# Delineation of saline soils in coastal India using satellite remote sensing

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**Characterizing soil salinity at the regional scale remains challenging despite decades of effort in soil mapping. Using satellite remote sensing, an effort has been made to identify the coastal saline soils in India. The study made use of the OLI sensor of the Landsat-8 satellite. The images were downloaded from the USGS EarthExplorer website. For multi-temporal studies, absolute radiometric calibration was done to minimize the impacts of changing atmospheric conditions, solar inclination and sensor view angle. Images were categorized using unsupervised classification, while a ground survey and Google Earth data were used for ground truthing. Three indices, namely normalized difference vegetation index (NDVI), salinity index (SI), and canopy response salinity index (CRSI), were used to identify soil salinity regions. For testing the vegetation index with soil salinity, 192 georeferenced soil samples from the Indian Sundarbans were collected. A relationship was developed between NDVI, SI and square of CRSI (CRSISQR) with $EC_e$ (electrical conductivity of saturation paste extract) and $EC_{1:2}$ (1 : 2; soil : water). For the coastal region, soils with CRSISQR < 0.16 were considered to be influenced by salinity since the relationship between $EC_e$ and CRSISQR had a maximum $R^2$ (0.50). It has been estimated that India has 12.94 lakh ha of saline soil within arable lands in all the coastal districts, and Gujarat (5.28 lakh ha), West Bengal (5.08 lakh ha), and Andhra Pradesh (1.06 lakh ha) were identified as the top three-salinity affected coastal states in the country.**

**Keywords:** Climate change, coastal regions, ground truthing, saline soils, satellite remote sensing.

ALTHOUGH soil salinity is a problem in agricultural areas across the world, there are no directly measured global inventories of it. With a few notable exceptions, all known regional-scale and worldwide soil salinity inventories are rough estimates based on qualitative rather than quantitative data[1,2]. Around the world, one-third of all agricultural areas are becoming saline, and salt-affected soils are causing problems in more than 100 countries[3,4]. According to an IPCC assessment[5], climate change will probably affect all of the main mechanisms for soil salinization, including the accumulation of soluble salts due to a shift in the hydrological balance, sea-salt intrusion and wind-borne salt deposition. It is anticipated that an increase in evapotranspiration rates and changes in precipitation patterns will decrease soil-leaching efficiency, leading to an increase in salt concentrations in topsoil layers[6,7]. Secondary salinization is anticipated to spread due to the expansion of irrigated regions, the increased demand for water under rising global temperature and inefficient drainage/irrigation techniques[8]. Additionally, the problem of seawater-induced soil salinization in coastal areas can worsen by increasing sea levels and the unsustainable use of freshwater supplies from coastal aquifers[7,9]. Along with extreme climatic conditions, natural hazards like cyclones and floods are affecting the natural environment, ultimately increasing the dynamics and vulnerability of the coastal regions[10]. Therefore, a quantitative global-scale analysis that describes the geographical distribution of soil salinity is required.

Since soil salinization is one of the key hazards affecting soil fertility, stability and biodiversity, producers, land and water resource managers, and policymakers need accurate, current and high-resolution assessments of soil salinity at different scales (i.e. field to regional scales)[11,12].

Electrical conductivity (EC) is a measure of salt content in the soil, which is generally estimated in soil–water solution or soil probe denoted as deci-Siemens per metre (dS $m^{-1}$) (ref. 13). However, conventional methods of field surveys and sample analysis are time-consuming, expensive and insufficient to cover enormous areas of land[14]. On the other hand, since the operation of the first Landsat satellites in

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the 1970s, remote sensing has been proven to be a rapid and dependable method for mapping soil properties across many scales, notably at the regional level[15]. From multi- and hyperspectral data, several spectral indices have been developed for monitoring and mapping surface and subsurface soil salinity[8]. For mapping soil salinity, two remote sensing techniques have been developed. The most widely used strategy consists of numerous spatial assessments of surface (bare-) soil reflectance. The other involves indirectly determining the soil's salinity in the root zone by analysing the plant canopy's reflectance. Since 1990, numerous options for tracking and mapping soil salinity have been made possible by multispectral sensors such as Landsat, SPOT, ASTER, IKONOS, MODIS and IRS series[16]. To identify soils affected by salt and waterlogging, Dwivedi and Sreenivas[17] employed LISS-III (linear imaging self-scanner) data from IRS-1C over the Indo-Gangetic Plains. In 2013, Scudiero *et al.*[18] mapped soil salinity for the whole west side of California's San Joaquin Valley using Landsat 7 ETM+ canopy reflectance images (also known as the canopy response salinity index, CRSI) and apparent electrical conductivity ($EC_a$)-directed soil sampling. Based on Landsat data from 1986/87 supported by ground truth, salt-affected soil maps were prepared at 1 : 250,000 scale for 14 states and a Union Territory of India[19]. For the entire country, salt-affected soils were estimated to cover 6.73 m ha, whereas in the coastal regions, salt-affected soils were projected to cover 1.237 m ha. Srinivas *et al.*[20] utilized LISS-III data from the Resourcesat-1/2 satellite acquired during 2015–16 to map the spatial land degradation status of India through visual interpretation and estimated 6.46 m ha as total salt-affected soils. However, district-level information on soil salinity, especially in the coastal regions, remains insufficient despite the dynamic nature of salinity in these areas.

In India, the mapping and characterization of salt-affected soils using conventional and remote sensing methods have been reviewed in detail by Singh *et al.*[21]. Remote sensing techniques could detect salt-affected soils directly from surface encrustation features of salts with varying mineralogy and indirectly by assessing the crop canopy or vegetation condition. However, the majority of the studies dealt with the direct measurement of surface soil salinity. Even though there has been a lot of work done in India to map salt-affected soils, it has only served as an inventory of degraded soils because it has been able to map salinity only on the surface of the soil and not the root zone of agricultural lands.

Recently, several studies have utilized Landsat-8 operational land imager (OLI) data to detect soil salinity. Davis *et al.*[22] compared Landsat-8 OLI and Sentinel-2 Multispectral Instrument (MSI) in identifying soil salinity using soil physio-chemical, spectral, statistical and image analysis techniques in coastal North Carolina, USA. Using an iterative ordinary least squares regression, it was found that the EC of field samples was sensitive to OLI bands 2 and 4 and MSI bands 2 and 4 respectively, suggesting that the two sensors have similar salinity modelling skills. A similar study was done at Urmia Lake in Iran, comparing soil salinity maps produced from Sentinel-2A and Landsat-8 using three different salinity indices and field data[23]. The EC data were correlated with the relevant soil salinity spectral index values obtained from the visible bands of satellite images using multiple and linear regression analysis. The findings showed that the indices obtained from the visible bands of both Sentinel-2A and Landsat-8 OLI provided appropriate estimates of soil salinity.

Even though soil salinity mapping has come a long way in recent years, regional-scale salinity evaluation is still in its infancy[8]. Coastal India suffers from soil salinity due to natural and human-induced activities. Also, there has been no recent regional-scale assessment of coastal soil salinity at district levels. The main objective of this study was to determine the capability of Landsat-8 OLI for mapping soil salinity in coastal India by applying spectral indices coupled with EC measurements of georeferenced soil samples.

## Materials and methods

### *Coastal India*

Coastal India is spread over nine states, two Union Territories (Puducherry and Dadra and Nagar Haveli and Daman and Diu) and two groups of islands (Andaman and Nicobar Islands in the Bay of Bengal and Lakshadweep and Minicoy Islands in the Arabian Sea), covering an area of 3.935 lakh sq. km distributed within 87 districts (Figure 1). The states Gujarat, Maharashtra, Karnataka, Goa and Kerala are located on the west coast of India, which is close to the Arabian Sea and the Indian Ocean, while Tamil Nadu, Andhra Pradesh, Odisha and West Bengal are located on the east coast, which is close to the Bay of Bengal and the Indian Ocean. India's coastal regions are blessed with a diversity of soil types. The soils vary from alluvial to lateritic and coarse sand to clay in texture, non-saline to highly saline, highly acidic to alkaline, highly variable in organic matter content, and well-drained to poorly drained with deficiency or toxicity of some nutrient elements[24]. More than six soil orders (Entisols and Inceptisols in West Bengal, Odisha, Kerala, Karnataka, Andhra Pradesh and Goa, Alfisols in Tamil Nadu and Maharashtra, Aridisols and Inceptisols in Gujarat, Mollisols and Entisols in Andaman, and Lakshadweep) are dominant in the coastal areas of India.

Climate-wise, the eastern and southwestern coastal regions experience significant rainfall (1300–2850 mm annually), while north Maharashtra and Gujarat experience low rainfall (450–1000 mm annually)[25]. These soils have been created from inland alluvial materials, coastal basalt deposits, severely weathered lateritic materials, etc. depending on the kind of formation. Therefore, they differ significantly in terms of texture, stratification and water permeability.

