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Soil Salinity Mapping Using Satellite Remote Sensing and In-Situ Measurements

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Abstract

Coastal areas of Bangladesh are being affected by climate change over the past four decades, and has become an escalating and notable issue in recent time. At the same time, the problem of soil salinity poses a considerable obstacle to crop production in the coastal regions of Bangladesh. Subsequently, conducting a soil salinity assessment is crucial for effective land use planning in agricultural crop production. Therefore, the aim of this research is to employ satellite remote sensing data to map soil salinity. For this study, observed electrical conductivity (EC) data are collected from SRDI, Khulna and four soil salinity (SI) indices are extracted using Landsat 8 Operational Land Imager (OLI) data from USGS Earth Explorer. According to the observed EC data, the maximum and minimum values represent the month of May 2023 and October 2022 respectively for all of the sites. The correlation coefficient between the observed EC and satellite-derived indices is more than 61% for maximum cases. Also, correlation coefficients fit better for Jalma and Batiaghata unions. The remote sensing indices have shown better performance in our present study. It can be inferred that the utilized soil salinity indices effectively identified the levels of soil salinity for this study.

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Introduction

Food security has become a highly discussed topic in association with increasing soil salinity for areas which depend on artificial irrigation, and thus soil salinity is causing stunted plant growth and crop failure at times specially in coastal belts of southern Bangladesh (Dasgupta *et al.*, 2014, 2015; García-Tejero *et al.*, 2011; Koevoets *et al.*, 2016; Mondal *et al.*, 2001). Major and minor salinity affected areas globally account for 955 Mha and 77 Mha respectively; importantly, out of these 58% is irrigated land which indicates the major cause of salinity is anthropogenic (Amin, 2004). On the other hand, increasing population and the competition for resources has posed a substantial threat on all available natural resources including water and soil (Cassman *et al.*, 2003; Corwin, 2021; Haque, 2006; Payo *et al.*, 2017; Salehin *et al.*, 2018). Therefore, proper management of soil in a scientific way becomes very important as soil supports almost all life on earth (Das *et al.*, 2020; Miltner *et al.*, 2012; Szabo *et al.*, 2016).

Salinity intrusion is a dynamic process which requires regular monitoring and management practices. So, it is not possible through resource and time rigorous traditional methods of determining soil-salinity. Salinity can occur due to numbers of factors apart from improper irrigation- engineering problems, soil erosion and soil dispersion (Qadir *et al.*, 2000). For areas with a history of water logging, the soil salinity becomes more acute (Bhutta and

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Smedema, 2007; Shah *et al.*, 2001). The plants intake the moisture leaving behind the dissolved salts in water (Konukcu *et al.*, 2006). After a period of time, this salt accumulates around the root nodules making further water intake impossible and this how increase in soil salinity causes decrease in moisture intake capacity of plants since their root nodules get blocked by salts (Egamberdieva *et al.*, 2016; Etehadnia *et al.*, 2008; Franzini *et al.*, 2019). Moreover, high concentration of salts in water causes reverse osmosis resulting in the wilting of plants causing their perishing (Arora *et al.*, 2018). This in turns affects the crop yield and causes heavy loss to farmers. Salinity in soil happened mainly due to natural causes such as frequent flooding but over the years, unscientific and improper irrigation management (Baig and Shahid, 2014). In agriculture science, soil is considered to be saline in conditions when there is sufficient amount of salts dissolved in root zone soil moisture to adversely affect the plant growth (Rengasamy *et al.*, 2003). Many studies claim soils to be saline in cases when soil electrical conductivity (EC) is more than $4 dSm^{-1}$ at 25^oC (Igartua *et al.*, 1994). Different plants have different tolerance for soil salinity levels beyond which their growth is adversely affected such as mostly negligible (0-2 dSm^{-1}), growth of sensitive plants is affected (2-4 dSm^{-1}), Growth of many plants is affected (4-8 dSm^{-1}), Only tolerant plants grow effectively (8-16 dSm^{-1}), Only few very tolerant plants grow (above 16 dSm^{-1}) (Xie *et al.*, 2009).

