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Research Article

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Develop a methodology for mapping and characterization of salt-affected soils in coastal and inland plains of Gujarat state (India) using remote sensing, field, and laboratory soil studies.

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Abstract:

Significant areas of salt-affected soils were distributed along the west coast and the inland plains of Gujarat State (India). Repeated seawater inundation in coastal plains, in-situ formation, and alkaline parent materials in inland areas, caused degradation of soil and water and declining productivity. The use of poor-quality (saline/ sodic) groundwater for agriculture and lack of natural drainage caused salinization in the coastal and inland plain. A thorough characterisation of salt-affected soils was required to assess the spatial extent and distribution using low-cost remote sensing data, and to understand complex salt composition and soil chemical properties for classification and management of soil salinity. The estimates of salt-affected soils were compared with the legacy datasets to understand salinity dynamics.

Indian Remote Sensing (IRS) R2 L3 data for 2014-15, 2016, and 2018 with improved resolution (23.5 m) were used to characterise salt-affected soils using visual and digital image (spectral) analysis and was integrated with ground truth survey (1573 sites), and physico-chemical characteristics of soil samples (up to 30 cm soil depth) and representative nine soil profiles for the characterization of sub-surface depths (150 cm depth). The geo-referenced image interpreted units were superimposed with soil sampling sites; and base map layers to delineate and assess spatial extent and distribution of soils using GIS. These soils were also characterized to assess nature and degrees of salinity/sodicity. Spatial interpolation studies using inverse distance technique were also conducted to assess the variations of soil salinity (ECe), sodicity/ alkalinity (pHs), and soluble cations (Na^+ , K^+ , Ca^{2+} , and Mg^{2+}) and anions (CO_3^{2-} , HCO_3^- , Cl^- , and SO_4^{2-}) for salinity management.

High reflectance from salt pan (commercial salt production) and crusts (massive structure of highly saline salt crystals and soil materials); healthy crops and waterlogged areas facilitated the delineation of barren and extremely salt-affected soils along the coastal plain. The mixed pixels for moderately to slightly salt-affected soils that showed reflectance from closely associated salt, soil, crop, and adequate moisture were delineated integrating image interpretation, ground truth, and laboratory analysis data of soil samples. A large number of irrigation / drainage channels and creeks in coastal and deltaic plains, and mudflats / mangrove swamps and arid conditions prompted the development of a wide range of salt-affected soils showing high clay content (P1, P4, and P5), high electrical conductivity ($\text{ECe} > 4.0 \text{ dS m}^{-1}$); and dominant Cl^- , Ca^{2+} , and Mg^{2+} salts, respectively. Higher Sodium Adsorption Ratio (SAR), CO_3^{2-} and HCO_3^- contents in saline-sodic soils (P3, P4, and P5) under

irrigation; higher Mg^{2+} than Ca^{2+} in coastal soils (P1) of the southern plain and higher K^+ in peninsular and coastal plains (P1, P2, P6 to P8), were prominent features, respectively.

Such database in digital format facilitates regional planning in reclamation and management of salt-affected soils to improve productivity. Following reclamation, these soils can be used for agriculture, horticulture and forestry plantation using controlled irrigation practices even in the Kuchchh region (Gujarat State) where arid/semiarid climate and poor quality groundwater are primary constraints for sustained agriculture.

Keywords: - coastal soil salinity, mapping, reclamation, management

1.0 Introduction

The increasing trend in the global distribution and extent of salt-affected soils from 834 million hectares [1] to 1.381 billion hectares [2] has affected human civilisation and sustainable agriculture and is a serious threat to food security in the coming decades [3]. Abrupt climatic change patterns influenced soil salinity dynamics and crop productivity [4]. Kramer et al. [5] indicated aridity, a primary factor apart from evapotranspiration (ET) and rainfall that changed the hydraulic conductivity of salt-affected soils. Yu et al. [6] used geo-statistics to show the distribution patterns of soil salinity along the river delta. FAO [2] also reported an increasing salinity (10.7 %) which affected agriculture and food security.

The field measurement of soil salinity is important to determine in-situ soil salinity and is collated with the laboratory measurement for higher accuracy of estimates. Selim et al. [7] developed a method to show spatial and temporal variations of soil salinity over a certain landscape and also used apparent electrical conductivity (EC_a) for in-situ measurement of soil salinity using the electromagnetic induction (EMI) method. Wang et al. [8] also developed a time- and cost-effective method for salinity measurement integrating remote sensing and a machine learning algorithm. Khare and Shah [9] studied the distribution of soil salinity appearing as salt pans between 1978 and 2012 using remote sensing and also related the increasing occurrence of salt-pan with the depletion of mangrove vegetation in the coastal tracts of Gujarat State. Joshi and Sahai [10] integrated remote sensing and field measurement data to delineate soil salinity along the coastal tracts (Saurashtra coast) of Gujarat. Sirgire et

al. [11] used a grid-based soil sampling method to assess the distribution of dominant soil properties such as alkalinity, calcareous materials, organic carbon, and exchangeable Ca^{2+} and Mg^{2+} and soluble Na^+ and Cl^- in the coastal (Jamnagar) district of Gujarat state. Salinity ingress through creeks and river channels in coastal areas is an important driver that extends soil salinity from coastal to inland plains. Raychoudhury and Krishnan [12] also reported the significant changes in salinity profile from coastal to inland areas between 2006 and 1997. Chauhan and Polara [13] also reported the variability of soil salinity as primary constraint to assess soil reclamation and management in Gir Somnath district, Gujarat. The analysis of socio-economic data also corroborated the salinity impact from coastal to inland areas [14]. The advances in soil salinity and the depletion of groundwater table depth per year for good quality groundwater were the primary indicators of soil salinisation in the coastal states [15]. The societal constraints for access to irrigation for small and marginal farmers also caused declining agricultural productivity and the increase of fallow land during the dry season [16].

Several interventions were suggested to supplement nutrients through nitrogen and phosphorus fertilisers [17]; maintain microbial biomass carbon [18; 19], a combination of compost [20] and growing *Sesbania* crops [21] to improve soil fertility, nutrient availability, and productivity in coastal salt-affected soils. Zhao et al. [22] used desulfurization of gypsum (DG) to reclaim saline-sodic soil for rice cultivation and also showed higher grain yield due to the improvement of osmotic potential, plants' water uptake, and restricted salt stress [22]. Patil et al. [23] suggested several soil reclamation measures using embankments (check loss of water), subsurface drainage (outflow), dugout ponds (storage of good quality water), and cultural practices (salt-tolerant rice varieties) in coastal saline areas of Maharashtra state. It also suggested the application of recommended dosages of nitrogen, phosphorus, and FYM (at 15 t ha^{-1} on average) to achieve higher rice yield. The aquaculture practice was also a viable alternative for profitable farming in the region. Rizwan et al. [24] compared various

tillage practices (chisel plough, modified chisel plough, and disc plough) and economical gypsum application @ 40% GR for complex saline soils. Prakash et al. [25] compared nutrient dynamics between treatments using slag-based gypsum on rice crop and reported equal efficacy of both that supplied nutrients and enhanced soil fertility and rice yield. Nirali C. [26] reported the critical salinity patterns in the coastal region of Saurashtra, comprising the Bhavnagar, Amreli, Gir Somnath and Junagadh district of Gujarat state. Nayak et al. [27] reported distinct properties such as salinity status, soil colour, textural and cracking patterns (slikenslide) of clayey soils showing low productivity in flat terrain near the Gulf of Cambay in the Gujarat State. Da Costa et al. [28] suggested marine gypsum as a better nutrient source for the recovery of sodic soils. Barot [29] reported the occurrence of salinity and the shortage of irrigation water and suggested rainwater harvesting, recharging and strengthening the state-level desalination programme in Gujarat. Siddha and Sahu [30] also suggested dykes for the management of seawater intrusion in coastal areas.

Several methods were used to assess the extent and distribution of salt-affected soils in coastal region. While mapping acid sulphate soils with imbalanced datasets and machine learning, Estevez et al. [31] developed a digital method using a random forest model to balance the datasets for classification and better prediction accuracy (85%). Demaette et al. [32] developed a unique method to prepare and retrieve the reflectance of soils using a canonical R^2 (=0.93). Kheyruri et al. [33] integrated the Google Earth Engine's (GEE) data and an artificial intelligence (AI) model and 168 research articles to analyse the parameters that affect surface water quality. El Bahjaouy [34] developed a composite methodology using ground data for a better performance of the modelled index (SI6) that showed higher spatial relation (R^2 = 0.80) and less error (RMSE= 0.084). Gore and Bhagwat [35] used the soil brightness index and visual interpretation of multi-temporal images to study temporal

changes of slight-, moderate- and severe salt-affected areas by 140%, 174% and 224% during 1977 to 1987, respectively, in Khambhat Taluka, Gujarat state.

Several agencies reported variable estimates of salt-affected soils in Gujarat state which remains inconclusive. *Khar* Land Development Board (KLDB) of Gujarat state, also known as GSLDC (<https://agri.gujarat.gov.in>) reported 1.2 million ha of saline lands based on soil survey during 1960. Other study [36] also reported 1.24 million ha using compilation of available data in the state departments. Dubey et al. [37] reported variable estimates using a systematic ground truth survey (1.2 million ha) and IRS data (1.6 million ha) to map soil salinity in Gujarat state. Indian Space Research Organization (www.isro.gov.in) also reported a comparable estimate of salt-affected soils (1.8 million ha) for the state of Gujarat. SAC [38] reported a higher estimate (10.26 million ha, 52.29 %) of degraded land using multispectral IRS data for Gujarat state. Mandal et al. [39] used GIS to compile salt-affected soils' maps (based on Landsat TM data of 1984) on 1:250,000 scale [40] for eight coastal states in India (2.5 million ha) and Gujarat state (1.254 million ha), Chinchmalatpure [41] compiled the available data of Gujarat state (2.1 million ha) and also for saline and alkali areas (0.54 million ha) in coastal (0.462 million ha) and inland (1.098 million ha) plains, respectively. Recent estimate on degraded lands (5.988 million ha, using IRS R2A 2015-16 data) [42] for Gujarat state, Further studies (using GIS) also showed the distribution of salt-affected soils in varied agro-eco-regions, geology, and rainfall zones and physiographic regions in Gujarat state, respectively, for precise planning and management [38, 43, 44]. Mandal et al. [45] used normalized difference salinity indices (NDSI), vegetation index (NDVI), canopy response salinity index (CRSI), Google Earth data to assess coastal saline soils (0.13 million ha) in selected coastal- states of India.

The scattered reports on soil and water qualities indicated complex soil properties, such as saline, sodic, and saline-sodic, variable extent ranging from 10 to 32% of the TGA,

and the distribution of salt-affected soils in coastal, deltaic, alluvial and peninsular plains and mudflat /mangrove swamp regions, respectively. A reliable database with quantified data such as ground truth and laboratory analysis for soil chemical properties and a comprehensive methodology (such as integrated use of remote sensing and ground validation) were thus necessary for mapping the extent, characteristics and distribution of complex salt-affected soils in varied physiography and landforms for systematic land use planning and improve productivity.

IRS R2A LISS III data with adequate swath and resolution (Table 1) was suitable to delineate on a larger (1:50,000) scale and also showed potential to capture spatial and spectral features in discrete bands for identification and characterization of salt-affected soils with reasonable accuracy [10; 34]. Using such technology, this study was aimed at (i) to develop a methodology for mapping salt-affected soils integrating remote sensing, ground truth and laboratory analysis data of soil samples on a 1:50,000 scale; (ii) compare with the legacy and related datasets (on 1:250,000 scale) for temporal changes, (iii) classify salt-affected soils (based on nature and degrees of salinity/ sodicity) to develop map legends and (iv) also suggest suitable management options for sustainable land use planning and facilitate ecosystem services in Gujarat state, India.

2.0. Materials and methods

2.1. Study area

The Gujarat state lies between 20° to 25°N latitude and 68° to 75°E longitude and covers 19.6 million ha. It was divided into five administrative divisions (north-, central-, and south-Gujarat, Kachchh, and Saurashtra), thirty-four districts, and 251 *talukas* (sub-divisions / *tehsils*) (<https://en.wikipedia.org>). Primary land uses include agriculture (52%) and forestry (11%), apart from fallow (6.3%), built-up land (2.7%), wastelands (21%), wetlands (3.4%), and water bodies (3.4%). It showed an extensive network of canals, such as Narmada, Sardar

Sarovar, and Kadana- Patdi. These canals supply water to 1.5 million ha of farmland across the state. Wells are a traditional source of irrigation in Gujarat [46]. The gross irrigated area (0.56 million ha) is 46% of the gross cropped area (1.2 million hectares). Broadly, five zones, such as Kachchh, Gujarat (N), east central, Saurashtra, and Gujarat (S) were identified. The highest average rainfall (1476 mm) was recorded in south Gujarat, while the least (456 mm) was in the Kachchh region (north of Gujarat). Physiography showed three main regions: an alluvial plain that covered the mainland and hilly tracts (8.35 million ha), the peninsular plain (Saurashtra region), and the desert land (the Rann of Kachchh). It supports soil types, broadly classified into black, red, alluvial, saline/alkali, lateritic, desert, and forest soils. These soils have varying characteristics and are suited for different agricultural uses. Regional soil properties indicated variations from clayey to loamy in Saurashtra; loamy and sandy in Kachchh and coastal; and varying soil types, such as salt-affected soils in plains and hilly terrains in the south of Gujarat. Soils were broadly classified into Vertisol, Inceptisol, and Alfisol in South Gujarat. The soils of central Gujarat (Anand, Kheda, Panchmahal, and Dahod districts) showed fine to coarse and medium (loamy) soil texture. Moderately deep soil was located in Surendranagar, Patan, Ahmedabad, and Sabarkantha districts. Major cash crops such as cotton, groundnut, tobacco, cumin, and sesamum are prominent apart from rice (*Oryza sativa*), wheat (*Triticum*), jowar (*Sorghum*), bajra (*Pennisetum glaucum*), maize (*Zea mays*), tur (*Cajanus cajan*), and gram (*Cicer arietinum*). The state reported a prominent agricultural growth (9.6%) and the gross state domestic product (GSDP) is projected to be US\$3, 39, 865.17 million, with a growth of 12% (FY 2025-26). Regarding GDP contribution to India, Gujarat's share has increased from 7.5% in 2010-11 to 8.1% in 2022-23. The food grain (6. 2 million tons) and cotton (4.3 million tons) productions were highest in the country. The fruit and vegetables production also contributed 9.5% and 6.7% in the country, respectively.