The issue with soil management includes increased salinity, waterlogging and drainage congestion. Localized problems with acid saline soils are also present in Kerala, the Sundarbans in West Bengal, and the Andaman Islands, demonstrating high acidity from sulphate salts such as pyrite and jarosite parent minerals. In the coastal regions, soil salinity changes seasonally. Due to the upward capillary migration of salty groundwater, salinity of the soil gradually increases after the rainy season until the start of the following monsoon season. These salts are washed and leached from the soil by rainwater, and so the majority of lands become non-saline during the rainy season.

Coastal regions are frequently inundated by saline seawater and submerged for a prolonged period. Mangrove vegetation is common in the regions. The arable cropping is limited due to the heavy textured soil, tropical climate and poor-quality groundwater. Rice is the most suitable crop in coastal India. Other than rice, cotton, sorghum, bajra, groundnut, pulses, vegetables, and plantation and fruit crops grow in limited areas of favourable land, climate and water.

## Data and methods

### *Landsat images*

Landsat-8, the latest available Landsat OLI imagery, was used for the study. In comparison with the previous Landsat series, Landsat-8 data are regarded as superior in many aspects, including higher radiometric and geometric resolution, better acquisition, and more spectral bands. These capabilities have enhanced the scientific applications of Landsat, especially for monitoring and characterizing natural and human-induced land-use/land-cover changes at the global scale[26]. Cloud cover is a consistent problem in all tropical regions. As this study aimed to delineate the salt-affected areas, the images need to be totally cloudless over the area of interest. These cloudless images were downloaded from the United States Geological Survey (USGS) EarthExplorer website, where archived satellite image data are available (https://earthexplorer.usgs.gov/). Basic georeferencing for Landsat-8 imagery is provided by USGS, and the study area was extracted using a district boundary map. In this study, all geographical datasets were projected to the Universal Transverse Mercator (UTM) projection system with the zone 42N, 43N, 44N and 45N World Geodetic System (WGS-1984) datum. For multi-temporal experiments, absolute radiometric calibration was done to minimize the impacts of changing atmospheric conditions, solar inclination and sensor view angle. A total of 63 scenes of Landsat-8 OLI from the dry season (February–May) of 2019–20 were downloaded, georeferenced and converted to spectral reflectance. ERDAS software was used for unsupervised classification to classify the images (version 2015). Band combination or layer stacking, geo-referencing, masking and sub-setting or cutting the area of interest were all done using Arc-GIS (10.5) software. Based on our expertise and the available auxiliary data of the ground survey, including Google Earth, identified a cluster of homogenous pixels that represented a waterbody, crop areas, fallow, forest cover and other related elements. After being initially categorized into 150 classes, the images were recoded to provide 5–6 broad land-use/land-cover classes.

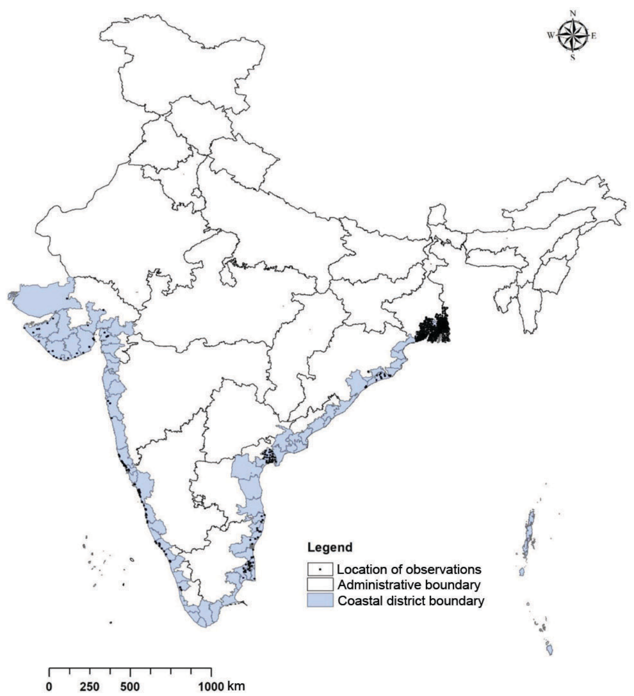



**Figure 1.** Coastal India demarcated with district boundaries and the location of observation points within each state.

To identify the saline areas, agricultural land and bare soil/fallow land were taken from each classified image. In the Indian Sundarbans regions in North 24 Parganas and South 24 Parganas districts of West Bengal, farmers also practice fishery followed by rice cultivation, and these areas were also extracted for delineating saline soils. Three indices, viz. normalized difference vegetation index (NDVI)[27], salinity index (SI)[28] and canopy response salinity index (CRSI)[18] were used in this study because of their past performances and popularity[18].

$$\mathrm{NDVI} = \frac{(\mathrm{NIR} - \mathrm{R})}{(\mathrm{NIR} + \mathrm{R})},$$

$$\mathrm{SI} = \sqrt{(\mathrm{G} \times \mathrm{R})},$$

$$\mathrm{CRSI} = \sqrt{\frac{(\mathrm{NIR} \times \mathrm{R}) - (\mathrm{G} \times \mathrm{B})}{(\mathrm{NIR} \times \mathrm{R}) + (\mathrm{G} \times \mathrm{B})}},$$

where B, G, R and NIR represent blue, green, red and near-infrared respectively, corresponding to bands 2, 3, 4 and 5 of Landsat-8 OLI.

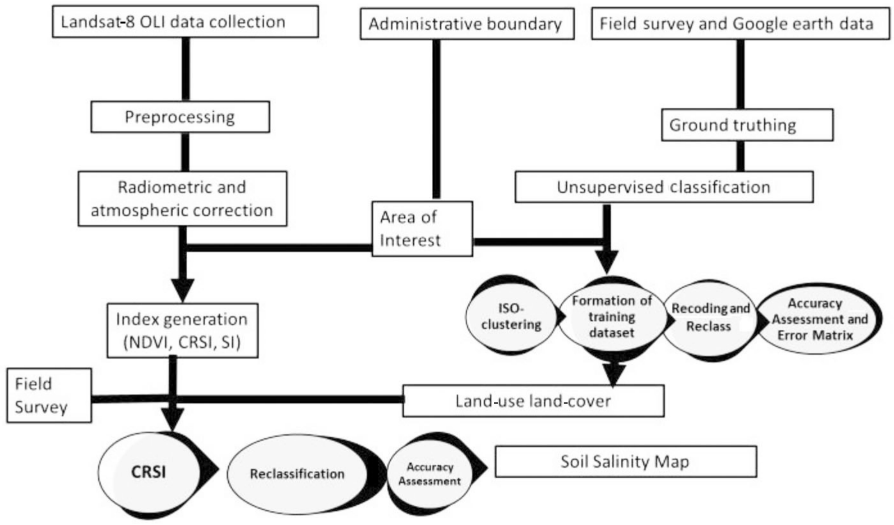



**Figure 2.** Flowchart of the methodology used for delineating coastal saline soils of India.

NDVI is a popular index utilized in many remote sensing applications[29,30]. Additionally, SI has been proven to help forecast soil salinity and sodicity[28,31]. CRSI was developed to capture the abrupt change in reflectance between red and NIR wavelengths, as well as the small peak of reflectance that is generally seen in the 400–500 nm wavelength range. This index was developed empirically; it is not connected to any physiological aspect of plants but to overall plant health[18].

Higher NDVI values typically indicate healthy vegetation conditions unaffected by soil salinity. Lower NDVI values could indicate salinity where there would be a loss of vegetation, an increase in soil salinity, and consequently, changes in spectral behaviour compared to non-saline soils. SI has a direct relationship with soil EC, whereas CRSI has an inverse relationship with soil salinity similar to NDVI.

## *Field sampling for ground-truth datasets*

A total of 192 georeferenced soil samples were collected from the top 20 cm depth of fallow land from February to May 2019. A portable GPS instrument (GeoXT model, Trimble Navigation Ltd, Sunnyvale, CA, USA), with positioning accuracy <1 m was employed to record the geographic positions. Samples were taken from the Sundarbans in coastal West Bengal during the dry season when maximum salt built-up exists on the topsoil. Soil samples were taken to the laboratory to measure their EC ($EC_e$, dS $m^{-1}$) and pH values in a saturation paste extract of soil–water suspension. The $EC_e$ measurements were used as a ground-truth dataset for soil salinity. The soil was also analysed for soil texture, EC (1 : 2 soil-water suspension; $EC_{1:2}$), and soil organic carbon (SOC) content. The respective spectral indices were extracted from the collected soil samples to establish a relationship between field observations and the indices. Linear regression analyses were used to correlate remote sensing data with field measurements.

