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Title	Spatio-temporal assessment and trend analysis of surface water salinity in the coastal region of Bangladesh
Author(s)	Shammi, Mashura; Rahman, Md. Mostafizur; Islam, Md. Atikul et al.
Citation	Environmental science and pollution research, 24(16), 14273-14290 https://doi.org/10.1007/s11356-017-8976-7
Issue Date	2017-06
Doc URL	https://hdl.handle.net/2115/70649
Rights	The final publication is available at Springer via http://dx.doi.org/10.1007/s11356-017-8976-7
Type	journal article
File Information	ESPR_R2 Final Submission.pdf



**Spatio-temporal assessment and trend analysis of surface water salinity in the coastal
region of Bangladesh**

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Abstract

The study was designed to collect water samples over two seasons- wet-monsoon season (n=96) (March-April) and dry-monsoon season (n=44) (September-October) to understand the seasonal variation in anion and cation hydrochemistry of the coastal rivers and estuaries contributing in the spatial trend in salinity. Hydrochemical examination of wet-monsoon season primarily revealed Ca-Mg-HCO₃ type (66%) and followed by Na-Cl type (17.70%) water. In the dry-monsoon season the scenario reversed with primary water being Na-Cl type (52.27%) followed by Ca-Mg-HCO₃ type (31.81%). Analysis of Cl/Br molar ratio vs. Cl (mg/L) depicted sampling area affected by seawater intrusion (SWI). Spatial analysis by Ordinary Kriging method confirmed approximately 77% sample in the dry-monsoon and 34% of the wet-monsoon season had shown SWI. The most saline intruded areas in the wet-monsoon seasons were extreme south-west coastal zone of Bangladesh, lower Meghna River floodplain and Meghna estuarine floodplain and South-eastern part of Chittagong coastal plains containing the districts of Chittagong and Cox's Bazar adjacent to Bay of Bengal. In addition, mid-south zone is also affected slightly in the dry-monsoon season. From the analyses of data, this study could further help to comprehend seasonal trends in the hydrochemistry and water quality of the coastal and estuarine rivers. In addition, it can help policy makers to obligate some important implications for the future initiatives taken for the management of land, water, fishery, agriculture and environment of coastal rivers and estuaries of Bangladesh.

Keywords: seawater intrusion (SWI), estuary, spatial salinity trend, non-parametric test, electric conductivity (EC), Na/Cl molar ratio, Cl/Br molar ratio.

1. Introduction

Coastal zones are transition environments, forming the interface between continent and ocean. The effects of human activity on coastal water resources usually reduce the flows of freshwater to estuaries; modifying estuarine mixing processes and extending marine influences further inland (Loitzenbauer and Mendes 2012). Bangladesh is considered as one of the most climate vulnerable countries in the world. In the southern part, it has approximately 710 km coastal line with highly susceptible areas to sea level rise. The coastal area in the southern part covers about 32% of total land area of the country (MoWR 2005) and are particularly vulnerable to climate change effects (Bhuiyan and Dutta 2012). Water salinity is regular hazards for many parts of southern Bangladesh. For example, Batiaghata Upazila, Khulna District in south-west coastal region of Bangladesh is the mostly saline affected area, where agriculture activities are mainly dependent on rainfall (Shammi et al. 2016). Previous study on groundwater in south-west part of Bangladesh confirmed the area was dominantly of Na–Cl type brackish water (Halim et al. 2010) due to the seawater influence and hydrogeochemical processes (Bahar and Reza 2010). Anthropogenic and bio-physical factors (e.g., upstream withdrawal of freshwater, cyclones) operating outside the geographical boundary of coastal region of Bangladesh contribute to increasing salinization in the southwest coastal area (Shameem et al. 2014). Nevertheless, it is very difficult to get the actual scenario of hydrochemistry of the coastal river and estuaries due to dynamic mixing. Estuary provides a unique experimental site to understand the effect of monsoonal river discharge on freshwater and seawater mixing (Ghosh et al. 2013). The estuaries that are typically characterized by gradients of ionic strength, pH and concentrations of the suspended particulate matter; provide an ideal environment to study the nature and extent of solute-particle interaction, and the resultant modification of the elemental