Remote Sensing and Geographic Information System (GIS) are offering efficient and inexpensive substitutes to normal soil salinity measurements. Remote sensing proves to be a non-intrusive and efficient tool that can be effectively utilized for monitoring soil salinity levels and mapping areas affected by salinity, thus saving valuable time (Katsaros *et al.*, 2002; A. Tripathi and Tiwari, 2020, 2021). For several decades, and since the advent of remote sensing as a sophisticated surveying tool with the launch of the first remote sensing satellite, Landsat-1, in the early 1970s, spaceborne remote sensing has been widely employed in agriculture (Zhang *et al.*, 2002). Nevertheless, there was still a lack of dedicated utilization of spaceborne remote sensing for studies related to soil health. (Wagner *et al.*, 1999). Due to the constraints associated with the availability of optical, thermal, and hyperspectral datasets, particularly during monsoon months when dense cloud covers are prevalent, there arose a requirement for all-weather data (Kim and Hong, 2007). It was in response to this need that microwave or Synthetic Aperture RADAR (SAR) remote sensing came into play. (Kim and Hong, 2007). Satellite remote sensing has a high spatio-temporal resolutions and are currently providing analysis ready data freely available (Jensen, 2009). Which can be used to produce spectral indices to estimate spatio-temporal soil salinity maps (Abbas *et al.*, 2013). A few of the indices are normalized differential salinity index (NDSI), vegetation soil salinity index (VSSI), different levels salinity indices (SI) indices, such as Soil salinity Index 1(SI-1) and Soil salinity Index 2 (SI-2). These alternatives have the potential to excel as substitutes for the commonly employed practices of salinity identification based on electrical conductivity (EC) based salinity identification practices (Allbed *et al.*, 2014b; Gorji *et al.*, 2017).

So, we can conclude that soil salinity has a great importance in case of sustainable food security specially for country like Bangladesh, where population growth rate is significantly high along with limited land resources and inadequate applications of science and technology. Hence, remote sensing technology may become a game changing tool for mapping accurately the soil salinity induced areas of coastal belts of southern Bangladesh.

Southern site of Bangladesh is costal area, very near to Bay of Bengal. Due to tidal, land of coastal areas is inundated regularly with sea water, which contains saline water. Because of storm surge associated with tropical cyclone large area are inundated with saline water and water is logged for long time. For our present study, we have chosen Batiaghata upazila of Khulna district from the coastal area based on the severity of soil salinity and in-situ data availability. Therefore, the objective of this study is to observe the soil salinity mapping using satellite remote sensing and in-situ measurements of the above-mentioned area.

Methods

Study area

This research has been implemented in some sites of Krishnanagar, Kismat Fultala and Fultala villages under Batiaghata (sub-district) of Khulna district which is in the coastal region of Bangladesh

Batiaghata is divided into two parts namely western and eastern by Kajibachha River. It is bounded by