## *Accuracy assessment*

Following the land-use/land-cover classification, accuracy assessment and kappa coefficient estimation were done using ArcGIS (10.5 version) software. The accuracy assessment of each classified image was performed with ground-truth data. Training points were generated based on the ground survey as well as Google Earth data as a reference to check the classification quality. Researchers nowadays improve land-cover classification accuracy by integrating free and publicly available high-resolution Google Earth images with Landsat OLI or ETM+ imagery, particularly in areas which are difficult to access[10,32,33]. Accuracy was quantified by developing a confusion matrix for each classified image and computing the corresponding user's accuracy, producer's accuracy, overall accuracy and the kappa coefficient of agreement. A similar accuracy assessment was carried out for soil salinity maps. For the accuracy assessment of saline soils of coastal India, around 832 soil sampling points collected by ICAR-Central Soil Salinity Research Institute (ICAR-CSSRI), Regional Research Station (RRS), Canning Town, West Bengal; ICAR-Central Coastal Agricultural Research Institute (ICAR-CCARI), Goa; University of Agricultural and Horticultural Sciences (UAHS), Shivamogga, and University of Agricultural Sciences (UAS), Dharwad and Acharya N. G. Ranga Agricultural University (ANGRAU), Bapatla, Andhra Pradesh, were used in this study (Figure 1). Additionally, a wide range of secondary data from the published literature was utilized to supplement the sampling locations to accurately assess the salinity maps[34–40]. Figure 2 presents the flowchart

**Table 1.** Characteristics of soils collected from Sunderbans in coastal West Bengal, India

| Parameters | Maximum | Minimum | Average | Standard deviation | Coefficient of variation (CV) |
|---|---|---|---|---|---|
| pH (1 : 2) | 8.17 | 3.96 | 5.72 | 0.903 | 15.79 |
| $EC_{1:2}$ (dS/m) | 13.85 | 0.103 | 1.52 | 1.68 | 110.68 |
| Organic C (%) | 1.25 | 0.224 | 0.791 | 0.253 | 32.06 |
| pHe | 8.69 | 3.6 | 6.78 | 0.86 | 12.7 |
| $EC_e$ (dS/m) | 36.34 | 0.273 | 4.26 | 4.66 | 109.4 |
| % Silt | 50.4 | 6.4 | 26.2 | 5.6 | 21.4 |
| % Clay | 63.4 | 21.8 | 49.1 | 8.01 | 16.3 |
| % Sand | 71.8 | 8.7 | 24.7 | 10.2 | 41.2 |

**Table 2.** Correlation matrix of the Landsat-8 spectral band with soil salinity

| Landsat-8 spectral bands | $EC_e$ | $EC_{1:2}$ |
|---|---|---|
| B2_Blue | 0.305* | 0.306* |
| B3_Green | 0.265* | 0.280* |
| B4_Red | 0.134* | 0.167* |
| B5_NIR | –0.455* | –0.427* |
| B6_SWIR-I | –0.301* | –0.260* |
| B7_SWIR-II | –0.235* | –0.194* |

*Correlation is significant at the 0.01 level.

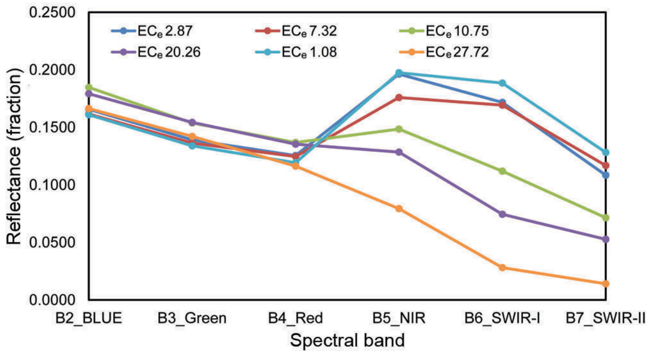



**Figure 3.** Spectral reflectance curves of different soil salinity levels (measured as electrical conductivity (EC) of salutation paste extract, $EC_e$) for Landsat-8 OLI.

of the methodology used for delineating saline soils of coastal India.

## Results and discussion

### *Soil properties*

Table 1 presents the maximum, minimum, mean, and coefficient of variation (CV) values for each soil parameter. Out of 192 soil samples, 153 were clayey in texture. The other four textural classes were clay loam, sandy clay, silty clay and sandy clay loam. On average, the entire Sundarbans region had heavy textured soil with clay, silt and sand content of 49%, 26%, and 25% respectively. Soil pH varied from acidic to neutral. About 21% of samples had pH < 5, indicating the presence of acid sulphate soils in the region. Only one sample recorded a pH >8. Out of 192 samples, 22, 69, and 101 samples had low (<0.5%), medium (0.51–0.75%), and high (>0.75%) SOC contents respectively. Around 22% of the samples analysed had more than 1% SOC. Overall, 87, 68, 25 and 12 samples had $EC_{1:2}$ <1, 1–2, 2–4, and >4 dS $m^{-1}$ respectively. On the other hand, 58, 66, 46 and 22 samples had $EC_e$ <2, 2–4, 4–8 and >8 dS $m^{-1}$ respectively. The spectral band value for each sampling point was extracted, and a correlation matrix was generated between $EC_e$ and $EC_{1:2}$ versus bands 2, 3, 4, 5, 6 and 7 of Landsat-8 OLI (Table 2). Bands B2 (blue), B3 (green), and B4 (red) showed positive correlation with salinity, while bands B5 (NIR), B6 (shortwave infrared 1) and Band B7 (shortwave infrared 2) showed negative $r$ values.

Figure 3 shows the spectral response patterns for soils under different salinity levels. Soils with higher $EC_e$ reflect more incident light energy in the visible spectrum (bands 2, 3 and 4) than soils with lower salinity levels, whereas it is the reverse for bands 5, 6 and 7. This helps in differentiating salt-affected soils from normal soils and vegetation[41]. Figure 4 illustrates the relationship of the three spectral indices, i.e. NDVI, SI and CRSI for Landsat-8 with $EC_e$ and $EC_{1:2}$. When the spectral indices for CRSI were determined in many sampling points; the computed results were imaginary. Thus, instead of CRSI, we used the square value of CRSI (CRSISQR) for each sampling point to establish a relationship with salinity. As EC increased, SI also increased whereas, there was an inverse relationship between NDVI, CRSISQR and $EC_e$, $EC_{1:2}$ respectively. The highest $R^2$ (0.50) was observed between $EC_e$ and CRSISQR. Based on the regression equation (Figure 4), a CRSISQR value <0.16 corresponding to $EC_e$ > 2 dS $m^{-1}$ was considered indicative of saline soils in the coastal regions. We classified $EC_e$ < 2 dS $m^{-1}$ as non-saline, $EC_e$ 2–4 dS $m^{-1}$ as slightly saline and $EC_e$ > 4 dS $m^{-1}$ as saline based on FAO reports[42,43] with corresponding CRSISQR values >0.16, 0.12–0.16 and <0.12 respectively.

### *Classification accuracy*

Figure 5 *a–j* depicts the land-use/land-cover and soil salinity maps of coastal regions in India comprising nine states and two Union Territories, as well as the Andaman