and isotopic fluxes from the rivers to the oceans (Samanta and Dalai 2016). Seawater intrusion (SWI) is a global issue (Werner et al. 2013) in coastal aquifers all over the world and predisposed to the influences of sea level rise and climate change. Surface water such as rivers and canals are impacted similarly by intruding seawater. Here, salinity refers to the total concentration of dissolved inorganic ions in water (Williams and Sherwood 1994) and often measured as electrical conductivity (EC) siemens/meter (Canedo-Arguelles et al. 2013). Temporal and spatial status of water salinity condition in Kumar-Modhumoti River in Gopalganj district showed that during the start of wet-monsoon months (March–April), the conductivity of river water was high due to low rainfall and upstream discharge. Conductivity ranged from 3.5 dS/m to 4.0 dS/m, while in the late wet-monsoon months (August–September), the conductivity of river water decreased (0.3–0.4 dS/m) (Shammi et al. 2012). Correlation of river discharge data of Gorai-Madhumati and conductivity of Madhumati River confirmed that salinity level was higher when upstream river inflow was below 500 m³/S (Shammi et al. 2012).

In addition, trend analysis provides a view for meteorological, hydrological and climatological variables in past and future time's changes (Kisi and Ay 2014). The main idea of trend analysis is to detect whether values of data are increasing, decreasing or stable over time. Detection of trend is a complex subject because of characteristics of data (Kisi and Ay 2014). In general, there are different parametric and nonparametric statistical techniques to check the existence or absence of trend in time series analysis and climate change studies but the nonparametric methods are used relatively wider in hydro-meteorological studies (Takeuchi et al. 2003). Nonparametric methods are appropriate for the series that have a significant skew and cannot be fitted with statistical distributions (Niazi et al. 2014). Since then, many nonparametric statistical tests have been developed to determine trends in data series. Mann–Kendall (Mann 1945;

Kendall 1975) test is one of the best trend detecting methods. This method is suitable for the nonnormal and is not sensitive to observed values. This test has been recommended for detecting trends in environmental time series data by the World Meteorological Organization (Niazi et al. 2014). On the otherhand, the Sen's slope method (Sen 1968) uses a linear model to estimate the slope of the trend (Salmi et al. 2002) with the extent of magnitude at a satisfactory significant level.

It is important to determine the possible impacts of sea level rise on salinity to devise suitable adaptation and mitigation measures and reduce impacts of salinity intrusion in coastal cities (Bhuiyan and Dutta 2012). Nevertheless, till to date, there are no studies depicting the actual hydrochemistry related to the salinity condition in the coastal rivers and estuarine waters of Bangladesh. Therefore, this study was designed to collect water samples over two seasons- wet-monsoon season and dry-monsoon season, to understand the seasonal variation in anions and cations hydrochemistry of the coastal rivers and esutaries contributing in the spatial trend in salinity. The study was further trailed by time-series analysis of salinity data using Mann-Kendall and Sen's slope test for 13 south-west zone rivers to find salinity trend in of southern regions of Bangladesh followed by existing policy analysis for the management of salinity affected areas.

2. Landform and hydromorphological settings

Bangladesh occupies an area of 143,998 km² and has a subtropical humid climate. Geographically, it extends from 20°34'N to 26°38'N latitude and from 88°01'E to 92°41'E longitude. Except the hilly southeast, most of the country is a low-lying plain land (Shahid 2010). The topography of the region is rather flat, and gently sloping towards the Bay of Bengal (Bhuiyan and Dutta 2012). The original morphology and hydrogeology of many low-lying

108 coastlands worldwide have been significantly modified over the last century through river
109 diversion, embankment built-up, and large-scale land reclamation projects. This led to a
110 progressive shifting of the groundwater–surface water exchanges from naturally to
111 anthropogenically driven (Da Lio et al. 2015). Hydrology of the coastal plains of Bangladesh
112 presents a complicated interaction of fresh water flow from the upstream, the tides and tidal
113 flows from the Bay of Bengal, tropical cyclones, storm surge and other meteorological effect
114 from the sea and the physiography of the coastal plains (FAO 1985). Understanding the mixing
115 between salt/fresh surface water and groundwater in coastlands is an issue of paramount
116 importance considering the ecological, cultural, and socio-economic relevance of the coastal
117 plains (Da Lio et al. 2015). Low-lying parts of four regions further inland Ganges River
118 floodplain, Old River floodplain comprising Arial Bil and Gopalganj Bil (low-lying lakes), lower
119 Meghna River floodplain and Meghna estuarine floodplain lie sufficiently close to the coast that
120 they could be affected by a rising sea-level at an early date (Brammer 2014a).