191 2.2. Materials

- 192 i) IRS R2A for 2017-2018, and IRS R2A LISS III geo-coded seasonal data (January- March,
193 April- May, and October-December) for 2014- 2015, 2016, and 2018 (Table 1).
194 ii) The topographical and open series maps (OSM)
195 iii) ILWIS (version 3.3) (www.itc.nl)
196 iv) Global Positioning System (GPS), steel tape, Munshell colour chart, spade, and auger
197 v) Ancillary supporting data/ reports/publications:
198 a) Soil map of Gujarat state (<https://icar-nbsslup.org.in>) (Table 2)
199 b) The wasteland atlas (www.nrsa.gov.in) on a 1:50,000 scale [47],
200 c) *Bhoomi* geo-portal (<https://bhoomigeoportal-nbsslup.in>),
201 d) Computerised database of salt-affected soils of Gujarat state [48].
202 e) ‘*Bhuban*’ - Indian geo-platform (<https://bhuvan.nrsc.gov.in>),
203 f) Reports and maps of <https://bisag-n.gov.in/>, the report “Characteristics of soils of
204 Saurashtra and Kachchh Region” (<https://guj-nwrws.gujarat.gov.in>), <https://www.icar.org.in/>,
205 success story of *Rashtriya Krishi Vikas Yojana* (<https://rkvy.da.gov.in/>), newspaper report
206 “Saline soil could double by 2050, affect crop production- CSSRI”
207 (<https://www.hindustantimes.com>), and report on soil degradations of Gujarat state [49]

208 **Table 1** Details of the satellite data used for mapping soil salinity in Gujarat state (India)

Details of satellite data	swath width	Resolution		Path / map No.	Row/ map No.	Date of acquisition
I. IRS R2A, Linear Imaging Self-Scanning III (LISS 3) Sensor, Projection: Universal Transverse Macerator (UTM), Datum: WGS 84 Ellipsoid: WGS 1984	141 km	Spatial 23.5 m	Spectral (μm)			
			B2: 0.52-0.59 (green),	89	55	18 March 2018
				90	55	23 March 2018
			B3: 0.62-0.68 (red),	90	56	23 March 2018
				90	57	04 March 2018
			B4: 0.77-0.86 (NIR),	91	55	28 March 2018
				91	56	04 March 2018
			B5: 1.55-1.70 (SWIR)	91	57	04 March 2018
				92	55	09 March 2018
				92	56	09 March 2018
				92	57	09 March 2018
				93	56	14 March 2018
				93	57	14 March 2018
				94	56	23 Feb. 2018

II: IRS R2A LISS 3 geocoded data using the Survey of India (SOI) topographical maps on 1: 50,000 scale (http://www.surve yofindia.gov.in).	141 km	23.5 m	B2: 0.52-0.59 (green band), B3: 0.62-0.68 (red band), B4: 0.77-0.86 (NIR band), B5: 1.55-1.70 (SWIR band)	94	57	23 Feb. 2018
				94	57	19 Nov. 2017
				94	58	23 Feb. 2018
				94	58	19 Nov. 2017
				F 43	G12	01 Nov. 2018
				F 43	G15	01 Nov. 2018
				F 43	G16	01 Nov. 2018
				F 43	M09	01 Nov. 2018
				F 43	M10	01 Nov. 2018
				F 43	M10	16 Dec. 2018
				F 43	M10	20 Feb. 2018
				F 43	M11	01 Nov. 2018
				F 43	M12	01 Nov. 2018
				F 43	M13	19 Dec. 2015
				F 43	M13	30 March 2015
				F 43	M14	01 Nov. 2018
				F 43	M14	16 Dec. 2018
				F 43	M14	20 Feb. 2018
				F 43	M15	08 Oct. 2015
				F 43	M15	19 Dec. 2015
				F 43	M15	22 May 2014
				F 43	M16	01 Nov. 2014
				F 43	M16	09 April 2014
				F 43	M16	24 Dec. 2015
				F 43	N01	11 Nov. 2014
				F 43	N02	11 Nov. 2014
				F 43	N03	11 Nov. 2014
				F 43	N04	11 Nov. 2014
				F 43	N05	11 Nov. 2014
				F 43	N06	11 Nov. 2014
				F 43	N07	11 Nov. 2014
				F 43	N08	11 Nov. 2014
				G 44	K02	28 Jan. 2016
				G 44	K03	28 Jan. 2016
				G 44	K04	28 Jan. 2016
				G 44	K07	28 Jan. 2016
				G 44	K08	28 Jan. 2016
				G 44	K13	21 March 2016

209 * IFOV (Instantaneous Field of View)

210 <https://earth.esa.int/eogateway/missions/resourcesat-2>

211

212

213 Table 2 Characteristics and classification of salt-affected soils^s

Map unit	Details of soil association on 1:250,000 scale and *categories of salt -affected soils (NRSA, 2007)	Soil classification using soil taxonomy	Area (ha), (%)
s	Soils of Alluvial and Aeo-fluvial (stabilized sand dunes) Plains		

76	Deep (5), drained (1), calcareous, loamy (1), erosion (2), Ssa3*; deep (5), drained (1), calcareous, loamy (3), erosion (1), Ssa2.	Typic Ustifluvents Fluventic Ustochrepts	7800 (0.04)
78	Deep (5), drained (3), calcareous, loamy (3), erosion (1), Ssa2; deep (4), drained (3), calcareous, loamy (3), erosion (1), Ssa2.	Typic Ustifluvents Typic Ustochrepts	9500 (0.05)
79	Deep (5), drained (2), calcareous, loamy (3), erosion (1), Ssa1; deep (4), drained (2), calcareous, loamy (3), erosion (1), Ssa1.	Typic Ustifluvents Fluventic Ustochrepts	44200 (0.23)
80	Deep (5), drained (2), calcareous, loamy (3), erosion (1), Ssa2; deep (4), drained (2), calcareous, loamy (3), erosion (1), Ssa2.	Typic Ustifluvents Fluventic Ustochrepts	15200 (0.08)
82	Deep (5), drained (2), calcareous, loamy (3), erosion (1), Ssa1; deep (5), drained (1), calcareous, loamy (3), erosion (2).	Typic Ustrophepts Fluventic Ustrophepts	10050 (0.05)
83	Deep (5), drained (2), loamy (3), erosion (1), Ssa1; deep (4), drained (2), calcareous, loamy (3), erosion (1), Ssa1.	Vertic Ustrophepts Vertic Ustrophepts	33600 (0.71)
87	Deep (5), drained (2), calcareous, loamy (1), erosion (1), Ssa2 and Sso1; deep (5), drained (3), loamy (3), erosion (1), Ssa1.	Typic Ustochrepts Typic Ustochrepts	153900 (0.79)
91	Deep (5), drained (2), calcareous, loamy (1), erosion (1), Ssa2 and Sso1; deep (5), drained (3), loamy (3), erosion (1), Ssa1.	Typic Ustochrepts Typic Ustochrepts	45500 (0.23)
114	Deep (3), drained (3), calcareous, loamy (3), erosion (1), Ssa1; deep (4), drained (2), calcareous, loamy (3), erosion (1).	Vertic Ustochrepts Typic Chromusters	18400 (0.09)
115	Deep (4), drained (2), calcareous, loamy (3), erosion (1), Ssa1; deep (5), drained (2), calcareous, loamy (3), erosion (1).	Vertic Ustochrepts Typic Chromusters	700 (0.004)
116	Deep (4), drained (3), calcareous, loamy (3), erosion (1), Ssa2; deep (5), drained (2), calcareous, loamy (3), erosion (2).	Vertic Ustochrepts, Typic Chromusters	115000 (0.59)
122	Deep (6), drained (2), calcareous, loamy (3), erosion (1), Ssa2; deep (6), drained (2), calcareous, loamy (3), erosion (2).	Typic Chromusters, Udic Chromusters	31800 (0.16)
131	Deep (6), drained (2), loamy (3), erosion (2), Ssa2; deep (6), drained (2), calcareous, loamy (3), erosion (2).	Typic Chromusters Udic Chromusters	63400 (0.32)
134	Deep (6), drained (2), loamy (3), erosion (1), Ssa2; deep (6), drained (3), calcareous, loamy (4), erosion (1), Ssa2.	Typic Chromusters Udic Chromusters	2800 (0.01)
135	Deep (6), drained (2), calcareous, loamy (4), erosion (1), Ssa2; deep (6), drained (2), calcareous, loamy (3), erosion (1), Ssa1.	Typic Chromusters, Vertic Ustochrepts	7900 (0.04)
136	Deep (6), drained (2), calcareous, loamy (4), erosion (1), Ssa1; deep (6), drained (2), calcareous, loamy (3), erosion (1), Ssa1.	Typic Chromusters Vertic Ustochrepts	63600 (0.32)
138	Deep (6), drained (2), loamy (4), erosion (1), Ssa2; deep (6), drained (2), calcareous, loamy (3), erosion (1).	Typic Chromusterts Typic Chromustrets	16500 (0.08)
140	Deep (6), drained (2), loamy (4), erosion (1), Ssa2; deep (6), drained (2), calcareous, loamy (3), erosion (1).	Udic Chromusterts Udic Chromustrets	19500 (0.10)
143	Deep (6), drained (3), calcareous, loamy (3), erosion (1), Sss3; shallow (2), drained (3), loamy (3), erosion (2); Sss3.	Typic Ustifluvents Typic Ustochrepts	11800 (0.06)
146	Deep (6), drained (3), loamy (3), erosion (1), Ssa2 and Sso1; deep (6), drained (3), loamy (1), erosion (1); Ssa1.	Typic Ustochrepts Typic Ustochrepts	115700 (0.59)
Soils of Aeolian Plains			
150	Deep (6), drained (1), calcareous, loamy (1), erosion (1), Ssa1; deep (6), drained (1), calcareous, sandy soil, erosion (1).	Typic Torrifluvents Typic Torripsamments	41300 (0.21)
151	Deep (6), drained (1), calcareous, loamy (1), erosion (1), Ssa3; deep (6), drained (1), sandy, erosion (1).	Typic Torrifluvents Typic Torripsamments	44300 (0.23)
152	Deep (6), drained (1), calcareous, loamy (1), erosion (1), Ssa2; deep (6), drained (1), calcareous sandy soils, erosion (1), Ssa2.	Aridic Ustochrepts Typic Torripsamments	147800 (0.70)
154	Deep (6), drained (1), calcareous, loamy (1), erosion (1), Ssa2; deep (6), drained (1), calcareous sandy soils, erosion (1), Ssa2.	Aridic Ustochrepts Typic Torripsamments	42000 (0.21)
156	Deep (6), drained (1), calcareous, loamy (1), erosion (1), Ssa2;	Aridic Ustochrept	41300

	deep (6), drained (1), calcareous, loamy (3), erosion (10), Ssa1.	Aridic Ustochrept	(0.21)
157	Deep (6), drained (1), calcareous, loamy (1), erosion (1), Ssa2; deep (6), drained (1), calcareous, loamy (3), erosion (1), Ssa1.	Aridic Ustochrept	2900 (0.01)
158	Deep (6), drained (1), calcareous, loamy (3), erosion (1), Ssa2; deep (6), drained (1), sandy soils, erosion (2), Ssa2.	Aridic Ustochrept Typic Torripsamments	40200 (0.21)
160	Deep (6), drained (1), calcareous, loamy (3), erosion (1), Ssa2; deep (6), drained (1), calcareous, loamy (1), erosion (1), Ssa2.	Aridic Ustochrepts Aridic Ustochrepts	74300 (0.38)
Soils of Mudflats			
161	Deep (6), drained (1), calcareous, loamy (1), erosion (1), Ssa2 and Sso1; deep (6), drained (2), calcareous, loamy (3), erosion (1), Ssa2 and Sso1.	Typic Ustifluvents Typic Ustochrepts	136200 (0.69)
162	Deep (6), drained (1), calcareous, loamy (1), erosion (1), Sss3; deep (4), drained (1), calcareous, loamy (3), erosion (2).	Typic Ustifluvents Typic Ustochrepts	116100 (0.59)
163	Deep (6), drained (1), calcareous, loamy (3), erosion (1), Ssa2 and Sso1; deep (6), drained (1), loamy (3), erosion (2).	Typic Ustochrepts Typic Ustochrepts	119700 (0.61)
164	Shallow (2), drained (2), calcareous, loamy (3), erosion (1), Sss3; deep (5), drained (2), calcareous, loamy (3), erosion (1), Ssa3 and Sso1.	Typic Ustochrepts Typic Ustochrepts	21100 (0.11)
165	Deep (6), drained (2), calcareous, loamy (3), erosion (2), Ssa3 and Sso2; deep (6), drained (1), calcareous, clayey, erosion (2), Ssa3 and Sso2.	Typic Ustochrepts Typic Ustochrepts	74700 (0.38)
166	Deep (5), drained (2), calcareous, loamy (3), erosion (1), Sss3; deep (5), drained (3), calcareous, loamy (3), erosion (1), Sss3.	Typic Ustochrepts Vertic Ustochrepts	106800 (0.54)
167	Deep (4), drained (1), calcareous, clayey, erosion (2), Ssa3 and Sso2; shallow (2), drained (1), calcareous, clay loam, erosion (2), Ssa3 and Sso2.	Typic Ustochrepts Typic Ustochrepts	162000 (0.83)
168	Deep (5), drained (1), clayey, erosion (2), Ssa3 and Sso2; deep (5), drained (1), clayey, erosion (2), Ssa3 and Sso2.	Typic Ustochrepts Vertic Ustochrepts	122900 (0.63)
169	Deep (6), drained (3), calcareous, loamy (3), erosion (1), Ssa3, and Sso1; deep (6), drained (3), calcareous, loamy (3), erosion (1), Sss3.	Typic Ustochrepts Typic Chromusterts	30400 (0.16)
Soils of Coastal Plains			
170	Deep (6), drained (3), calcareous, loamy (3), erosion (1), Ssa3 and Sso2; deep (6), drained (3), calcareous, loamy (3), erosion (1), Ssa3 and Sso2.	Typic Salorthids Typic Halaquepts	5100 (0.03)
171	Deep (6), drained (3), calcareous, loamy (3), erosion (1), Ssa3; deep (5), drained (3), loamy (3), erosion (1), Ssa3.	Typic Halaquepts Typic Halaquepts	28500 (0.15)
172	Deep (6), drained (3), calcareous, loamy (3), erosion (1), Ssa3; deep (6), drained (2), calcareous, loamy (3), erosion (1), Ssa2.	Typic Halaquepts Typic Chromusterts	24500 (0.13)
173	Deep (5), drained (3), calcareous, loamy (3), erosion (1), Ssa3; deep (6), drained (3), calcareous, loamy (3), erosion (1), Ssa3.	Vertic Halaquepts Typic Chromusterts	42900 (0.22)
174	Deep (6), drained (3), calcareous, loamy (3), erosion (2), Ssa3; deep (6), drained (3), calcareous, loamy (3), erosion (3), Ssa3.	Aeric Halaquepts Typic Halaquepts	79400 (0.41)
175	deep (6), drained (2), calcareous, loamy (3), erosion (1), Ssa3; deep (6), drained(2), calcareous, loamy (3), erosion (2), Ssa2.	Typic Ustochrepts Typic Ustopepts	17200 (0.09)
176	Deep (4), drained (2), calcareous, loamy (3), erosion (1), Ssa2; drained (2), calcareous, loamy (3), erosion (1), Ssa2.	Typic Chromusterts Vertic Ustochrepts	25700 (0.13)
Soil of Piedmont Plains			
212	Deep (4), drained (1), calcareous, loamy (3), erosion (2), Ssa2; deep (5), drained (1), loamy (3), erosion (2), Ssa2.	Typic Ustochrepts Vertic Ustochrepts	2500 (0.01)

213	Deep (4), drained (1), calcareous loamy (3) erosion (2), Ssa2 and Sso1; deep (4), drained (1), calcareous, loamy (3), erosion (1), Ssa2 and Sso1.	Typic Ustochrepts Vertic Ustochrepts	12400 (0.06)
214	Deep (4), drained (2), calcareous, loamy (3), erosion (1), Ssa2 and Sso1; deep (5), drained (1), calcareous, loamy (3), erosion (1), Ssa2 and Sso1.	Typic Ustochrepts Vertic Ustochrepts	31500 (0.16)
215	Deep (6), drained (1), calcareous, loamy (3) erosion (2), Sss1; deep (5), drained (1), calcareous, loamy (3), erosion (1), Sss1.	Typic Ustochrepts Typic Chromusterts	45300 (0.23)
217	Shallow (2), drained (1), calcareous, loamy (3), erosion (1), Sss1; deep (5), drained (1), calcareous, loamy (3), Ssa1.	Typic Ustochrepts Typic Ustochrepts	22100 (0.11)
218	Shallow (2), drained (1), calcareous, loamy (3), erosion (2), Ssa2 and Sso1; deep (5), drained (1), calcareous, clay loam, erosion (2), Ssa2 and Sso1.	Typic Ustochrepts Typic Ustochrepts	24500 (0.13)
220	Deep (5), drained (1), calcareous, loamy (3), erosion (1), Ssa2 and Sso1; shallow (3), drained (1), calcareous, loamy, erosion (2).	Typic Ustochrepts Lithic Ustochrepts	67100 (0.34)
222	Shallow (2), drained (1), calcareous, loamy (3), erosion (1), Ssa1; deep (4), drained (1), calcareous, loamy (3), erosion (1).	Typic Ustochrepts Entic Chromusterts	26010 (0.13)
240	Shallow (2), drained (1), calcareous, loamy (3), erosion (1), Ssa1; shallow (2), drained (1), calcareous, loamy (3), erosion (2).	Vertic Ustochrepts Typic Ustochrepts	2400 (0.12)
244	Deep (4), drained (1), calcareous, loamy (3), erosion (1), Ssa1; deep (5), drained (1), calcareous, loamy (3), erosion (2)	Vertic Ustochrepts Fluventic Ustochrepts	2300 (0.01)
252	Shallow (2), drained (1), calcareous, loamy (3), erosion (1), Ssa1; shallow (2), drained (1), calcareous, loamy (3), erosion (1), Ssa1.	Vertic Ustochrepts Typic Chromusterts	99400 (0.51)
253	Deep (5), drained (1), calcareous, loamy (3), erosion (2), Ssa1; deep (5), drained (1), calcareous, loamy (3), erosion (2), Ssa1.	Vertic Ustochrepts Typic Chromusterts	15200 (0.08)
254	Deep (5), drained (1), calcareous, loamy (3), erosion (1), Sss1; deep (5), drained (1), calcareous, loamy (3), erosion (1).	Vertic Ustochrepts Typic Chromusterts	139100 (0.71)
256	Shallow (2), drained (1), calcareous, loamy (3), erosion (2), Sss1; deep (4), drained (1), calcareous, loamy (3), erosion (2), Ssa1.	Vertic Ustochrepts, Typic Chromusterts	40000 (0.20)
260	Deep (5), drained (1), calcareous, loamy (3), erosion (1), Sss1; shallow (2), drained (1), calcareous, loamy (3), erosion (2).	Vertic Ustochrepts Typic Ustochrepts	48000 (0.24)
261	Deep (5), drained (1), calcareous, loamy (3), erosion (1), Ssa2 and Sso1; shallow (2), drained (1), calcareous, loamy (3), Ssa1.	Vertic Ustochrepts Typic Ustochrepts	51200 (0.26)
263	Deep (5), drained (1), calcareous, loamy (3), erosion (2), Sss1; deep (5), drained (1), calcareous, loamy (3), Ssa2 and Sso1.	Vertic Ustochrepts Fluventic Ustochrepts	43400 (0.22)
265	Deep (5), drained (1), calcareous, loamy (3), erosion (2), Sss1; deep (6), drained (1), loamy (3), erosion (2), Ssa2 and Sso1.	Vertic Ustochrepts Fluventic Ustochrepts	47800 (0.24)
266	Deep (5), drained (2), calcareous, loamy (3), erosion (2), Sss1; deep (6), drained (1), loamy (3), erosion (2), Ssa2 and Sso1.	Vertic Ustochrepts Fluventic Ustochrepts	13500 (0.07)
270	Deep (4), drained (1), calcareous, loamy (3), erosion (1), Ssa1; shallow (2), drained (1), calcareous, loamy (3), erosion (1).	Typic Chromusterts Vertic Ustochrepts	101900 (0.52)
271	Deep (4), drained (1), calcareous, loamy (3), erosion (2), Sss1; shallow (2), drained (1), calcareous, loamy (3), erosion (2), Ssa1.	Typic Chromusterts Vertic Ustochrepts	240600 (1.23)
Soil of Coastal Plains (West Coasts)			
272	Deep (6), drained (3), calcareous, loamy (3), Ssa3 and Sso2;	Typic Salorthids	12900