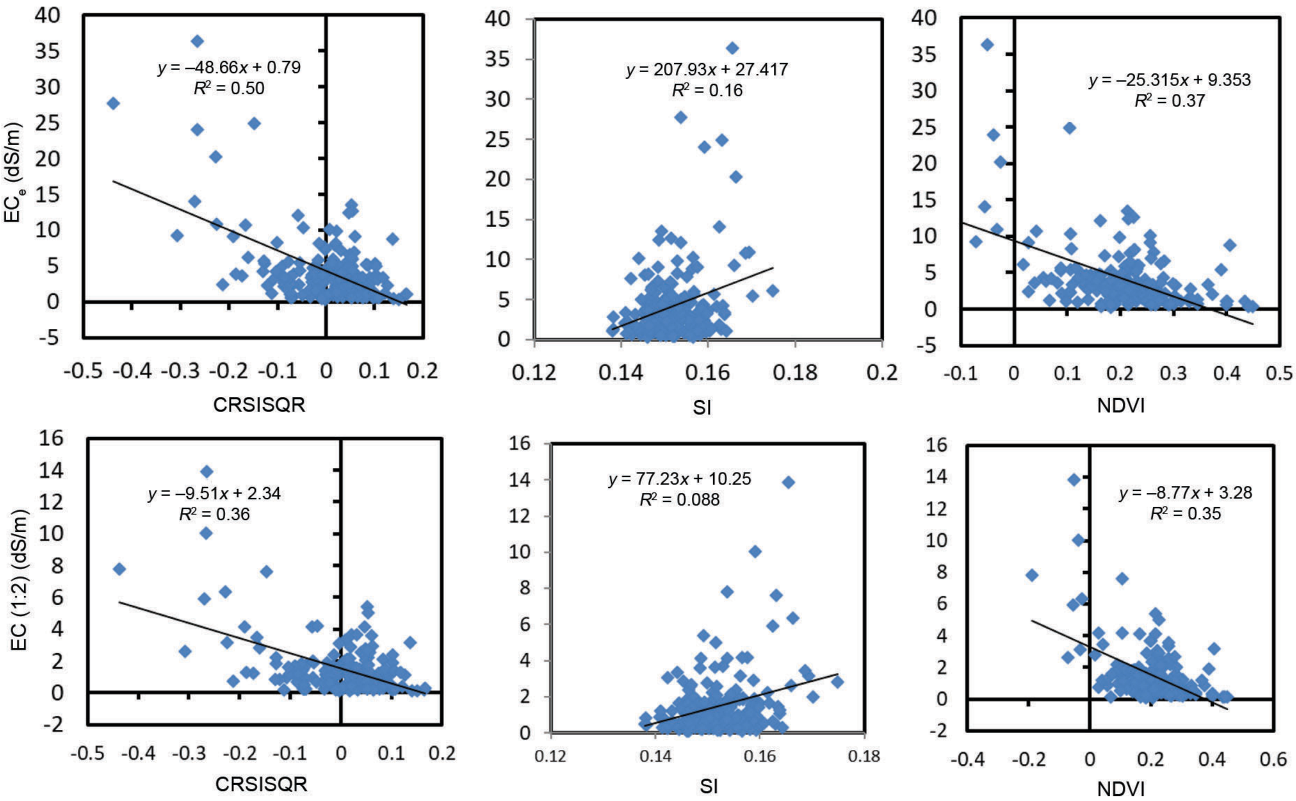



**Figure 4.** Relationship between soil salinity ($EC_e$ and $EC_{1:2}$ soil–water system) and the three spectral indices, viz. CRSISQR (square of canopy response salinity index); SI (salinity index) and NDVI (normalized difference vegetation index).

and Nicobar Islands. We checked the classification results against predefined training points generated using the ground survey as well as Google Earth data. Table 3 shows the classification accuracy of different land-use classes. Across the states, overall accuracy ranged from 0.85 to 0.95, with kappa statistics of 0.82–0.92. User's and producer's accuracy values of individual classes were consistently high, ranging from 0.70 to 1.00 and 0.73 to 1.00 respectively. Individual state salinity maps were merged through mosaicking to accurately assess soil salinity maps. The salinity values of observation points were grouped into non-saline ($EC_e < 2$ dS $m^{-1}$), slightly saline ($EC_e$ 2–4 dS $m^{-1}$) and saline ($EC_e > 4$ dS $m^{-1}$) for accuracy assessment. Results showed an overall accuracy of 0.87 with a kappa coefficient of 0.71. The producer's accuracy varied between 0.74 and 0.93, while the user's accuracy varied between 0.71 and 0.90. Overall classification accuracy levels, and the kappa coefficient indicated that the land-use/land-cover and salinity classes were accurate and consistent for quantitative analysis.

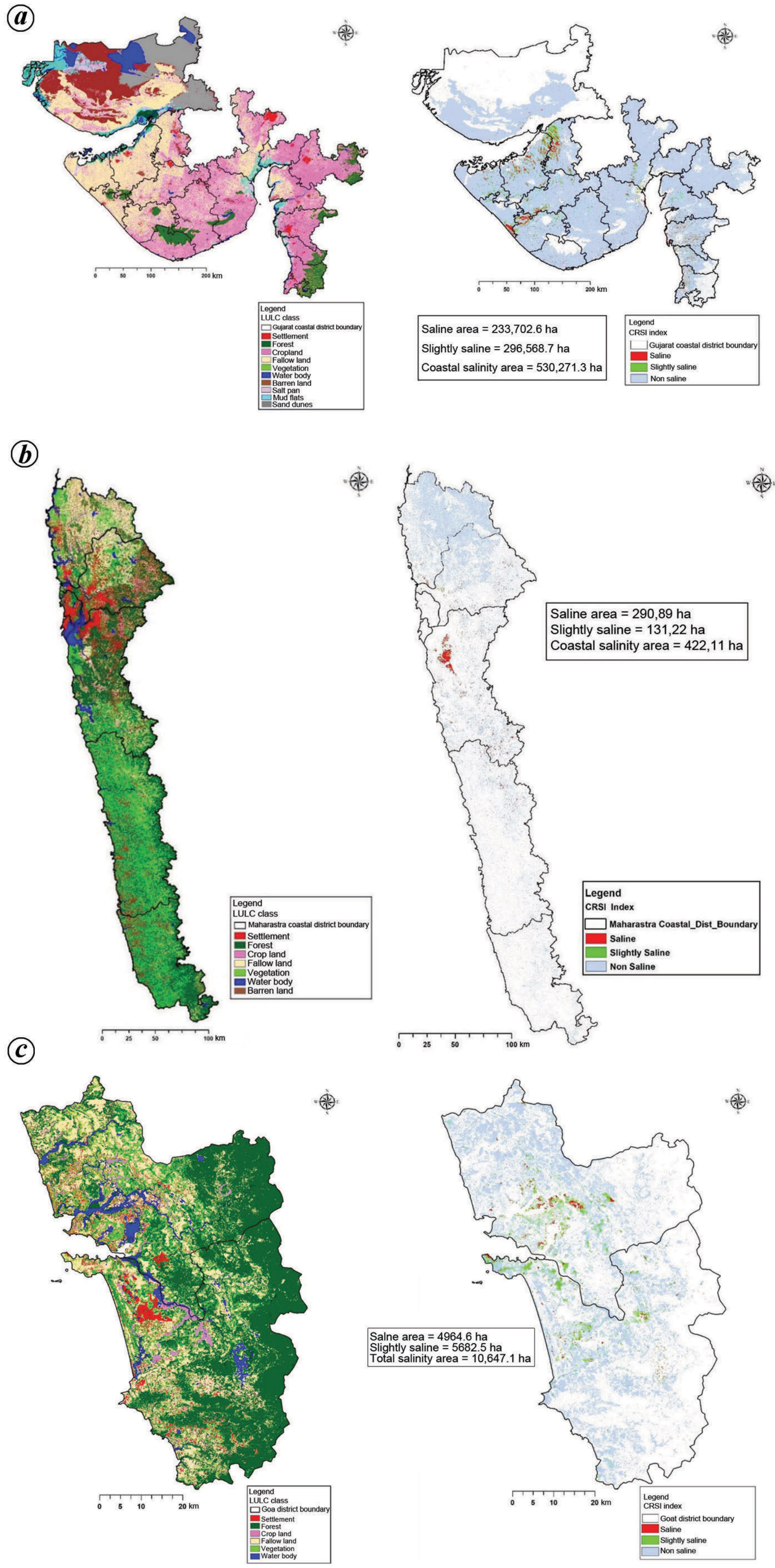
## *State-wise distribution of coastal salt-affected soils*

For micro-level planning in salinity mitigation, the extent and distribution of saline soils at the district level in each coastal state were estimated.

### *West coast*

*Gujarat and Dadra and Nagar Haveli and Daman and Diu (DNHDD):* In India, the longest coastline is in Gujarat, which falls in the region of Kathiawar. The coastline of this state is 1859 km long and is surrounded by the Arabian Sea. Figure 5 *a* shows the land-use/land-cover map of Gujarat and DNHDD. The salt pan covers an area of 1992.6 sq. km, whereas crop and fallow land occupy 59.8% of the area. This state has a maximum saline soil of 527,952 ha, with around 40% area of the total coastal saline soils of India. The highest coastal saline soils are confined in Jamnagar district (18.9%), followed by Morbi (13.9%), Junagarh (10.9%), Rajkot (8.2%), Surat (7.6%), Bhavnagar (5.8%) and Devbhumi Dwarka (5.6%; Table 4). These seven districts occupy 70.8% of the coastal saline soils in the state. In this study, an increase of 27.6% in area has been recorded compared to an earlier estimate of 413,868 ha salt-affected soils in coastal Gujarat by Mandal *et al.*[19]. Around 2319 ha salt-affected soils were estimated in Dadra and Nagar Haveli and Daman and Diu.

