Catena 222 (2023) 106786

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

Spatio-temporal variability in soil and water salinity in the south-central coast of Bangladesh

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ARTICLE INFO

Keywords:
Climate change
Salinity
Landsat imagery
Coastal areas
Bangladesh

ABSTRACT

Salinity in soils and water of coastal tracts in Bangladesh, one of the major challenges for agriculture, varies significantly due to multiple stressors, including the consequences of rapid changes in the climate pattern. However, their dynamics has not been studied in detail accentuating its importance for the management of agriculture. Here, we examined such changes along zones - defined by spatial proximity from the seafront towards inland in the south-central coast of Bangladesh. Samples of soil and water were collected at single-month intervals between November 2020 and June 2021. In April, a comprehensive soil sampling was conducted to examine spatial variability in relation to soil type and land use. Moreover, Landsat imagery-based salinity index was calculated. Our results showed that soil and water salinity gradually increased from January onwards and peaked during May. It decreased gradually from the seafront to inland, suggesting direct and indirect intrusion of salinity from the sea. A significant non-linear relationship was found between Landsat imagery-based salinity index and measures values ($r^2 = 0.79$, $p < 0.01$), indicating the Landsat imagery- based estimate could potentially be used for agriculture. Our observation also showed that salinity to soil and water was significantly low in highlands, croplands, and interior of polders as compared respectively to that of low land, fallow land, and exterior of polders. Our estimation of salinity in soil and water of the south-central coast of Bangladesh was significantly higher than that of historical records. This study, thus, would contribute to contemporary policy issues on cropland management along coastal Bangladesh.

1. Introduction

The coastal regions of Bangladesh are particularly vulnerable to climate change (Bhuiyan et al., 2012). The impacts of climate change can be multiple, including a relatively higher air temperature and more frequent extreme weather events, changing rainfall patterns, rising sea levels, and increased saltwater invasion and intrusion. By the end of this century, the average global air temperature is expected to rise by up to 2 °C (Olsson et al., 2014), suggesting a greater warming rate than the earth has experienced in the past 10,000 years (Short & Neckles, 1999). The world's coastal areas and deltas have been stated to experience sea-level rise due to climate change-mediated rise in atmospheric temperature (He & Silliman, 2019; Sherin et al., 2020). For instance, the global sea surface was raised by 19.5 cm 2004 from 1870 (Rhodes, 2018). Model-based projections estimated that sea levels will continue to rise in the future and in extreme cases, it can be up to a meter at the end of this century.

Sea level rise has multiple consequences, including the inundation of low-lying areas of the world, such as a large part of the Maldives and Bangladesh, one of the largest active deltas in the world. Specifically, Bangladesh is highly vulnerable to sea-level rise since it is only a few meters above sea level. Given its low-lying geography, a large area near the coast will be regularly inundated with tidal influence (i.e., high tide). An increase in sea level may cause an extensive forced migration of population, while this migration could have severe consequences for densely populated countries like Bangladesh (Szabo et al., 2016). Moreover, sea-level rise will change ecosystems and their services including primary productivity due to changes in soil and water salinity.

A part from sea level rise, increased salt intrusion in both rivers and the underground aquifer may also occur due to the reduced freshwater flows resulted from a negligible rainfall during the dry seasons (November-April) in Bangladesh. Thus, there is a possibility of increasing salinity in the tidal freshwater precinct (Megonigal & Neubauer, 2019). A rapid change in salt invasion and intrusion poses a

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https://doi.org/10.1016/j.catena.2022.106786
Received 1 June 2022; Received in revised form 8 November 2022; Accepted 9 November 2022
Available online 28 November 2022

serious risk of salinization in areas that were not affected before. However, the rate of soil salinization depends multiple factors including concentration of salts in the water, rate of its exposure and management practices adopted for restriction of salinization (Haque, 2006).

Soil salinity has adverse effects on most arable crops with effects ranging from partial to complete yield loss, which varies with soil type, crop species and their salt resistance capacities (Sheldon et al., 2017; Shrivastava & Kumar, 2015). Currently, salinity is one of the most limiting factors for agricultural production in the coastal region of Bangladesh (SRDI, 2019) since a large fraction of the coast estimating at some 10560 km^2 (out of 16890 km^2) is variably affected with salinity (Miah et al., 2020; Srdi, 2010). However, the level of soil salinity also varies along the coast with gradients ranging from 2 up to 16 dSm^{-1} (Mahmud et al., 2010). Usually, the salinity is relatively higher along the shoreline; in most cases, topsoil salinity is higher than deep soil (Ahmed et al., 2020). Despite there is general trend that salinity increases from the inlands to the coast, a number of factors can change soil salinity, including the installation of barriers to limit the intrusion of saline water (i.e., polder), agronomic practices (crop cultivation with mulching) and topography of the land (high *vs.* low lands). Moreover, the flushing of saline water with fresh water also changes soil salinity. All these suggest that there could be substantial variability in soil salinity across the coastal districts.

In the coastal area of Bangladesh, there is an apparent variation in soil salinity depending on the season (Salehin et al., 2018). Topsoil salinity is low during the wet season from June to October and starts to rise in January and peaks in April or May (Salehin et al., 2018). As a result, wet season crops such as *Aman* rice is grown in *Kharif-II* (1st July-15th October) (Clarke et al., 2015). On the contrary, crop cultivation is nearly impossible or difficult during dry periods, particularly during *Rabi* (16th October- 15th March) and *Kharif-1* (16th March-30th June) seasons, due to the high soil and water salinity. As a consequence, a vast majority of the lands remain fallow during the dry seasons with estimates at ~ 40–45% and ~ 30–35% during *Rabi* and *Kharif-1* seasons, respectively (Rafiquzzaman et al., 2010; Rahman et al., 2017). However, the soil salinity may also vary between months of a year and between years since its drivers (e.g., fresh water flow from upstream, rainfall, and evapotranspiration) are dynamic in nature.

Management practices can also affect soil salinity intrusion and development. For instance, establishing a barrier to restrict saline water intrusion (e.g., a polder or an earthen dyke) can reduce saline intrusion and, thus, soil salinity. In a number of studies, it was indicated that the salinity inside the polder is lower compared to its adjacent unrestricted areas (Haque et al., 2014). Moreover, the cultivation of crops and their agronomic management practices (e.g., mulching and application of fertilizer) can reduce soil salinity. For instance, the cultivation of crops with tillage breaks down the topsoil crust and capillary pores reducing evaporative loss of water, which results in less accumulation salt in the topsoil (Bezborodov et al., 2010).

Given that soil and water salinity are dynamic in nature and vary with several factors, including changes in freshwater flow from the upstream, salinity water intrusion rate into the soil, the salt buffering capacity of the soil, and other agronomic management practices, the extent and level of soil and water salinity in the coastal area of Bangladesh are possibly changing with time and space. A few recent studies have been conducted in Bangladesh to investigate the variations of salinity near the southwest coastal areas (Comilla and Noakhali districts) (Ahmed et al., 2020; Das et al., 2020), but similar studies were not conducted in the southern part (Patuakhali, Borguna, Jalakhati, and Barishal districts). However, no recent comprehensive study examined water and soil salinity on the south-central coast after 2009, although there are numerous indications that salinity is increasing with time (Dasgupta et al., 2015b; Srdi, 2010). Therefore, up-to-date soil and river water salinity information is needed to understand their changes with time and space.

Although laboratory-based analysis of soil and water salinity could provide a reliable estimate, it is often difficult to collect samples from large areas, making it inconvenient for collecting data for the whole area. As an alternative, satellite image-based salinity analysis could be a good option. Several previous studies applied normalized difference salinity index (NDSI) to determine soil salinity from Landsat imagery (Ghazali et al., 2020; Günal et al., 2021; Rahman and Ferdous, 2017).