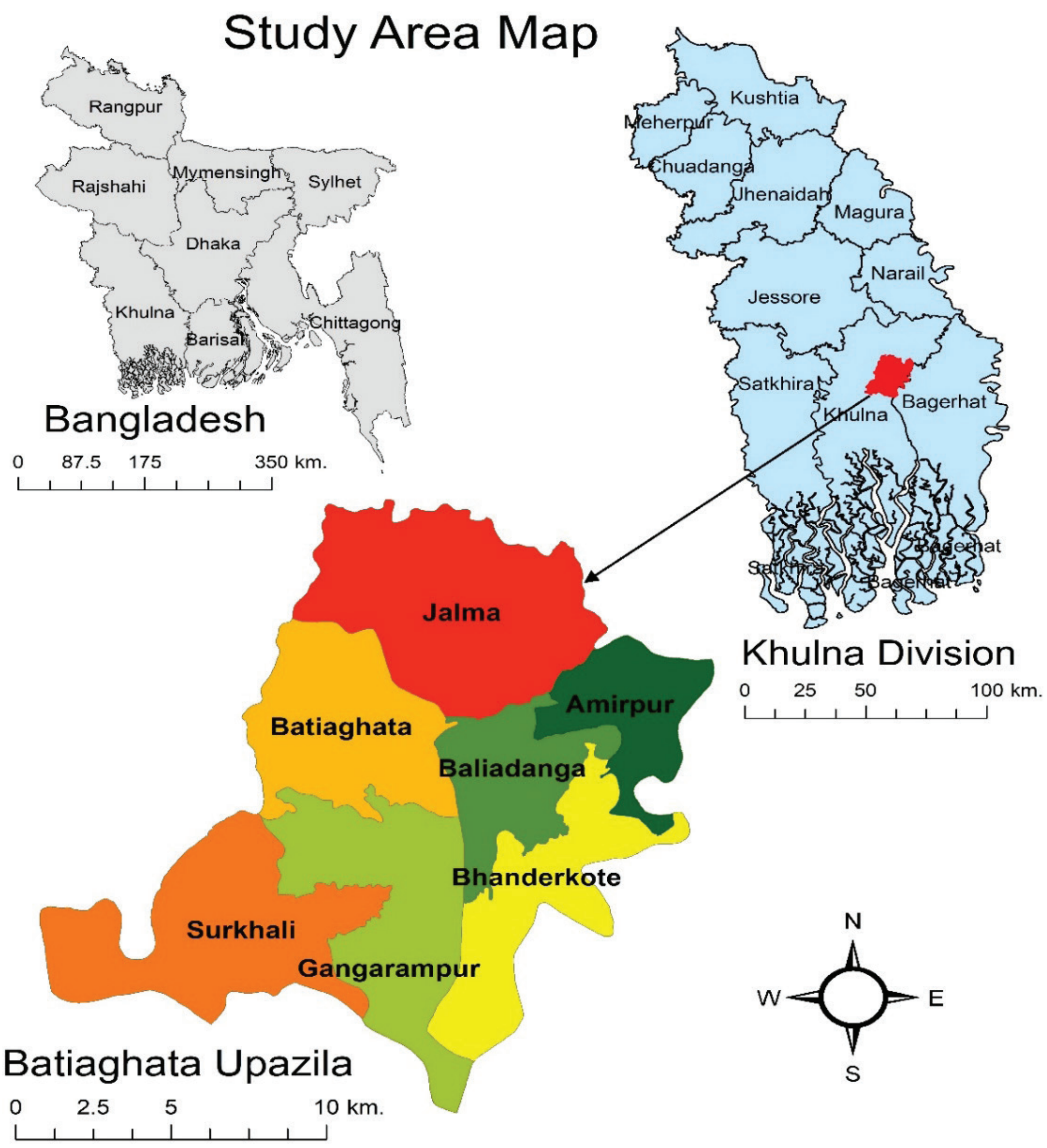

Figure 1. Study area map

Rupsa, Rampal and Fakirhat upazilas on the east, Dumuria and Paikgaccha upazilas on the west, Kotowali & Sonadanga thanas and Dumuria upazila on the north, Dakope, Rampal and Paikgachha Upazila on the south. It has an area covered by 235.32 square kilometers, located between 22^o 34' and 22^o 46' north latitudes and in between 89^o 24' and 89^o 37' east longitude.

Table 1. Description of the field data chosen

Upazila	Union	Site Name	Site No.	Latitude	Longitude
Batiaghata	Batiaghata	Krishnanagar_1	1	22.71022	89.7583
		Krishnanagar_2	2	22.71005	89.7582
		Kismat Fultala_1	3	22.72508	89.5216
		Kismat Fultala_2	4	22.72594	89.5215
	Jalma	Fultala_1	5	22.70847	89.5287
		Fultala_2	6	22.70763	89.5287

It having a population of 1, 71,752 according to the 2022 Bangladeshi census which population density is 730 square kilometers. Male's contribution of total population is 86,685 and female is 85,067 approximately. The main rivers of Batiaghata upazila are Kazibachha, Shoilmari. The average of maximum and minimum rainfall for Batiaghata Upazila is 172.60 mm and 152.40 mm respectively. Simultaneously, the average of maximum and minimum temperature is 31.7^{o} and 22.3^{o}. The range of cultivation dominating in this area is rice, watermelon, shrimp and other fish. The study area is covered in salt sediment formed by the accumulation of floods and water surface. The salient feature of soil salinity in the study area is significantly affected by various degrees of soil salinity. The following table represents the geographical information of the study site we have conducting the research. Map of the study are shown in Figure 1. Observed EC data are obtained from SRDI for the 4 sites of Batiaghata union and 2 sites of Jalma union. The description of sites are given in Table 1.

