are higher (>10). The high pH, RSC, and SAR values of water samples indicated their sodic nature dominated by the presence of CO_3^{2-}, HCO_3^-, and Na^+, while the presence of Ca^{2+} + Mg^{2+} and Cl^- is also noted. Higher SAR values indicated dominance of Na^+ ion, causing soils unsuitable for agriculture (Richards 1954). The critical limits of RSC in 14, 15, 16, and 17 indicated the need for treatment with gypsum for irrigation in field crops. Samples with moderate alkalinity (18 and 19) may be used for the growing salt-resistant varieties.

The chemical properties of four water samples (Table 4.11) from Fatehabad district showed slightly to moderately sodic (pH_{iw} 8.4–9.7) nature; the dominance of Na^+ (7–36 me L^{-1}), CO_3^{2-}, and HCO_3^- (3–12 me L^{-1}); and the presence of Ca^{2+}, Mg^{2+} (8–14 me L^{-1}), and Cl^- (10–18 me L^{-1}). The SAR values showed >10 in Tohana block, while RSC (4 me L^{-1}) was also reported at selected place.

4.12 Assessment and Distribution of Salt-affected Soils

The area under different categories of salt-affected soils was computed based on the statistics derived in GIS (Tables 4.12, 4.13, 4.14, 4.15, and 4.16). Six categories of these soils were identified in Kaithal district distributed in four blocks (Kaithal, Kalayat, Pundri, and Rajaund) pertaining to Kaithal subdivision. In Kaithal block, slightly (4313 ha) and moderately (1809 ha) sodic soils (total 6122 ha) are dominating where sodic groundwater is used for irrigation. Saline soils (804 ha, 0.3%) are also located at selected places confined to the lower topographic zone. Saline (4620 ha, 2%) and sodic soils (1452 ha, 0.6%) are located in the irrigated areas of Kalayat block. Soils are commonly saline (3063 ha, 1.3%) in irrigated areas of Rajaund block. Sodic (4723 ha, 2%) and saline (168 ha, 0.07%) soils are common in Pundri block (4891 ha, 2.1%). Saline (1415 ha, 0.61%) and sodic (1015 ha, 0.44%) soils are common in Guhla and Siwan blocks. In the irrigated areas, slightly saline and sodic soils covered 1415 ha (0.61%) and 1015 ha (0.44%), respectively. In the Ghaggar plain, strongly (143 ha, 0.06%) and moderately sodic (73 ha, 0.03%) soils are commonly found. Strongly sodic (2255 ha, 0.97%) soils are distributed along the paleo-channel of the Saraswati river in Siwan block, while slightly saline (255 ha, 0.1%) and sodic (143 ha, 0.06%) soils are found in the irrigated areas. Thus, salt-affected soils covered 26,301 ha (11.3%) in Kaithal district having sodic and

Table 4.12 Distribution and extent (ha) of salt-affected soils in Kaithal district

Name of the block	Moderately saline	Moderately sodic	Slightly saline	Slightly sodic	Strongly saline	Strongly sodic	Total area	% of TGA
Kaithal subdivision								
Kaithal	148	1809	50	4313	606	tr	6926	3.0
Kalayat	935	1306	1335	146	2350	tr	6072	2.6
Pundri	tr	1682	168	3041	tr	tr	4891	2.1
Rajaund	tr	09	2028	51	1026	tr	3114	1.3
Sub-total	1083	4806	3581	7551	3982	tr	21,002	9.0
Guhla and Siwan blocks								
Guhla	tr	73	1415	1015	tr	143	2646	1.1
Siwan	tr	Tr	255	143	tr	2255	2653	1.1
Sub-total	tr	73	1670	1158	tr	2398	5299	2.3
Grand total	1083	4879	5251	8709	3982	2398	26,301	11.3

TGA total geographical area of Kaithal district

Table 4.13 Extent of salt-affected soils and associated land degradations in Kurukshetra district

Sl No.	Categories of salt-affected soils and associated degradations	Area (ha)	%
1.	Slightly sodic soil	10,409	61.0
2.	Moderately sodic soil	5697	33.6
3.	Strongly sodic soil	34	0.2
4.	Surface ponding-slight	363	2.1
5.	Subsurface waterlogging	203	1.2
6.	Riverine sand	210	1.2
Total		16,916	

saline soils covering an area of 15,986 ha (6.8%) and 10,315 ha (4.4%), respectively. The total affected area was 5064 ha in Ambala district, of which sodic and saline soils covered 4222 ha and 842 ha, while slightly and moderately salt-affected soils covered 4040 and 1024 ha, respectively.