Considering these facts, we conducted a comprehensive study with the objectives to examine the spatial and temporal changes in soil and water salinity in the south-central coastal areas of Bangladesh.

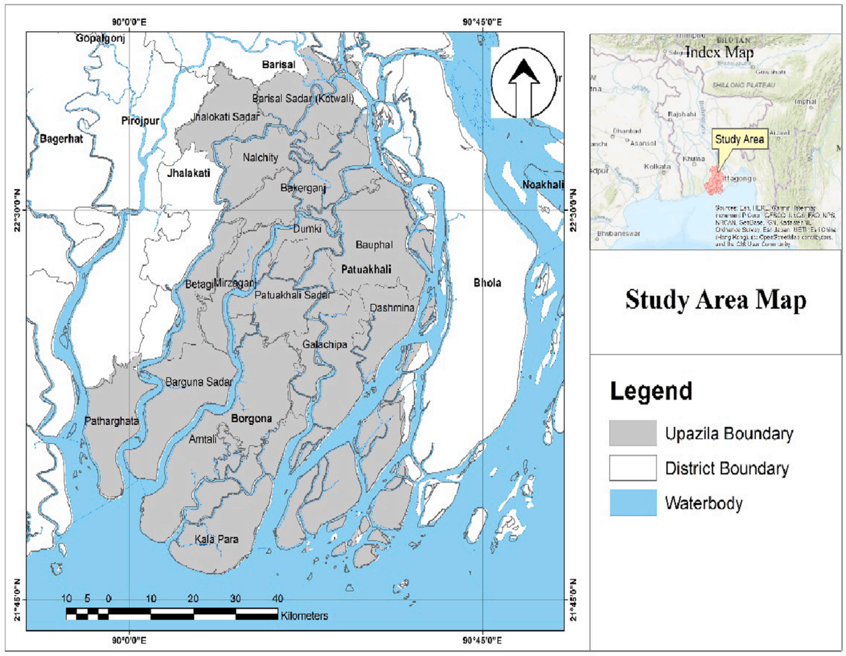
2. Materials and methods

2.1. Study area

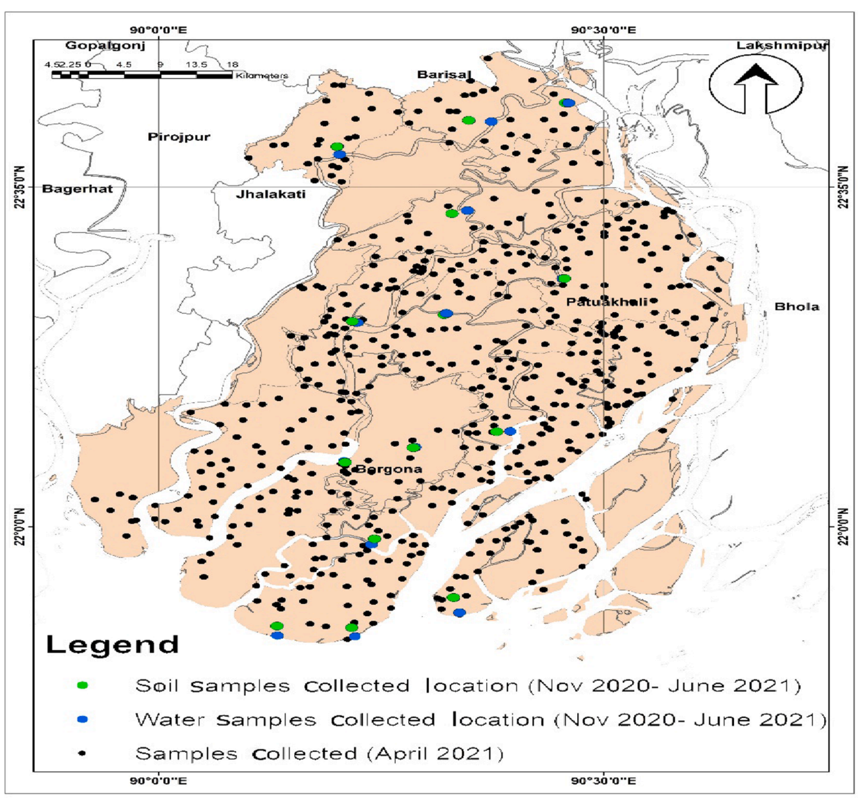
This study was conducted in the south-central coastal part of Bangladesh, a part of the Bengal delta (Fig. S10). Salinity is one of the foremost hydrological problems in the delta. The water and soil salinity levels vary across the delta (Table S4 and S5). This study area covers fourteen Upazilas (sub-units of districts) in four districts (Barishal, Jalakhati, Patuakhali, and Borguna districts) (Fig. 1A, shown with the gray areas). Geographically the study area is located between latitudes- 21.819°N to 22.754°N and longitudes- 89.990°E to 90.449°E. This region has numerous tidal rivers and creeks, and its elevation is only a few meters (up to 3 m) above sea level (Brammer, 2014). A part of the area is protected from tidal water with a few meters of raised earthen embankments, known as a polder. According to BARC (2010), the water level during monsoon period in the medium–low and medium–high land is 90–180 cm and a maximum of 90 cm, respectively while the high land water remains above the normal flood level. The study area receives most of the annual rainfall during June-October while a negligible amount of rainfall occurs in the rest of the period (Yu et al., 2019). The temperature also fluctuates in the year with the highest temperature in the months of March-May, and the lowest is in December-January (Fig. S8 and S9).

2.2. Data collection

For the current study, secondary data were collected from literature and reports, while primary data on soil and water properties were collected through direct sampling. Samples (soil and water) were collected between November 2020 and June 2021 along the gradient from near the seafront to the 120 km inland of the Bay of Bengal (Fig. 1B). A stratified sampling procedure (a field that has been partitioned into many subunits) was applied to collect soil and water samples (see Supplementary Material S1). The study area was divided into three zones from the south (seafront) to the north (the inland), while a similar grouping was applied from the east to the west (details in Figs. S1 and S2). However, for our convenient access to the sites the sampling locations differed slightly in geographical location. Global Positioning System (GPS) technology was used to locate the collection sites of soil and water samples. From each location, soil samples were collected inside and outside the polder. Soil samples (0 to 20 cm deep) were randomly collected from 3 or 4 places and composited before analysis. Water samples were collected from the water surface of the rivers (Kirtankhola, Biskhali, Bighai, Pyra, Laukhati, Tetulia, Galachipa, Andermanik, and Kuakata sea) and cannels using plastic bottles. The salinity of all the soil and water samples was evaluated by measuring the electrical conductivity (EC) in the laboratory. Specifically, 5 g of soil was shaken with 50 ml of distilled water for 30 min, and then reading was taken with an EC meter (Hanna Instrument 86304 N, Woonsocket, Rhode Island, USA). The measured EC values were then converted to equilibrium conductivity (EC_e) as a measure of actual soil salinity using conversion factors reported in the literature (Lam et al., 2022; Mahmud et al., 2010; Wang et al., 2017). Similarly, we also measured the salinity level in water by recording the EC values in the water using an EC meter. In addition, a comprehensive soil sampling (562 samples) was done in April following



A



B

Fig. 1. The geographical location of the study area (A) and sample collection points (B).

stratified sampling techniques (Fig. S2) as discussed before (Fig. 1B) since the salinity is expected to be relatively high in this month. The soil samples were collected based on land type (medium–low, medium–high and high land) and land use (crop land and fallow land). Following the similar method, we also determined soil salinity while we also measured the soil moisture using gravimetric method. Briefly, a moist sample of about 20 g was weighed, and then dried at 105 °C for 48 h. Next, the dried soil was reweighed, and the water loss is calculated as a percent using the formula below (Dobriyal et al., 2012).

$$\%\text{Soil moisture} = 100 \times (\text{Weight of wet soil (g)} - \text{Weight of dry soil (g)}/\text{Weight of dry soil (g)}) \quad (1)$$

2.3. Satellite-based salinity index determination

Furthermore, we also collected Landsat images (OLI) taken on 24th March 2021 to get cloud- free images. All images were accessed through the United States Geological Survey (USGS), website- EarthExplorer (usgs.gov). The study areas were covered by 137 paths and 45 rows. The spatial resolution of the band was 30 m.

