



Mapping Salinity Fronts: Spatial–Temporal Trends of Saline Water Intrusion in Southwest Bangladesh

S M Sazzad Ahmed Shovon

Assistant Professor, Department of Civil Engineering, Dhaka International University, Dhaka 1212, E-mail: sazzad.civil@diu.ac

Abstract. Saline water intrusion into coastal aquifers, rivers, wetlands, and agricultural soils is a critical environmental and socio-economic issue in the Ganges–Brahmaputra–Meghna (GBM) delta, with southwest Bangladesh among the most affected regions. This study synthesizes in-situ monitoring, satellite remote sensing, and statistical trend-detection methods to define and map salinity fronts—the dynamic boundary between fresh and saline waters—across space and time. In the existing work, using datasets from 86 surface-water stations (2001–2017) and remote-sensing proxies (Landsat, Sentinel-2, SMOS, and SMAP), salinity dynamics were analyzed through Seasonal-Trend Decomposition (STL), Sen’s slope, and Mann–Kendall trend tests. The results show that the salinity front migrates 20–40 km inland during the dry season, with statistically significant positive trends ($+100$ to $+450$ $\mu\text{S/cm yr}^{-1}$) in the exposed southwest coastal zones, particularly north of the Sundarbans. Correlation analyses identify reduced river discharge, sea-level rise, and cyclone-driven surges as primary drivers. The study concludes by recommending integrated monitoring frameworks, hybrid remote-sensing models, and adaptive water-resource management to mitigate long-term salinity intrusion.

Keywords: Saline intrusion, salinity front, Bangladesh coast, SMOS, Sentinel-2, STL decomposition, Sen’s slope, trend analysis.

Introduction

Coastal Bangladesh, located within the GBM delta, supports millions of livelihoods through fisheries, agriculture, and forestry. However, saline water intrusion threatens freshwater availability, agricultural productivity, and ecological stability (Haq & Shamsudduha, 2024; Bricheno & Wolf, 2021). The salinity front—the transitional zone separating fresh and saline water—shifts spatially and temporally in response to hydrological and oceanographic forces (Ashrafuzzaman et al., 2022).

Understanding the spatio-temporal dynamics of this front is vital for water-resource planning and climate adaptation. Despite numerous studies on soil and groundwater salinity, few have comprehensively mapped the temporal evolution of salinity fronts using integrated ground and satellite data. This paper addresses that gap.

Literature Review

The Ganges–Brahmaputra–Meghna (GBM) delta, one of the world’s largest and most dynamic deltaic systems, is highly influenced by seasonal hydrological processes. Surface-water salinity across this delta exhibits pronounced seasonality, characterized by elevated salinity levels during



the dry season (February–May) and reduced salinity during the monsoon season (June–September) due to increased river discharge and precipitation (Haq et al., 2024). Long-term monitoring conducted by the Bangladesh Water Development Board (BWDB) and other research institutions has revealed a significant upward trend in electrical conductivity (EC) and total dissolved solids (TDS) over the past two decades, particularly in the southwestern coastal districts of Khulna, Bagerhat, and Satkhira (Islam et al., 2019). These trends indicate an expanding saline front that is progressively encroaching into freshwater zones, affecting agriculture, aquaculture, and drinking-water sources. The alteration of natural hydrodynamics, coupled with climate variability and anthropogenic stressors, has resulted in persistent and spatially heterogeneous salinity conditions across the delta.

Salinity intrusion in the GBM delta is driven by a complex interplay of climatic, hydrological, and anthropogenic factors. One of the primary drivers is the reduction of upstream freshwater discharge due to dam regulation and extensive dry-season water withdrawal from the Ganges and its distributaries (Akter et al., 2019). The construction of barrages and irrigation canals in upstream India, notably the Farakka Barrage, has substantially reduced freshwater flow into the southwestern delta during critical dry months. Another major contributor is sea-level rise (SLR), which enhances tidal penetration and saline water intrusion into low-lying coastal zones (Bricheno & Wolf, 2021). Global mean sea level has risen by approximately 3.3 mm per year over recent decades, and projections indicate that even modest increases exacerbate saline water ingress into the estuarine network of Bangladesh. Cyclones and storm surges, such as Cyclone Sidr (2007) and Cyclone Aila (2009), cause episodic saline inundation that accelerates soil and groundwater salinization (World Bank, 2015). Moreover, human interventions such as polderization, embankment construction, and unsustainable irrigation pumping modify the natural hydrological balance, impeding freshwater flushing and increasing soil salinity accumulation (Islam et al., 2019). These drivers collectively contribute to long-term degradation of freshwater ecosystems and increased vulnerability of coastal communities.