121 The physical geography of Bangladesh's coastal area is more diverse and dynamic than is
122 generally recognised. Failure to recognise this has led to serious misconceptions about the
123 potential impacts of a rising sea-level on Bangladesh with global warming (Brammer 2014b).

124 Estuaries are a transition zone between continental and marine environments and record the
125 complex interaction of these two discrete environments in terms of physical phenomena (e.g.
126 mixing of fresh and saline water, tidal and wave action, sediment transport) and chemistry. They
127 play an important role in understanding the continental input via rivers to the oceans (Ghosh et al.
128 2013). Sea salinity intrusion is a major concern in the southern part of the river system, as the
129 rivers are affected by tides and is an important issue in these rivers. Most of the area is protected
130 with polders against river flooding (Bhuiyan and Dutta 2012). The coastal zone is exposed to the

131 risk of tropical cyclones in the wet-monsoon and dry-monsoon seasons, with the associated risk
132 of storm surges in areas close to the coast ([Brammer 2014b](#)).

134 3. Methodology

135 3.1. Study area

136 The study area for surface water encompasses the coastal south part of the Bengal Basin. The
137 sampling area were selected in the southern part of Bangladesh taking into account the south-east
138 coastal zone to south-west zone of Bangladesh. Geographically, sampling points extended from
139 20°34'N to 23°40'N latitude and from 88°01'E to 92°41'E longitude (Figure 1). Most part of the
140 sampling points lied on the Ganges and Meghna River and their many tributaries and
141 distributaries except south-east part of Chittagong coastal plains and Bay of Bengal.

142 3.2. Description of the available data

143 A various multidisciplinary data are highly needed for the study of sea water intrusion (SWI) to
144 provide reliable results ([Trabelsi et al. 2016](#)). Surface water samples were collected in 500 ml
145 plastic bottle for two different seasons March-April 2012, wet-monsoon season (n=96) and
146 September-October 2012, dry-monsoon (n=44) to broadly cover the seasonal variation following
147 the standard guidelines (APHA, 1998). However, due to seasonal drying up of the rivers, similar
148 points that were covered in the wet-monsoon season could not be covered in the dry-monsoon
149 season due to inaccessibility by waterways. The chemical analysis was carried out following the
150 procedure as described by [Islam et al. \(2016\)](#). The samples were collected followed by filtering
151 through 0.45 µm membranes. Temperature (°C), pH, electrical conductivity (EC) and total
152 dissolved solid (TDS) were measured in-situ by Portable Multi-Meter (Hach, sensION+

MM150). Chemical components such as EC, TDS, major cations and anions were used to identify seawater intrusion (Trabelsi et al. 2016).

Major anions such as chloride (Cl^-), nitrate (NO_3^-), sulfate (SO_4^{2-}), phosphate (PO_4^{3-}) and fluoride (F^-) were measured by ion chromatography. Carbonate (CO_3^{2-}) and bicarbonate (HCO_3^-) were determined by titration with HCl. Major cations, calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+) and potassium (K^+), were determined by using AAS (Varian 680FS). The trace elements, manganese (Mn), iron (Fe), boron (B), iodine (I), bromine (Br), and silicon dioxide (SiO_2) were determined by using Spectrophotometer (DR 2800). Overall data reproducibility for ions was within $\pm 10\%$. Cation and anion charge balance ($< 10\%$) was an added proof for the precision of the data. Chemical analyses were carried out in Bangladesh Council of Scientific and Industrial Research (BCSIR) and Bangladesh University of Engineering and Technology (BUET) laboratory, Dhaka.

3.3. Geostatistical modelling of EC of the study area

To understand the area-wide distribution of salinity occurrences over two seasons in the study area ordinary Kriging (OK) method for spatial analysis of EC were adopted. The OK method, which is referred to as partial spatial estimation or interpolation, is a method to estimate the value of regionalized variables at unsampled location based on the available data of regionalized variables and structural features of a variogram (Webster and Oliver 2001). The OK estimates are determined by Eq. (i).

$$\hat{z}(x_0) = \sum_{i=1}^n \lambda_i z(x_i) \quad \dots \dots (i)$$

where $\hat{z}$ is the estimated value of an attribute at the point of interest x_0 , z is the observed value at the sampled point x_i , λ_i is the weight assigned to the sampled point, and n represent the

number of sampled points used for the estimation (Webster and Oliver 2001). The attribute is usually called the primary variable, especially in geostatistics. To ensure that the estimates are unbiased, the sum of the weights λ_i must be equal to one. The spatial distribution maps of EC and Na/Cl ratio in surface water was done by ArcGIS version 10.1.