	deep (5), drained (3), calcareous, loamy (3), Ssa3 and Sso1.	Typic Halaquepts	(0.07)
273	Deep (6), drained (3), calcareous, loamy (3), erosion (1), Ssa3 and Sso1; shallow (1), drained (1), calcareous, loamy, erosion (2).	Typic Salorthids Lithic Ustorthents	4800 (0.02)
274	Deep (6), drained (3), calcareous, loamy (3), erosion (1), Sss3; deep (6), drained (3), clayey, Sss3.	Typic Salorthids Vertic Halaquepts	58400 (0.30)
275	Deep (6), drained (3), calcareous, loamy (3), erosion (1), Sss3; deep (6), drained (3), calcareous, loamy (3), erosion (1), Sss3.	Typic Salorthids Typic Salorthids	16600 (0.08)
276	Shallow (3), drained (1), calcareous, clayey, erosion (2), Sss1; Shallow (1), drained (1), calcareous, loamy, erosion (2), Ssa1.	Lithic Calciorthids Lithic Torriorthents	46500 (0.24)
277	Deep (6), drained (3), calcareous, loamy (3), erosion (1), Sss1; Deep (6), drained (1), calcareous, loamy (3), erosion (2), Ssa1.	Ustretic Camborthids Typic Calciorthids	19800 (0.10)
278	Deep (6), drained (3), calcareous, loamy (3), erosion (1), Sss1; Deep (5), drained (2), calcareous, loamy (3), erosion (1), Sss1.	Ustretic Camborthids Ustochreptic Camborthids	16800 (0.09)
279	Deep (5), drained (1), calcareous, loamy (3), erosion (2), Sss1; Deep (5), drained (2), calcareous, loamy (3), erosion (1), Ssa2 and Sso1.	Ustochreptic Camborthids, Ustretic Camborthids	2400 (0.01)
284	Shallow (1), drained (1), calcareous, loamy, erosion (2), Sss1; deep (4), drained (1), calcareous, loamy (3), erosion (2), Ssa1.	Lithic Torriorthents Typic Torrifluents	31100 (0.16)
289	Shallow (2), drained (3), calcareous, loamy (3), erosion (1), Ssa3 and Sso2; deep (6), drained (3), clayey, Ssa3 and Sso2.	Typic Halaquepts Typic Salorthids	65100 (0.33)
290	Deep (6), drained (3), calcareous, fine, Ssa3 and Sso2; deep (6), drained (3), calcareous, fine, Ssa3 and Sso2.	Typic Halaquepts Typic Halaquepts	31300 (0.16)
291	Deep (5), drained (3), calcareous, fine, Ssa3 and Sso2.	Typic Halaquepts	32100 (0.16)
292	Deep (6), drained (2), calcareous, fine, Ssa1 and Sso2; deep (6), drained (3), calcareous, fine, Ssa3.	Vertic Halaquepts Typic Salorthids	8400 (0.04)
293	Deep (6), drained (3), calcareous, fine, Ssa3 and Sso2; deep (6), drained (3), calcareous, fine, Ssa3.	Vertic Halaquepts Typic Salorthids	11100 (0.06)
294	Deep (6), drained (3), calcareous, fine, erosion (1), Ssa2 and Sso1; deep (5), drained (1), calcareous, loamy (3), Ssa2 and Sso1.	Aeric Haplaquepts Fluventic Ustochrepts	4600 (0.02)
299	Deep (4), drained (2), calcareous, fine, erosion (2), Ssa3 and Sso1; deep (4), calcareous, loamy (3), erosion (2), Ssa3.	Vertic Ustrophepts, Typic Ustrophepts	3800 (0.02)
301	Shallow (3), drained (1), calcareous, clayey, erosion (2), Ssa3; shallow (2), drained (1), calcareous, loamy (3), erosion (2), Ssa2.	Lithic Ustrophepts, Typic Ustochrepts	22600 (0.12)
302	Deep (4), drained (1), calcareous, fine, erosion (2), Ssa3 and Sso1; deep (4), drained (1), calcareous, loamy (3), erosion (2), Ssa3.	Vertic Ustochrepts, Typic Ustochrepts	27500 (0.14)
303	Deep (4), drained (2), calcareous, fine, erosion (2), Ssa3; shallow (2), drained (1), calcareous, loamy (3), erosion (2), Ssa2.	Vertic Ustochrepts Fluventic Ustochrepts	5200 (0.03)
304	Deep (4), drained (1), calcareous, fine, erosion (2), Sss1; shallow (2), drained (1), calcareous, loamy (3), erosion (2), Ssa2.	Vertic Ustochrepts Fluventic Ustochrepts	23600 (0.12)
305	Deep (4), drained (2), calcareous, fine, erosion (2), Ssa1; shallow (3), drained (2), calcareous, clayey, erosion (2), Ssa1.	Vertic Ustochrepts Lithic Ustochrepts	26900 (0.14)
306	Deep (5), drained (2), calcareous, fine, erosion (1), Ssa3; deep	Vertic Ustochrepts	71500

	(5), drained (2), calcareous, fine, erosion (1), Ssa2.	Typic Chromusterts	(0.36)
307	Deep (5), drained (1), calcareous, fine, erosion (1), Ssa3 and Sso1; deep (5), drained (1), calcareous, fine, erosion (1), Ssa3 & Sso1.	Vertic Ustochrepts Typic Chromusterts	80900 (0.41)
310	Deep (6), drained (1), calcareous, fine, erosion (1), Ssa3 and Sso2; deep (4), drained (2), calcareous, fine, erosion (1), Ssa2.	Typic Chromusterts Typic Ustrophepts	58900 (0.30)
Soils of Pediments			
328	Deep (6), drained (1), calcareous, loamy (3), erosion (2), Ssa3; deep (6), drained (1), calcareous, loamy (3), erosion (2), Ssa3.	Ustochreptic Camborthids, Typic Camborthids	21300 (0.11)
Soils of Arid Plains			
336	Deep (5), drained (2), calcareous, fine, erosion (1), Ssa3 and Sso2; shallow (2), drained (1), loamy (3), erosion (1), Ssa3.	Typic Natrargids Typic Calciorthids	37500 (0.19)
337	Deep (4), drained (2), calcareous, fine, erosion (1), Ssa2; deep (5), drained (2), calcareous, fine, erosion (2).	Typic Paleargids Ustochreptic Camborthids	2900 (0.01)
338	Deep (4), drained (2), calcareous, loamy (1), erosion (2), Ssa2; deep (5), drained (1), calcareous, sandy loam, erosion (2), Ssa2.	Typic Calciorthids Ustochreptic Calciorthids	42700 (0.22)
339	Deep (6), drained (1), calcareous, loamy (1), erosion (1), Ssa2; shallow (2), drained (1), calcareous, fine, erosion (1), Ssa2.	Typic Camborthids Typic Camborthids	56100 (0.29)
340	Deep (5), drained (1), calcareous, loamy (1), erosion (1), Ssa2; deep (6), drained (2), calcareous, fine, erosion (1), Ssa2.	Typic Calciorthids Ustertic Camborthids	128100 (0.65)
343	Deep (5), drained (1), calcareous, loamy (3), erosion (1), Ssa2; deep (5), drained (2), fine, erosion (1), Ssa2.	Typic Caciorthids Ustertic Camborthids	24500 (0.13)
344	Deep (5), drained (1), calcareous, loamy (3), erosion (1), Ssa2 and Sso1; deep (4), drained (1), calcareous, loamy (3), erosion (1), Ssa2 and Sso1.	Typic Caciorthids Ustochreptic Camborthids	30700 (0.16)
345	Shallow (2), drained (1), calcareous, loamy (3), erosion (2), Ssa1; shallow (2), drained (1), calcareous, loamy (3), erosion (2), Ssa2.	Typic Calciorthids Typic Torriothents	30700 (0.16)
346	Shallow (2), drained (2), calcareous, loamy (3), erosion (2), Ssa3, and Sso1; deep (4), drained (1), calcareous, loamy (3), erosion (2), Ssa1.	Typic Calciorthids Typic Ustochreptic Camborthids	18100 (0.09)
347	Shallow (2), drained (1), calcareous, loamy, erosion (2), Ssa2; deep (4), drained (1), calcareous, loamy (1), erosion (2), Ssa1.	Ustochreptic Calciorthids Typic Camborthids	18400 (0.009)
353	Deep (4), drained (1), calcareous, loamy (3), erosion (2), Ssa2 and Sso1; deep (5), drained (1), loamy (3), erosion (2), Ssa3 & Sso1.	Ustochreptic Camborthids, Typic Calciorthids	45300 (0.23)
354	Deep (5), drained (2), calcareous, loamy (3), erosion (1), Ssa3 and Sso1; deep (5), drained (1), loamy (3), erosion (1), Ssa1.	Duric Camborthids Typic Calciorthids	179800 (0.92)
355	Deep (5), drained (1), calcareous, loamy (3), erosion (1), Ssa3 and Sso1; deep (5), drained (1), calcareous, fine, erosion (1), Ssa3 & Sso1.	Duric Camborthids Typic Camborthids	20500 (0.10)
357	Deep (5), drained (1), calcareous, loamy (3), erosion (1), Ssa3 and Sso1; deep (5), drained (1), calcareous, sandy, erosion (2), Ssa3.	Duric Camborthids Typic Torripsamments	33400 (0.17)
359	Deep (5), drained (1), calcareous, loamy (1), erosion (2), Ssa3 and Sso1; deep (5), drained (1), calcareous, loamy (3), erosion	Typic Torriorthents Typic Calciorthids	83100 (0.42)

(2), Ssa3.

Soils of Mudflats

361	Deep (4), drained (3), calcareous, loamy (1), erosion (1), Ssa3; deep (6), drained (3), calcareous, loamy (3), erosion (1), Ssa3.	Typic Camborthids Typic Salorthids	58100 (0.30)
362	Deep (6), drained (3), calcareous, loamy (3), erosion (1), Ssa3; deep (6), drained (1), calcareous, sandy, erosion (1), Ssa2.	Typic Salorthids Typic Torripsamments	77000 (0.39)
363	Deep (6), drained (3), calcareous, fine, erosion (1), Ssa3 and Sso1; deep (5), drained (3), loamy (3), erosion (1), Ssa3 and Sso1.	Typic Salorthids Typic Salorthids	41500 (0.21)
364	Deep (5), drained (3), calcareous, fine, erosion (1), Ssa3, and Sso1; deep (5), drained (3), loamy (3), erosion (1), Ssa3, and Sso1.	Typic Salorthids Typic Salorthids	110100 (0.56)
365	Deep (6), drained (3), calcareous, loamy (3), erosion (1), Ssa3 and Sso1; deep (6), drained (2), calcareous, loamy (3), erosion (1), Ssa2 and Sso1.	Ustochreptic Camborthids Typic Camborthids	28700 (0.15)
366	Deep (6), drained (1), calcareous, sandy, erosion (1), Ssa2; deep (6), drained (1), loamy (1), erosion (1), Ssa2.	Typic Torripsamments Typic Calciorthids	44700 (0.23)
367	Deep (6), drained (1), calcareous, loamy (3), erosion (1), Sss3; deep (6), drained (1), calcareous, loamy (1), erosion (1), Ssa3.	Aridic Ustochrepts Aridic Ustochrepts	16600 (0.08)
Soils of Coastal Plains			
368	Deep (5), drained (1), calcareous, loamy (3), erosion (1), Ssa3 & Sso1; deep (4), drained (1), calcareous, fine, erosion (1), Sss2.	Typic Camborthids Typic Natrargids	19500 (0.10)
369	Deep (5), drained (2), calcareous, fine, erosion (1), Ssa2 & Sso1; deep (4), drained (1), calcareous, loamy (1), erosion (3), Ssa2.	Ustretic Camborthids Typic Camborthids	6800 (0.03)
370	Deep (5), drained (3), calcareous, loamy (1), erosion (1), Ssa3 & Sso2; deep (5), drained (2), calcareous, sandy, erosion (2), Ssa2.	Typic Fluvaquents Aquic Ustipsamments	20000 (0.10)
Total			5289260 (26.45)

214 \$[43], Depth classes: 1= Very shallow, 2= moderately shallow, 3= shallow, 4= moderately
 215 deep, 5= deep, and 6= very deep; Drainage classes: 1= well/excessive drained, 2= moderately
 216 well drained, 3= poorly/ imperfectly drained, Erosion classes: 1= slight, 2= moderate, and 3=
 217 severe; Textural classes: 1= coarse, 2= moderate, 3= fine, and 4= very fine; slight categories
 218 of salt-affected soils such as Ssa1, Sso1 and Sss1 are excluded due to their potential
 219 productivity is comparable to non-salt-affected soils except in vertisols areas

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2.3. Methodology

2.3.1. Image analysis for mapping of salt-affected soils

False colour composites (FCC) were prepared using combination of bands for B432 (NIR, red, and green) and B543 (SWIR, NIR and red), respectively, for image interpretation. The imageries were geo-referenced using standard Universal Transverse Mercator (UTM) coordinate and were processed for linear stretching (1%) and resampling using a user-defined corner coordinate that covered the study area. Imageries were also processed for principal component analysis (PCA) to segregate the homogenous pixels and mixed pixels represented by characteristic features of complex salt-affected soils, surface crop cover, and moisture status in soil profiles [50]. Unsaturated (slicing and clustering) classification was also used to study digital (pixel) variations of images before visual image analysis. Spectral analysis was also carried out to study spectral signatures for different land use classes [51; 52]. Seasonal imageries were processed to study the characteristics and spectral signatures at pre- and post-monsoon seasons, emphasizing soil moisture status also (Table 3). Imageries were interpreted visually using shape, size, patterns etc. and the spectral signatures on the FCC (Table 3) [39; 51]. The legacy data of salt-affected soils on a 1:250K [10; 41; 45] and on a 1:50K scale [52; 51] were also used for image interpretation [53] and assess the distribution and spatial extent of salt-affected soils (Table 2).

An on-screen-digitisation method was used to delineate the image-interpreted units and was stored as a thematic (segment) map using GIS. The image interpreted units were validated using ground truth (soil sampling sites) and soil studies (soil profiles) followed by the laboratory analysis of soil samples for the physico-chemical properties. A point map was prepared to show the location of soil sampling sites (latitude and longitude) and was overlaid the segment map (image interpreted units) to create a polygon map of salt-affected soils (Figure 1).