*Maharashtra:* This state has a coastline of 707 km known as the Konkan coast. It is bordered in the east by the Western Ghats mountain range, west by the Arabian Sea, north by the Daman Ganga river, and south by the Gangavalli river. The districts of Mumbai, Thane, Raigad, Ratnagiri,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0 50 100 200 km
Legend
LULC class
Gujarat coastal district boundary
Settlement
Forest
Cropland
Fallow land
Vegetation
Water body
Barren land
Salt pan
Mud flats
Sand dunes
0 50 100 200 km
Saline area = 233,702.6 ha
Slightly saline = 296,568.7 ha
Coastal salinity area = 530,271.3 ha
Legend
CRSI index
Gujarat coastal district boundary
Saline
Slightly saline
Non saline
b
Legend
LULC class
Maharastra coastal district boundary
Settlement
Forest
Crop land
Fallow land
Vegetation
Water body
Barren land
0 25 50 100 km
Saline area = 290,89 ha
Slightly saline = 131,22 ha
Coastal salinity area = 422,11 ha
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CRSI Index
Maharastra Coastal_Dist_Boundary
Saline
Slightly Saline
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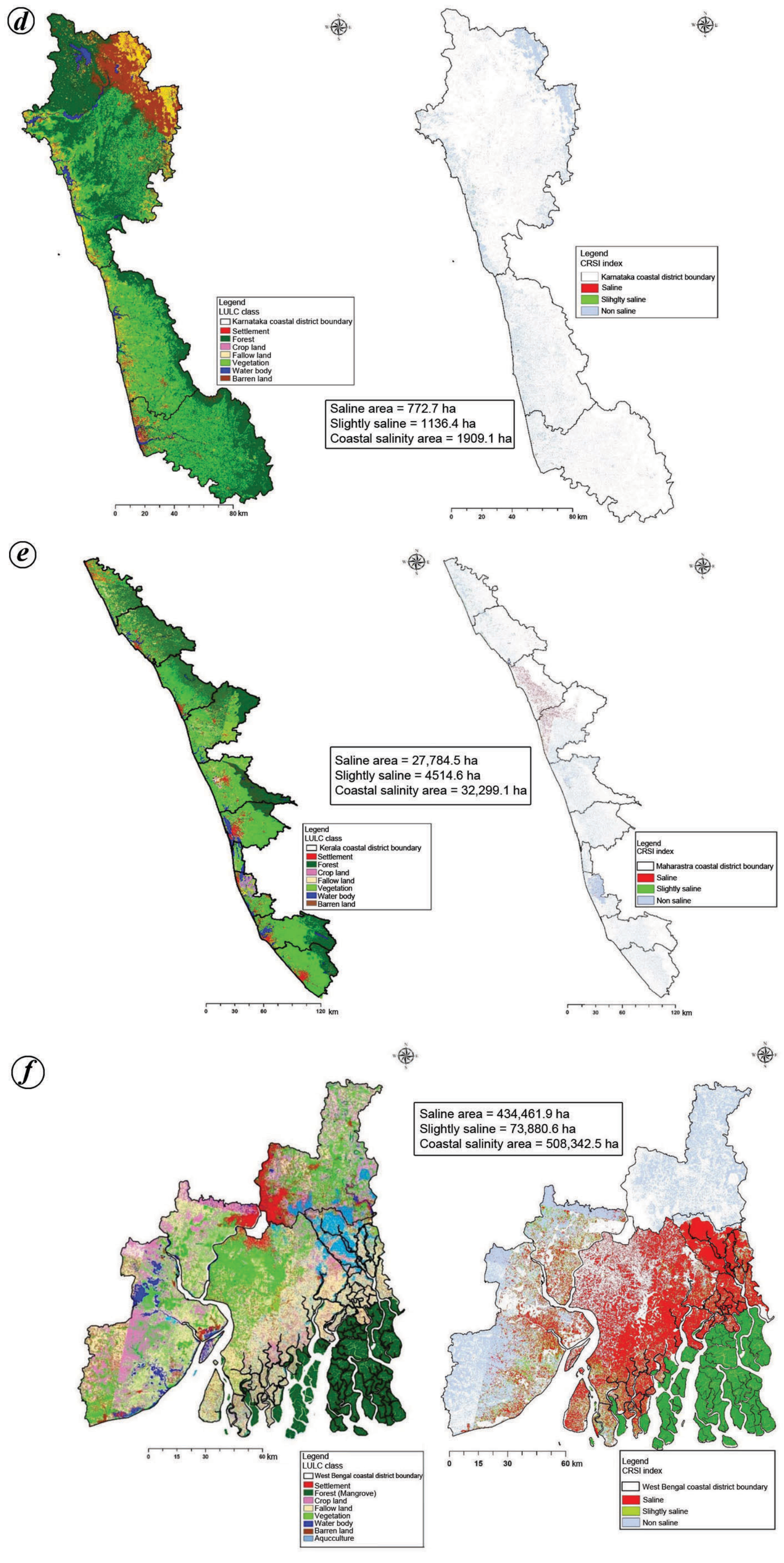
Goa district boundary
Settlement
Forest
Crop land
Fallow land
Vegetation
Water body
Salne area = 4964.6 ha
Slightly saline = 5682.5 ha
Total salinity area = 10,647.1 ha
0 5 10 20 km
Legend
CRSI index
Goat district boundary
Saline
Slightly saline
Non saline

(*Contd*)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Karnataka coastal district boundary
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Forest
Crop land
Fallow land
Vegetation
Water body
Barren land
Legend
CRSI index
Karnataka coastal district boundary
Saline
Slihgty saline
Non saline
Saline area = 772.7 ha
Slightly saline = 1136.4 ha
Coastal salinity area = 1909.1 ha
0 20 40 80 km
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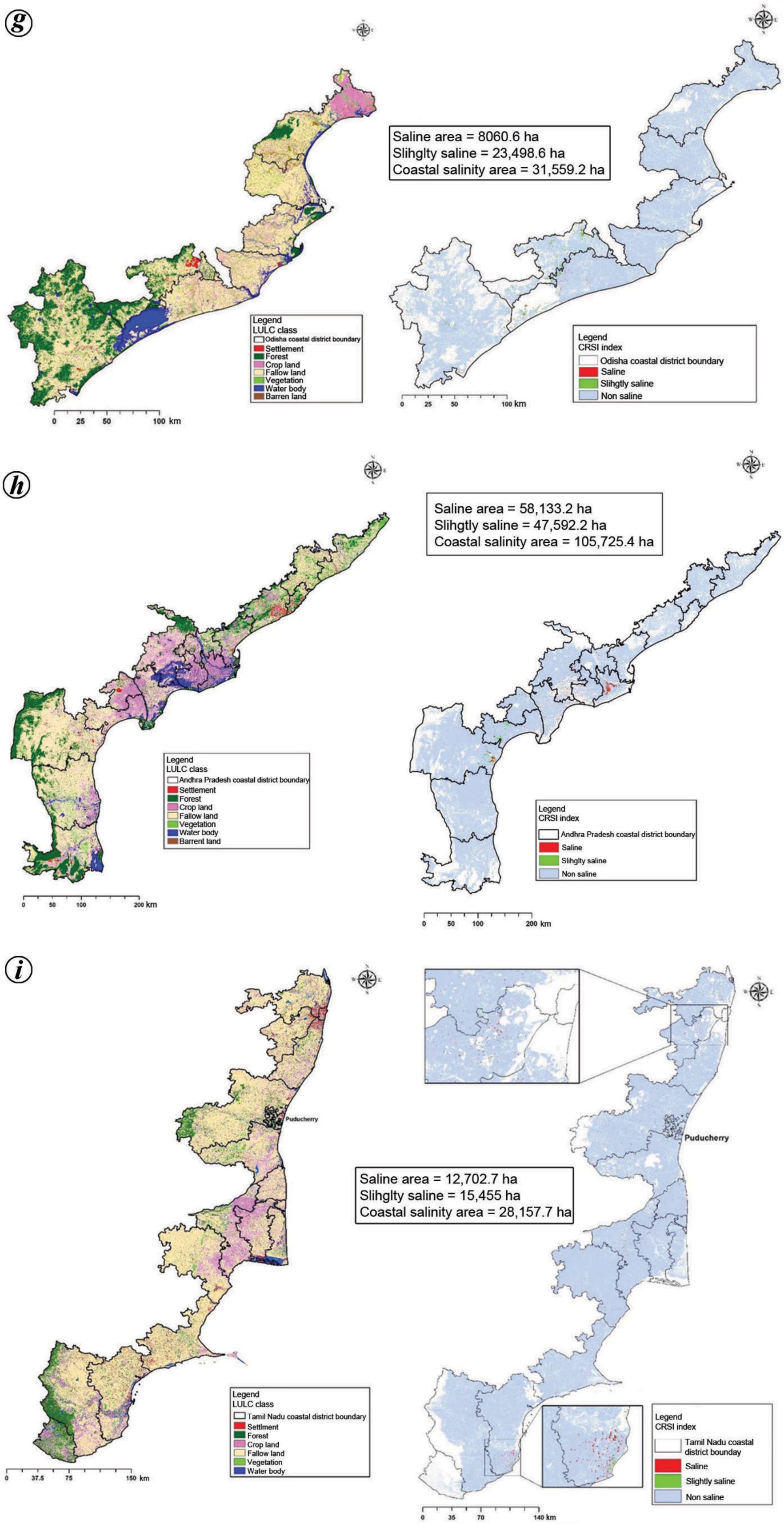
e
Saline area = 27,784.5 ha
Slightly saline = 4514.6 ha
Coastal salinity area = 32,299.1 ha
Legend
LULC class
Kerala coastal district boundary
Settlement
Forest
Crop land
Fallow land
Vegetation
Water body
Barren land
Legend
CRSI index
Maharastra coastal district boundary
Saline
Slightly saline
Non saline
0 30 60 120 km
0 30 60 120 km
f
Saline area = 434,461.9 ha
Slightly saline = 73,880.6 ha
Coastal salinity area = 508,342.5 ha
0 15 30 60 km
Legend
LULC class
West Bengal coastal district boundary
Settlement
Forest (Mangrove)
Crop land
Fallow land
Vegetation
Water body
Barren land
Aqucculture
0 15 30 60 km
Legend
CRSI index
West Bengal coastal district boundary
Saline
Slihgtly saline
Non saline