3.4. Statistical analysis

Pearson Correlation matrix was performed with 2-tailed test of significance at standard $\alpha = 0.05$. Principal component analysis (PCA) is one of the most commonly used multivariate statistical methods in natural sciences, which was developed by Hotelling (1933) in the thirties from original work of Pearson Correlation matrix (Jiang et al. 2015). The main objective of this method is to simplify data structure by reducing the dimension of the data (Jiang et al., 2015). Total 13 variables containing pH, EC, TDS, Ca^{2+} , Mg^{2+} , Na^+ , K^+ , Cl^- , CO_3^{2-} , HCO_3^- , NO_3^- , SO_4^{2-} and PO_4^{3-} were chosen for Correlation matrix and PCA analysis mainly because of their contribution to salinity and dominance in natural waters. The statistical analysis was done by Origin 9.0 software package of OriginLab (USA) and also used for subsequent calculations. After the application of PCA, a varimax normalized rotation was applied to minimize the variances of the factor loadings across variables for each factor. In this study, all principal factors with eigen values which are greater than 1 were taken into account. The first three factors were able to account for were.

3.5. Hydrochemistry analysis

To understand the hydrochemistry of the sampling water, GW Chart Software (USGS) was used and to classify water types in both seasons the Piper trilinear analysis was done via generating the Piper diagram (Piper 1953).

3.6. Historical Trend analysis by Mann-Kendall

The nonparametric MK test (Mann 1945; Kendall 1975) has been commonly used to assess the significance of monotonic trends in climatological, meteorological and hydrological data time series (Kisi and Ay 2014). The rank-based non-parametric Mann-Kendall method is adopted to study trends in the annual series. The choice of this method is based on the fact that it has the advantage of being less sensitive to outliers over the parametric method (Otache et al., 2008). The MK test statistic (S) is calculated in the following Eqs

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^n \text{sgn}(x_j - x_i) \quad \dots \dots \dots \text{(ii)}$$

$$\text{sgn}(x_j - x_i) = \begin{cases} +1 & x > 0 \\ 0 & x = 0 \\ -1 & x < 0 \end{cases} \quad \dots \dots \dots \text{(iii)}$$

Where, where x_i and x_j are the data values at times i and j, and n indicates the length of the data set. While a positive value of s indicates an increasing trend, negative of s indicates a decreasing trend. The following expression, as an assumption, is used for the series where the data length $n > 10$ and data are approximately normally distributed (variance ($\sigma^2 = 1$) and mean ($\mu = 0$) value) .

$$\text{Var}(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^p t_i(t_i-1)(2t_i+5)}{18} \quad \dots \dots \dots \text{(iv)}$$

In this equation, P is the number of tied groups, and the summary sign (Σ) indicates the summation over all tied groups. t_i is the number of data values in the Pth group. If there are not the tied groups, this summary process can be ignored. After the calculation of the variance of

time series data with Eq. (ii), the standard Z value is calculated according to the following Eq.
(v).

$$Z = \begin{cases} \frac{s - 1}{\sqrt{\text{var}(s)}}, & \text{if } S > 0 \\ 0, & \text{if } S = 0 \\ \frac{s - 1}{\sqrt{\text{var}(s)}}, & \text{if } S < 0 \end{cases}$$

... ..(v)

The calculated standard Z value is compared with the standard normal distribution table with two-tailed confidence levels ($\alpha = 10\%$, $\alpha = 5\%$ and $\alpha = 1\%$). If the calculated Z is greater $|Z| > |Z_{1-\alpha}|$, then the null hypothesis (H0) is invalid. Therefore, the trend is statistically significant. Otherwise, the H0 hypothesis is accepted that the trend is not statistically significant, and there is no trend in the time series (trendless time series) (Kisi and Ay 2014).