The methodology is subdivided into three parts: (i) Remote sensing data collection, processing and mapping; (ii) Field data collection, processing and analysis; and (iii) Validation. They are described below-

Remote Sensing Data Collection, Processing, and Mapping

The present study used Landsat 8 OLI collected data and accessed from USGS Earth Explorer (https://earthexplorer.usgs.gov/). The data is freely available and open access. Landsat 8 OLI have a total of 11 spectral bands including two thermal channels. In the study, one Landsat imagery has been collected to extract soil salinity through four different spectral indices (Acquisition date-10th May 2023). The data was extracted, processed and analyzed in ArcGIS platform. Among all of the 11 bands, band 2, band 3, band 4 and band 5 have been used to extract various indices. There are numbers of spectral indices and vegetation indices available. And we have selected four distinct indices which are widely used and promising. The selected indices are Normalized Differential Salinity Index (NDSI), Vegetation Soil Salinity Index (VSSI), Salinity Index 1 (SI-1) and Salinity Index 2 (SI-2). The methods used to estimate the indices and related sources are presented in the Table 2.

Table 2. Description of the selected indices

Spectral indices	**Description**	**Method**	**Source**
NDSI	Normalized Differential Salinity Index	(R - NIR)/(R + NIR)	(Allbed et al., 2014a; Khan et al., 2005)
VSSI	Vegetation Soil Salinity Index	(2XG) – {5X(R+NIR}	(Dehni & Lounis, 2012)
SI-1	Salinity Index 1	(R/ NIR) x 100	(Allbed et al., 2014a; N. K. Tripathi et al., 1997)
SI-2	Salinity Index 2	(B – R) / (B + R)	(Allbed et al., 2014a)

Note: B: Blue band, G: green band, R: red band, NIR: Near infrared band

Field data collection, processing, and analysis

Field data were collected from Soil Research Development Institute, Khulna from June 2022 to May 2023. It is to be noted that soil salinity involves examining the soil physical properties through collecting the soil sample, drying, and estimating EC values through a laboratory chemical analysis. Then the data has been processed and analyzed using excel template. After processing the data, we conclude that the pick values are for the month of May.

Results and Discussion

In this section temporal distribution of observed electrical conductivity for respective study sites and satellite derived induces are discussed. Observed EC data are available for June 2022 to May 2023 only for the study sites of Batiaghata and Jalma unions. On the other hand, satellite derived induces are extracted for all of the unions (07) of Batiaghata Upazila.

Satellite remote sensing derived induces

The following satellite derived indices NDSI, VSSI, SI-1 and SI-2 are discussed below. The imagery acquisition date is 10th May 2023, so we have a correlation with the maximum value of observed electrical conductivity for the month of May.

Normalized differential salinity index (NDSI)

Table 3 shows NDSI indices for the study area (Batiaghata Upazila). Among these unions, maximum (50891400 ha) and minimum (19141200 ha) area coverage are obtained for Jalma and Amirpur union respectively. NDSI indicates a highest maximum value (0.067924) for the Shurkhali Union whereas Batiaghata union experience lowest maximum value (0.011761). The indices have obtained a maximum (0.516915) and minimum (0.424436) range for Gangarampur and Amirpur union respectively. Additionally, on the basis of standard deviation, best fit and highest deviation are found for Amirpur and Baliadanga union respectively. The spatial distribution is shown in figure 2.

According to correlation coefficient all indices fit better for Jalma than Batiaghata union. From observed electrical conductivity data, Jalma (10.6) union has less value than Batiaghata (11.1). From the indices absolute mean value of Jalma (0.20512) has less than Batiaghata (0.23114) union.

Table 3. Description of the NDSI indices for the study area

SL.	UNION	AREA	MIN	MAX	RANGE	MEAN	STD
1	Amirpur	19141200	-0.41267	0.011761	0.424436	-0.2021	0.079392
2	Baliadanga	20779200	-0.4149	0.034667	0.449564	-0.1742	0.100961
3	Batiaghata	34221600	-0.45846	0.030004	0.488461	-0.23114	0.086136
4	Bhanderkote	28778400	-0.41414	0.048936	0.463074	-0.18886	0.084982
5	Gangarampur	38086200	-0.453	0.063918	0.516915	-0.21908	0.100604
6	Jalma	50891400	-0.46958	0.041881	0.511456	-0.20512	0.081512
7	Surkhali	43533000	-0.44552	0.067924	0.513444	-0.18922	0.098565