(*Contd*)


g
Saline area = 8060.6 ha
Slihglty saline = 23,498.6 ha
Coastal salinity area = 31,559.2 ha
Legend
LULC class
Odisha coastal district boundary
Settlement
Forest
Crop land
Fallow land
Vegetation
Water body
Barren land
0 25 50 100 km
Legend
CRSI index
Odisha coastal district boundary
Saline
Slihgtly saline
Non saline
0 25 50 100 km
h
Saline area = 58,133.2 ha
Slihgtly saline = 47,592.2 ha
Coastal salinity area = 105,725.4 ha
Legend
LULC class
Andhra Pradesh coastal district boundary
Settlement
Forest
Crop land
Fallow land
Vegetation
Water body
Barrent land
0 50 100 200 km
Legend
CRSI index
Andhra Pradesh coastal district boundary
Saline
Slihglty saline
Non saline
0 50 100 200 km
i
Puducherry
Saline area = 12,702.7 ha
Slihglty saline = 15,455 ha
Coastal salinity area = 28,157.7 ha
Legend
LULC class
Tamil Nadu coastal district boundary
Settlment
Forest
Crop land
Fallow land
Vegetation
Water body
0 37.5 75 150 km
Legend
CRSI index
Tamil Nadu coastal district bounday
Saline
Slightly saline
Non saline
0 35 70 140 km

(*Contd*)

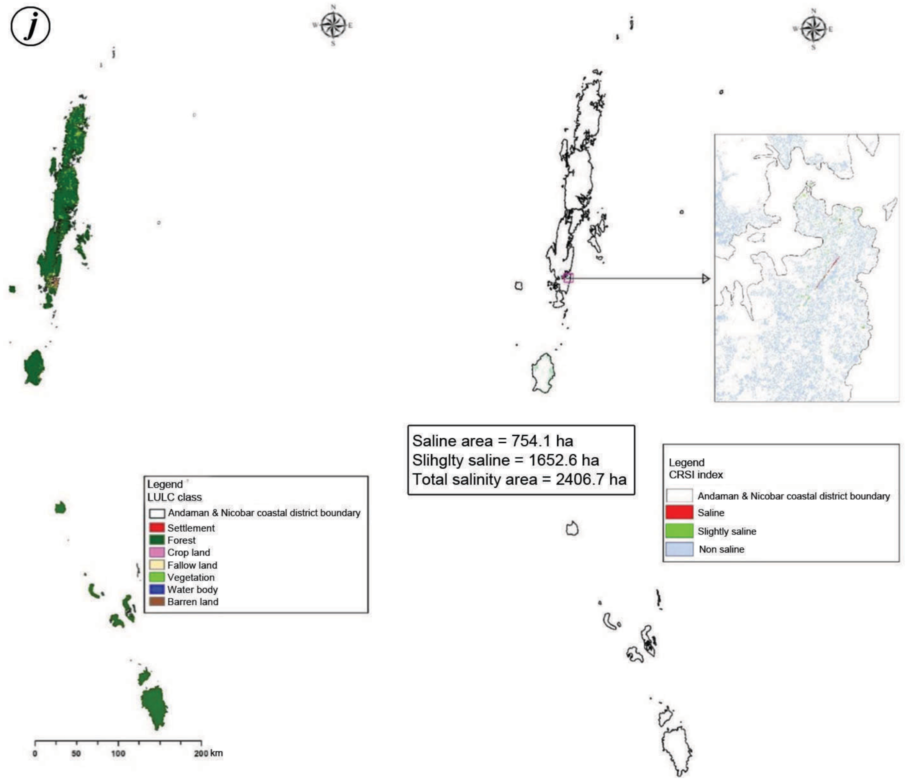



**Figure 5.** Land use/land cover and salinity maps of (***a***) coastal Gujarat, Dadra and Nagar Haveli, and Daman and Diu; (***b***) coastal Maharashtra; (***c***) Goa; (***d***) coastal Karnataka; (***e***) coastal Kerala, (***f***) coastal West Bengal; (***g***) coastal Odisha; (***h***) coastal Andhra Pradesh; (***i***) coastal Tamil Nadu and Puducherry and (***j***) Andaman and Nicobar Islands.

Sindhudurg and Palghar comprise the state's coastline region. Around 35.6% of coastal Maharashtra is under forest land, whereas fallow and cropland cover 22% of the area (Figure 5 *b*). Significant portions of its coastal saline soils are found in the districts of Raigad (26,501 ha, 62.8%) and Thane (7129 ha, 16.9%) (Figure 5 *b* and Table 4). The coastal saline soils in these districts are due to the periodic inundation of cultivable land by creeks/seawater during high tides, and the distribution of fine-textured soil with poor hydraulic conductivity that causes impeded drainage in the region.

*Goa:* This is the smallest Indian state with a coastline of length 129.4 km, and the entire state is within the coastal area. The Arabian Sea forms its western coast, and it is bordered by Maharashtra in the north and Karnataka in the east and south. Forest cover occupies an area of 48.3%, and fallow and cropland cover an area of 30.7% of the state (Figure 5 *c*). Goa's soil is reddish in colour and rich in ferric-aluminium oxides. A total of 10,647 ha of saline soil in Goa is distributed in North and South Goa with an area of 5904 ha and 4743 ha respectively (Figure 5 *c* and Table 4).

*Karnataka:* The 301.6 km long Kanara coast is Karnataka's coastline region. The Konkan in the north, the Western Ghats in the east, the Kerala Plains in the south and the Arabian Sea in the west define the boundaries of this region. Forest and other vegetation occupy 70.7% area, whereas crop and fallow land occupy around 12% area (Figure 5 *d*). There are three coastal districts and the highest coastal saline soils are distributed in Uttara Kannada (1071 ha), followed by Dakshin Kannada (574 ha) and the least in Udupi district (265 ha; Figure 5 *d* and Table 4). The coastal soils in Karnataka are mostly coarse-textured with low cation exchange capacity and bases.

*Kerala:* This state has a coastline of 590 km and is known as the Malabar coast. It begins from the western coast of Karnataka, runs through entire Kerala and reaches Kanyakumari in Tamil Nadu. Forest and vegetation occupy an area of 69%, while fallow and crop land cover an area of 12% of coastal Kerala (Figure 5 *e*). Out of ten coastal districts, more than 81% of saline soils are distributed in Kozhikode (15,068 ha, 46.7%) and Malappuram (11,015 ha, 34.1%) (Figure 5 *e* and Table 4). Acid-saline soils are also present in the coastal regions of Kerala.

## *East coast*

*West Bengal:* The coastal plain of West Bengal is located in four coastal districts, viz. Purba Medinipur, Howrah,