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Figure1 Methodology for mapping salt-affected soils in Gujarat State

2.3.2. Preparation of a soil' database

The ground truth survey was conducted to collect soil and associated data such as land use, terrain, irrigation/ drainage and aquifer characteristics, etc., using a GPS that records the locations of soil sampling sites. A suitable grid measuring about 4 km x 6 km was used to collect soil samples from 1576 soil sampling sites pertaining to the salt-affected areas from 15 districts of Gujarat state (<http://pri.gujarat.gov.in>). Six representative soil profiles (P1 to P8) were also studied to know and understand soil formation processes (Table 4) and to assess salinity and sodicity status at surface (0-15 cm) and sub-surface (15-30, 30-60, 60-90, and 90-120 cm) soil depths, respectively [50]. The soils were analyzed for pHs (of saturated soil paste) and E_{ce} (of saturated paste extract, in dS m⁻¹), organic carbon (O. C., in %), cation exchange capacity (CEC, c mol. (p⁺) kg⁻¹), exchangeable sodium percentage (ESP), texture (sand %, silt %, and clay %), soluble salt composition (Na⁺, K⁺, Ca²⁺, Mg²⁺, CO₃²⁻, HCO₃⁻, Cl⁻, and SO₄²⁻ ions, me L⁻¹), and CaCO₃ (< 2mm fraction, %) using standard procedure [54; 55]. Based on the pHs, E_{ce}, ESP, and SAR values, the soils were classified as saline (S_{sa}), sodic (S_{so})₂ and saline-sodic (S_{ss}) and sub-categorized into slight (1), moderate (2), and strong (3) using standard methodology [51; 54].

2.3.3. Preparation of a base map and a database for soil attributes

The UTM (zone 43), datum (WGS 1984) and ellipsoid (WGS 84) parameters was used to geo-reference the topographical and open series maps (OSM) on a 1:50,000 scale, using the tie-point method (ILWIS software). The thematic layers of administrative and political boundaries (national, international, state, and district), infrastructure (roads and railways), irrigation and drainage (rivers/ canals), and settlement (state/ district/ block HQs and villages) were digitised and edited to assess the map accuracy using an affine transformation coefficient [56]. A composite base map of the study area was prepared by overlaying the geo-referenced thematic layers using GIS. A composite database of salt-

278 affected soils was also prepared integrating the polygons of salt-affected soils and base map
279 layers using digital overlay. An attribute table was also prepared, entering GPS-assisted soil
280 sampling sites (latitude and longitude), ground truth and laboratory analysis data of soil
281 samples in a GIS framework (Figure 2), and was linked to the spatial (map) data to develop a
282 relational database. The attribute maps were also prepared to show the spatial distribution of
283 surface soil properties such as pHs, ECe, Na⁺, K⁺, Ca²⁺, Mg²⁺, CO₃²⁻, HCO₃⁻, Cl⁻, and
284 SO₄²⁻ values. The interpolation of surface soil properties was carried out to study spatial
285 variations using an inverse distance method. It produces a raster map (2 bytes per pixel) and
286 the statistical parameters such as mean, standard deviation, median, and prediction values
287 (Figures 3 to 10). The polygons of salt-affected soils and base maps layers were annotated for
288 the legends, such as north direction, scale, boundary, settlement, graticules etc. (Figure 11).
289 The extent of salt-affected soils was calculated based on the area statistics from histogram
290 analysis (Table 5). The raster map for district boundaries was superimposed (using cross-
291 operation in ILWIS) with the salt-affected soils- map to prepare a cross-table that presented
292 the district-wise distribution of salt-affected soils and a cross-map that showed the spatial
293 distribution of salt-affected soils in fifteen districts of Gujarat state (Table 6). A
294 comprehensive methodology (Figure 1) was also presented for mapping of salt-affected soils.

295

296 Figure 2 Distribution of soil samples sites in Gujarat state (Legends (Physiography): 1: The
297 West Coast: Kachchh Peninsula, 2: Rann of Kachchh, 3: The West Coast: Kathiwar
298 peninsula, 4: The West Coast: Gujarat Plain, 5: The Central Highlands: Aravalli Range,
299 6:The Western Hills: North Sahyadri [42])

4.0. Results and Discussion

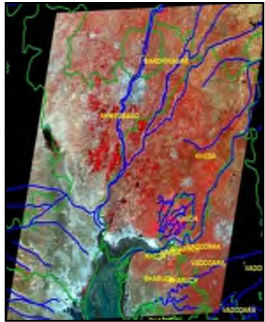
4.1. Image interpretation

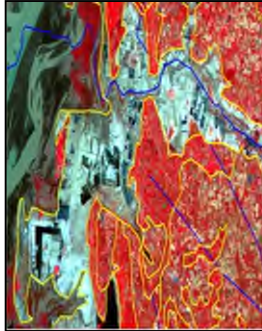
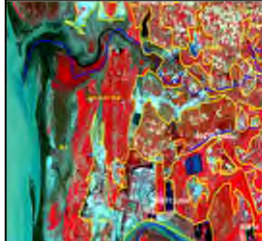
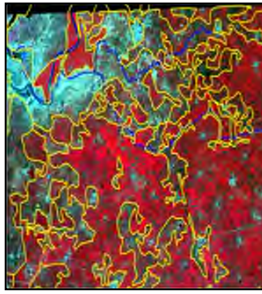
Spatial characteristics of salt-affected soils were presented using nine representative scenarios (S1 to S9) which were distributed in different landforms and agro-climatic zones in the study area (Table 3). S1 represented the areas of extreme soil salinity in the Kachchh peninsula and showed sporadic crop cover in scattered red and natural vegetation in green (pastures and scrubs with poor vegetative growth), moist salty surface in grey and dry salt and sand in white to yellowish white, and irrigation water channels and sea surface in blue to deep blue colours, respectively. The seasonal imageries also showed partial inundation of large areas with little or no vegetative cover, desert sandy and salt-affected soils due to high evaporation rate, arid climate, and salty groundwater in coastal areas. Ground truth studies identified irrigation using salty groundwater, the conversion of sandy soils to commercial agricultural purposes and also high soil E_{Ce} [57]. The use of micro-irrigation and the water-saving and high-value horticulture crops were also practiced in localized areas.

S2 represented severe soil salinity in Banaskantha and Mehsana districts (P6, P7, and P8) in the inland and coastal plains. Salt pan and salty land showed white to greyish white colour along the seacoast. Low cropping density, coarse sand and barren surface were characteristic features in coastal areas. Moderate and sporadic cropped areas were prominent in the inland alluvial (red to colour) and coastal plains (spotted red).

S3 showed soil salinization in the coastal plain (Bhavnagar, Junagarh, and Amreli districts) intercepted by numerous irrigation and prominent drainage channels. A few cropped and forest covered areas (red to brown); natural vegetation (light red), creeks (curvilinear lines), barren lands (white to yellowish white) spreading from coastal to inland plains, dried up salty lands (white tone) along the sea coast were common image features during

Table 3 Image interpretation for spatial characterization of salt- affected soils

Categories of soil degradations (S)	Salient features in IRS LISS III R2A imagery	Landform, climate, soil	Natural/anthropogenic factors	False Colour composite (B432)*
S1: Distribution of soil salinity along the sea coasts (in districts: Kachchh and Jamnagar) in arid/ semiarid climatic zone (P2)	Sporadic crop cover in red, natural vegetation in green, salty surface in grey /white and sea water/ canal in blue/dark blue colours were common features in the selected areas.	P2, a Ssa3, from the arid/ semi-arid region of the Kachchh Peninsula	Flat alluvial (tidal) plain along the coasts, numerous water channels redistribute salts along the plain (Refer to Table 2 map unit No. 76-83)	
S2: Severe soil (P6) salinity in the semiarid/ sub-humid plains (of Banaskantha and Mehsana districts) (Ref: Table 2 map unit No. 87-192).	Good agricultural practices were visible in the inland plains, several river/water channels extended from inland towards coastal plain, salt pan/salty surface were distinguished based on the spectral signatures	P6, a strongly saline soil of the alluvial plain in central Gujarat under the arid/ semi-arid zone	Primary land units include coastal, aeolian, aeofluvial, alluvial, and pediment plains, saline water ingress in the mudflats/ mangrove swamps	
S3: Numerous drainage channels (blue lines) favored soil salinization and distribution in the coastal plains (districts: Amreli, Bhavnagar, and Junagarh)	Little cropped areas, large areas of forestry, natural vegetation, prominent drainage channels, creeks (as curvilinear lines) and barren lands (without any vegetation) spreading from coastal to inland plains, dried up salty lands (white tone) along the sea coast.	Soil salinity varied from moderate (Ssa2) to strongly (Ssa3) saline in alluvial, and coastal plains, mud-flat.	Kachchh peninsula, pediments, arid plain, mud-flats and coastal plains are primary land units (Refer to Table 2 map unit No. 283-370). [39] Blue lines represents irrigation network.	
S4: Soil salinity in the alluvial (P3) and coastal plains (P4) of Bharuch, Kheda, Vadodara, and Ahmedabad districts (Table 2 map unit 86-192)	Sporadic crop covers, salt pan and salt crusts along the coastal fringe; salinity distribution due to ingress of saline water in the inland plains; lack of fresh water sources restricted common practices of agriculture.	P3, a Sss2, moderately saline-sodic soil in the alluvial plain, P4, a Ssa3, coastal saline soil under irrigation.	Coastal, mudflats, aeolian, aeofluvial, and pediments are common landforms in Kathiwar peninsula. Most of the perennial rivers are draining salts along with its course.	
S5: Extreme soil salinity (salt pan) along the sea coast (Coastal plain) (Refer to Table 2 map unit No. 283-370).	Limited areas are under the agriculture due to the lack of good-quality water for irrigation; most degraded lands were also used for the aquaculture practices. Primary problems include waterlogging and salinity.	Extreme salinity were developed in salt pan due to repeated ingress of saline sea water	Coastal, deltaic, and mudflats are common landforms. Limited farming practices include agriculture which is dependent on the fresh water from the perennial rivers.	

S6: Salt pan, mud flats and mangrove swamps along the coastal plains. (P6) viewed in the IRS March data (Refer to Table 2 map unit No. 283-370). S7: Salt crust and moderate soil salinity within the cropped areas (alluvial plain) (P1) along the (Tapi) river delta.	Limited agriculture and cropped areas, marshy land in mudflats, salt pans and surface salt crusts, and waterlogging are common features. The aquaculture practices and / or animal husbandry are viable alternatives for the livelihood of farmers Agriculture (crop area) is primary land use along the Tapi river basin. Salt pan and waterlogging were characterized based on spatial and spectral properties. Barren white tiny spots represent the moderate salinity areas.	Repeated submergence by saline seawater favored developing strong (Ssa3) soil salinity in the coastal ecosystem. P1 (Sss2), a moderately saline soil, developed in the deltaic alluvial plain in a sub-humid climate zone.	Mudflats, coastal and deltaic plains and mangrove swamps are common landforms. Limited irrigation facilities are available. Water quality is poor to very poor due to the continuous ingress of saline seawater Deltaic, coastal plains, mudflats, mangrove swamps and alluvial plains are common landforms. Perennial rivers are primary source of irrigation. (Refer to Table 2 map unit No. 283-370).	
S8: Moderate to high soil salinity (P5) in the deltaic plains, Dist. Surat (Ref. Table 2 map unit No. 283-370). S9: Development of soil salinity along the creeks (P7 and P8) (Ref. Table 2: map unit No. 283-370).	Salt pan, aquaculture (with boundary) and agriculture are common features in the deltaic plain. Strong and moderate salinity were identified as white spots within the cropped areas. Creeks favour developing high soil salinity and water-logging during the tidal inundation by the saline sea water in the coastal areas. Due to high salinity and repeated submergence, agriculture is limited in these areas.	Soil profile data showed high salinity in the 0-55 cm depth and low salinity beyond it. High salinity (17-49 dS m⁻¹) is a typical characteristic in the inland saline plains of Gujarat.	Coastal, deltaic plains, mudflats/ mangrove swamps and alluvial/ aeolian plains are common landforms. . Waterlogging is also a common feature. . Coastal, deltaic, alluvial, mudflat and mangrove swamps are common landforms. Periodic inundation of saline water prompted developing poor soil and water quality.	
				
				

326 March. Ground truth studies revealed variable soil salinity ranging from moderate (Ssa2) to

327 strongly (Ssa3) saline in the alluvial and coastal plains, and in mud-flat /mangrove swamps.

328 S4 showed large areas under the barren wastelands, a few cropped areas, natural

329 vegetation, and forest (with distinct boundaries) in the south of Gujarat state (Bharuch,

330 Kheda, Vadodara, and Ahmedabad districts). Soil salinity varies from moderate (Ssa2) in

331 partially cropped areas (P3, Table 3) to strong (Ssa3) in barren wastelands (P4) along the

332 coastal creeks. Sporadic crop covers (light red), salt pan (smooth white), and crusts (irregular

333 white in small patches) were common features along the coastal fringe. The periodic ingress

of saline seawater favored in developing soil salinity and the lack of fresh water restricted common agricultural practices in the inland plain.

The satellite imagery (S5) indicated limited areas under agriculture (scattered red) due to the lack of irrigation facility (Bharuch and Vadodara districts). These areas were also used for salt production (salt pan, smooth white tone) along the sea coast under the coastal plain. Field validation indicated common utilisation of degraded soils for aquaculture practices using village ponds or reservoirs (black tone).

Salt pan was also identified in the IRS -March data along the creeks, mud flats, and mangrove swamps in the coastal areas of south Gujarat (S6). The limited agricultural areas (scattered red), marshy land (dark tone) in mudflats, and surface salt crusts (white) were common features (P6, Table 3). Field validation also revealed common practices such as aquaculture and animal husbandry.

Common features in S7 include salt pan (strong spectral signatures from white salt and a clear boundary), waterlogging (dark colour) and moderate salinity, showing barren tiny white spots. Small patches of salt crust and moderate soil salinity were also identified within the cropped areas in the alluvial plain (P1, Table 3) along the Tapi_river delta. Perennial rivers are the primary source of irrigation for agriculture.

Moderate to high soil salinity (P5, Table 3) was a characteristic feature of soils in the deltaic plain (District Surat) (S8). Localised salt pan, commercial aquaculture (black-to-blue-black tone), and agriculture (spotted crop cover in red tone) were common image features of the deltaic plain. Ground truth survey identified soils with strong (Sssa3) and moderate (Ssa2) salinity as white spots within the cropped areas. Waterlogging was a common feature in the irrigated areas.

Creeks were common source that develop high soil salinity and waterlogging during the tidal inundation by the saline seawater in the coastal areas (S8 and S9). Due to high soil

salinity and repeated submergence, agriculture is limited in these areas. Periodic inundation by saline water led to the development of poor soil and water quality along the creeks (P7 and P8, Table 3).

4.2. Characterization of soils for salinity management

The soils showed differentiating characteristics ranging from moderate (Ssa2) to strongly saline (Ssa3) and moderately saline-sodic (Sss2) to strongly saline-sodic (Sss3) in P2 and P3 from the arid plain. It also showed moderately saline-sodic soil (P1) from the coastal plain of sub-humid region under poor soil and groundwater; moderate to strong salinity (Ssa2 –Ssa3) in P4 and P5 in the Ukai- Kakarpar canal command area, and strong salinity (Ssa3) in P6, P7 and P8 from the inland alluvial plain, respectively (Table 4).

Alkaline soil pHs (8.4- 8.6), moderate ESP (12.7- 22.5), $\text{CO}_3^{2-} + \text{HCO}_3^-$ (3.0- 4.0 me L^{-1}) salts, high ECe (9.4- 20.0 dS m^{-1}) and SAR (>13, 19.2 -23.9) values were characteristic features of Pedon 1 (P1). Sodium (71.1 -82.3 me L^{-1}) and chloride (89.0- 106.0 me L^{-1}) were prominent anions. Mg^{2+} (6.6-10.9 me L^{-1}) content was higher than Ca^{2+} (2.0- 4.6 me L^{-1}). Na^+/Cl^- ratios were < 1. Low to moderate ESP values (12.7- 22.5), and clay loam texture (40.1- 46.7%) restricted soil pH (Sss2) and a complex nature of soil [58]. Gypsum application (@ 2-3 tons ha^{-1}) and irrigation is needed to neutralise sodicity and remove excess salts.

Pedon 2 (P2) was a strongly saline soil (ECe, 15.5- 22.1 dS m^{-1}) dominated by Na^+ (118.1- 186.3 me L^{-1}), K^+ (16.8- 20.0 me L^{-1}), Ca^{2+} (6.1- 43.0 me L^{-1}), Mg^{2+} (19.7- 33.8 me L^{-1}), and Cl^- (195- 274 me L^{-1}) ions. Low ESP (12.6- 16.2) and pHs (8.2-8.5) indicated the initiation of alkalinity in a sandy loam soil, while high SAR (15.2- 34.2) resulted from the use of saline/sodic groundwater. The pedon (P2) should be treated with good-quality irrigation water for flushing and follow micro-irrigation practices to reduce salt-load.