Table 4. Description of the VSSI indices for the study area

SL.	UNION	AREA	MIN	MAX	RANGE	MEAN	STD
1	Amirpur	19141200	0.125473	0.210793	0.085319	0.158498	0.013072
2	Baliadanga	20779200	0.125301	0.218432	0.093131	0.164369	0.019326
3	Batiaghata	34221600	0.118363	0.213872	0.09551	0.155657	0.014946
4	Bhanderkote	28778400	0.126797	0.218116	0.091319	0.161018	0.015498
5	Gangarampur	38086200	0.12061	0.221404	0.100793	0.158131	0.018012
6	Jalma	50891400	0.120361	0.216214	0.095853	0.160178	0.014667
7	Surkhali	43533000	0.12008	0.221148	0.101069	0.16431	0.019923

Vegetation soil salinity index (VSSI)

Table 4 shows VSSI indices for the study area (Batiaghata Upazila). Among these unions, maximum (50891400 ha) and minimum (19141200 ha) area coverage are obtained for Jalma and Amirpur union respectively. VSSI indicates a highest maximum value (0.221404) for the Gangarampur Union whereas Amirpur union experience lowest maximum value (0.210793). The indices have obtained a maximum (0.101069) and minimum (0.085319) range for Surkhali and Amirpur union respectively. Based on standard deviation, best fit and highest deviation are found for Amirpur and Baliadanga union respectively. According to correlation coefficient all indices fit better for Jalma than Batiaghata union. From observed EC values for Jalma union (10.6) has less value than those of Batiaghata union (11.1). From the indices, mean value of Jalma union (0.160178) has more than those Batiaghata union (0.155657).

Salinity index-1 (SI-1)

Figure 2 shows SI-1 indices for the study area (Batiaghata Upazila) and the values are tabulated Table 5. It contains area coverage of all unions along with maximum, minimum, ranges, mean and standard deviation of the indices. The maximum (50891400 ha) and minimum (19141200 ha) of area coverage among these unions are obtained for Jalma and Amirpur union respectively. SI-1 indicates a highest maximum value (114.5748) for the Surkhali union whereas Amirpur union experience lowest maximum value (102.3802). The indices have obtained a maximum (76.21626) and minimum (60.80477) range and for Surkhali and Amirpur union respectively. Additionally, based on standard deviation best fit and highest deviation are found for Amirpur union for Baliadanga union respectively. According to correlation coefficient all indices best fit for Jalma than Batiaghata union. From observed EC data of Jalma (10.6) union has less value than that of Batiaghata (11.1). From the indices mean value for Jalma union (66.79378) has more than that for Batiaghata (63.30811) union.

Table 5. Description of the SI-1 indices for the study area

SL.	UNION	AREA	MIN	MAX	RANGE	MEAN	STD
1	Amirpur	19141200	41.57543	102.3802	60.80477	67.12234	11.35968
2	Baliadanga	20779200	41.35311	107.1824	65.82932	71.66277	15.57184
3	Batiaghata	34221600	37.1312	106.1863	69.05514	63.30811	12.31645
4	Bhanderkote	28778400	41.42889	110.2907	68.86182	69.13243	12.70357
5	Gangarampur	38086200	37.64645	113.6564	76.00994	65.28431	14.92003
6	Jalma	50891400	36.09373	108.7423	72.64854	66.79378	12.39735
7	Surkhali	43533000	38.35856	114.5748	76.21626	69.4117	14.95359