**Table 3.** Accuracy assessment of land-use/land-cover classes and soil salinity

| Land class | User's accuracy | Producer's accuracy | Land class | User's accuracy | Producer's accuracy | Land class | User's accuracy | Producer's accuracy |
|---|---|---|---|---|---|---|---|---|
| Coastal Gujarat, Dadra and Nagar Haveli and Daman and Diu | | | Coastal Maharashtra | | | Goa | | |
| Cropland | 0.80 | 0.80 | Cropland | 0.70 | 0.88 | Cropland | 0.80 | 1.00 |
| Fallow land | 0.80 | 0.73 | Fallow land | 0.80 | 0.80 | Fallow land | 0.80 | 1.00 |
| Settlement | 0.90 | 0.90 | Settlement | 1.00 | 0.83 | Settlement | 1.00 | 0.91 |
| Water body | 0.90 | 0.82 | Water body | 1.00 | 1.00 | Water body | 1.00 | 1.00 |
| Vegetation | 1.00 | 0.91 | Vegetation | 0.70 | 0.78 | Vegetation | 1.00 | 0.83 |
| Forest | 0.80 | 1.00 | Forest | 0.80 | 0.80 | Forest | 1.00 | 0.91 |
| Salt pan | 0.80 | 0.89 | Barren land | 0.90 | 0.82 | | | |
| Barren land | 0.90 | 0.90 | | | | | | |
| Mud flat | 0.90 | 0.82 | | | | | | |
| Sand dune | 0.90 | 1.00 | | | | | | |
| Overall accuracy | | 0.87 | Overall accuracy | | 0.89 | Overall accuracy | | 0.93 |
| Overall kappa | | 0.86 | Overall kappa | | 0.87 | Overall kappa | | 0.92 |
| Coastal Karnataka | | | Coastal Kerala | | | Coastal West Bengal | | |
| Cropland | 0.80 | 0.80 | Crop land | 0.80 | 0.89 | Cropland | 0.90 | 0.82 |
| Fallow land | 0.80 | 0.89 | Fallow land | 0.90 | 1.00 | Fallow land | 0.90 | 0.82 |
| Settlement | 1.00 | 0.91 | Settlement | 0.90 | 0.82 | Settlement | 0.80 | 0.80 |
| Water body | 0.80 | 1.00 | Water body | 1.00 | 1.00 | Water body | 1.00 | 0.91 |
| Vegetation | 1.00 | 0.91 | Vegetation | 0.90 | 0.82 | Vegetation | 0.70 | 0.88 |
| Forest | 1.00 | 0.83 | Forest | 1.00 | 0.91 | Forest (mangrove) | 1.00 | 1.00 |
| Barren land | 0.80 | 0.89 | Barren land | 0.90 | 1.00 | Aquaculture | 1.00 | 1.00 |
| | | | | | | Barren land | 0.90 | 1.00 |
| Overall accuracy | | 0.89 | Overall accuracy | | 0.91 | Overall accuracy | | 0.90 |
| Overall kappa | | 0.87 | Overall kappa | | 0.90 | Overall kappa | | 0.89 |
| Coastal Odisha | | | Coastal Andhra Pradesh | | | Coastal Tamil Nadu and Puducherry | | |
| Cropland | 0.90 | 0.82 | Cropland | 1.00 | 0.91 | Cropland | 0.90 | 0.82 |
| Fallow land | 1.00 | 0.83 | Fallow land | 0.80 | 0.80 | Fallow land | 0.90 | 0.75 |
| Settlement | 0.80 | 0.80 | Settlement | 0.80 | 0.89 | Settlement | 0.80 | 0.80 |
| Water body | 0.90 | 0.82 | Water body | 0.90 | 1.00 | Water body | 0.80 | 0.89 |
| Vegetation | 0.70 | 1.00 | Vegetation | 1.00 | 1.00 | Vegetation | 0.90 | 1.00 |
| Forest | 0.80 | 1.00 | Forest | 1.00 | 0.83 | Forest | 0.80 | 0.89 |
| Barren land | 1.00 | 0.91 | Barren land | 0.90 | 1.00 | | | |
| Overall accuracy | | 0.87 | Overall accuracy | | 0.91 | Overall accuracy | | 0.85 |
| Overall kappa | | 0.85 | Overall kappa | | 0.90 | Overall kappa | | 0.82 |
| Andaman and Nicobar islands | | | Lakshadweep and Minicoy Islands | | | Salinity classes of coastal India | | |
| Forest | 1.00 | 0.83 | Forest | 1.00 | 0.91 | Non-saline | 0.90 | 0.93 |
| Water body | 0.90 | 1.00 | Water body | 0.90 | 1.00 | Slightly saline | 0.71 | 0.77 |
| Fallow land | 0.80 | 0.80 | | | | Saline | 0.80 | 0.74 |
| Settlement | 0.80 | 0.89 | | | | | | |
| Cropland | 1.00 | 0.91 | | | | | | |
| Barren land | 0.90 | 1.00 | | | | | | |
| Vegetation | 1.00 | 1.00 | | | | | | |
| Overall accuracy | | 0.91 | Overall accuracy | | 0.95 | Overall accuracy | | 0.87 |
| Overall kappa | | 0.90 | Overall kappa | | 0.90 | Overall kappa | | 0.71 |

North and South 24 Parganas, and has a coastline of length 158 km along the mainland with 3800 sq. km delta territories. Coastal West Bengal has about 2133 sq. km of mangrove forest area (Figure 5*f*). Fallow, cropland and aquaculture areas occupy about 8272 sq. km area. The West Bengal coast has the second-highest saline soil after Gujarat, at 508,343 ha, and covers around 38% of Indian coastal saline soils. The South 24 Parganas district has around 61.6% of saline soils and the remaining 16.9%, 14.1% and 7.4% are distributed in Purba Medinipur, North 24 Parganas and Howrah districts respectively (Figure 5*f* and Table 4). There was around 15.2% increase in the coastal saline soils in the state, as reported by Mandal *et al.*[19]. This could be because of sea-level rise as well as the increase in storm surges, which led to periodic saline water inundation in the region[44,45]. Out of 3.13 lakh ha of saline soils in South 24 Parganas, 2.11 lakh ha is distributed in the 13 administrative blocks of the Indian Sundarbans. In the North 24 Parganas district, out of 0.72 lakh ha salt-affected soils, 0.68 lakh ha saline soil is distributed in only six blocks of the Indian Sundarbans and the remaining 0.04 lakh ha is distributed in other 16 blocks of the district.

**Table 4.** District-wise extent and distribution of saline soils in coastal India

| West Coast | | East Coast | |
|---|---|---|---|
| District | Saline soil (ha) | District | Saline soil (ha) |
| Gujarat | | West Bengal | |
| Kachcha | 14,490.6 | Purba Medinipur | 85,763.4 |
| Jamnagar | 99,526.3 | Howrah (Haora) | 37,643.3 |
| Rajkot | 43,446.0 | South 24 Parganas | 313,329.4 |
| Porbandar | 24,976.6 | North 24 Parganas | 71,606.4 |
| Junagadh | 57,309.1 | Total | 508,342.5 |
| Amreli | 18,200.9 | Odisha | |
| Bhavnagar | 30,495.0 | Ganjam | 10,954.4 |
| Ahmedabad | 20,016.6 | Khordha | 9,843.0 |
| Anand | 3,285.8 | Puri | 6,972.4 |
| Bharuch | 23,180.0 | Jagatsinghpur | 708.0 |
| Vadodara | 4,846.0 | Kendrapara | 880.1 |
| Surat | 40,167.1 | Bhadrak | 964.7 |
| Navsari | 17,145.8 | Balasore | 1,236.6 |
| Valsad | 16,942.3 | Total | 31,559.2 |
| Devbhumi Dwarka | 29,501.8 | Andhra Pradesh | |
| Gir Somnath | 11,090.9 | Anakapalli | 805.1 |
| Morbi | 73,331.4 | Bapatla | 14,198.1 |
| Total | 527,952.2 | East Godavari | 5,620.1 |
| Dadra and Nagar Haveli, and Daman and Diu | | Eluru | 11,869.3 |
| Daman | 971.9 | Guntur | 4,275.7 |
| Diu | 413.5 | Kakinada | 1,999.8 |
| Dadra and Nagar Haveli | 933.7 | Konaseema | 18,973.8 |
| Total | 2,319.1 | Krishna | 13,145.7 |
| Maharashtra | | Prakasam | 16,675.2 |
| Thane | 7,129.2 | SPSR Nellore | 3,323.6 |
| Raigad | 26,500.6 | Srikakulam | 1,818.8 |
| Mumbai | 345.7 | Tirupati | 2,424.6 |
| Ratnagiri | 4,459.7 | Visakhapatanam | 1,155.2 |
| Sindhudurg | 970.0 | Vizianagaram | 1,565.8 |
| Palghar | 2,805.8 | West Godavari | 7,874.6 |
| Total | 42,211.0 | Total | 105,725.4 |
| Goa | | Tamil Nadu | |
| North Goa | 5,904.5 | Kanyakumari | 155 |
| South Goa | 4,742.6 | Tirunelveli | 910.2 |
| Total | 10,647.1 | Thanjavur | 1,435.5 |
| Karnataka | | Pudukkottai | 290.0 |
| Uttara Kannada | 1,070.7 | Ramanathapuram | 409.1 |
| Udupi | 264.8 | Thoothukudi | 1,147.0 |
| Dakshina Kannada | 573.6 | Karaikal | 93.6 |
| Total | 1,909.1 | Nagapattinam | 770.1 |
| Kerala state | | Cuddalore | 4,456.1 |
| Kasaragod | 2,132.7 | Viluppuram | 6,642.0 |
| Kannur | 1,599.8 | Kanchipuram | 3,059.7 |
| Kozhikode | 15,068.4 | Tiruvallur | 4,145.0 |
| Malappuram | 11,015.3 | Tiruvarur | 700.1 |
| Thrissur | 497.7 | Mayiladuthurai | 1,119.2 |
| Ernakulam | 115.7 | Chengalpattu | 2,088 |
| Alappuzah | 1,517 | Total | 27,420.6 |
| Kollam | 243.5 | Puducherry | 737.1 |
| Thiru | 32.3 | Andaman and Nicobar Islands | 2,406.7 |
| Mahe | 76.6 | | |
| Total | 32,299.0 | | |
| Lakshadweep and Minicoy Islands | Not detected | | |

*Odisha:* The districts of Balasore, Bhadrak, Jagatsinghpur, Kendrapara, Puri, Khordha and Ganjam make up the 506 km of Odisha's coastline. The Lower Ganges Plain in the north, the Bay of Bengal in the east, Andhra Pradesh in the south, and the Eastern Ghats in the west define the boundaries of this region. Chilika, the largest lake in the country, is in this state. About 75.6% of coastal Odisha remains fallow during the dry season (Figure 5 *g*). The total coastal saline soils occupy 31,559 ha in the state, of which 34.7%, 31.2% and 22.1% are spread over Ganjam, Khordha and

Puri districts respectively, covering 88% coastal saline soils (Figure 5 *g* and Table 4). Littoral deposits of estuarial intrusion of brackish tidal water from the sea through creeks cause an increase in salinity. Due to the high groundwater table in low-lying areas, subsoil salinity increases during monsoon season.