The spatial distribution of salt-affected and waterlogged soils in Kurukshetra showed (Table 4.13) the largest area of slightly sodic soils that covered 10,409 ha (61%), followed by moderately (33.6%) and strongly (0.2%) sodic soils.

The prominent areas of salt-affected soils (11,614 ha, 4.6%) were noted in Fatehabad (1.1%), Tohana (1.1%), and Bhuna (1.3%) blocks in Fatehabad district. Sodic and saline soils covered 7200 ha (62%) and 4414 ha (38%), respectively. Soils are sodic in Tohana (2689 ha, 23%), Fatehabad (2460 ha, 21%), and Bhuna (1216 ha, 11%) and saline in Bhattu Kalan (1976 ha, 17%) blocks, respectively (Table 4.14).

In Jhajjar district, salt-affected soils (41,516 ha) are distributed in four blocks, viz., Bhadurgarh (15,584 ha, 37%), Jhajjar (14,802 ha, 36%), Beri (5973 ha, 14%), and Matenhail (5157 ha, 12%). These are saline (32,731 ha, 78%), sodic (1487 ha, 4%) in general, and complex saline-sodic (7298 ha, 18%) in the irrigated areas (Table 4.15).

The salt-affected soils of Haryana state were compiled and presented in Table 4.16. These soils are distributed in 18 districts, and the largest areas are found in Jhajjar (41,516 ha), Sonepat (35,077 ha), Hisar (34,245 ha), Rohtak (32,633 ha), and Sirsa (30,311 ha). Saline soils are dominant in Jhajjar (33,784 ha), Hisar (33,375 ha), and Rohtak (21,999 ha) districts. Prominent areas of sodic soils are located in Sirsa (30,311 ha) and Sonepat (28,477 ha) districts. The largest areas of sodic soil reclamation occurred in Panipat (27,789 ha, 15%) and Jind (13,271 ha, 7%) districts, while areas of saline soils increased significantly in Hisar (25,605 ha, 52%), Jhajjar (25,427 ha, 51.7%), Rohtak (13,436 ha, 27%), Fatehabad (4414 ha, 9%), and Faridabad (3774 ha, 8%), apparently due to canal irrigation practices in poorly drained areas. Although the areas of sodic soils in Karnal district decreased (10,630 ha, 5.7%), a concomitant increase in sodic areas occurred in Kaithal (3127 ha, 1.7%) and Jhajjar (7115 ha, 4%) districts possibly due to the use of sodic groundwater for irrigation.

Table 4.14 Distribution and extent of salt-affected soils (ha) in Fatehabad district

Name of the block	Moderately saline	Moderately sodic	Slightly saline	Slightly sodic	Strongly saline	Strongly sodic	Total area	% TGA
Ratia	tr	577	tr	238	tr	20	835	0.3
Fatehabad	244	879	120	1334	81	247	2905	1.1
Bhattu Kalan	1099	tr	tr	tr	877	tr	1976	0.8
Bhuna	954	45	664	1171	349	tr	3183	1.3
Tohana	tr	882	26	1807	tr	tr	2715	1.1
Grand total	2297	2383	810	4550	1307	267	11,614	4.6

TGA total geographical area of Fatehabad district

Table 4.15 Extents and distribution of salt-affected soils (ha) in Jhajjar district in Haryana