We used the GIS-based Normalized Difference Salinity Index (NDSI) to determine the soil salinity index (Aldakheel et al., 2005; Shukurov, 2020). We calculate this based on the following equation:

$$NDSI = \frac{R - NIR}{R + NIR} \quad (2)$$

2.4. Statistical and other analysis

The collected data were analyzed using JMP 8 software (JMP Statistical Discovery LLC). After checking model assumptions, we performed ANOVA (analysis of variance) using location as a fixed factor. After the ANOVA, Tukey's HSD (α = 5%) was used to compare the treatment groups. The soil and water salinity data were analyzed using the month and distance from the sea (i.e., 0–20 km, 21–40 km, 41–60 km, 61–80 km, 81–100 km, and 101–120 km) as a fixed factor. We also divided three zones (low, medium, and high salinity) and analyzed the variation of salinity between those zones. Similarly, the EC values of soil samples collected in April 2021 were analyzed using land type, land uses, and distance from the sea (km) as fixed factors. Moreover, soil salinity variation inside and outside the polder was analyzed for November 2020 (when salinity is relatively low) and for May 2021 (when the salinity is relatively high) using polder and location as fixed factors (i.e., two-way ANOVA). We prepared a spatial soil salinity map for April 2021 based on salinity classes and land types to illustrate the variation in soil salinity across different locations using ArcGIS 10.8

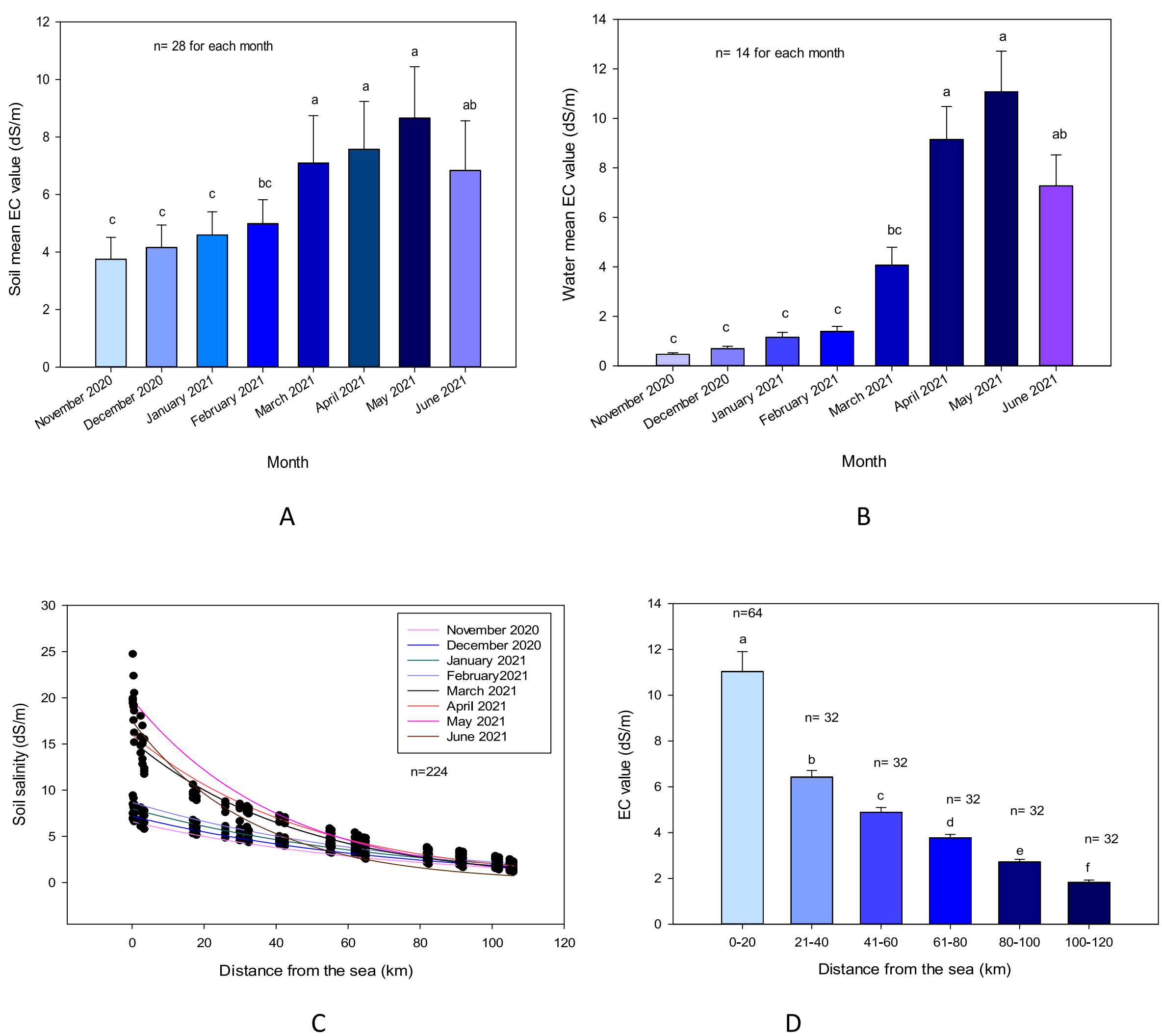


Fig. 2. Monthly and spatial variation of soil and water salinity in the southern coastal areas in Bangladesh (November 2020 -June 2021). Panel A and B represents the monthly soil and water salinity variation, Panel C and D represents the monthly spatial variation of soil salinity with distance from the sea (km), Panel E and F represents the monthly spatial variation of river water salinity with distance from the sea (km), and panel G represents variation of soil EC value in different salinity zone. Mean that do not share the same letters are different (Tukey's b, α = 5%). The error bars represent the standard error of the means.