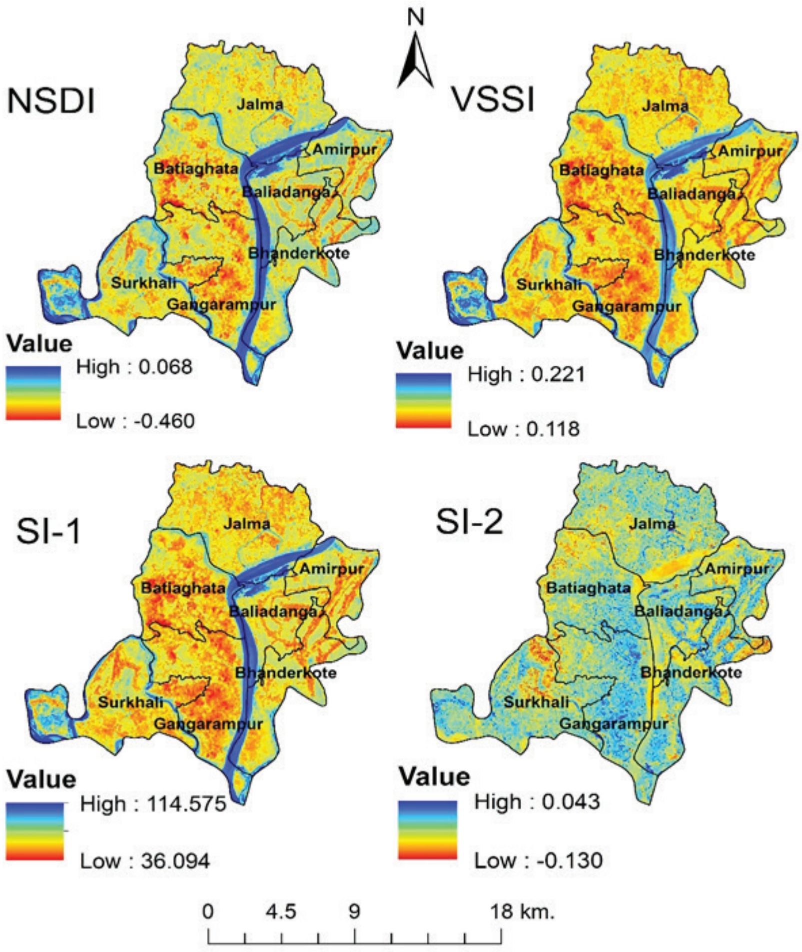

Figure 2. Spatial distribution of satellite-derived indices

Salinity index-2 (SI-2)

Figure 2 shows SI-2 indices for the study area (Batiaghata Upazila) and values of indices are tabulated in Table 6. It contains area coverage of all unions along with maximum, minimum, ranges, mean and standard deviation of the indices. Among these unions, the maximum (50891400 ha) and minimum (19141200 ha) area coverage are obtained for Jalma and Amirpur union respectively. SI-2 indicates a highest maximum value (0.043081) for the Jalma Union whereas Baliadanga union experience lowest maximum value (0.006952). The indices have obtained a maximum (0.168469) and minimum (0.107446) ranges for Jalma and Baliadanga union respectively. Additionally, on the basis of standard deviation, best fit and highest deviation are found for Gangarampur and Bhanderkote unions. According to correlation coefficient all indices best fit for Jalma than Batiaghata union. From observed EC data Jalma (10.6) union has less value than those of Batiaghata (11.1). From the indices mean absolute value of Batiaghata (0.04986) has more than that of Jalma (0.04941) union. It is logical because EC (salinity) and VSSI are linearly related. So, we can predict others union EC values also with the help of Jalma and Batiaghata indices and correlation. So, Gangarampur has less salinity and Amirpur has more salinity among all unions.

Table 6. Description of the SI-2 indices for the study area

SL.	UNION	AREA	MIN	MAX	RANGE	MEAN	STD
1	Amirpur	19141200	-0.13161	0.013729	0.145342	-0.04974	0.016112
2	Baliadanga	20779200	-0.10049	0.006952	0.107446	-0.04711	0.015136
3	Batiaghata	34221600	-0.12754	0.032547	0.160086	-0.04986	0.014963
4	Bhanderkote	28778400	-0.12059	0.011578	0.132166	-0.04731	0.016332
5	Gangarampur	38086200	-0.13422	0.011442	0.145659	-0.04279	0.014829
6	Jalma	50891400	-0.12539	0.043081	0.168469	-0.04941	0.014833
7	Surkhali	43533000	-0.1397	0.009632	0.149334	-0.04859	0.015461

Observed electrical conductivity

Observed EC data are obtained for four places for Batiaghata and two places for Jalma union from SRDI, Khulna. Details of the sites are shown in table 1. Temporal distribution of observed electrical conductivity at Batiaghata and Jalma unions are described as following sub-section.