382 **Table 4** Physico-chemical properties of benchmark salt-affected soils of Gujarat state

Depth (cm)	pH	ECe dSm ⁻¹	Na+	K+	Ca ²⁺	Mg ²⁺	CO ₃ ²⁻	HCO ₃ ⁻	Cl ⁻	SO ₄ ²⁻	ESP	SAR	Clay ----(%)----	Silt	OC %
Soils of the subhumid regions along the coastal plain (south Gujarat)															
P1: 20°37'48.0"N72°55'48.0"E, Sss2, Mg ²⁺ > Ca ²⁺ , high clay, ESP and SAR, Vil. Dandi, Dist. Valsad, Gujarat.															
0-18	8.4	11.9	71.1	17.0	2.0	10.8	3.0	95.0	2.7	22.5	19.9	44.9	23.2	0.2	
18-60	8.5	20.0	71.4	18.4	4.6	9.2	3.0	105.0	4.1	15.9	19.2	42.7	19.7	0.1	
60-120	8.6	9.4	70.9	16.8	2.2	6.6	3.0	89.0	3.4	14.8	23.9	40.1	24.2	0.1	
102-170	8.5	11.4	82.3	18.8	3.9	10.9	4.0	106.0	5.1	12.7	21.4	46.7	22.6	0.1	
Soils of the arid and semiarid regions are severely affected by soil and groundwater salinity (west of Gujarat).															
P2: 23°54'54.0"N70°2'1.2"E, Ssa3, high in K+, Cl ⁻ , Ca ²⁺ ++Mg ²⁺ and SAR. Vil. Suramsar Dist. Kachchh Gujarat															
0-15	8.2	22.1	186.3	20.0	43.0	33.8	2.1	274.0	2.7	14.9	21.6	21.2	14.9	0.2	
15-50	8.3	16.8	118.1	17.0	35.5	24.8	2.6	187.0	3.1	16.2	15.2	22.2	16.2	0.1	
50.75	8.4	17.2	155.8	17.0	10.8	21.0	3.1	195.0	3.4	14.1	27.6	24.1	14.1	0.1	
75-115	8.5	15.5	173.8	16.8	6.1	19.7	3.0	211.0	4.1	12.6	34.2	13.9	12.6	0.1	
Soils of the semiarid region, irrigated by wells, groundwater, and canals (Narmada canal) in north Gujarat.															
P3: 22°22'12.0"N71°58'48.0"E, Ssa2, dominant ions: CO ₃ ²⁻ , HCO ₃ ⁻ , SO ₄ ²⁻ , Ca ²⁺ , and Mg ²⁺ , Dist. Ahmedabad															
0-5	8.5	11.4	79.9	1.6	8.7	16.2	3.8	9.7	3.1	51.2	21.2	16.0	25.9	13.3	0.35
5-30	8.3	16.8	125.7	1.8	22.7	43.1	3.6	175.0	3.4	51.0	19.0	15.4	24.8	12.8	0.28
30-83	8.1	24.5	199.1	2.4	47.1	54.7	3.2	293.0	4.1	50.2	18.9	19.7	27.1	14.1	0.22
83-150	8.0	31.1	313.5	3.0	87.8	60.0	2.9	456.6	2.7	58.4	15.9	25.8	25.9	16.7	0.11
Irrigated saline soils of the Ukai- Kakarpar canal command area (coastal plain, south Gujarat)															
P4: 21°41'41.35"N72°58'49.8"E, Ssa3, high HCO ₃ ⁻ , clayey, Vil. Ambhata, Tehsil Kukni, Dist. Bharuch, Gujarat.															
0-10	7.7	24.7	157	0.5		95	12.5	230	6.7	23.1	16.1	40	25	0.53	
10-38	7.8	17.3	133	0.6		40	12.5	150	6.2	24.2	21.0	40	28	0.33	
38-60	7.9	13.6	106	0.6		30	10.0	120	5.6	22.3	19.3	42	28	0.19	
60-100	7.9	12.3	98	0.7		25	10.0	110	2.5	15.4	19.6	44	32	0.23	
100+	8.4	7.4	63	0.7		10	11.0	60	2.7	11.8	19.9	42	24	0.19	
P5: 21°22'30"N72°44'30"E, Ssa2 (0-55 cm), Sso2 (55-112+ cm), high HCO ₃ ⁻ , clayey, Vil. Bhatgam, Olpad, Surat.															
0-8	7.3	19.7	71.5	0.6		26	10.0	180	8.9	19.9	14.0	39	27	1.2	
8-55	7.9	16.0	125.3	0.8		36	12.5	140	8.0	16.8	20.8	41	27	0.5	
55-68	8.9	5.2	47.1	0.7		5.5	13.5	37	1.6	15.7	20.1	44	29	0.2	

68-112	9.0	4.2	36.6	0.5	5.0	11.5	29	1.5	14.6	16.4	47	30	0.2	
112+	9.1	3.9	34.0	0.5	5.0	15.0	22	1.8	12.8	15.2	41	27	0.1	
Soils of semiarid region (NE Gujarat) covered the Aravalli range, peninsular plain and mud flats/ mangrove swamps														
P6: 24°12'11.0"N72°44'40.9"E, Ssa3, high Na+, K+, Ca ²⁺ , Mg ²⁺ , SO ₄ ²⁻ , Vil. Lotia, Dist. Banaskantha, Gujarat.														
0-10	7.8	90.0	220.0	74.8	28.0	33.0	3.5	34.3	242.0	15.8	40	6.5	2.9	0.44
10-68	7.9	21.0	72.0	65.7	3.0	5.0	3.3	8.0	68.5	12.6	36	11.9	10.5	0.31
68-138	8.1	17.7	50.0	45.5	2.0	2.5	4.0	5.5	47.9	11.3	33	8.8	7.0	0.22
P7: 23°51'8.17"N71°37'49.0"E, Ssa3, high Na+, K+, Ca ²⁺ , Mg ²⁺ , SO ₄ ²⁻ , Vil. Ganjisar, Banaskantha, Gujarat.														
0-15	7.2	40.0	187.0	66.8	3.0	5.0	1.8	27.5	166.0	16.8	93	7.6	3.5	0.36
15-30	7.5	27.0	75.0	54.9	9.0	10.0	2.0	11.5	81.5	14.9	25	7.9	4.5	0.25
30-45	7.7	17.2	58.0	45.7	5.0	5.0	1.5	3.3	63.0	13.8	26	8.2	5.1	0.22
45-60	7.7	19.9	47.5	56.7	7.0	5.0	2.5	6.8	49.5	12.7	20	8.8	3.9	0.13
P8: 31°33'43.13"N75°1'39.7"E, Ssa3, high Na+, K+, Ca ²⁺ , Mg ²⁺ , SO ₄ ²⁻ Vil. Jandala, Dist. Banaskantha, Gujarat.														
0-15	7.1	49.0	101.0	55.8	33.0	27.0	1.5	20.0	139.3	11.8	18	8.9	5.4	0.23
15-30	7.5	37.0	77.0	56.9	16.5	19.5	1.8	11.8	99.5	12.1	18	7.6	6.7	0.21
30-45	7.6	38.0	102.0	45.8	10.5	15.5	2.0	18.8	107.5	13.4	28	8.8	10.1	0.22
45-60	7.4	30.0	113.0	71.2	20.0	18.0	1.8	19.0	130.0	10.5	26	10.1	5.9	0.11
60-70	7.6	30.0	109.0	46.8	10.0	13.0	1.8	15.3	115.0	11.0	32	6.0	4.4	0.11

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Pedon 3 (P3) was a sandy clay loam soil irrigated by poor quality groundwater. Soil salinity ranges from moderate to strong at surface and sub-surface depths (ECe 11.4-31.1 dS m⁻¹), respectively. Higher Na⁺ (79.9- 313.5 me L⁻¹), Ca²⁺ (8.7- 87.8 meL⁻¹), Mg²⁺ (16.2- 60.0 me L⁻¹), HCO₃⁻ (9.7- 456.6 me L⁻¹) and SO₄²⁻ (50.2- 58.4 me L⁻¹) contents showed the dominance of neutral and alkaline salts. Low ESP (15.9-21.2, >15) and high SAR (15.9- 21.2, >13) indicated low alkalinity. The soil alkalinity was partially neutralized by SO₄²⁻ ions and was classified as Ssa3. Flushing of salts using good-quality irrigation water was suggested.

Pedon 4 (P4) was an irrigated soil located in the Ukai Kakarpar canal command area (South of Gujarat). Soil properties indicated moderate to high ECe (7.4- 24.7 dS m⁻¹) and SAR (16.1- 21.0) at surface and sub-surface depths, respectively. Dominant salts include Na⁺ (63- 157 me L⁻¹), Ca²⁺++Mg²⁺ (10- 95 me L⁻¹), Cl⁻ (60- 230 me L⁻¹), and HCO₃ (10.0- 12.5 meL⁻¹). ESP values were higher at surface (23.1- 24.2) and low at sub-surface (11.8- 22.3) depths. The low soil pHs was attributed to the high clay content in a clay loam soil. The alkaline parent material (such as basalt) and the poor-quality groundwater were primary sources of salts [59; 60]. Irrigation with good-quality water was suggested for reclamation prior to arable cropping.

Pedon 5 (P5) was an irrigated black cotton soil (Vertisol) showing clay loam texture (40% clay), high ECe (16.0- 19.7 dsm⁻¹) at the surface (0- 55 cm) (Ssa2) and pHs (8.9- 9.1) at sub-surface depths (55-112+ cm), respectively. Na⁺ (34.0-125.3 meL⁻¹), Cl⁻ (22- 180 meL⁻¹), Ca²⁺++Mg²⁺ (5- 36 meL⁻¹) and CO₃²⁻++HCO₃⁻ (10-15 meL⁻¹) were dominant ions. SAR (14.0-20.8) and ESP (12.8-19.9) were higher due to alkaline salts and clay content. Higher ECe at surface was attributed to lower topography and needs removal salts either by flushing for reclamation or installation of sub-surface drainage.

P6, P7, and P8 were located in the northeast (NE) of Gujarat in Banaskantha district (Desert Soil) which is surrounded by the Aravalli range in the north, the peninsular plain and

marine deposits covering Kachchh, Patan, and Mehsana districts. These soils were strongly saline (Ssa3). ECe ranges from 90.0 to 17.7 dS m⁻¹ (P6), 40.0 to 17.2 dS m⁻¹ (P7) and 49.0 to 30.0 dS m⁻¹ (P8), respectively. P6 showed dominant ions such as Na⁺ (220 -50 me L⁻¹), K⁺ (74.8- 45.5 me L⁻¹), Ca²⁺ (28- 2 me L⁻¹), Mg²⁺ (33- 2.5 me L⁻¹), Cl⁻ (34.3- 5.5 me L⁻¹), and SO₄²⁻ (242- 47.9 me L⁻¹) and also high SAR values (33-40). Soil texture varies from sandy to sandy loam, respectively. The ESP values were below the critical limit. The soil should be reclaimed with good- quality water. Soil salinity and salt composition in P7 and P8 decreased from surface to sub-surface depths in the peninsular plain and the salty Rann. Depth-wise Na⁺ contents and SAR values for P7 and P8 indicated abrupt salt distribution in the soil profile due to saline groundwater. High contents of K⁺ (66.8 -45.7 me L⁻¹ in P7 and 56.9 - 45.8 me L⁻¹ in P8) and SO₄²⁻ (166- 49.5 me L⁻¹ in P7 and 139.3- 99.5 me L⁻¹ in P8) indicated the lack of natural drainage. Cl⁻ contents were higher (27.5-11.5 me L⁻¹) in P7 and prominent in P8 (20.0- 11.8 me L⁻¹). ESP was below the critical limit. Irrigation with good-quality water was suggested to remove salts from the root zone.

4.3. Spatial variation of soil salinity

The district-wise distribution of soil samples sites throughout the study area indicated an even distribution in Gujarat state (Figure 2). Digital overlay with parent materials [43] indicated the prominent distribution in the marine sediments along the coasts, the recent alluvium in central Gujarat, the *Umia and Bhuj* Beds (Mesozoic), and the Deccan Trap (Tertiary Mesozoic). It also indicated prominent distribution in physiography regions [43] such as Gujarat Plain (West Coast), Kathiwar and Kachchh Peninsula, and the Rann of Kachchh, respectively.

Soil attribute maps were prepared to show the spatial variation of ECe, Na⁺, Ca²⁺, Mg²⁺, CO₃²⁻, HCO₃⁻, Cl₂ and SO₄²⁻ values in the study area (Figures 4-10). High ECe values (0.23- 165.0 dS m⁻¹) were located in the Kachchh Peninsula and also along the coastal

439 plains of the west (Kathiwar Peninsula) and the south Gujarat plain (Figure 3). Na⁺ contents
440 (0.04- 4683.04 me L⁻¹) were higher in the Rann of Kachchh, Kathiwar peninsula, and south
441 Gujarat plain, respectively (Figure 4). High Ca²⁺ and Mg²⁺ contents (Figures 5 and 6) were
442 located in the Rann of Kachchh, the alluvial plain of South Gujarat (District: Surat, Bharuch,
443 Valsad, and Kheda) and the Kathiwar peninsula (District: Ahmedabad, Surendranagar and
444 Bhavnagar). Mg²⁺ content dominated over Ca²⁺ in South Gujarat and arid regions. CO₃²⁻ +
445 HCO₃⁻ contents were higher in Kheda, Bharuch and Surat districts and also the arid regions
446 of Kachchh, Mehsana, and Ahmedabad districts (Figures 7 and 8). Cl⁻ content was higher in
447 South Gujarat and arid plains of Kachchh, Kheda, Ahmedabad, Bharuch, and Surat districts
448 (Figure 9). SO₄²⁻ content was also higher in Kachchh, Ahmedabad, Kheda, Bharuch, and
449 Surat districts (Figure 10). Histogram data from spatial interpolation studies revealed the
450 number of pixels (Y-axis) was higher for E_{Ce}, HCO₃⁻, CO₃²⁻, Ca²⁺, Mg²⁺, and SO₄²⁻ located
451 in the arid /semiarid and coastal regions.

Figure 3 Distribution of ECe values of soil samples in Gujarat state

4.4. Spatial extent and distribution of soil salinity

The extent (ha) and distribution (district-wise) of salt-affected soils in Gujarat state (Figures 11 and Tables 5 and 6) indicated different categories of saline (Ssa1, Ssa2, and Ssa3) and sodic (Sso1, Sso2, and Sso3) soils that covered 69.4% and 30.6 %, respectively (Table 5). Strongly saline soils (Ssa3) were distributed in the coastal and peninsular plains (35.2%). Slight (Ssa1, 28.6 %) and moderate (Ssa2, 6 %) saline soils were confined to the inland alluvial and arid plains, respectively. Slightly sodic soils (Sso1, 26.3%) were primarily located in arid region (north Gujarat). Sso2 (2.9%) and Sso3 (1.5%) were common in the alluvial (central) and black (south Gujarat) soil areas underlain by the alkaline parent materials.

Legacy data (Table 6) of salt-affected soils (1996) indicated higher extent of saline-sodic soils (65%) than the exclusive saline (35 %) soil [44]. For management purposes, saline-sodic soils were classified suitably as a saline or a sodic soil (with natric horizon) based on the ionic ratio such as $(\text{Na}^+/\text{Cl}^-)$, $\{(2\text{CO}_3^{2-} + \text{HCO}_3^-)/(\text{Cl}^- + 2\text{SO}_4^{2-})\}$ and $\{\text{Na}^+ / (\text{Cl}^- + 2\text{SO}_4^{2-})\}$ [61]. Similar data for the mapping of salt-affected soils also revealed variable estimates (1.6 and 1.1 million ha) on a reconnaissance scale (1:250,000) integrating IRS 1A and 1B L2 data of 1993-1994 and ground truth, respectively (37). Systematic soil studies for mapping degraded soils on a scale of 1:250, 000 (Table 2) also estimated 5.3 million ha [43]. Sreenivas et al. [42] also mapped soil degradations (5.98 million ha) integrating IRS R2A L3 (2015-2016) with limited ground truth data on a scale of 1:50,000 (comparable scale).