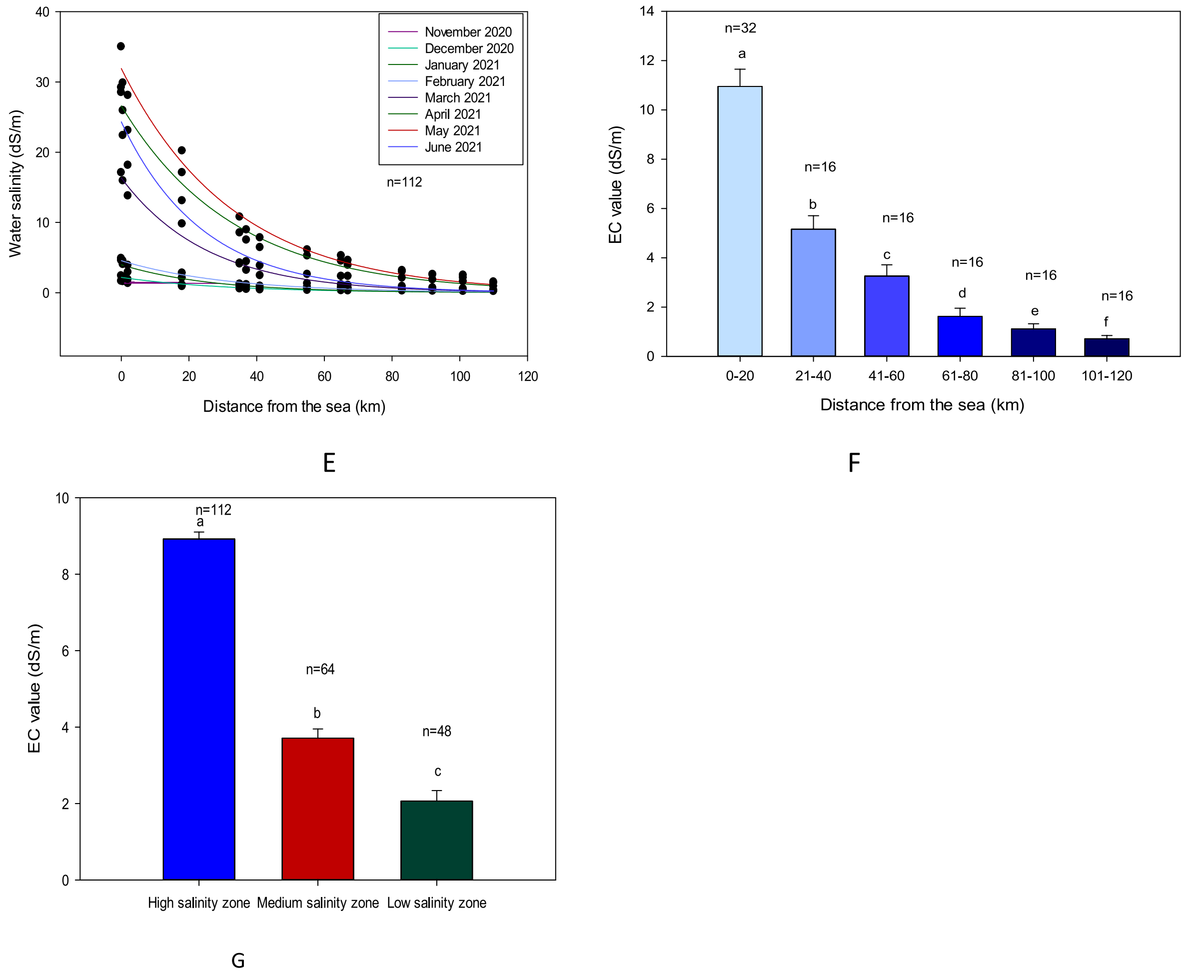


Fig. 2. (*continued*).

software (ESRI, Redlands, California, USA). Different graphs were made using the Sigma plot 14.0 software package (Systat Software Inc, Chicago, USA). Moreover, linear and non-linear relationships were used to examine the associations of variables.

3. Results

3.1. Temporal and spatial variation of salinity in 2020–2021

In the southern coastal districts of Bangladesh, soil and water salinity varied significantly in different months (i.e., November 2020 to June 2021 (Fig. 2A and 2B, $p < 0.05$). The soil and water salinity started to increase from November, and it peaked in May and then started to decline in June. In November, the lowest soil mean EC value was 3.75 dSm^{-1}, and the highest was 8.65 dSm^{-1} in May 2021. Similarly, the mean EC value of river water was below 1.0 dSm^{-1} in November. After this month, the salinity of the river water progressively increased until May (11.65 dSm^{-1}) and gradually went down after the beginning of June (7.63 dSm^{-1}).

There was a significant relationship between soil salinity and distances from the sea, with higher salinity values observed close to the sea (Fig. 2C). The soil salinity, measured in various months, was non-linearly associated with the distance of sample collection from the sea. For all months, the value of r^2 was 0.93 or higher ($p < 0.01$). The regression slope increased for drier months (Table 1) and soil salinity reduced as the distance from the sea increased. Similarly, the monthly river water salinity was plotted against distances from the sea, showing a non-linear relationship (Fig. 2E). In most cases, the r^2 values were 0.95

Table 1
Non-linear correlation matrix between soil salinity and distance from the sea (km). The following equation was applied: $Y = ae^{-bx.}$

Month	Model parameter		Equation	r^2 Value	*P*-Value
	a	b			
November 2020	6.59	−0.014	$Y = 6.59e^{-0.014x}$	0.98	0.01
December 2020	7.18	−0.013	$Y = 7.18e^{-0.013x}$	0.98	0.01
January 2021	7.99	−0.013	$Y = 7.99e^{-0.013x}$	0.98	0.01
February 2021	8.67	−0.013	$Y = 8.67e^{-0.013x}$	0.98	0.01
March 2021	15.38	−0.021	$Y = 15.38e^{-0.021x}$	0.93	0.01
April 2021	16.03	−0.020	$Y = 16.03e^{-0.020x}$	0.93	0.01
May 2021	19.78	−0.024	$Y = 19.78e^{-0.024x}$	0.93	0.01
June 2021	17.63	−0.030	$Y = 17.63e^{-0.030x}$	0.95	0.01

Table 2
Non-linear correlation matrix between river water salinity and distance from the sea (km). The following equation was applied: $Y = ae^{-bx.}$

Month	Model parameter		Equation	r^2 Value	*P*-Value
	a	b			
November 2020	1.34	−0.027	$Y = 1.34e^{-0.027x}$	0.96	0.01
December 2020	1.85	−0.032	$Y = 1.85e^{-0.032x}$	0.96	0.01
January 2021	3.55	−0.042	$Y = 3.55e^{-0.042x}$	0.95	0.01
February 2021	3.82	−0.033	$Y = 3.82e^{-0.033x}$	0.97	0.01
March 2021	12.70	−0.039	$Y = 12.70e^{-0.039x}$	0.96	0.01
April 2021	24.70	−0.030	$Y = 24.70e^{-0.030x}$	0.98	0.01
May 2021	30.22	−0.031	$Y = 30.22e^{-0.031x}$	0.98	0.01
June 2021	19.44	−0.036	$Y = 19.44e^{-0.036x}$	0.97	0.01

or higher ($p < 0.01$) suggesting a good non-linear relationship between river water salinity and distance from the sea (Table 2). When the salinity of the study area is compared for subzones (i.e., three zones), a significantly variation was observed with larger values for the area near the seafront ($p < 0.05$, Fig. 2G).

3.2. Spatial variation of soil salinity in April 2021

The spatial soil salinity map indicates that soil EC values vary between 2.0 and 18.0 dSm^{-1} in April 2021 (Fig. 3A). Soil salinity was relatively higher (>8 dSm^{-1}) near the coastal regions and decreased for distant areas from the coast. Similar to the measurement-based salinity analysis, the NDSI value was also low (representing a high salinity) near the coast, while it increased for inland areas (Fig. 3B). Out of 4944 km^2 study area, the area under slightly saline, moderate saline, high, and severely saline category was 714, 1481, 2311 and 438 km^2, respectively.

Moreover, the EC values of soil samples collected in April were analyzed using land type as a fixed factor (Fig. 3C). The average EC value was relatively higher in medium–low land (5.56 dSm^{-1}) in comparison to medium–high (3.13 dSm^{-1}) and high land (1.75 dSm^{-1}). According to land types, the overall trend of soil salinity was in the order of medium–low > medium–high > high. When the salinity was compared under six categories in the direction of the South (the seafront) to the North (inland), a significant variation was observed, a phenomenon also reported in the earlier section (Fig. 3D). Specifically, the salinity was 9.0 dSm^{-1} and 2.1 dSm^{-1} at 0–20 and 101–120 km distance from the sea, respectively. The EC values were similar for all the subzones in the direction of the East to the West (Fig. 3E). Besides, soil EC value also varied significantly with the land uses ($p < 0.05$, Fig. 3F). The salinity measured in the fallow lands were relatively higher than the croplands (7.24 dSm^{-1} *vs* 3.08 dSm^{-1}).