*Andhra Pradesh:* The coastal region of Andhra Pradesh is 1014 km long along the Coromandel coast between the Eastern Ghats and the Bay of Bengal. Presently, coastal areas in Andhra Pradesh are confined to 15 districts, viz. Srikakulam, Vizianagaram, Visakhapatnam, Anakapalli, Kakinada, East Godavari, Konaseema, West Godavari, Krishna, Guntur, Eluru, Bapatla, Prakasam, SPSR Nellore and Tirupati. Figure 5 *h* shows the coastal land-use distribution of Andhra Pradesh where fallow and cropland occupy 70.3% area. Around 105,725 ha of saline soils are distributed within the coastal region, with 71% of the area spread within five districts, i.e. Konaseema (17.9%), Prakasam (15.8%), Bapatla (13.4%), Krishna (12.4%) and Eluru (11.2%). Mandal *et al.*[19] have reported 77,598 ha as salt-affected soils of Andhra Pradesh. Large irrigation projects in the Krishna and Godavari basins, and an increase in aquaculture areas might increase the salt-affected areas in the region. Singh[46] also reported that a considerable area of agricultural land is converted to aquaculture, leading to an increase in the soil salinity of the region.

*Tamil Nadu and Puducherry:* Along the Coromandel coast, Tamil Nadu's coastline stretches for 950 km. In the north, it is bordered by Andhra Pradesh, east by the Bay of Bengal, south by the Kaveri Delta and west by the Eastern Ghats. The fallow and cropland extend over 83.7% of the area of the coastal region of the state (Figure 5 *i*). The total coastal saline soils in Tamil Nadu are spread over 27,421 ha area, and the highest salinity area is in Viluppuram (24.2%), followed by Cuddalore (16.3%), Tiruvallur (15.1%) and Kanchipuram (11.2%), covering more than 66% of the coastal saline soils of the state (Figure 5 *i* and Table 4). Seawater intrusion in the deltas and secondary salinization due to intensive irrigated agriculture are the main causes of soil salinization in the state.

*Andaman and Nicobar Islands, and Lakshadweep Islands:* The Andaman and Nicobar Islands have a total area of 7569.9 sq. km and are part of the hot, humid and slightly humid island ecoregion, which is rich in biodiversity. They are situated 1200 km east of the Indian mainland in the Bay of Bengal. The major area of the Island is under forest cover (Figure 5 *j*). Tidal flooding is common in coastal regions. Utilizing remote sensing techniques, merely 2407 ha of saline soils within arable lands, representing only 0.3% of the entire area of the Island has been identified. This could be attributed to the dense vegetation cover in the Islands. Notably, delineating saline areas within forested vegetation poses challenges when employing satellite remote sensing (Figure 5 *j* and Table 4).

The Lakshadweep Islands are a collection of coral islands in the Arabian Sea that are around 400 km south of the Indian mainland (southern tip of the Indian Peninsula). The total area is 434.8 sq. km, with a major portion under forest and waterbody. The parent material of the soil was formed through physical weathering of the organogenic calcium carbonate, as the Islands are mostly made of coral limestone. The soils are light-textured, predominantly sand or loamy sand and occasionally sandy loam[47]. The soil is rich in organic matter with an average organic carbon content of 2.5% (0.77–4.78%) on the surface horizon. The soils in the Islands are porous, extremely drained and poor in water-holding capacity. They are permeable, and therefore, rainwater infiltrates quickly into the underlying substratum of coral limestone[47]. No saline soil was detected on the Lakshadweep Islands.

The present study reveals that the total saline soils occupy 12.94 lakh ha in coastal India. In terms of their distribution, coastal Gujarat has the highest area (5.28 lakh ha), followed by West Bengal (5.08 lakh ha), Andhra Pradesh (1.06 lakh ha), Maharashtra (0.42 lakh ha), Kerala (0.323 lakh ha), Odisha (0.316 lakh ha), Tamil Nadu (0.27 lakh ha), Goa (0.11 lakh ha), Karnataka (0.019 lakh ha) and Dadra and Nagar Haveli and Daman and Diu (0.023 lakh ha), Puducherry (0.007 lakh ha area), and the Andaman and Nicobar Islands (0.024 lakh ha) of saline soils (Figure 6). Mandal *et al.*[26] estimated the total salt-affected soils for the coastal regions of India as 25.01 lakh ha, of which 18.28 lakh ha was identified as saline soils and 6.73 lakh ha as sodic soils. They only presented the database of salt-affected soils without revealing the procedure for estimation. Earlier, Mandal *et al.*[19] estimated the total salt-affected soils in the coastal regions to be 12.37 lakh ha using Landsat data from 1986–87. In the present study agriculturally important soils were considered to estimate saline soils. Other physiographic aspects like mud flats, mangrove swamps or salt pans were not considered for the estimation. Additionally, despite the restricted distribution of sodic soils in the coastal regions of India, these spectral indices cannot distinguish between saline and sodic soil areas. According to the findings of this study, soil salinity indices from Landsat-8 OLI can be used to identify and estimate soil salinity with a desirable level of accuracy. Maps can be used for both macro- and micro-planning in the management and reclamation of saline soils in coastal regions of India.

## Conclusion

Traditional field measurements and laboratory analysis limit monitoring soil salinity on the landscape and regional scale. During the past three decades, soil salinity has been rapidly and affordably monitored using satellite imaging from field size to regional scale. The findings of this study

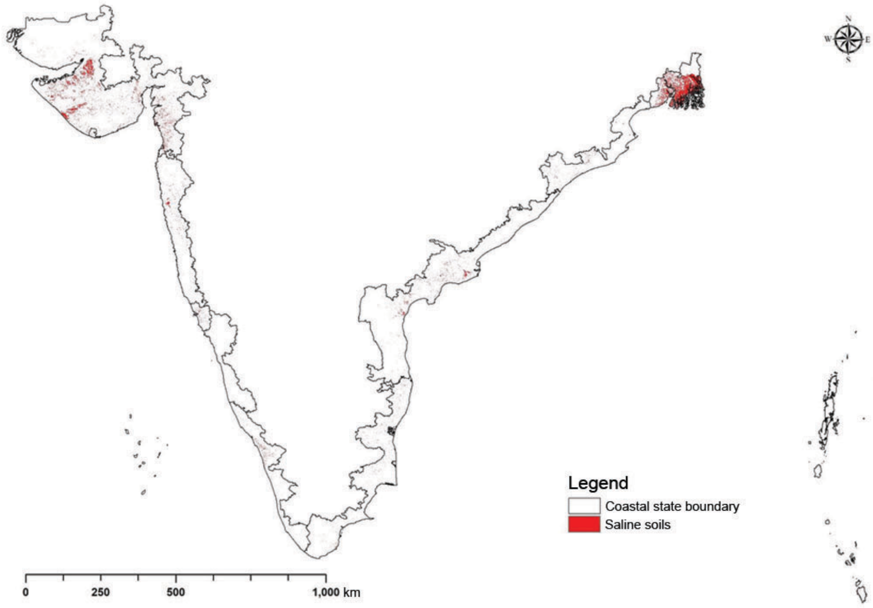



**Figure 6.** Distribution of saline soils in arable lands of coastal India.

suggest that the spatial variability of soil salinity in coastal India can be predicted with reasonable accuracy using Landsat-8 data. The findings imply that combining data from crop and soil parameters with Landsat-8 reflectance can produce a viable salinity prediction model for the entire coastal region of India. Among the vegetation indices examined, the canopy response salinity index demonstrated the most promising alignment with observed data. Sustained and consistent monitoring of fluctuations in soil salinity is imperative to effectively address the impacts of climate change. Given that India's coastal zone remains particularly susceptible to the consequences of climate change and rising sea levels, remote sensing emerges as the only viable approach to assess salinity levels rapidly and reliably in this region.

*Competing interests:* The authors declare that there is no conflict of interest.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