474 **Table 5** Categories of salt –affected soils: spatial extent and temporal changes in Gujarat state

Categories of salt-affected soils and (code*)	Estimates of 2023 [#]		Estimates of 1996 ^{\$}		Changes in acreage	
	Areas (ha)	%	Areas (ha)	%	Areas (ha)	%
Saline- slight (Ssa1)	1866200	28.21	432953.32	19.48	+1433246.68	+64.5
Saline- moderate (Ssa2)	397589	06.01	235621.38	10.60	+161967.62	+07.28
Saline-strong (Ssa3)	2326005	35.17	114474.11	05.15	+2211530.89	+99.5
Total (saline)	4589794	69.39	783048.81	35.24	+3806745.19	+171.32
Sodic- slight (Sso1)	1738041	26.27	tr.	tr.	tr.	tr.
Sodic- moderate (Sso2)	190137	02.87	tr.	tr.	tr.	tr.
Sodic- strong (Sso3)	96198	01.45	tr.	tr.	tr.	tr.
Total (sodic)	2024376 ^{**}	30.60	tr.	tr.	tr.	tr.
Saline- sodic- slight (Sss1)	tr.	tr.	850915.57	38.29	+887125.43	+39.92
Saline- sodic- moderate (Sss2)	tr.	tr.	172677.51	07.77	+17459.49	-0.78
Saline- sodic- strong (Sss3)	tr.	tr.	415358.09	18.69	-319160.09	-14.36
Total (saline-sodic)	tr.	tr.	1438951.17 ^{\$}	64.76	+585424.83	+24.78
Total areas (ha)	6614170 ^{&}		2222000		+4392170.02	+196.1

475 [#]estimates prepared using IRS R2A L3 (2014-2018) and ground truth data (GPS-tagged soil
476 sampling sites- 1576 Nos.), ^{\$}estimates prepared integrating Landsat TM (1984) and limited
477 ground truth data and mapped on a scale of 1:250,000 during 1996 [40], * [51], (+) represents
478 increase (-) represents decrease and reclaimed soils, tr.=traces ^{**}merged data of sodic and
479 saline-sodic soils, used for sodic soil reclamation, ^{\$}saline-sodic soils were treated mostly as
480 sodic for soil (sodic) reclamation purposes, depending on soil texture, pHs (of saturated
481 paste), ECe (dS m⁻¹) (of saturated extract), ionic composition, ESP, SAR, and groundwater
482 quality (for soils developed by anthropogenic origin),

483

Figure 11 Spatial distribution of salt-affected soils in Gujarat

484

4.5. Temporal assessment of soil salinity

The estimates of salt-affected soils were compiled to assess the changes from 1995 to 2023 [37; 40; 48; 62] and were presented in Table 6. The recent estimate in 2023 (6614170 ha, 6.6 million ha) indicated the prominent areas in arid regions and coastal areas such as Kachchh (29.7%), Surendranagar (9.5%), Ahmedabad (8.4%), Banaskantha (8.2%), Jamnagar (7.9%), Junagarh (6.4%), Bhavnagar (5.7%), Bharuch (5.0%), Rajkot (4.1%), Surat (4.1%), Mehsana (3.5%), Amreli (1.9%), and Kheda (1.9%) districts, respectively [63]. The salt-affected areas increased significantly in Rajkot (94%), Kachchh (59%), Kheda (38.7%), Vadodara (37.8%), Amreli (36.9%), Jamnagar (18.8%), Surendranagar (17.1%), Junagarh (13.8%), Ahmedabad (11.7%), Bharuch (11.6%), Surat (10.7%), and Banaskantha (10.6%) district compared to 1996, respectively. A comparative study of salt-affected areas between 2023 (on 1:50K) and 1995 (by ground truth study¹ and IRS 1A data² on 1:250K) indicated significant changes in Kachchh (40.7%¹ and 36%²) followed by Kheda (12.4%¹ and 8.4%²), Jamnagar (10.7%¹ and 8.3%²), Mehsana (9.3%¹ and 8.4%²), Amreli (7.4%¹ and 4.9%²), Ahmedabad (3.9%¹ and 11.4%²), Surendranagar (3.9%¹ and 5.1%²), Bhavnagar (2.4%¹ and 8.3%²), Surat (2.3%^{1,2}), Banaskantha (2.2%¹ and 1.9%²), Bharuch (1.3%^{1,2}) and Valsad (1.3%^{1,2}) district, respectively.

517 **Table 6** Aerial extent (ha), district-wise distribution and temporal changes (2023 vs. 1996) of salt-affected soils in Gujarat state

518

SN	Name of the district	Classified extent of salt-affected soils based on the estimates of 2023						Total areas (2023)***	Total areas (1996)**	% of change	Estimates of 1995*		
		Ssa1	Ssa2	Ssa3	Sso1	Sso2	Sso3				Saline*	Sodic*	IRS 1A / 1B*
1	Kachchh	631440.4	119048.5	906654.6	153798.5	48149.4	72512.8	1931604.2	620456	+59.0	436109	17404	607446
2	Banaskantha	47071.8	tr.	315032.0	83780.4	84554.8	tr.	530439.0	295449	+10.5	24289	tr.	32100
3	Mehsana	217771.0	tr.	9599.51	tr.	tr.	tr.	227370.6	244286	-00.7	97936	5820	143116
4	Ahmedabad	143843.8	20281.6	103201.4	271643.6	tr.	tr.	538970.4	278504	+11.7	36283	7086	194234
5	Kheda	tr.	tr.	712.9	115237.0	8113.5	tr.	124063.4	37934	+38.7	126762	11840	143056
6	Vadodara	1291.14	tr.	tr.	86684.3	tr.	tr.	87975.4	3871	+37.8	tr.	950	950
7	Bharuch	161103.3	37456.3	27354.2	95387.9	tr.	tr.	321301.7	62329	+11.6	14259	tr.	14259
8	Surat	28221.2	4797.7	33739.7	194203.0	2758.9	tr.	263720.5	26344	+10.6	26289	tr.	26289
9	Valsad	156.30	290.3	35226.6	51100.9	tr.	tr.	86774.2	14841	+03.2	14252	tr.	14252
10	Surendranagar	54801.8	7022.5	248490.5	303964.8	tr.	tr.	614279.7	233930	+17.1	42500	tr.	87224
11	Rajkot	16171.7	943.5	162106.7	87372.7	tr.	tr.	266594.6	57758	+93.9	5820	tr.	41056
12	Jamnagar	197793.2	116398.0	62850.4	134755.7	tr.	tr.	511797.3	94102	+18.8	121277	tr.	140544
13	Junagarh	88249.7	52145.4	274349.8	tr.	tr.	tr.	414744.9	108432	+13.8	17930	tr.	20456
14	Amreli	12150.0	2291.6	13733.1	50539.0	26718.8	20499.4	125932.0	43898	+36.9	82731	tr.	83361
15	Bhavnagar	212195.8	24575.0	57077.4	60117.9	14514.5	120.9	368601.7	99866	+12.0	26850	tr.	141617
	Total	1812261.3	385250.5	2250128.9	1688585.9	184809.9	93133.1	6414170	2222000		1071287	43100	1689960
	Grand total (ha)												1114387

519 *IRS 1A/1B (1991-92) and ground truth studies [36] and **Landsat TM (1984) on 1:250K [47] ***IRS L3 R2 data (2018-20) on 1:50k scale

520

5.0. Conclusion

A comprehensive database was generated for salt-affected soils on 1:50K integrating IRS LISS III data with ground truth and laboratory analysis of soils for Gujarat state. Barren degraded areas (salt pan and crust) were easily identified using strong reflectance of salts at the soil surface while complex sodic soils were difficult to map due to mixed pixels for the intricately associated soil, crop, and water features. Significant areas of salt-affected soils were distributed along the coastal tracts periodically inundated by saline sea water and also in the arid, semiarid and black soil areas underlain by poor-quality groundwater. Soils were broadly classified as saline and sodic for the management of complex salt-affected soils. Current estimates indicate a significant increase in salt-affected soils (compared to the legacy data) due to repeated soil salinisation in the inhospitable areas such as mud flats/ mangrove swamps and along the creeks in the coastline. Prominent changes in Rajkot (93.98%) and Kachchh (59%) districts indicated the relative expansion of soil salinity in the coastal areas and also in Kheda (38.76%), Vadodara (37.85%) and Amreli (36.91%) districts due to poor quality groundwater used for agriculture. Saline soils were dominating (69%) in coastal region and sodic soils were (31%) confined to the inland plains. Salt-affected soils showed high SAR and ECe in the lower topographic regions, soil salinity was higher at the surface and decreased at the sub- surface depths. The reverse trend (that is higher at sub-surface and lower at surface) exhibited the influence of poor quality (saline/ sodic) groundwater in coarse to medium texture soils. Spatial variability indicated higher ECe, Na⁺, Ca²⁺, and Mg²⁺ ions near the west coast (Kachchh and Kathiwar peninsula) while CO₃²⁻, HCO₃⁻, Cl⁻, and SO₄²⁻ were dominant in the western hills (North Sahyadri) and central Highlands (Aravalli range), respectively. Soil texture was fine in the south and coarse (sandy) in the north and northwest of Gujarat. Such a database can be suitably used for planning management of salt-affected soils in Gujarat and also for similar other regions.

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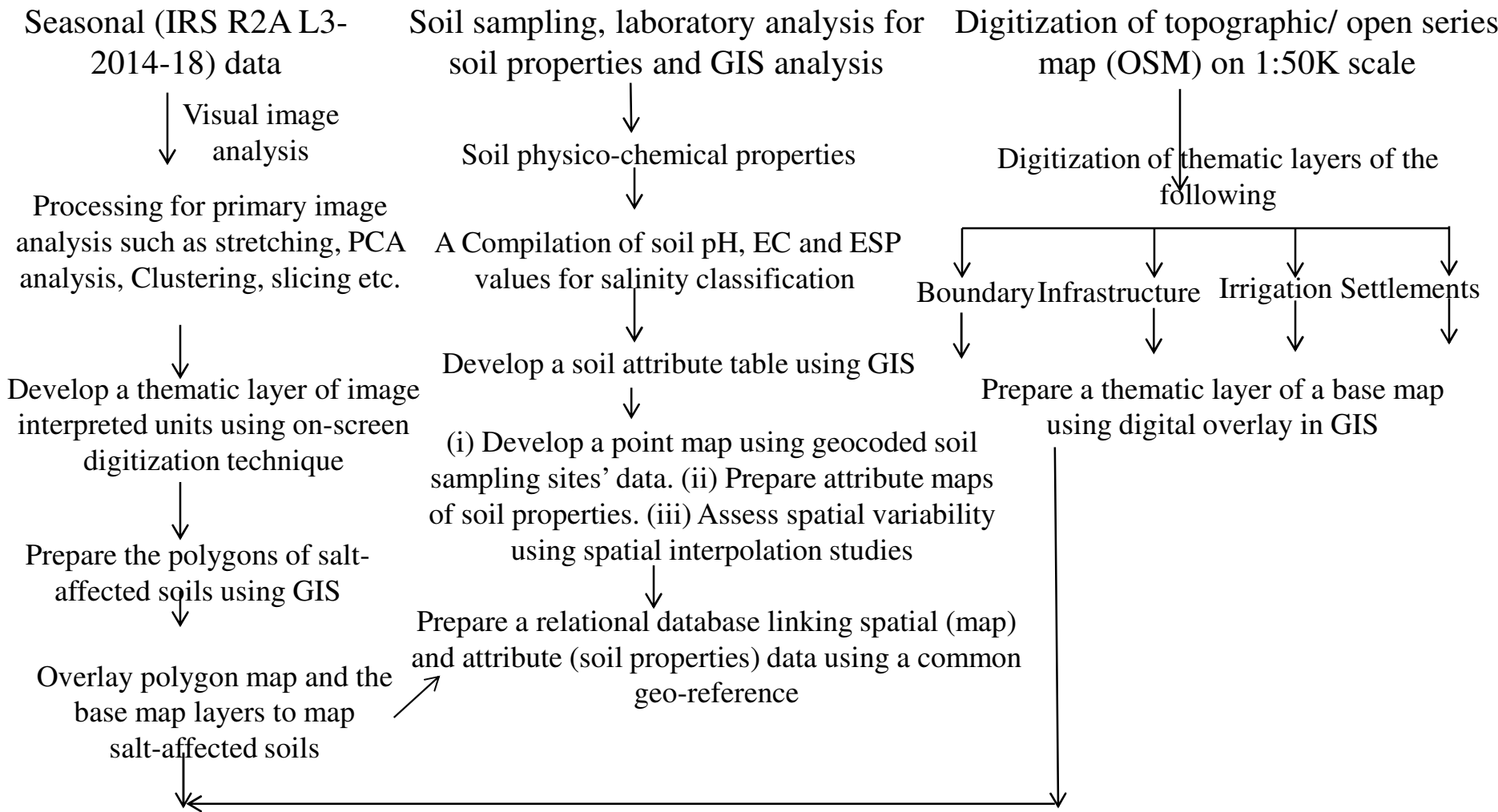


Figure1 Methodology for mapping salt-affected soils in Gujarat state

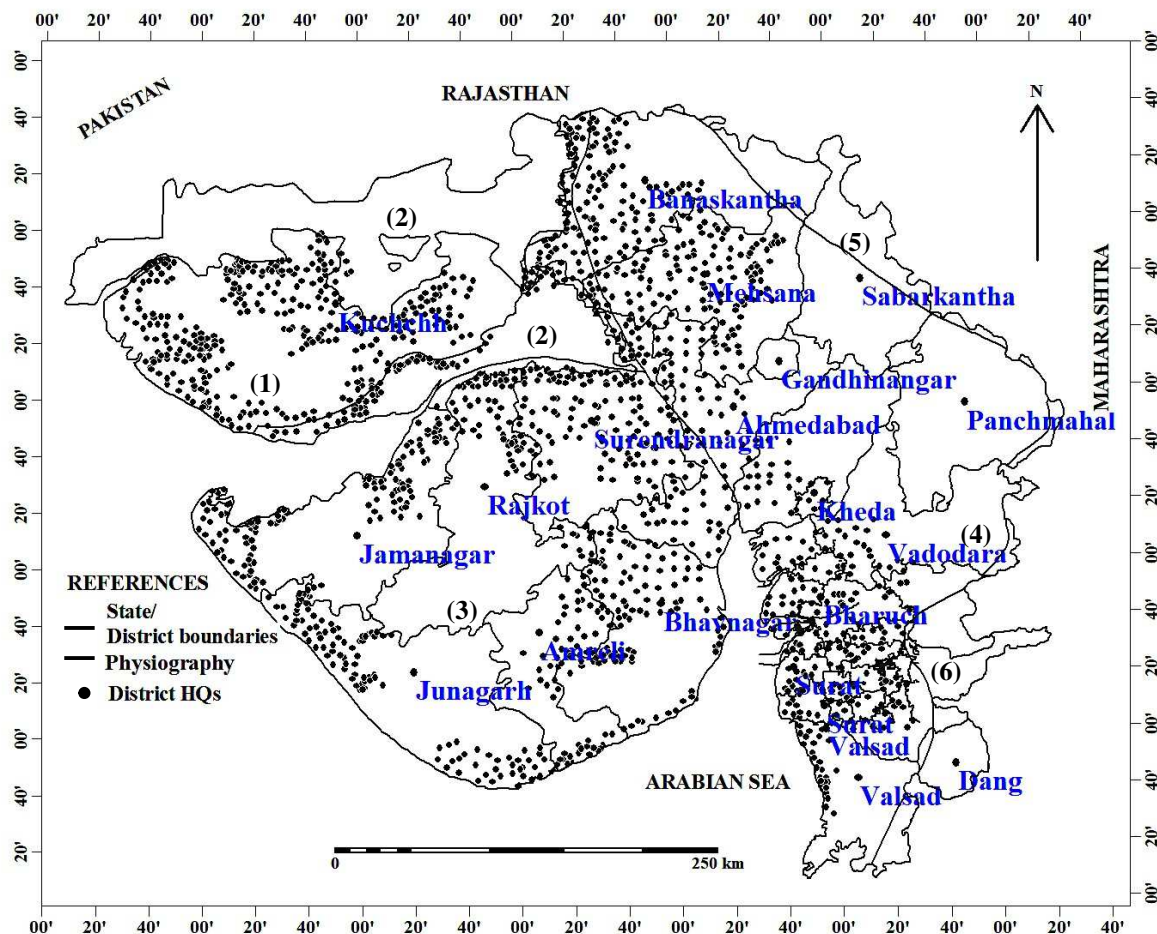


Figure 2 Distribution of soil samples sites in Gujarat state (Legends (Physiography): 1: The West Coast - Kachchh Peninsula, 2: Rann of Kachchh, 3: The West Coast: Kathiwar peninsula, 4: The West Coast: Gujarat Plain, 5: The Central Highlands: Aravalli Range, 6: The Western Hills: North Sahyadri [42])