Temporal distribution of observed EC at Batiaghata union

The lowest (3 dS/m) and highest (11.2 dS/m) EC values are found at the month of October and May respectively for Krishnanagar_1 whereas lowest (2.9 dS/m) and highest (11) value of EC are found at the month of October and May for Krishnanagar_2. It's clearly identifying that the pick value is represent for the month of May at both sites. It can be concluded that value of Krishnanagar_1 is relatively higher than that for Krishnanagar_2.

The lowest (2.9 dS/m) and highest (11.0 dS/m) value of EC are found at the months of October and May respectively for Kismat Fultala_1 whereas lowest (2.9 dS/m) and highest (11.1 dS/m) value of EC are found at the month of October and May respectively for Kismat Fultala_2. Among all of the values of EC, lowest (2.9 dS/m) is experience by the month of October at Kismat Fultala_1 and Kismat Fultala_2, on the other hand maximum (11.1 dS/m) is found for Krishnagar_1. It's clearly identified that the pick value is represent for the month of May at both sites. It can be concluded that the value of Kismat Fultala_2 is relatively higher than that of Kismat Fultala_1. Finally, it can be summarized that value of EC at Krishnanagar_1 is relatively higher than that of other three sites.

Temporal distribution of observed EC at Jalma union

The lowest (2.8 dS/m) and highest (10.5 dS/m) values of EC are found at the months of October and May respectively for Fultala_1 whereas lowest (2.7 dS/m) and highest (10.7 dS/m) values of EC are found at the month of October and May respectively for Fultala_2. Among all of the values, lowest (2.7 dS/m) is experience by the month of October at Fultala_2, on the other hand maximum (10.7 dS/m) is found for Fultala_2 also. It's clearly identifying that the pick value is represent for the month of May at both sites. It can be concluded that a variation of value of EC at Fultala_2 is relatively more than that of Fultala_1. The soil salinity of Batiaghata union is more than that of Jalma union. Because Batiaghata union is closer to Bay of Bengal than Jalma union (Figure 1).

Correlation analysis and validation

The coefficient determination of the indices derived from satellite remote sensing output and observed data are $R^2 = 0.5831$, $R^2 = 0.6116$, $R^2 = 0.9470$ and $R^2 = 0.5963$ for NDSI, VSSI, SI-1 and SI-2 respectively for Batiaghata union whereas $R^2 = 0.5854$, $R^2 = 0.6116$, $R^2 = 0.9431$ and $R^2 = 0.8764$ for NDSI, VSSI, SI-1 and SI-2 respectively for Jalma union. The result of validity of soil salinity derived from remote sensing indices and in-situ measurement has highly correlation which beyond the 61% for maximum cases. Correlation coefficients fit relatively better for Jalma union than Batiaghata union. However, the remote sensing induces from SI model has better performance.

Conclusions

The climate change has diverse impact across the saline prone rural coastal areas of Bangladesh. The present study was undertaken to understand the spatial distribution of the soil salinity using satellite remote sensing data and to observe its relationship with in-situ measurements. The key findings of the research work is as follows-

- The maximum and minimum values are represented for the month of May 2023 and October 2022 respectively for all of sites according to the observed data.
- The correlation coefficient of satellite derived salinity and in-situ measurements are found about 61% for maximum indices. Highly correlated areas are Jalma union and Batiaghata union respectively.
- The remote sensing indices have demonstrated prominent performance in the present study.

There is potential of satellite remote sensing datasets to investigate further soil salinity mapping and monitoring at neighborhood scale. Subsequently, frequent in-situ datasets may be incorporated for spatio-temporal modeling and future prediction.

Authors Contribution

Conceptualization, M.A.E.A. and M.M.; methodology, M.M.; software, M.M.; validation, M.A.E.A., K.K.M. and M.M.; formal analysis, M.A.E.A., K.K.M. and M.M.; investigation, M.A.E.A., K.K.M. and M.M.; resources, M.A.E.A. and M.M.; data curation, K.K.M. and M.M.; writing—original draft preparation, M.M.; writing—review and editing, M.A.E.A., M.M.R., K.K.M., M.A.K. and M.M.; supervision, M.A.E.A and M.M. All authors have read and agreed to the published version of the manuscript.

Conflict of Interest

Authors declare no conflict of interest.

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Data Availability Statement

Data will be made available on request to the corresponding author.

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