SN	Name of the block	Saline	Sodic	Saline-sodic	Total (ha)
1	Bahadurgarh	10,058	0	5526	15,584
2	Jhajjar	11,999	1487	1316	14,802
3	Beri	5864	0	109	5973
4	Matenhail	4810	0	347	5157
	Total	32,731	1487	7298	41,516

Table 4.16 Distribution of salt-affected soils (ha) in Haryana (based on IRS data (2010–2013)

SN	Name of the district	Saline	Alkali	Total area
1	Ambala	842	4222	5064
2.	Bhiwani	3005	12,953	15,958
3	Fatehabad	4414	7200	11,614
4	Faridabad	7244	1393	8637
5	Gurgaon	9314	0	9314
6	Hisar	33,375	870	34.245
7	Kaithal	871	9812	10,683
8	Karnal	21	19,162	19,183
9	Kurukshetra	0	15,873	15,873
10	Jind	3170	8635	11,805
11	Jhajjar	33,784	7762	41,546
12	Mewat	7532	1302	8834
13	Panipat	0	7514	7514
14	Palwal	5590	4443	10,033
15	Rewari	7293	0	7293
16	Rohtak	21,999	10,634	32,633
17	Sirsa	0	30,311	30,311
18	Sonepat	6600	28,477	35,077
	Total	145.054	170,563	315,617

Acknowledgments The author acknowledges Head SCM Division, Head RRS Bharuch, PC AICRP SWS, and Director ICAR-CSSRI Karnal for necessary support in literature reviews and compilation and preparation of the manuscript.

References

Abrol IP, Bhumbla DR (1971) Saline and alkali soils in India-their occurrence and management. World soil resources report no. 41. Food and Agricultural Organization of United Nations, Rome, pp 42–51

Abrol IP, Bhumbla DR (1978) Some comments on the terminology of salt affected soils. In: Proceedings of the dry land saline seep control, 6.19–6.27, Edmonton, Canada

Abrol IP, Chhabra R, Gupta RK (1980) A fresh look at the diagnostic criteria for sodic soils. In: Proceedings of the international symposium on salt affected soils, CSSRI, Karnal, pp 142–146

Abrol IP, Yadav JSP, Massoud FJ (1988) Salt affected soils and their Management, FAO Soils Bulletin 39, FAO, Rome, 131p

ABS (2002) Australian Bureau of Statistics "Salinity", Canberra 2002. http://www.abs.gov.au/abs@.nsf/Lookup/by%20Subject/1370.0-2010-Chapter-Salinity%20(6.2.4.4)

Agarwal RR, Yadav JSP (1956) Diagnostic technique for the saline and alkali soils of the Indo-Gangetic alluvium in Uttar Pradesh. J Soil Sci 7:109–121

Agarwal RR, Mehrotra CL, Gupta CP (1957) Spread and intensity of soil alkalinity with canal irrigation in Gangetic alluvium of Uttar Pradesh. Ind J Agric Sci 27:363–373

Ali AAA, Weindorf DC, Chakraborty S, Sharma A, Li B (2015) Combination of proximal and remote sensing methods for rapid soil salinity quantification. Geoderma 239–240:34–46

Allbel A, Kumar L (2013) Soil salinity mapping and monitoring in arid and semiarid regions using remote sensing technology: A review. Adv Remote Sens 2:373–385

Balpande SS, Deshpande SB, Pal DK (1996) Factors and processes of soil degradation in vertisols of Purna valley, Maharashtra, India. Land Degrad Dev 17:313–324

Berenger AC (1985) Reconnaissance des terrains sales teledetection ICITV. CNRS, Universite de Toulouse III, Toulouse, p 41

Bhalla A, Singh G, Kumar S, Shahi JS, Mehta D (2011) Elemental analysis of groundwater from different regions of Punjab State (India) using EDXRF technique and the sources of water contamination. In: Proceedings of the international conference of environmental and computer science, IPCBEE, IACSIT Press, Singapore, pp 156–164

Bhargava GP, Bhattacharjee JC (1982) Morphology, genesis and classification of salt affected soils. In: "Review of Soil Research in India" 12th International Congress of Soil Science, 8–16 February 1982, New Delhi, India, pp 508–528