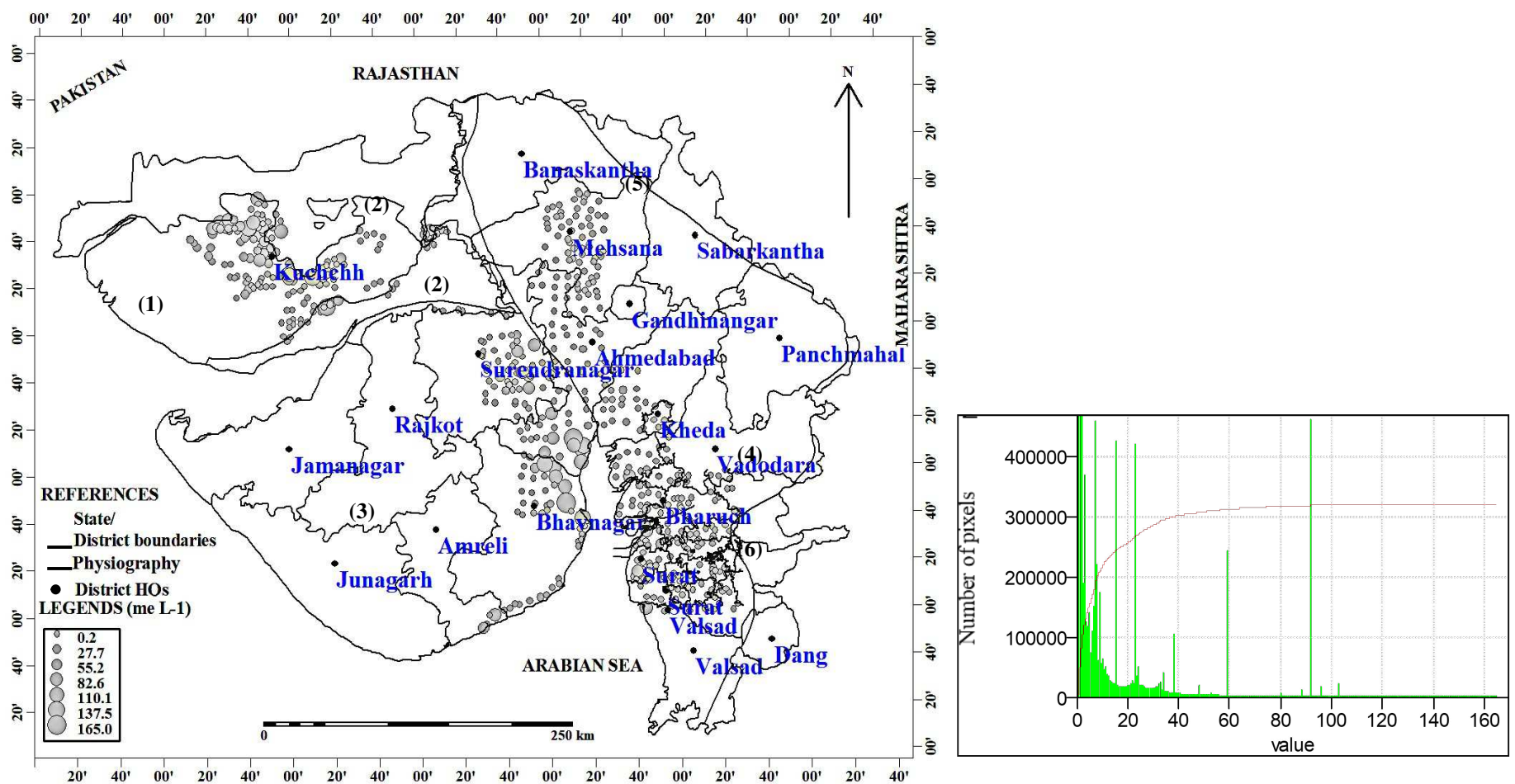
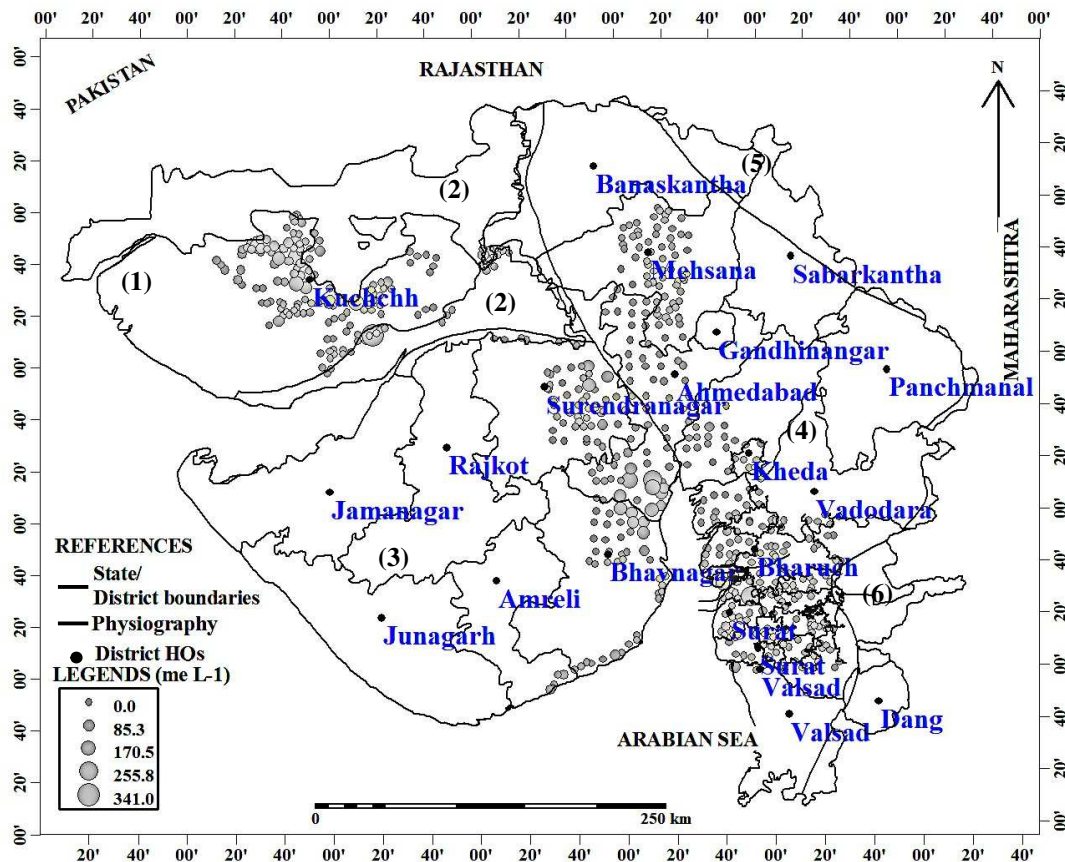
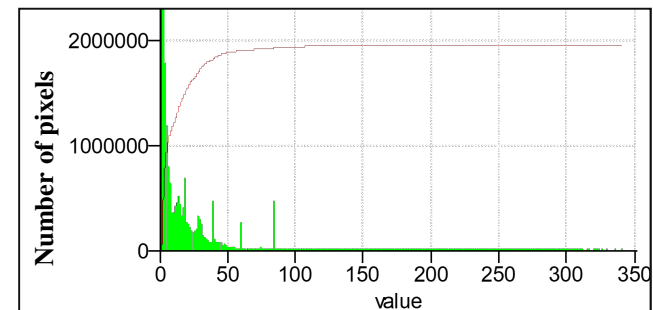


Figure 3 Distribution of ECe values of soil samples in Gujarat state

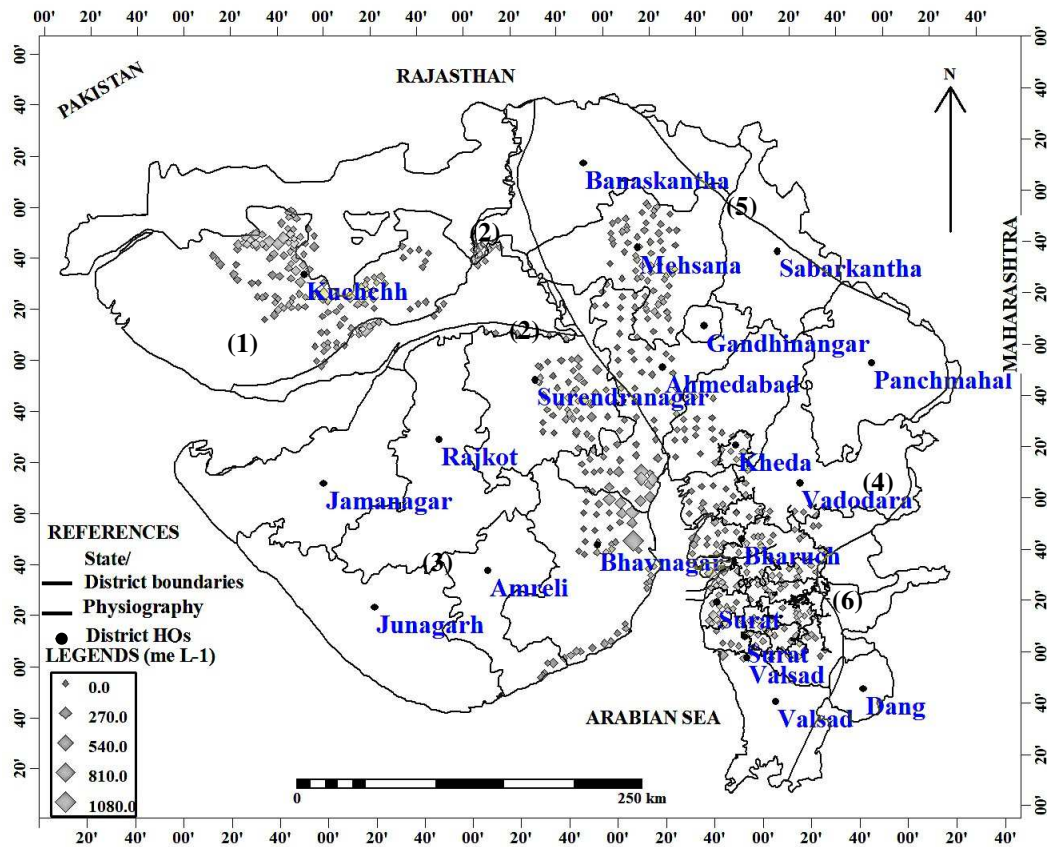


Spatial distribution of Ca^{2+} values (range 0 to 341 me L⁻¹)

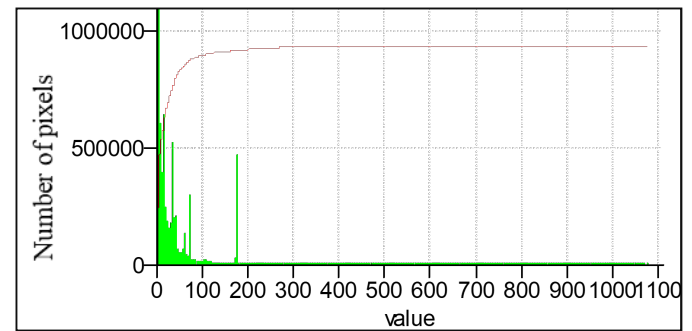


Spatial correlation of Ca^{2+} values:
Histogram analysis (Mean=12.76,
Std. Dev.= 16.30)

Figure 5 Distribution of Ca^{2+} content of soil samples in Gujarat state

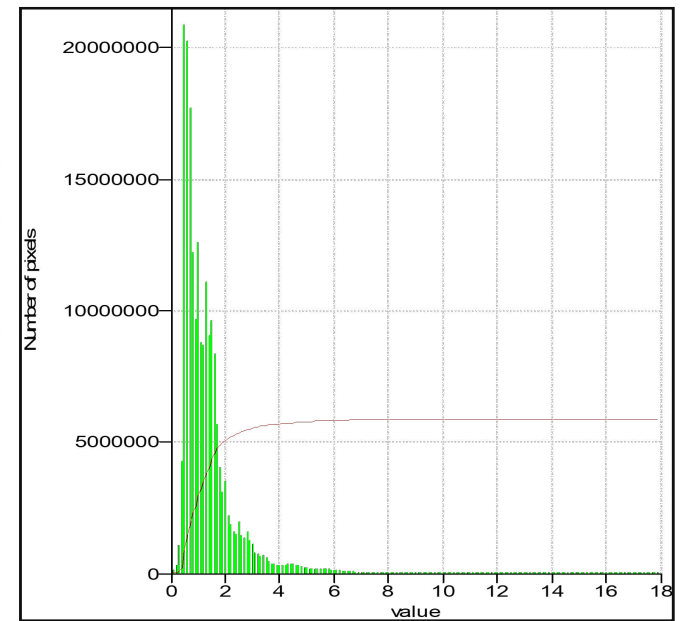
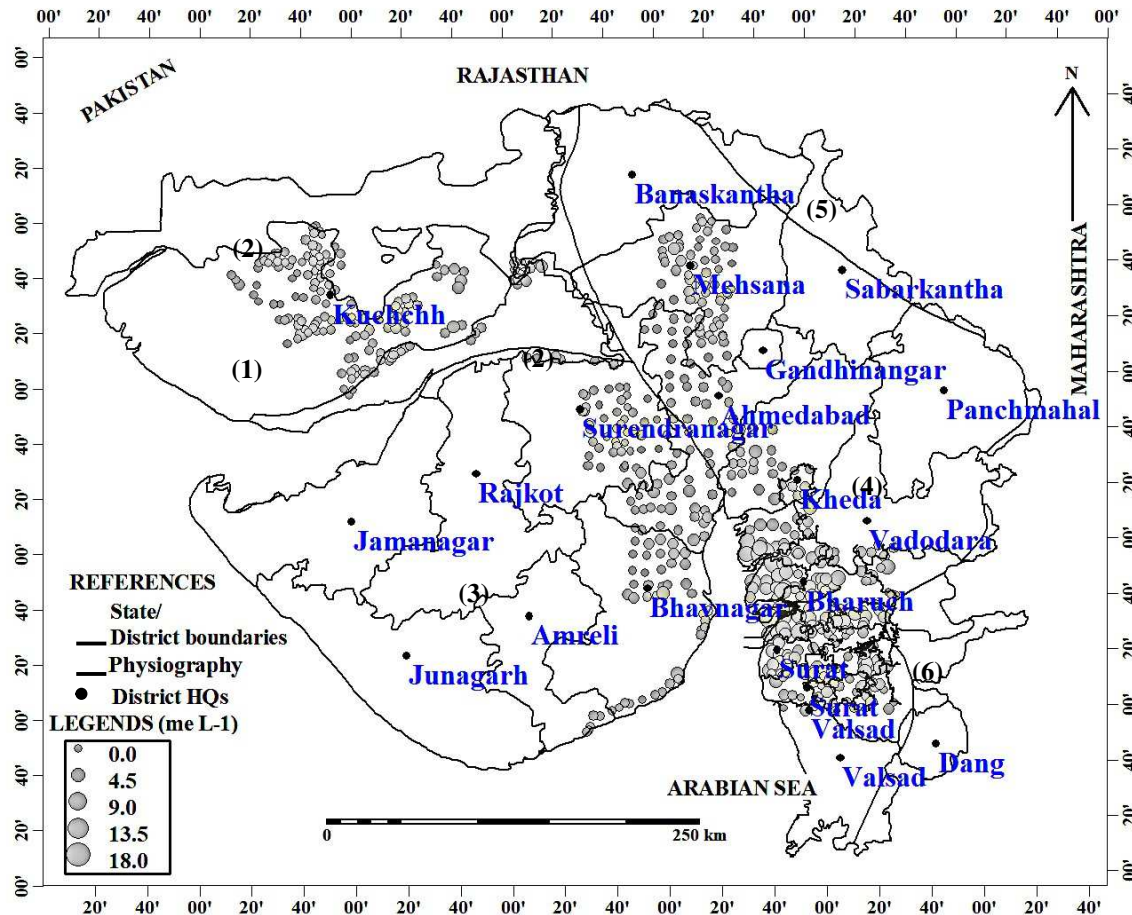


Spatial distribution of Mg^{2+} values (range 0 to 1080 me L⁻¹)



Spatial interpolation of Mg^{2+} values:
Histogram analysis (Mean= 22.69,
Std. Dev. =37.54)