3.3. Variation of soil salinity inside and outside of the polders in 2020–2021

Our analysis of salinity variations between inside and outside the polders showed that it was much lower inside the polder than outside (for instance, 5.95 dSm^{-1} *vs* 6.90 dSm^{-1} in November 2020 and 16.98 dSm^{-1} *vs* 24.70 dSm^{-1} in May 2021 for Rangabali Upazila) (Fig. 4A and 4B). However, overall the variation in soil salinity between inside and outside the polder was much pronounced in locations near to the sea (Fig. S6).

3.4. Historical comparison of soil salinity

In 1973, there were no salinity-affected areas in Barishal and Jalakhati districts (Fig. 5A). In the same time, about 53% and 75% of total cultivated land were affected by salinity in Patuakhali and Borguna districts, respectively. However, the levels of soil salinity were slightly (2–4 dSm^{-1}) to moderate (4–8 dSm^{-1}). In almost all south-central coastal regions, the land affected by salinity increased in 2009 compared to 2000 (Fig. 5B and 5C) while the changes was even more pronounced in 2021. For instance, the salinity affected area in the Patuakhali and Borguna regions was about 85% of the total cultivated land (Fig. 5D) with more lands under severe (>16 dSm^{-1}) and highly saline (8–16 dSm^{-1}) affected category. Similarly, a conversion of agricultural lands from non-saline to saline category was observed but with a relatively lower rate of change. Specifically, salt-affected area in Barishal and Jalakhati districts was more ~ 30% and 45% of the cultivated land (Fig. 5D). This implies that the saline areas in the southern coastal areas extended and that the salinity level increased over time.

3.5. Relationships

We found a significant non-linear relationship between our measured soil salinity data (April 2021) with Landsat imagery based analysis ($r^2 = 0.79$, $p < 0.01$) (Fig. 6A). Moreover, the soil salinity positively associated with water salinity ($r^2 = 0.69$, $p < 0.01$) (Fig. 6B). Besides, we found linear relationship between soil moisture and soil salinity. In case of medium low land, the relationship between soil moisture and soil salinity was positive (Fig. 6C). Similarly, for medium high and high land, we found negative linear relationships between soil moisture and soil salinity (Fig. 6D & 6E).

4. Discussion

4.1. Spatial variation of salinity

Salinity varies with a number of factors including the capillary rise of saline groundwater, saline water intrusion, and management practices (Rahman et al., 2017). The extent and level of soil and water salinity in the coastal areas of Bangladesh are possibly changing with time and space. Different factors (climate, topography, and soil type) are also responsible for the spatial distribution of soil salinity (Xu et al., 2019). From measurement-based and NDSI analyses, it is evident that soil salinity varied significantly with locations (i.e., distance from the sea). Specifically, soil salinity was relatively higher in locations where the rate of saline water exposure is high (Fig. 3, 4 and 5). According to the detailed analysis, the variation of soil salinity within a zone varied significantly (Fig. 2 and 3). These findings are in contrast to many previous reports that categorized the whole areas under one salinity class (Ahmed et al., 2020; Das et al., 2020; Rahman et al., 2017). One of the possible reasons of this divergence is that many of the previous studies did not thoroughly survey the soil samples, while we did a detailed soil survey. These spatial variabilities in soil salinity might have been contributed by exposure to saline water, the capillary rise of groundwater and management practices (discussed in the later section). Similarly, spatial variation of river water salinity mostly depends on the degree of inward infiltration of tides and freshwater flow from the rivers (Dasgupta et al., 2015a). In the south-central coastal districts, freshwater comes from two large rivers (the Padma and the Lower Meghna river) (Dasgupta et al., 2015a). However, during the dry period, silt deposition in the rivers' tributaries caused by the construction of dams and/or embankments (Dasgupta et al., 2015a) reduces the freshwater flow of the rivers which increases salt water intrusion. (Mondal et al., 2013). In the study area's southern part (near the coast), freshwater flow reduces during the dry seasons, and river water is contaminated with salt water from the Bay of Bengal. On the contrary, in the northern part, there is a large river (the Meghna and its tributaries) that flows fresh water all year and thus restricts the salinity intrusion resulting in a lower salinity in that area. That is why we found a spatial variation of river water salinity in our study areas.

4.2. Temporal variation of salinity

Soil salinity can vary due to multiple causes including changes in exposure to saline water (i.e., distance from the sea), soil moisture, and cropping season. In our study, we observed significant variation in soil and water salinity during the dry periods in the southern coastal areas of Bangladesh. The salinity is relatively high in the drier months. Specifically, we observed a significant rise in soil and water salinity from the months of November 2020, and it peaked in the month of May 2021 and then started to decline again in the month of June 2021. Similar to our study, previous studies also reported that soil and water salinity gradually increases from November and declines sharply at the end of May (Dasgupta et al., 2015a,b; Rahman et al., 2019). In a recent study, SRDI (2017) reported soil salinity in Patuakhali Sadar and Kalapara Upazila, respectively at 4.3 dSm^{-1} and 6.2 dSm^{-1} in April, which was lower than our measured values. Similarly, Dasgupta et al. (2015a) reported the historical soil salinity variations (2001 and 2009) in the southern coastal areas of Bangladesh. Compared to these reports, our measured salinity was also much higher. This is plausible because the salt might have