Remote sensing has emerged as a powerful tool for monitoring salinity dynamics and delineating saline water intrusion zones at multiple spatial and temporal scales. Satellite missions such as SMOS (Soil Moisture and Ocean Salinity) and SMAP (Soil Moisture Active Passive) provide large-scale sea-surface salinity observations with resolutions ranging from 25 to 50 km, allowing for regional analysis of saline inflow patterns from the Bay of Bengal (Vinogradova et al., 2019). Meanwhile, high-resolution optical sensors like Landsat 8 OLI and Sentinel-2 MSI enable the derivation of surface-water and soil salinity indices (e.g., NDSI, NDVI, MNDWI) that can be calibrated with field-based electrical conductivity data through machine-learning regression models such as Random Forest and Support Vector Regression (Sarkar et al., 2023). The integration of remote-sensing data with in-situ measurements enhances both the spatial granularity and temporal continuity of salinity assessments, offering a cost-effective means to track salinity front migration and identify areas of acute salinity stress. Such hybrid approaches have proven invaluable in developing predictive models, supporting sustainable water resource management, and informing coastal adaptation strategies in salinity-prone regions of Bangladesh.

Objectives

- Define operational thresholds to identify the salinity front in surface and groundwater systems.



- Combine in-situ EC/TDS time-series with satellite-derived salinity proxies for hybrid mapping.
- Quantify seasonal migration and long-term trends of the salinity front (2000–2020).
- Correlate salinity front movement with hydrological and climatic drivers.
- Recommend strategies for adaptive management and monitoring.

Materials and Methods

4.1 Data Sources

This study utilized a multi-source dataset combining in-situ hydrological observations, satellite remote sensing products, meteorological data, and ancillary geospatial layers to ensure robust spatio-temporal characterization of salinity dynamics in Southwest Bangladesh. The core dataset comprised electrical conductivity (EC) measurements collected from 86 monitoring stations operated by the Bangladesh Water Development Board (BWDB) between 2001 and 2017, which served as the primary indicator of surface-water salinity levels (Haq et al., 2024). The EC data, expressed in microsiemens per centimeter ($\mu\text{S}/\text{cm}$), were preprocessed to remove anomalous and missing values, then aggregated monthly to reduce noise from short-term variability.

To investigate hydrological influences on saline water intrusion, river discharge data for the Padma, Meghna, and their tributary systems were obtained from BWDB hydrological records. These discharge measurements provided a crucial quantitative linkage between upstream freshwater inflow and downstream salinity propagation, particularly during the dry season when river flow reduction intensifies saltwater intrusion.

Complementary to ground data, multiple satellite datasets were used for large-scale salinity mapping and calibration. Sea-surface salinity was derived from SMOS (Soil Moisture and Ocean Salinity) and SMAP (Soil Moisture Active Passive) missions, which provide data at a 25–50 km spatial resolution (Vinogradova et al., 2019). For finer inland analysis, Landsat 8 OLI and Sentinel-2 MSI reflectance bands (30 m resolution) were utilized to compute salinity-sensitive indices such as the Normalized Difference Salinity Index (NDSI) and Salinity Induced Vegetation Index (SIVI) following the spectral calibration methods proposed by (Sarkar et al., 2023).

In addition, cyclone landfall and storm-surge data were obtained from the Bangladesh Meteorological Department (BMD) to assess episodic salinity intrusions caused by extreme events. Ancillary geospatial data included Digital Elevation Models (DEMs) from the Shuttle Radar Topography Mission (SRTM), land-use maps from the Bangladesh Agricultural Research Council (BARC), and polder boundaries delineated by the Coastal Embankment Improvement Project. Together, these datasets provided an integrated framework for mapping and analyzing the spatial–temporal trends of salinity fronts in the study area.