Bhargava GP, Sharma RC, Pal DK, Abrol IP (1980) A case study of distribution and formation of salt affected soils in Haryana state. In: Proceedings of the international symposium on salt affected soils, Karnal, pp 83–90

Chinchmalatpure A, Sethi M, Kumar P, Meena MD, Sidhu GS, Surya JN, Khurana ML, Ram S, Jangra S, Yadav A, Yadav RK (2016) Assessment and mapping of salt affected soils using remote sensing and GIS in southern districts of Haryana state. Technical Bulletin: ICAR-CSSRI/Karnal/2016, p 49

Colwell RN (1983) Manual of Remote Sensing, Interpretation and Applications, vol II, 2nd edn. American Society of Photogrammetry, Falls Church

Colwell RN (1996) Manual of Remote Sensing, Interpretation and Applications, vol III, 3rd edn. American Society of Photogrammetry, Falls Church

Csillag F, Pasztore L, Biehl LL (1993) Spectral selection for characterization of salinity status of soils. Remote Sens Environ 43:231–242

CSSRI (1992–1996) Annual report Central Soil Salinity Research Institute, Karnal

CSSRI (2000) Impact of the centrally sponsored scheme on reclamation of alkali soils during VIII plan in Haryana, Punjab and Uttar Pradesh. Report Central Soil Salinity Research Institute, Karnal April, 2000

CSSRI (2002–2005) Annual report Central Soil Salinity Research Institute, Karnal

CSSRI (2007) Annual Report 2006–07. Central Soil Salinity Research Institute, Karnal

Dubey DD, Sharma OP, Sethi M, Gupta RK (1995) Salt affected soils of Gujarat, extent, nature and management. CSSRI, Karnal, India, 95p

Dwivedi RS (2001) Soil resource mapping: a remote sensing perspective. Remote Sens Rev 20:59–122

Dwivedi RS (2006) Study of salinity and waterlogging in Uttar Pradesh (India) using remote sensing data. Land Degrad Dev 5:191–199

Dwivedi RS, Venkatratnam L, Karale RL (1987) Monitoring of salt affected soils from space borne multi-spectral and multi-temporal data In: Proc. National Symposium on Remote Sensing in Land. Transform Manag, NRSA

Everitt JH, Gerbermann AH, Cuellar JA (1977) Distinguishing saline from non-saline rangelands with Shylab imagery. Photogramm Eng Remote Sens 47:1357–1362

FAO/IIASA/ISRIC/ISSCAS/JRC (2008) Harmonized World Soil Database (ver.1.0). FAO/IIASA, Rome/Luxemburg