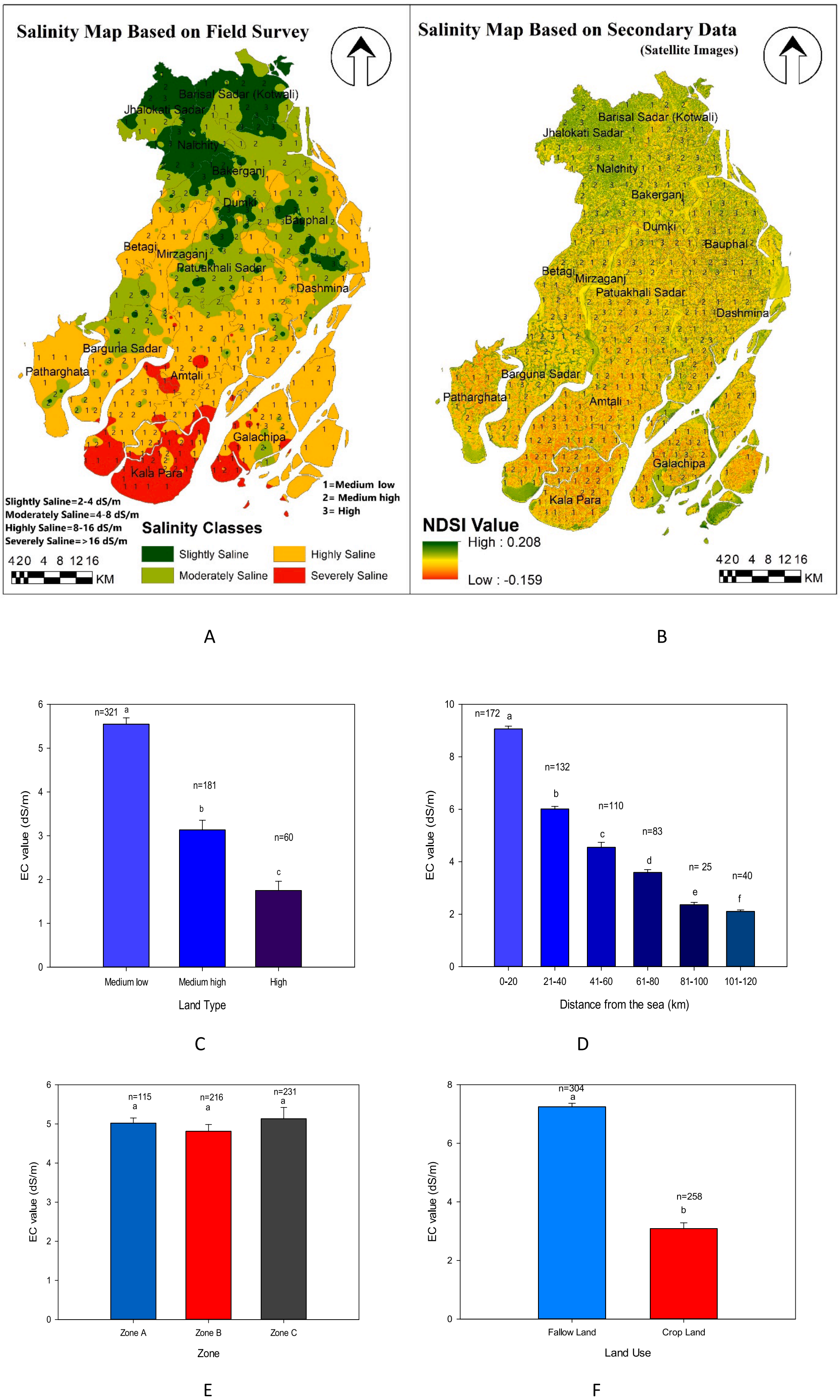


Fig. 3. Spatial distribution of soil salinity in the south-central coast of Bangladesh (April 2021). Panel A represents the measurement-based variability classification (April 2021), Panel B represents the satellite based soil salinity index (NDSI), Panel C represents variations of soil EC value in different land types, Panel D represents spatial variations of soil EC value in east to west from the coast (different distances from the sea), and Panel E represents the variation of soil EC value from south to north from the coast (divided three-zone), and Panel F represents the variations of salinity based on land use activities. Each bar represents the mean EC value (dSm^{-1}) of soil salinity. Mean that do not share the same letters are different (Tukey's b, $\alpha = 5\%$). The error bars represent the standard error of the mean.

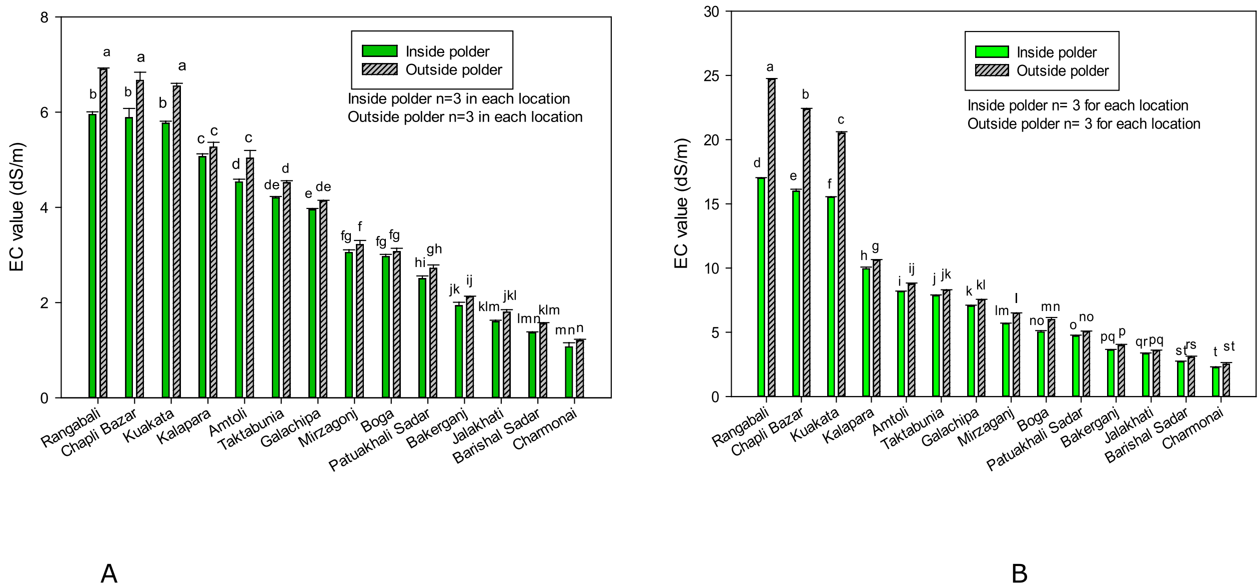


Fig. 4. Variation of soil EC value inside and outside of the polder. Panel A represents the salinity variations in November 2020, and Panel B represents the variations of salinity in May 2021. Means that do not share the same letters are different (Tukey's b, α = 5%). The error bars represent the standard error of the mean.

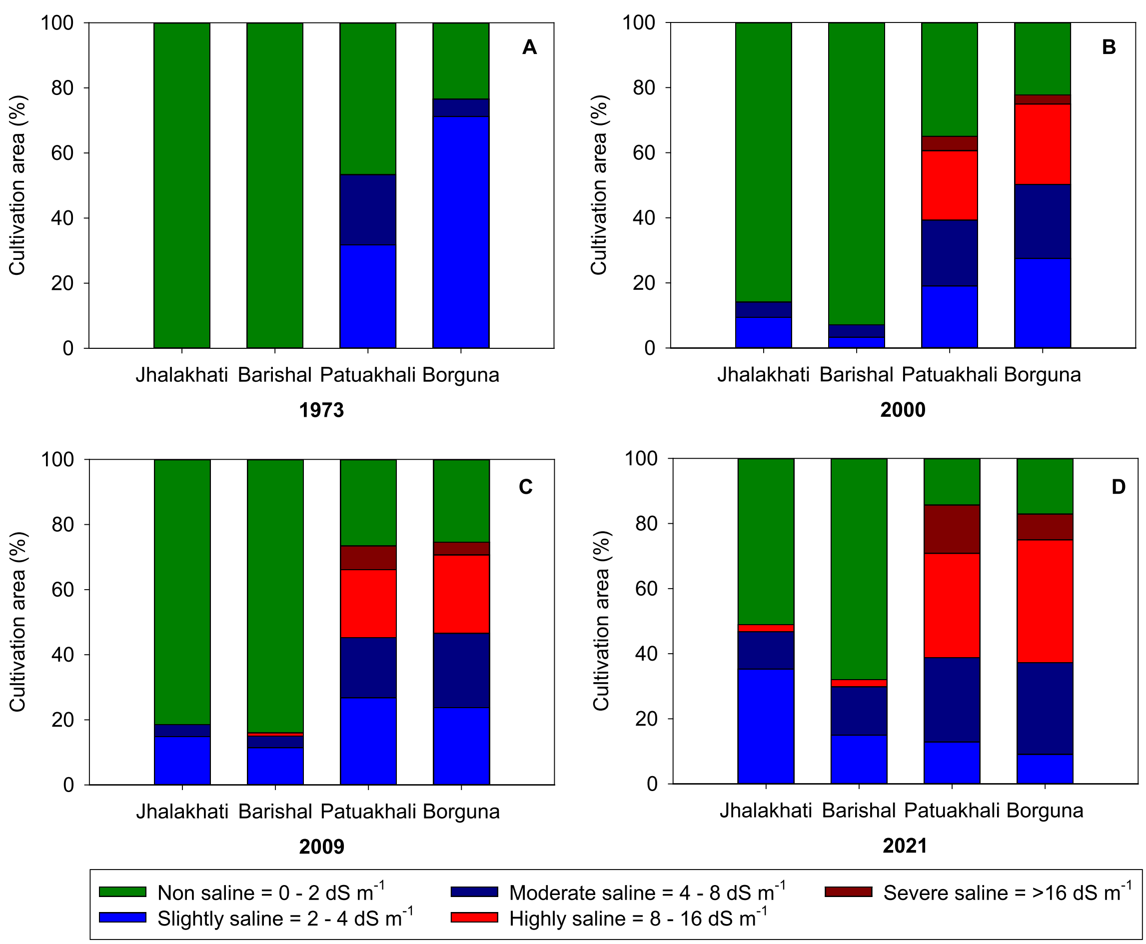


Fig. 5. Comparison of soil salinity affected areas between 1973 (A), 2000 (B), 2009 (C), and 2021 (D) (measured) in the southern coastal regions of Jalakhati, Barishal, Patuakhali, and Borguna district. Each bar represents the different salinity-affected areas in percentage (%).