3.7. Trend analysis by Sen's Test

True slope in time series data (change per unit time) is estimated by procedure described by Sen (1968) in case the trend is linear. The method requires a time series of equally spaced data (Shahid 2010). The magnitude of trend is predicted by the Sen's slope estimator (Q_i). The magnitude of trend is predicted by the Sen's slope estimator (Q_i).

$$(Q_i) = \frac{x_j - x_k}{J - K}$$

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For $i=1, 2, \dots, N \dots \dots (vi)$

Where, x_j and x_k are data values at times j and k ($j > k$) respectively. The median of these N values of Q_i is represented as Sen's estimator. $Q_{med} = \frac{Q(N+1)}{2}$ if N is odd,

And $Q_{med} = \left[\frac{QN}{2} + \frac{Q(N+2)}{2} \right] / 2$ if N is even. Positive value of Q_i indicates an increasing trend and negative value of Q_i shows decreasing trend in time series.

3.8. Toolkit used for Mann-Kendall and Sen's slope test

To investigate the salinity trend of coastal rivers of Bangladesh annual data series of 13 rivers of Gorai-Madhumati River networks were taken into justification. Average salinity data of each months EC data were calculated following the annual average of the calendar year (2004-2011). Missing value were calculated using interpolation techniques. To analyse historical trend of river salinity, two freeware tool kits were used. One is GSI Mann-Kendall excel tool kit developed by GSI Environmental Inc. based on the methodology of Aziz et al (2003) and was used for constituent salinity trend analysis of the southern rivers of Bangladesh over a period of times. Annual average value was calculated from the monthly data of the rivers. The Mann-Kendall test for trend analysis, as coded in GSI Toolkit, relies on three statistical metrics (Aziz et al. 2003): The 'S' Statistic: Indicates whether concentration trend of salinity vs. time is generally decreasing (negative S value) or increasing (positive S value). The Confidence Factor (CF): The CF value modifies the S Statistic calculation to indicate the degree of confidence in the trend result, as in 'Decreasing' vs. "Probably Decreasing" or "Increasing" vs. "Probably Increasing." Additionally, if the confidence factor is quite low, due either to considerable variability in concentrations vs. time or little change in concentrations vs. time, the CF is used to apply a preliminary "No Trend" classification, pending consideration of the Coefficient of Variation (COV). The COV is used to distinguish between a "No Trend" result (significant scatter in concentration trend vs. time) and a "Stable" result (limited variability in concentration vs. time) for datasets with no significant increasing or decreasing trend (e.g. low CF). 2nd toolkit used in

this study was the MAKESENS 1.0 Excel template freeware program developed by Finnish Meteorological Institute, Helsinki, Finland (Salmi et al. 2002). Mann–Kendall test and Sen’s slope estimating trends in the time series of annual values were calculated following equations described in section 3.5 and 3.6.

4. Results

4.1. Physico-chemical properties of coastal rivers and estuarine waters in the study area

Summary of the hydro-chemical properties of coastal rivers and estuarine waters collected from of the study areas during wet-monsoon and dry-monsoon period are given in Table 1. It is revealed from the table that wide ranges and large standard deviations were observed for most parameters, indicating chemical composition of coastal river water was affected by various processes. During wet-monsoon pH of the water ranged from minimum 6.20 to maximum 8.24 with an average value of 7.72 ± 0.58 . The dry-monsoon pH value ranged from a minimum of 7.20 to maximum of 11.00 with an average value of 8.24 ± 0.82 . These results suggested that during wet-monsoon the water was slightly acidic to slightly alkaline, while during dry-monsoon the water pH fell in neutral to more alkaline. Nevertheless, the average pH revealed that the water was overall slightly alkaline in both seasons due to the variation of mixing river water and seawater, which was typical to estuary. However, to this date there are no previous reports on downstream estuarine river condition in Bangladesh.