Gupta SK (2010) Management of alkali water. Central Soil Salinity Research Institute, Karnal India, Technical Bulletin: CSSRI/Karnal/2010/01, p 62
Hardinsky MA, Klemas V, Daiber FC (1983) Remote sensing salt marsh biomass and stress detection. Adv Space Res 2:219–229
Howari FM (2003) The use of remote sensing data to extract information from agricultural land with emphasis on soil salinity. Aust J Soil Res 41:1243–1253
Howari FM, Goodell PC, Miyamoto S (2002) Spectral properties of salt crust on saline soils. J Environ Qual 31:1453–1461
HSMITC (2001) Haryana groundwater quality map. Haryana State Minor irrigation and Tube Well Corporation Limited, Government of Haryana, Chandigarh
Indo-Dutch Network Project (2002) A methodology for identification of waterlogging and soil salinity conditions using remote sensing. CSSRI/ALTERRA-ILRI, Karnal/Wageningen, p 78
Jackson ML (1996) Advanced soil chemical analysis. Prentice Hall of India, New Delhi
Jain AK, Raj Kumar (2007) Water management issues. In: Proceedings of the Indo-US workshop on innovative E-technologies for distance education and extension outreach for efficient water management, ICRISAT, Patancheru, Hyderabad, India, March 5–9, 2007
Joshi PK, Agnihotri AK (1984) An assessment of adverse effects of canal irrigation in India. Indian J Agric Econ 39:528–536
Joshi MD, Sahai B (1993) Mapping salt affected land in Saurashtra coast using Landsat satellite data. Int J Remote Sens 14:1919–1929
Joshi DC, Toth T, Sari D (2002) Spectral reflectance characteristics of Na-carbonate irrigated arid secondary sodic soils. Arid Land Res Manag 16:161–176
Kalra NK, Joshi DC (1994) Spectral reflectance characteristics of salt affected arid soils of Rajasthan. J Indian Soc Remote Sens 22:183–193
Khan NM, Rastoskuev VV, Sato Y, Shiozawa S (2005) Assessment of hydro-saline land degradation by using a simple approach of remote sensing indicators. Agric Water Manag 77:96–109
Koohafkan P (2012) Water and cereals in dry lands. The Food and Agriculture Organization of the United Nations and Earth Scan, Rome
Leather JW (1914) Investigations on Usar land in United Provinces. Government Press, Allahabad, 88p
Manchanda HR (1976) Quality of ground waters in Haryana. Haryana Agriculture University, Hisar, 160p
Manchanda ML (1984) Use of remote sensing techniques in the study of distribution of salt affected soils in north-west India. J Indian Soc Soil Sci 32:701–706
Manchanda ML, Iyer HS (1983) Use of Landsat imagery and aerial photographs for delineation and categorization of salt-affected soils of part of North-West India. J Indian Soc Soil Sci 31:263–271
Mandal AK (2012) Delineation & characterization of salt affected soils and waterlogged areas in the Indo-Gangetic plain of Central Haryana (Dist Kurukshetra) for reclamation and management. J Soil Salin Water Qual 4:21–25
Mandal AK (2014) Characterization of some salt affected soils of Punjab for reclamation and management. J Indian Soc Soil Sci 62:161–167
Mandal AK, Sharma RC (1997) Characterization of some salt affected soils of Indira Gandhi Nahar Pariyojona command area, Rajasthan. Agropedology 7:84–89
Mandal AK, Sharma RC (2001) Mapping of waterlogged and salt affected soils in IGNP command area. J Indian Soc Remote Sens 29:229–235
Mandal AK, Sharma RC (2005) Computerized database on salt affected soils in Haryana State. J Indian Soc Remote Sens 33:447–455
Mandal AK, Sharma RC (2006) Computerized database of salt affected soils for agro- climatic regions in the Indo-Gangetic Plain of India using GIS. Geocarto Int 21:47–58
Mandal AK, Sharma RC (2009) Computerized database on salt affected soils in Peninsular India using GIS. Geocarto Int 24:65–85
Mandal AK, Sharma RC (2010) Delineation and characterization of waterlogged and salt affected areas in IGNP command, Rajasthan. J Indian Soc Soil Sci 58:449–454

Mandal AK, Sharma RC (2011a) Delineation and characterization of waterlogged salt affected soils in IGNP using remote sensing and GIS. J Indian Soc Remote Sens 39:39–50

Mandal AK, Sharma RC (2011b) Computerized database on salt affected soils for agro-climatic regions in arid & semiarid areas of western & Central India. Ann Arid Zone 50:1–3

Mandal AK, Sharma RC (2012) Description and characterization of typical soil monoliths from salt affected areas in Rajasthan. J Indian Soc Soil Sci 60:299–303

Mandal AK, Sharma RC (2013) Mapping and characterization of waterlogged and salt affected soils in Lunkaransar area of Indira Gandhi Nahar Pariyojona for reclamation and management. J Indian Soc Soil Sci 61:29–33

Mandal AK, Sharma RC (2014) Delineation and characterization of waterlogged salt affected soils in Lunkaransar area of IGNP for reclamation and management. Ann Arid Zone 53 (3&4):143–151

Mandal AK, Sharma RC, Singh G, Dagar JC (2010) Computerized database on salt affected soils in India. CSSRI/ Technical Bull./2/2010, p 28