accumulated over time. We also observed that surface water salinity varied seasonally, and it was relatively high during the dry periods of the year. Dasgupta et al. (2014a) observed, similarly to our study, that the maximum water salinity in the Andermanik river in May 2011 was 19.8 dS m^{-1} which was lower than our measured value 20.29 dS m^{-1}. There are several reasons for temporal salinity variations. Firstly, capillary

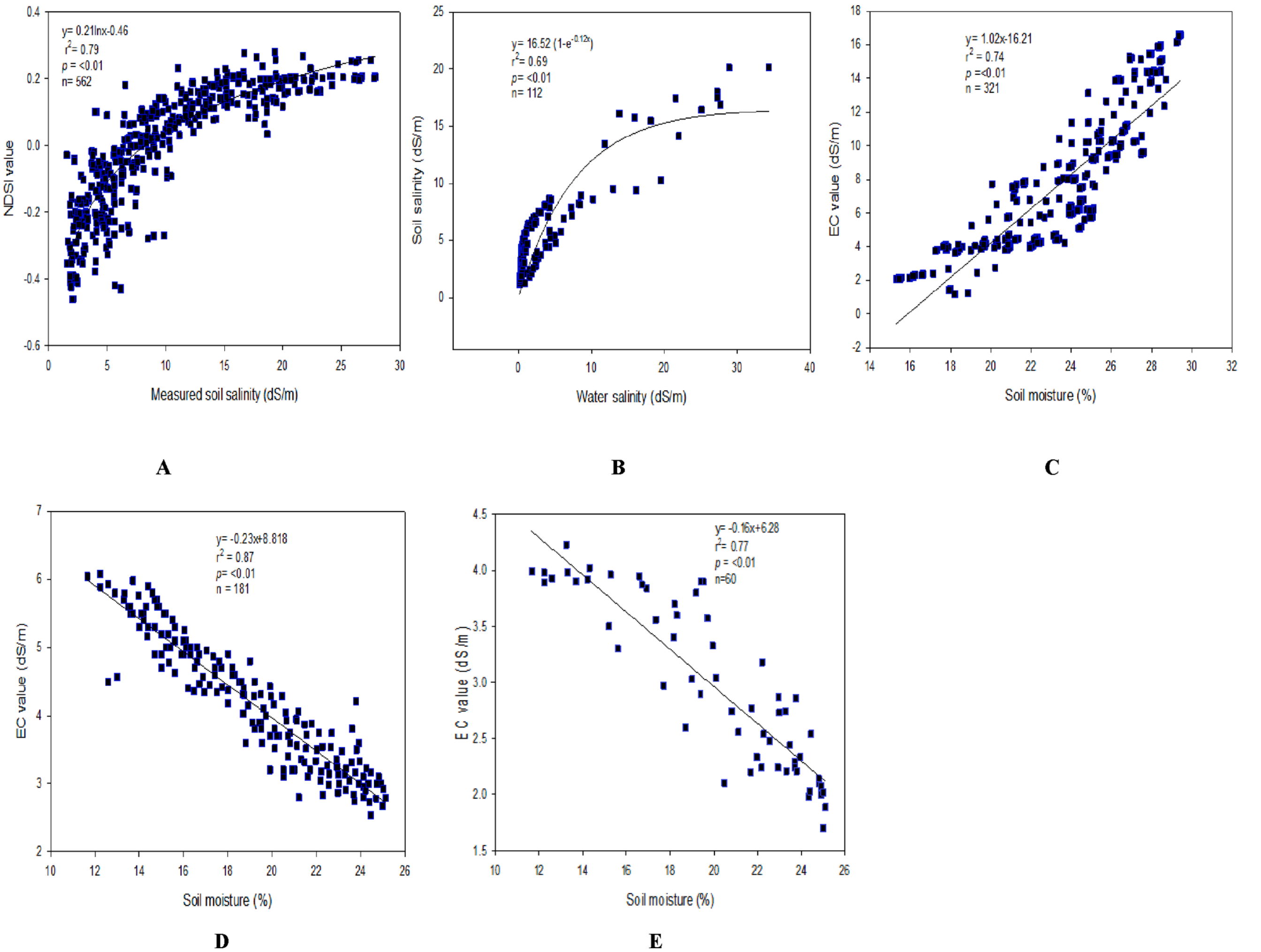


Fig. 6. Panel A represents the non-linear relation between NDSI value and measured soil salinity, panel B represents non-linear correlations between soil and water salinity. While panel C, D and E represents linear relationship between soil moisture and soil EC value for medium–low land, medium–high land, and high land, respectively.

raise of groundwater is one of the most dominant factors. During the dry season, due to low rainfall, salts cannot leach out, and thus salt accumulates on the soil surface because of capillary raise (Fall, 2017; Lv et al., 2013; Rahman et al., 2017; Thiam et al., 2019). Consequently, most of the land in the south-central coastal regions remains fallow during the dry seasons (He et al., 2014). In contrast, high rainfall in the rainy seasons (June-September) lead to the leaching of the accumulated salt resulting in lower soil salinity. Secondly, the inundation of soil with salt water may be one of the other important factors that contributed to the development of soil salinity in the coastal areas of Bangladesh.

River water salinity is relatively high during the dry seasons (November -May), primarily caused by the reduced freshwater flow from the transboundary Ganges River (Dasgupta et al., 2015a). The tidal water often directly inundates medium low land, and possibly the groundwater level is very close to the surface (<1.0 m) (Salehin et al., 2018). Therefore, a large amount of salts accumulate into the soil. As a result, soil salinity may rise depending on the exposure of salt water and its level of salinity. A significant positive relationship was observed between soil moisture and soil EC values for medium low land (Fig. 8), which is the opposite of the existing literature (Dasgupta et al., 2015a; SRDI, 2019). In contrast, there was a negative relationship between soil moisture and soil EC value in medium–high and high land indicating that a decrease in soil moisture increases soil salinity. Due to the scarcity of rainfall (decline soil moisture), the groundwater level is low at that time (Salehin et al., 2018). Consequently, the salt was accumulated on the top soil due to capillary raise (Salehin et al., 2018), a common phenomenon usually observed in many saline soils. Moreover, we found a significant positive correlation between river water and soil salinity suggesting that saline water intrusion is one of the prime diverse for salinization in the coastal area of Bangladesh.

4.3. Topography and management affects soil salinity

Salinity can also vary due to changes in the land type and management practices. We observed an uneven distribution of soil salinity in the southern coastal areas due to the topography (i.e., elevations from the sea). Two different scenarios were observed- a) salinity was high in the low-lying areas of zone A (i.e., areas directly exposed to the sea), and b) salinity was low in the high lands in the zones which is away from the coast. This noticeable result possibly occurred due to direct saltwater intrusion to the low-lying areas, while capillary rise may be the main driving force for the salinity development in the high lands of the area away from the sea. The direct exposure of saline water to the soil occurs in areas where there is no barrier (polder). In some areas, saline water may also enter into the field by leakage of vulnerable polders. Subsequently, when the dry season approaches, the soil becomes dry and increases salinity in the surface soil (Lv et al., 2013).