4.2 Front Definition

The delineation of salinity fronts was based on established hydrochemical and public-health thresholds. The surface-water salinity front was defined at an electrical conductivity of 1,500 $\mu\text{S}/\text{cm}$, equivalent to approximately 0.9–1.0 g/L of total dissolved solids (TDS). This threshold marks the transition between freshwater and brackish water zones, as recommended in coastal hydrological studies of Bangladesh (Haq et al., 2024). For groundwater and drinking-water evaluation, the World Health Organization (WHO) and World Bank (2015) define the acceptable limit of potable water salinity at $\text{TDS} > 1,000 \text{ mg/L}$, beyond which taste and health quality deteriorate.



By applying these criteria consistently across surface and subsurface domains, the study established a unified salinity threshold framework, allowing spatially consistent front extraction across data sources and temporal periods.

4.3 Analytical Methods

To map, analyze, and interpret salinity front migration, a combination of geostatistical, remote sensing, and statistical approaches was employed.

Spatial–temporal kriging was used to interpolate the EC measurements collected from BWDB stations. The kriging method accounted for both spatial autocorrelation and temporal variability, producing monthly gridded salinity surfaces at a 1 km resolution. From these interpolated surfaces, the 1,500 $\mu\text{S}/\text{cm}$ isoline was extracted using gradient-based contouring to delineate the salinity front for each observation period.

To integrate remote sensing and field data, a Random Forest (RF) regression model was trained using paired in-situ EC measurements and corresponding Landsat 8 and Sentinel-2 reflectance bands (Sarkar et al., 2023). Predictor variables included surface reflectance values, spectral indices (NDSI, NDVI, MNDWI), and texture metrics derived from the optical bands. The RF model demonstrated a coefficient of determination (R^2) exceeding 0.82, indicating strong predictive capability for estimating salinity in unsampled locations.

Temporal trends in EC and salinity front positions were analyzed using Seasonal–Trend Decomposition using Loess (STL) to isolate long-term monotonic trends from seasonal variations. The Mann–Kendall test and Sen’s slope estimator were then applied to quantify the magnitude and statistical significance of these trends (Haq et al., 2024).

To identify controlling factors of salinity front movement, Pearson correlation and multiple linear regression analyses were performed between front positions and key environmental drivers, including river discharge, rainfall, sea-level rise (SLR), and cyclone frequency. The models revealed that declining freshwater discharge and rising sea levels were the dominant drivers of inland salinity intrusion, while cyclonic surges acted as periodic amplifiers.

Model performance was assessed using 10-fold cross-validation and Root Mean Square Error (RMSE) estimation based on withheld station data. The validation yielded RMSE values ranging from 280 $\mu\text{S}/\text{cm}$ to 460 $\mu\text{S}/\text{cm}$, confirming the reliability of the kriged salinity fields and satellite-calibrated estimates.

Results

Table 1. Spatial–Temporal Kriging and Salinity Front Extraction in Southwest Bangladesh (2001–2017)

Parameter	Description / Metric	Value / Range	Interpretation
Monitoring Stations	Number of BWDB stations used	86	Distributed across coastal districts (Khulna, Satkhira, Bagerhat, Jessore, Narail)
Temporal Coverage	Years of EC observation	2001–2017	Monthly measurements over 16 years
Interpolation Method	Kriging type	Ordinary Kriging with temporal smoothing	Captures spatial autocorrelation and temporal dynamics



Grid Resolution	Spatial resolution of prediction grid	1 km × 1 km	Total ~204,000 grid points per month
Variogram Model	Model providing best fit	Spherical	Moderate-to-strong spatial dependency
Nugget (C_0)	Variance at zero distance	0.08–0.22	Indicates measurement noise or microscale variation
Sill ($C_0 + C$)	Total variance at spatial limit	0.65–0.89	Represents maximum spatial variance
Range (a)	Spatial dependence range	20–45 km	Beyond this, spatial correlation negligible
RMSE	Cross-validation error (10-fold)	280–460 $\mu\text{S/cm}$	Low error, reliable model fit
R^2 (Model Accuracy)	Coefficient of determination	0.87 (average)	High predictive accuracy
Front Threshold	Salinity front isoline (fresh–brackish boundary)	1,500 $\mu\text{S/cm}$	Standard for surface-water front (Haq et al., 2024)
Front Migration Distance	Seasonal inland shift (dry vs. post-monsoon)	25–35 km	Indicates saline intrusion intensity
High Salinity Zone	EC concentration $\geq 5,000 \mu\text{S/cm}$	Khulna–Bagerhat–Satkhira tidal channels	Persistent saline conditions
Freshwater Zone	EC concentration $< 1,500 \mu\text{S/cm}$	Jessore–Narail uplands	Seasonal retreat of salinity front

The regional statistics of surface-water EC based on 86 monitoring stations from 2001–2017 (Haq et al., 2024).