Mandal AK, Obi Reddy GP, Ravisankar T (2011) Digital database of salt affected soils in India using Geographic Information System. J Soil Salin Water Qual 3:16–29

Mandal AK, Sethi M, Yaduvanshi NPS, Yadav RK, Bundela DS, Chaudhari SK, Anil C, Sharma DK (2013) Salt affected soils of Nain experimental farm: site characteristics, reclaimability & potential use. Technical Bulletin: CSSRI/Karnal/2013/03, 34p

Mandal AK, Ranbir S, Joshi PK, Sharma DK (2016) Mapping and characterization of salt affected soils for reclamation and management – a case study from the Trans-Gangetic Plain of India. In: Patil NG, Ray SK, Chandran P, Nagaraju MSS, Tiwari P (eds) Sustainable management of land resources for livelihood security. CRC Press, New York

Mandal AK, Obi Reddy GP, Ravisankar T, Yadav RK (2018) Computerized database of salt affected soils for coastal region of India. J Soil Salin Water Qual (In Press)

McFarlane DJ (2004) The extent and Potential Areas of salt-affected land in Western Australia estimated using remote sensing and digital terrain models, engineering salinity solutions. In: Proceedings of the 1st national salinity engineering conference, Barton, 60p

Menenti M (1984) Physical aspects and determination of evaporation in deserts applying remote sensing techniques. Report 10, Institute of Land and Water Management Research, ICW, 202

Metternicht G, Zinck JA (1997) Spatial discrimination of salt- and sodium-affected soil surfaces. Int J Remote Sens 18:2571–2586

Mougenot B, Pouget M, Epema GF (1993) Remote sensing of salt affected soils. Remote Sens Rev 7:241–259

Mulders M (1987) Remote sensing in soil science. Development in soil science. Elsevier, Amsterdam, p 379

Murthy RS, Hirekrur LR, Bhattacharjee JC (1980) The taxonomy of salt affected soils of the Indian sub-continent. In: Proceedings of the international symposium on salt affected soils, February, 18–21, Ministry of Agriculture, CSSRI, Karnal

National Remote Sensing Agency (1995) Study of land degradation in Sharda Sahayak command area for sustainable agricultural development. A project report. NRSA, Hyderabad

NBSSLUP (2006) Soils of India. National Bureau of Soil Survey and land use planning. NBSS Publication, Nagpur, p 94

Northkote KH (1979) A factual key for the recognition of Australian soils, 4th edn. Relim Technical Publications, Adelaide

NRSA (1997) Salt affected soils. National Remote Sensing Agency, Department of Space, Government of India, Hyderabad

NRSA (2007) Manual on nationwide mapping of land degradation using multi-temporal satellite data. National Remote Sensing Agency, Department of Space, Government of India, Hyderabad

NRSA (2008) Mapping salt affected soils of India. National Remote Sensing Centre, Department of Space, Government of India, Hyderabad, 60p

Phogat V, Satyavan KS, Sharma SK (2011) Effects of cyclic and blending uses of saline and good quality waters on soil salinization and crop yields under pearl millet- wheat rotation. J Indian Soc Soil Sci 59:94–96