Management practices such as the cultivation of crops, mulching, etc., can reduce soil salinity. We found a significant variation in soil salinity between cropland and fallow land (Fig. 5D). The cropland salinity was reasonably lower than the fallow land. Because cropland is usually covered with crops and the groundwater levels remain low. However, soil salinity levels rise in the fallow land due to the capillary rise of the shallow groundwater table. Additionally, dry-season crop cultivation mainly depends on irrigation water. Because during the dry periods, the rivers, canals, and ponds water are highly salinized. Farmers often depend on groundwater to irrigate their fields (Rahman et al., 2019). Therefore, excessive groundwater use raises the water table and carries brackish water into the aquifers (Foster et al., 2018). Subsequently, it increases salinity in the root zone of the crop.

The seawater moves inside the rivers during tidal flow, which may cause soil salinization (Yadav et al., 2020). Polders are installed in some southern coastal districts to protect the land from river water intrusion. Restriction of direct exposure of soil to river water can reduce soil salinity development. We found a significant effect of polder installation in the southern coastal areas of Bangladesh. The salinity was significantly lower inside the polder than outside. Haque et al. (2014) found that near the southern coastal regions, soil salinity inside the polder is lower than outside the polder. These results suggest that the installation of a polder can be an effective method of soil salinity reduction in coastal areas of Bangladesh. Nevertheless, it depends on the proper management of the polder. Because of natural calamities (cyclones and storm surges) and high tide, the polder overflowed with saline water. Due to poor water management (e.g., drainage) creates water logging inside the polder (Ghosh and Mistri, 2020) and increases soil and water salinity (Haque et al., 2014).

4.4. *Historical variability of salinity*

Salinity levels are not stable over across the years, while it is increasing over time. In 1973 there were no salinity-affected areas in Jalakhati and Barisal districts, but in 2021, 45% and 30% of total cultivated land were affected by salinity, respectively. Similarly, in both Patuakhali and Borguna districts, about 85% of total cultivated land was affected by salinity in 2021. However, in 1973 it was 53% and 75% for Patuakhali and Borguna districts. The rapid change in soil salinity might be associated with the soil's exceeding salt buffering capacity (i.e., the ability of the soil to resist change). Soil Resources Development Institute (SRDI) reported an average salinity increase of about 0.74% per year (Srdi, 2010). According to the SRDI and our salinity-measured data, in the southern coastal districts, there has been a considerable increase in soil salinity over the last 12 years (2009 compared to 2021). The salinity level is likely to rise in the coming decades due to changes in weather and climate. Dasgupta et al. (2015b) predicted that salinity in 2050 will be much higher than in 2009, and in 2050 approximately 39% of coastal land will be affected by salinity. Climate change, declining rain intensities, and increasing evapotranspiration over the years, combined with sea-level rise, will lead to higher salinity levels in 2050 compared to 2009. These results indicate that salinity levels are increasing, and climate change will exacerbate the problems in the future.

4.5. *Effect of salinity on crop cultivation*

Salinity is one of the most important constraints for crop production in coastal areas (Clarke et al., 2015; Rahman et al., 2019). In the coastal regions, salinity directly affects dry season (*rabi* season) crops. During the dry periods, the water and soil salinity remains high, especially between March and May. We observed that near the coast and in the intermediate zone, salinity is above the threshold levels (>4.0 dS/m) for most crops. Close to the coast, crop cultivation is impossible in severe cases. About 15% of the prevailing cropland remains fallow due to salinity (Ministry of Agriculture, 2013). Nevertheless, in the northern part (Barishal and Jalakhati district) of the coastal zone, salinity is much lower than in the south (Barguna and Patuakhali district). So, in the northern part, *boro* rice is primarily cultivated during the *rabi* season (Ibrahim et al., 2017). On the other hand in the Patuakhali and Borguna districts, most of the land remains fallow because of severe soil salinity and insufficient water for irrigation (Rahman et al., 2017). Therefore, Fallow-T. aman- Fallow (*rabi-Kharif 1-Kharif 2*) is the dominant cropping pattern (yearly sequence of a growing crop) in 33 Upazilas out of 42 in the south-central coastal districts (Ibrahim et al., 2017). The second and third dominant cropping patterns are Mungbean – Fallow – T. Aman and Boro – Fallow – T. Aman, respectively (Ibrahim et al., 2017). Spatial and temporal variations of soil salinity, soil properties (physical and chemical), and climate are the dominant factors for the variability of cropping patterns (Carcedo et al., 2022). These variable cropping patterns directly impact on the cropping intensity (the number of crops from the same field during one agricultural year) of that region. Subsequently, the average cropping intensity of the south-central coastal districts is only 164% (BBS, 2021). Therefore, increasing cropping intensity is important because it could significantly improve national food security.

4.6. *Measurement-based salinity values and satellite-based salinity index*

Understanding the spatial variability in soil salinity is often challenging since it requires direct soil sampling from a large area, making it laborious and cost-intensive. However, in alternative to measurement-based estimates, remote sensing-based salinity estimation can often provide reliable estimates provided data are validated and customized for a location (Günal et al., 2021; Saleh, 2017; Zribi et al., 2011). Here, we found a significant relationship between measurement-based salinity values and satellite-based salinity index. Our results can provide a basis for future research in monitoring the soil salinity in the coastal area.

4.7. *Limitations and scope for further research*

We collected soil salinity data of the study area for the year 1973, 2000, and 2009 from the SRDI (Soil Resource Development Institute) annual report, 2010. The data were reported as average values for different categories of soil salinity (such as low, medium, and high), while the total area under each category was also reported. However, it is unknown how many samples were taken to generate the values.

This study needs to be extended for several years and to other regions in the coastal areas of Bangladesh to create a comprehensive dataset. In addition, parameters related to soil nutrients (micro and macro), groundwater level, and soil texture should also be included. Besides, further validation of satellite-based salinity indexes is needed for its application in Agriculture.

5. Conclusion:

The number of saline-affected regions in Bangladesh's southern districts has increased over the last few decades. The salinity was unevenly distributed in different Upazilas of southern coastal districts. Near the coastal Upazilas, salinity levels were much higher than Upazilas moved to the north of the coast. Additionally, there were a variety of land types within an Upazila. Variations in salinity levels were observed by land type. The salinity levels in highlands were generally lower than those in medium lands. Moreover, the saltiness of soil and river water changed differently during the dry months. Salinity levels gradually increased from November and reached their highest in May. There was a strong correlation between salinity (soil and water) and distance from the sea. The soil and water salinity were high near the shoreline and unsuitable for crop production. A comparison of historical salinity-affected areas with our measured data shows that salinity-affected areas increased over time. The saltiness of the soil is>8.0 dSm^{-1}. Additionally, river water salinity ranges from 20 to 30 dSm^{-1} by the end of the dry season. Due to high salinity levels, most coastal areas remain uncultivated during the dry season. For this reason, the cropping intensity in the south-central coastal districts is below 164%. So, in the south-central coastal regions, improved cropping practices (mulching, salt-tolerant varieties, deep-tillage, etc.) and polder management are required. Therefore, appropriate zone-specific salinity mitigation strategies should be formulated to limit further soil salinization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgement

We are grateful to the regional head of the Barisal and Patuakhali SRDI office for their information during data collection. We greatly thank the Upazila Agriculture Officer (UAO) of Bauphal, Dasmina, Patuakhali Sadar, Mirzagonj, Amtoli, Borguna, Klapara, Jalakhati, and Barisal Sadar for their valuable information and support during the data collection.

Founding.

This paper is part of a PhD study financially supported by Nuffic OKP Project "Climate Smart Agriculture for a Resilient Coastal Bangladesh (project number OKP-BGD 103561)".

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.catena.2022.106786.

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