The ocean’s influence on continental waters can be monitored by their salinity, since where this influence is greater, so is the salinity. Similarly, the effects of freshwater discharged from hydrographic basins can be observed in the ocean in terms of reduced salinity through dilution (Loitzenbauer and Mendes, 2012). EC values during wet-monsoon and dry-monsoon range from 65.90 to 34,800 $\mu\text{S}/\text{cm}$ with an average value of $2,168.59 \pm 5,753.56 \mu\text{S}/\text{cm}$ and 228 to 57,300

278 $\mu\text{S}/\text{cm}$ with an average value of $11083.27 \pm 17573.81 \mu\text{S}/\text{cm}$. EC is directly related to the values
 279 of TDS in both seasons. TDS values varied from the minimum value of 25.20 to the maximum
 280 value of 18,440 mg/L in wet-monsoon season. On the other hand in dry-monsoon the value
 281 varied from 114 mg/L to 28600 mg/L with an average value of $5,716 \pm 8,921.83 \text{ mg/L}$. To
 282 mention here, 15 samples which had exceeded the value of $\text{TDS} > 1,000 \text{ mg/L}$ indicating brackish
 283 sea water in the wet-monsoon season of which 4 samples were actually from the Bay of Bengal.
 284 On the other hand, in dry-monsoon season approximately 56% sample had exceeded the value of
 285 $\text{TDS} > 1,000 \text{ mg/L}$ indicating brackish sea water, of which 5 were from Bay of Bengal. While in
 286 the wet-monsoon season the contribution of TDS and EC was from seawater, in the dry-monsoon
 287 season it was due to the heavy river discharge carrying sediments and industrial pollutants from
 288 upstream and mixing with brackish seawater.

289 An understanding of salinity dynamics can be useful in the management of coastal water
 290 resources and for assessing possible limitations their used through salt penetration ([Loitzenbauer](#)
 291 [and Mendes 2012](#)). Therefore, on a spatial basis (Figure 2), the distribution of the EC values
 292 showed variable trends over the south regions. Based on the spatial map (a) the most saline
 293 intruded areas (sample $n=96$) can be listed in the wet-monsoon seasons are- (i) extreme south-
 294 west coastal zone of Bangladesh including the districts of Khulna, Satkhira, Bagerhat, Jessore and
 295 Gopalganj; (ii) lower Meghna River floodplain and Meghna estuarine floodplain comprising the
 296 districts of Bhola, Noakhali and Feni and (iii) south-east part of Chittagong coastal plains
 297 containing the districts of Chittagong and Cox's Bazar near Bay of Bengal; and (b) The little
 298 affected mid-south zone particularly Barisal, Jhalkathi, Patuakhali and Barguna. In the dry-
 299 monsoon season (Figure 2b), out of 44 samples, the extreme south-west districts data were not
 300 collected, except Gopalganj district. From the spatial data analysis (Figure 2b), it is witnessed

that in the dry season the district was affected by salinity. The above mentioned lower Meghna River floodplain and Meghna estuarine floodplain comprising the districts of Bhola, Noakhali and Feni and South-east part of Chittagong coastal plains containing the districts of Chittagong and Cox's Bazar near Bay of Bengal showed higher salinity concentration than that was in the wet-monsoon season. Even mid-south zone particularly Barisal, Jhalkathi, Patuakhali, Pirojpur and Barguna have been found to be affected.

In principle, salinity can refer to any inorganic ions, while in practise it is mostly the result of the following major ions: Na^+ , Ca^{2+} , Mg^{2+} , K^+ , Cl^- , SO_4^{2-} , CO_3^{2-} , and HCO_3^- (Williams 1987). River water of the study area was clearly dominated by Na^+ , Mg^{2+} , Ca^{2+} , Cl^- , HCO_3^- , and SO_4^{2-} during both of the seasons. During wet-monsoon and dry-monsoon seasons approximately 68.63% and 82.9% of the total cations and anions contributing to salinity were from Cl^- which is prevalent from the pie chart analysis (Figure 3a-b). In the wet-monsoon season the orders of salinity contributing anions and cations were in the order of $\text{Cl}^- > \text{HCO}_3^- > \text{SO}_4^{2-} > \text{Na}^+ > \text{Ca}^{2+} > \text{Mg}^{2+} > \text{CO}_3^{2-}$. In the dry- monsoon season the order was $\text{Cl}^- > \text{Na}^+ > \text{SO}_4^{2-} > \text{HCO}_3^- > \text{Ca}^{2+} > \text{K}^+ > \text{Mg}^{2+} > \text{CO}_3^{2-}$. Increased load of Cl^- , Na^+ , SO_4^{2-} , HCO_3^- in the dry-monsoon season may depict the opposite view due to landward movement of seawater. With respect to TDS and EC samples of wet-monsoon and dry-monsoon seasons had shown the abundance of the major ions is in the following order: $\text{Na}^+ > \text{Ca}^{2+} > \text{K}^+ > \text{Mg}^{2+}$ and $\text{Cl}^- > \text{SO}_4^{2-} > \text{HCO}_3^- > \text{NO}_3^- > \text{CO}_3^{2-}$. The severe anions and cations variation in the dry-monsoon season may be attributed to the reduction of flows of freshwater through increased upstream abstraction and increases of intrusion from sea to land. The greater the penetration of marine influence into the land, the lower is the availability of freshwater, which becomes brackish through its mixture with saline waters (Loitzenbauer and Mendes 2012).