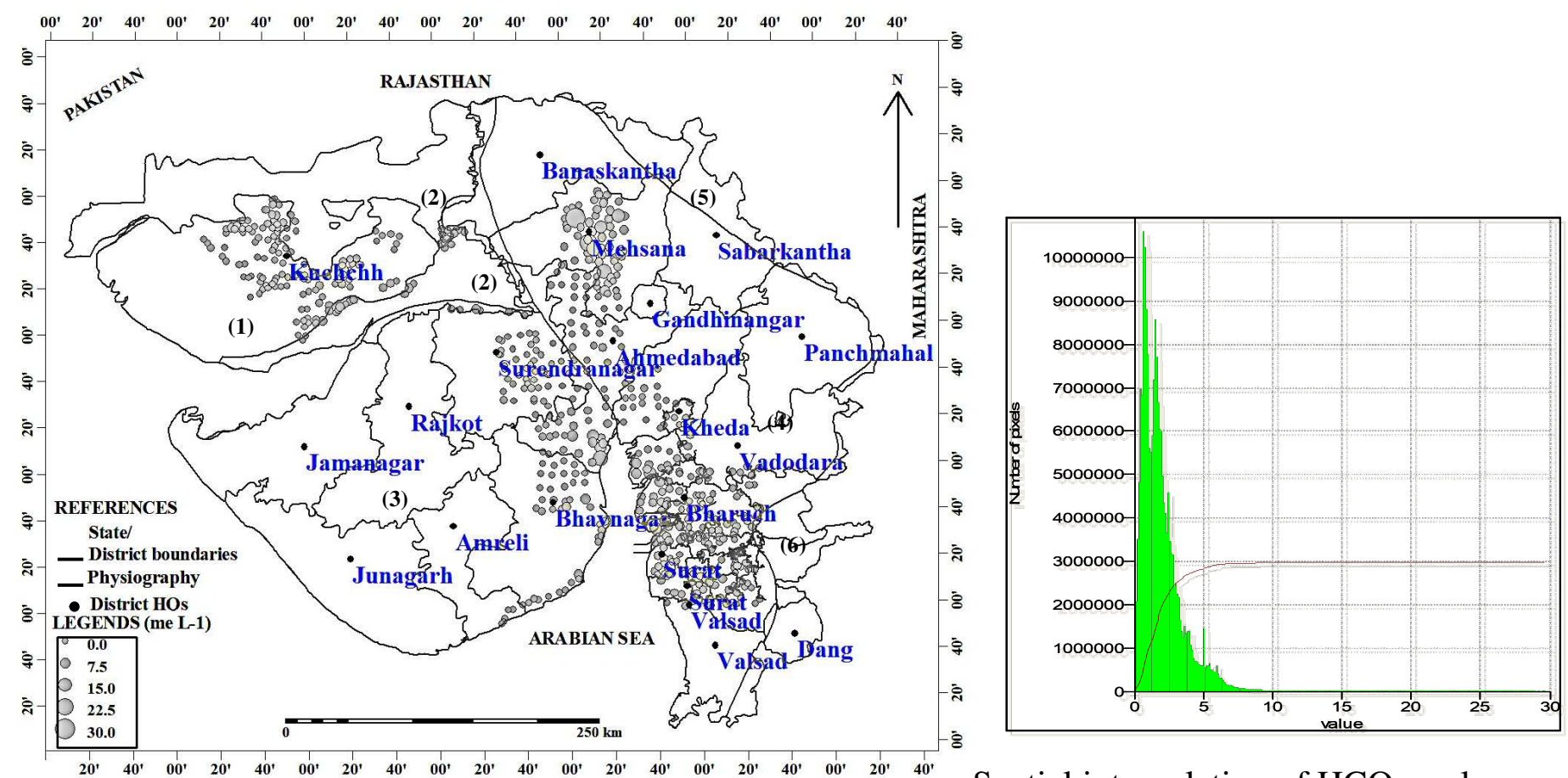
Figure 6 Distribution of Mg^{2+} content of soil samples in Gujarat state



Spatial distribution of CO_3^{2-} values (range 0 to 18 me L⁻¹)

Spatial interpolation of CO_3^{2-} values: Histogram analysis
(Mean=1.30, Std. Dev.= 0.96)

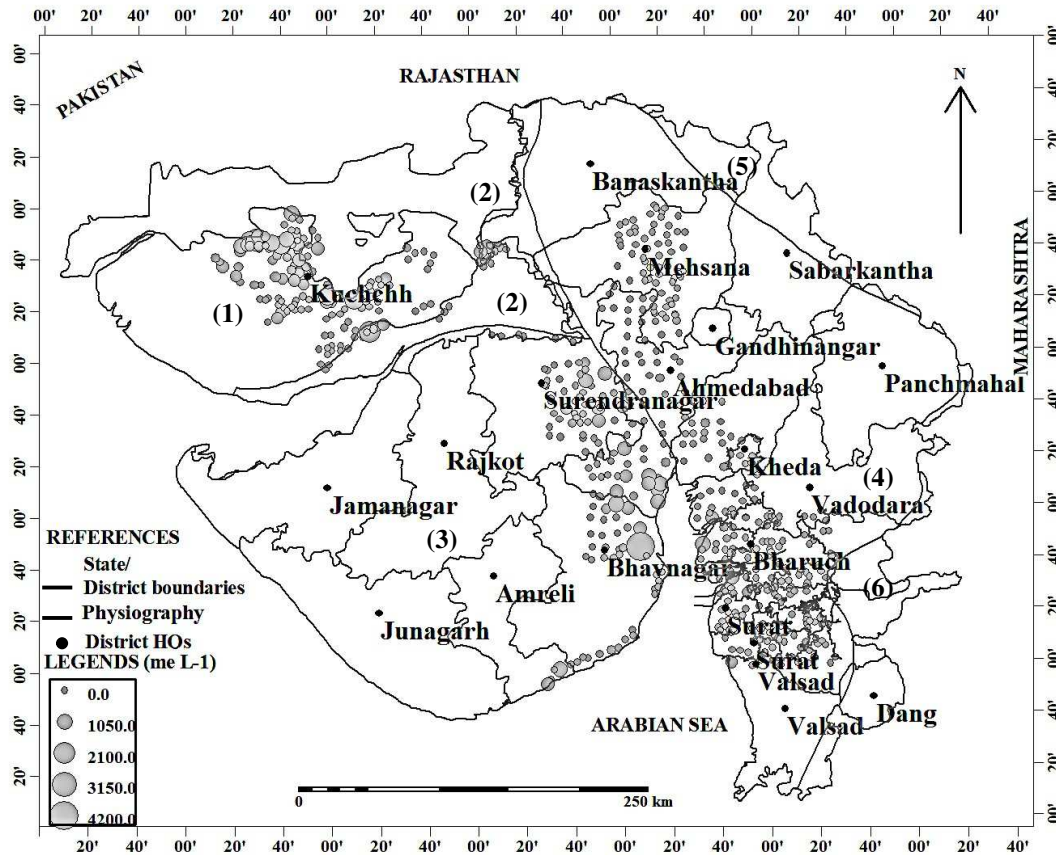
Figure 7 Distribution of CO_3^{2-} content of soil samples in Gujarat state



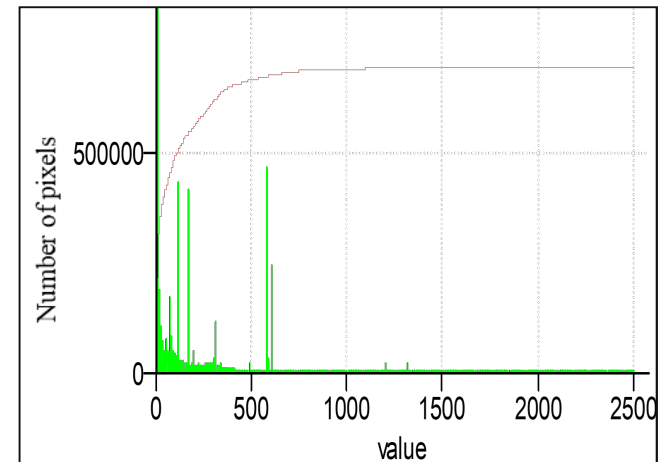
Spatial distribution of HCO_3^- values (range 0 to 30 me L⁻¹)

Spatial interpolation of HCO_3^- values:
Histogram analysis (Mean=1.92, Std.
Dev. =1.44)

Figure 8 Distribution of HCO_3^- content of soil samples in Gujarat state

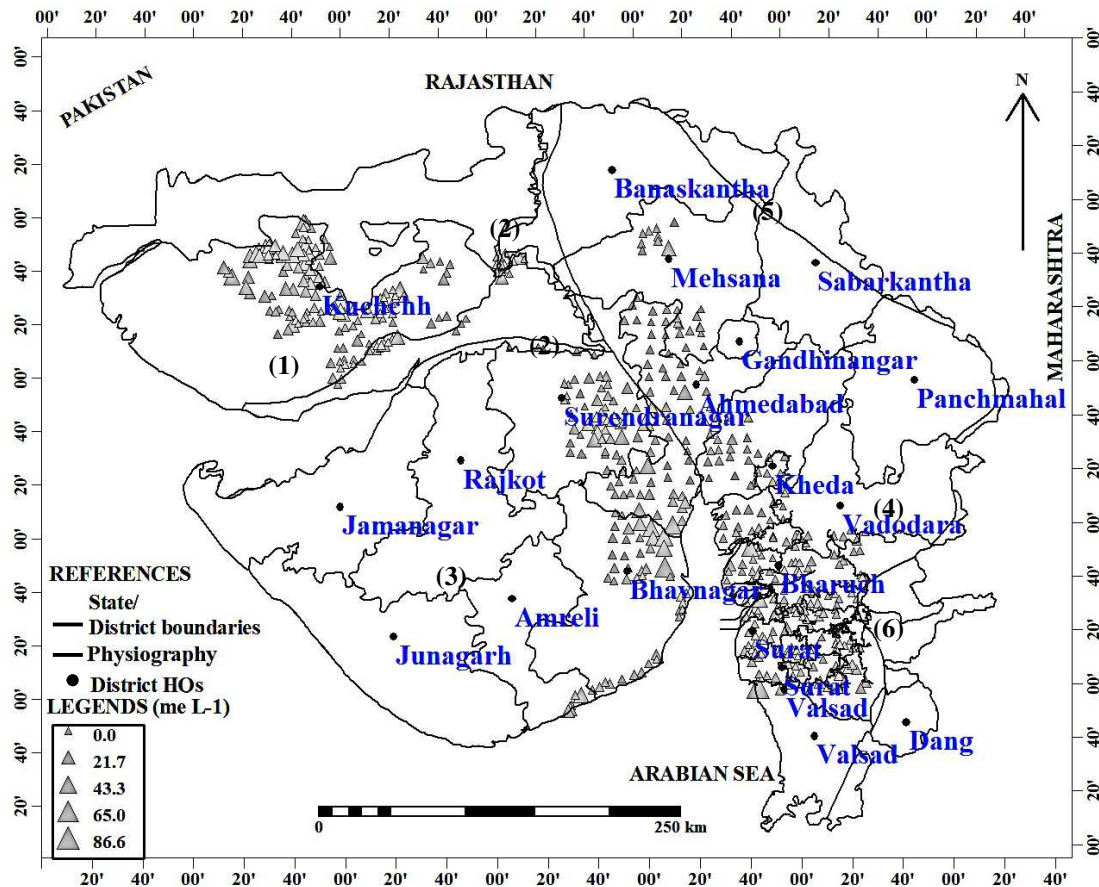


Spatial distribution of Cl⁻ values (range 0 to 4200 me L⁻¹)

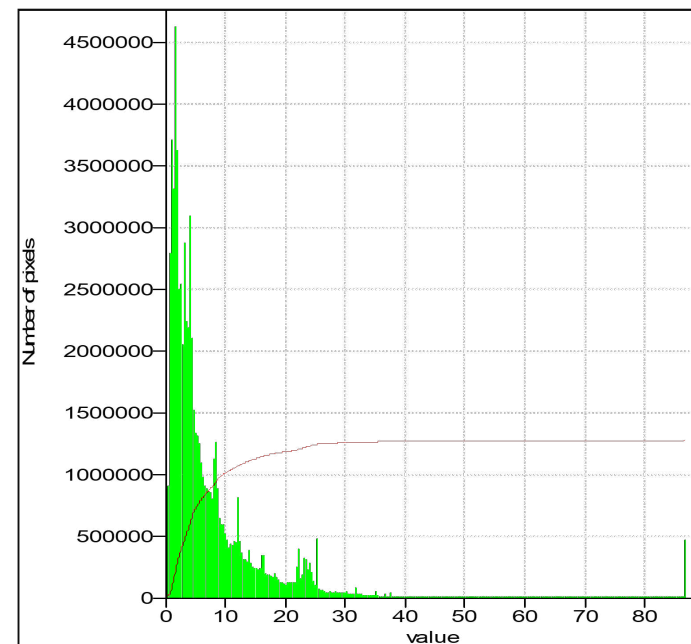


Spatial interpolation of Cl⁻ values:
Histogram analysis (Mean=106.25,
Std. Dev. =169.07)

Figure 9 Distribution of Cl⁻ content of soil samples in Gujarat state

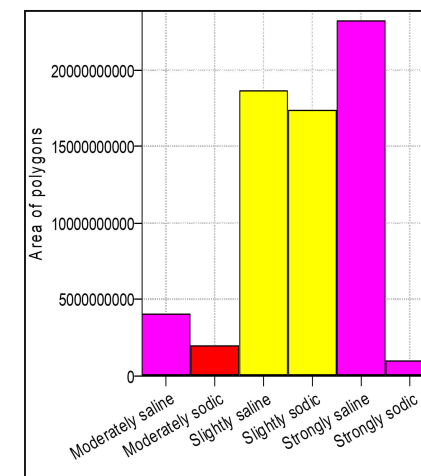
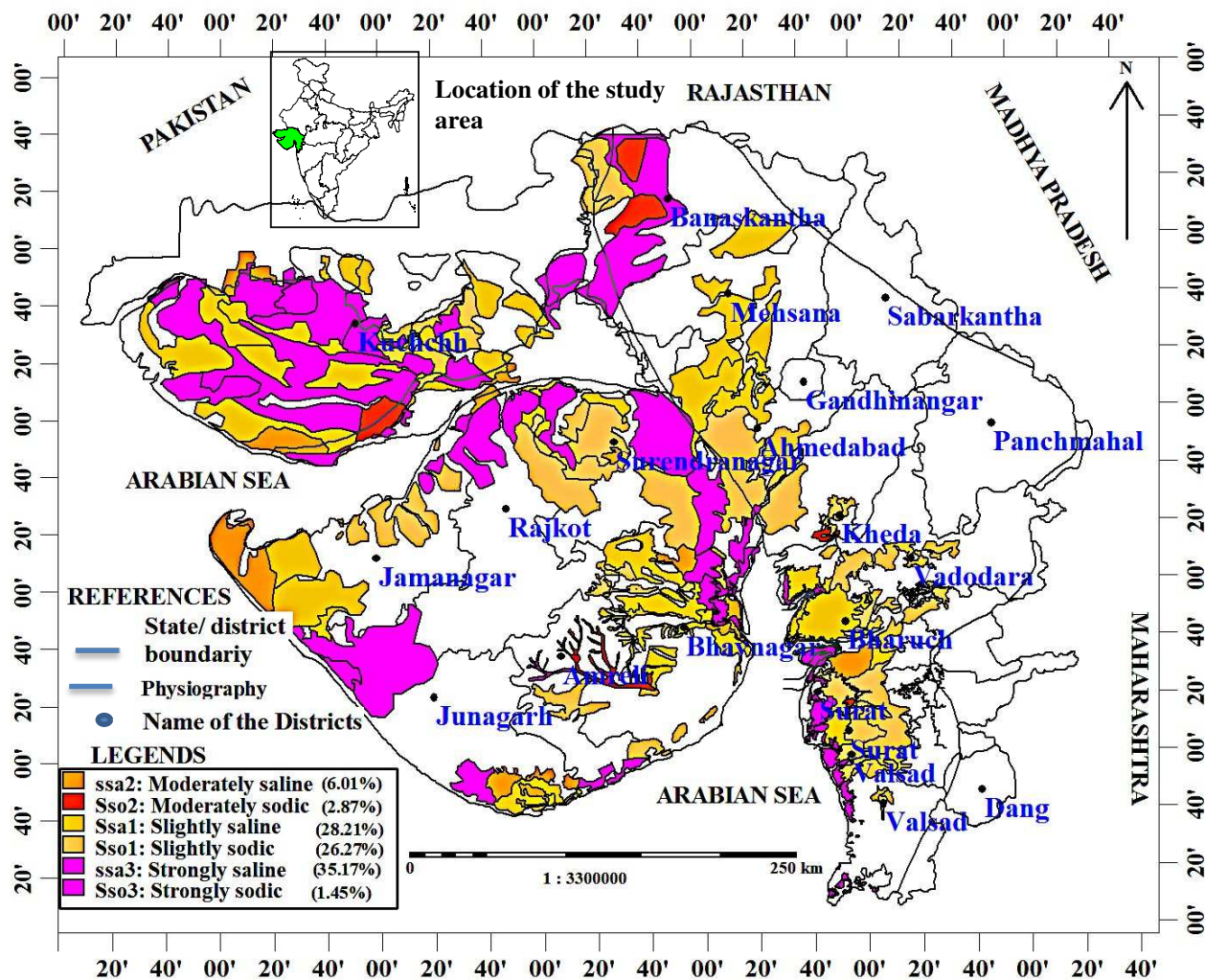


Spatial distribution of SO_4^{2-} values (range 0 to 86.6 me L⁻¹)



Spatial interpolation of SO_4^{2-} values:
Histogram analysis (Mean=7.07, Std.
Dev. =8.23)

Figure 10 Distribution of SO_4^{2-} content of soil samples in Gujarat state



Distribution of salt-affected soils in Gujarat (X axis: Categories of salt-affected soils, Y axis: Area of polygons in meters)

Figure 11 Spatial distribution of salt-affected soils in Gujarat