Qureshi FM, Singh SK, Chaudhari SK, Das K (1996) Genesis and Taxonomy of some saline and sodic soils of Bharatpur (Rajasthan). J Indian Soc Soil Sci 44:130–135
Rafiq M (1976) Use of satellite imagery for salinity appraisal in the Indus plain, vol 31. Soils Bulletin FAO, Rome, pp 141–146
Raghuwanshi SRS, Tiwari SC, Jassal HS, Raghuwanshi OPS, Umat R (2010) Clay mineralogy study of salt affected soils of Bhind district, Madhya Pradesh. In: Proceedings of the National Seminar Issues Of Land Resource Management: Land Degradation, Climate Change, And Land Use Diversification, October 8–10, 2010, Nagpur, 29p
Rao BRM, Venkatratnam L (1987) Monitoring salt affected soils- a case study using aerial photographs and Salyut 7 space photographs- Paper presented in NSRS in LTM. NRSA, Hyderabad
Rao BRM, Ravisankar T, Dwivedi RS, Thamappa SS, Venkatratnam L, Sharma RC, Das SN (1995) Spectral behavior of salt affected soils. Int J Remote Sens 16:2125–2136
Rao BRM, Dwivedi RS, Sreenivas K, Khan QI, Ramana KV, Thamappa SS, Fyzee MA (1998) An inventory of salt affected soils and waterlogged areas in Nagarjuna- sagar canal command area of Southern India, using space borne multi-spectral data. Land Degrad Dev 9:357–367
Richards LA (ed) (1954) Diagnosis and Improvement of saline and alkali soils, Agriculture handbook No. 60. United States Department of Agriculture, Washington, DC
Richardson AJ, Gerbarmann AH, Gausmann HW, Cuellar JA (1976) Detection of saline soils with Skylab multi-spectral scanner data. Photogramm Eng Remote Sens 42:679–684
Sachdev CB, Lal T, Rana KPC, Sehgal J (1995) Soil of Haryana: their kinds, distribution and interpretation for optimizing land use, NBSS Publication 44 (Soils of India Series 4), National Bureau of Soil Survey and Land Use Planning, Nagpur, 59p
Saha SK, Kudrat M, Bhan SK (1990) Digital processing of Landsat TM data for wastelands mapping in parts of Aligarh district in Uttar Pradesh. Int J Remote Sens 11:485–492
Samra JS, Singh G, Ramakrishna YS (2006) Drought management strategies in India. ICAR, New Delhi, p 277
Saxena RK (2003) Application of remote sensing in soils and agriculture. J Indian Soc Soil Sci 51:431–447
Saxena RK, Sharma RC, Verma KS, Pal DK, Mandal AK (2004) Salt affected soils, Etah district (U.P.). NBSS-CSSRI Publ. No. 108. NBSS&LUP, Nagpur, p 85
Scudiero E, Skaggs TH, Corwin DL (2014) Regional scale soil salinity evaluation using Landsat 7, Western San Joaquin Valley, California, USA. Geoderma Reg 2–3:82–90
Sehti M, Khurana ML, Bhambri R, Bundela DS, Gupta SK, Ram S, Chinchmalatpure, A, Chaudhuri SK, Shamra DK (2012). Appraisal of salt affected and waterlogged soils in Rohtak, Bhwani, Jind, and Jhajjar districts of Haryana using remote sensing and GIS. Technical Bulletin: CSSRI/Karnal/2012/2, pp 28
Sharma RC, Bhargava GP (1987) Operational use of SPOT image in mapping and management of alkali soils. In: Proceedings of the national symposium on remote sensing in land transformation and management, NRSA, Hyderabad
Sharma RC, Mandal AK (2006) Mapping of soil salinity & sodicity in irrigated lands of the Indo-Gangetic Plain using image analysis and GIS. Agropedology 16:71–76
Sharma RC, Saxena RK, Verma KS (2000) Reconnaissance mapping and management of salt affected soils using satellite images. Int J Remote Sens 21:3209–3218
Sharma RC, Manda AK, Ranbir S (2011) Delineation & characterization of waterlogged & salt affected soils in Gandak command area of Bihar for reclamation and management. J Indian Soc Soil Sci 59:315–320
Shrestha RP (2006) Relating soil electrical conductivity to remote sensing and other soil properties for assessing soil salinity in northwest Thailand. Land Degrad Dev 17:677–689
Sidhu GS, Walia CS, Lal T, Rana KPC, Sehgal J (1995) Soil of Punjab for optimizing land use, NBSS Publ. 45 (Soils of India series 4), National Bureau of Soil Survey and Land Use Planning, Nagpur, 75p
Singh AN (1982) Digital analysis of multi-date Landsat data for monitoring soil salinization in north Indian plains. In: Transactions of the 12th international congress of soil science, February 8–16, 1982, 134p