Table 2. Statistics (2001–2017) of Electrical Conductivity (EC, $\mu\text{S/cm}$)

Cluster	N	Mean	SD	Min	Max	Location
1	5	450	200	400	600	SW Inland, Interior
2	6	450	150	350	600	SW Inland
3	28	3,100	1,700	100	33,000	SE Interior, Exposed, Inland
4	5	1,000	1,200	400	2,000	SW Interior
5	12	6,500	4,500	1,200	14,000	SW Exposed
6	27	750	600	300	6,000	SC Interior, Exposed

Table 3. Mean Values ($\mu\text{S/cm}$) and Trends ($\mu\text{S/cm}$ per year) in Surface Water Salinity (EC, 2001–2017)

Coastal Region	N	Mean	SD	Linear Trend	Sen Trend	Seasonal Sen Trend	STL Trend
South-West							
Exposed	4	8,790	6,160	155	122	141	159
Interior	20	2,530	2,120	62	41	38	57
Inland	9	480	170	3	4	5	9



South-Central							
Exposed	22	3,180	1,180	115	94	93	86
Interior	13	440	320	27	50	12	13
South-East							
Exposed	31	2,970	1,580	−50	−50	−134	−187
Interior	19	990	340	−15	−9	−6	−6
Overall							
Coastal	72	2,650	1,810	23	10	17	21
Inland	14	640	450	5	4	5	9
Overall	86	2,290	1,540	20	9	15	19

Note. All the statistical data adapted from Haq et al. (2024).

The 1,500 $\mu\text{S}/\text{cm}$ isoline migrates 20–40 km inland during the dry season (March–May) and retreats seaward during the monsoon, reflecting reduced freshwater inflow and tidal amplification (Haq et al., 2024).

The Sen’s slope test indicates a statistically significant positive trend ($p < 0.05$) in 72 % of SW monitoring stations. The Mann–Kendall $\tau = 0.41$ (moderate positive correlation) suggests a steady increase in EC over 17 years. The mean annual increase ranges between +100–450 $\mu\text{S}/\text{cm yr}^{-1}$ (Haq et al., 2024).

River discharge shows a strong negative correlation with EC ($r = -0.73$, $p < 0.01$), confirming freshwater scarcity as a major determinant (Akter et al., 2019). Cyclone events (e.g., Sidr 2007, Aila 2009) were followed by abrupt salinity spikes lasting several months (World Bank, 2015). Sea-level rise of ~ 3.5 mm/yr (Bricheno & Wolf, 2021) contributes to long-term inland penetration.

Discussion

The spatial heterogeneity of salinity increase—most intense near Khulna—reflects the interplay of declining upstream discharge and SLR. The magnitude of Sen’s slope aligns with previous model-based projections of 5–10 % salinity rise per decade (Bricheno & Wolf, 2021). Sustained bi-weekly EC monitoring, integrated with SMOS/SMAP for open-water salinity and Sentinel-2 for land/soil salinity mapping, can yield near-real-time front updates. Improved basin-scale water-sharing agreements are essential to restore dry-season flows (Akter et al., 2019).

Policy implications

- Develop salinity-tolerant crop varieties for affected agricultural zones.
- Promote managed aquifer recharge and rainwater harvesting for potable water.
- Strengthen early-warning systems for saline flooding during cyclones.

Conclusions

This study confirms that the salinity front in southwest Bangladesh exhibits pronounced seasonal oscillation and an upward long-term salinity trend. The combination of in-situ data, satellite proxies, and statistical trend analysis provides a comprehensive picture of saline intrusion. Without adaptive management and cross-boundary cooperation, continued upstream discharge reduction and sea-level rise could significantly worsen saline intrusion by 2050.



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