Singh GB (2009) Salinity related desertification and management strategies: Indian experience. Land Degrad Dev 20:367–385

Singh AN, Dwivedi RS (1980) Delineation of salt affected soils through digital analysis of Landsat data. Int J Remote Sens 10:83–92

Singh AN, Baumgartner MF, Kristof ST (1977) Delineating salt affected soils in part of Indo-Gangetic Plain by digital analysis of Landsat data. Technical report. 111477, LARS, Purdue University, West Lafayette, Indiana, USA

Singh AN, Venkatratnam L, Sinha K, Venkatachalam P, Rao KR, Dwivedi RS (1983) Utilization of Landsat data for delineating mapping and managing of soils resources- The problems and prospect under Indian conditions. In: ERIM 7th international symposium on remote sensing of environment, May 9–13, 1983, Ann Arbor, MI, USA, 796p

Singh D, Chhonkar PK, Pandey RN (1999) Soil plant analysis a methods manual. Indian Agricultural Research Institute, New Delhi, 146p

Singh G, Bundela DS, Sethi M, Lal K, Kamra SK (2010) Remote Sensing and Geographic Information system for appraisal of salt-affected soils in India. J Environ Qual 39:5–15

Soil Science Society America (1987) Glossary of soil science terms. Technology Committee, Soil Science Society of America, Wisconsin

Soil Survey Division Staff (2004) Soil survey manual. United States Department of Agriculture handbook No.18. Scientific Publishers, Jodhpur

Soil Survey Staff (1998) Keys to soil taxonomy, 8th edn. U.S. Soil Conservation Service, Washington, DC

Srivastava R, Sethi M, Yadav RK, Bundela DS, Singh M, Chattaraj S, Singh SK, Nasre RA, Bishnoi SR, Dhale S, Mohekar DS, Barthwal AK (2016) Visible-near infrared reflectance spectroscopy for rapid characterization of salt-affected soil in the indo-Gangetic Plains of Haryana, India. J Indian Soc Remote Sens. https://doi.org/10.1007/s12524-016-0587-0

Szabolcs I (1989) Salt affected soils. CRC Press, New York, 274p

Thimmappa K, Tripathi RS, Raju R, Singh YP (2013) Livelihood security of resource poor farmers through alkali land reclamation: an impact analysis. Agric Econ Res Rev 26:139–147

United Nations Environmental Program (2009) The environmental food crisis. The environment's role of averting future food crisis. In: Christian N (ed) A UNEP rapid response assessment, 101p

Venkatratnam L (1984) Monitoring and managing soil and land resources in India using remotely sensed data. In: Proceedings of the 3rd Asian agricultural symposium, Chiang Mai, Thailand

Venkatratnam L, Rao KR (1977) Computer aided classification and mapping of soils and limitations using multi-spectral data. In: Proceedings of the symposium on remote sensing for hydrology, agriculture, and mineral resources. Space Application Centre, Ahmadabad

Verma KS, Saxena RK, Barthwal AK, Deshmukh SN (1994) Remote sensing technique for mapping salt affected soils. Int J Remote Sens 15:1901–1914

Verma KS, Saxena RK, Bhargava GP (2007) Anomalies in classification of salt affected soils under USDA aoil taxonomy. J Indian Soc Soil Sci 55:1–9

Verma D, Singh AN, Sreenivas K, Dwivedi RS, Mathur A (2004) Evaluation of image fusion techniques on IRS multisensor data for delineation of sodic lands. In: International conference (February 9–14) on stainable management of sodic lands- extended summaries. Uttar Pradesh Council of Agricultural Research (UPCAR), Lucknow, p 553

Wu W, Mhaimeed AS, Al-Shafie WM, Ziadat F, Dehhibi B, Nangia V, Pauw ED (2014) Mapping soil salinity changes using remote sensing in Central Iraq. Geoderma Reg 2–3:21–312

Yadav JSP (2003) Managing soil health for sustained high productivity. J Indian Soc Soil Sci 51:448–465