324 It was observed from the sample analysis that mean value of NO_3^- varied with the season from
 325 0.1 mg/L to 43 mg/L in wet-monsoon season and 0.09 mg/L to 6.95 mg/L in the dry monsoon
 326 season. The reason for seasonal nitrogen variation may be attributed to the nonpoint run off of
 327 agricultural input of fertilizers and pesticides. Rainfall-runoff increased NO_3^- load in the wet-
 328 monsoon season while in dry-monsoon the load was reduced. Variation of PO_4^{3-} remained
 329 identical in both seasons with an average value of 0.31 ± 0.80 mg/L. In addition, fluoride, iodide
 330 and bromide all three anions were found to be higher in wet-monsoon season. In the wet-
 331 monsoon season concentration of fluoride, iodide and bromide varied from minimum 0 mg/L to
 332 3.51 mg/L, 0 to 20.35 mg/L and 0 to 12.66 mg/L, respectively. Moreover, in the dry-monsoon
 333 season the values of fluoride, iodide and bromide varied from 0 to 2.43 mg/L, 0.02 to 3.55 mg/L
 334 and 0 to 2.24 mg/L respectively. Likewise all other anions and cations concentration, there was
 335 colossal deviation of Fe concentration in both seasons. Concentration of Fe varied from a
 336 minimum value of 0.05 to maximum value of 52.3 in the wet-monsoon season. While in the dry
 337 monsoon season the minimum value started at 0.02 mg/L to maximum value of 37.60 mg/L.
 338 Correspondingly B and Mn concentration in the wet-monsoon season accounted for 0.28 mg/L
 339 and 0.14 mg/L on an average, whereas in dry-monsoon season the values accounted for 0.51
 340 mg/L and 0.70 mg/L, respectively. The rise in the metal concentration might be related to the
 341 upstream sediment carrying the metals rising in the dry-monsoon.

342 To find out more on the interrelations among various anions and cations in respect to EC and
 343 TDS, Pearson's correlation matrix was prepared for wet-monsoon season (Table 2) and dry-
 344 monsoon season (Table 3) taking into account of 13 hydrochemical variables including pH, EC,
 345 TDS, Ca^{2+} , Mg^{2+} , Na^+ , K^+ , Cl^- , CO_3^{2-} , HCO_3^- , NO_3^- , SO_4^{2-} and PO_4^{3-} . According to Table 2,
 346 statistically positive significant correlations were found between EC and TDS ($r = 0.99$).

Subsequently, TDS and EC showed strong significant correlation with K^+ ($r= 96$ and 97), Cl^- ($r=99$ and 99) and SO_4^{2-} ($r=95$ and 96). Other strong correlation that were observed from the matrix were K^+ and Cl^- ($r=97$) and K^+ and SO_4^{2-} ($r= 0.96$). Moreover, Mg^{2+} , Ca^{2+} , Na^+ , K^+ , Cl^- , CO_3^{2-} and SO_4^{2-} all had shown a weak but significant correlation with EC and TDS. The results may be attributed to the high salinity nature of coastal river water along with precipitation and heavy discharge from upstream. In addition, pH was negatively correlated with Mg^{2+} and CO_3^{2-} anion. Likewise in the **dry-monsoon season** statistically positive significant correlations were found between EC and TDS ($r = 0.99$) (Table 3). Successively, TDS and EC showed strong significant correlation with Cl^- ($r=99$) and K^+ ($r= 96$ and 97). Mg^{2+} , Ca^{2+} , Na^+ , K^+ , Cl^- , HCO_3^- and SO_4^{2-} all showed weak but significant correlation with EC and TDS. This was further confirmed by Principle component analysis (PCA) (Table 4, Figure 4a-b).

PCA is a multivariate statistical method complementary to classical approaches of hydrogeochemical research (Morell et al. 1996). PCA provides a quick visualization and shows correlation among different water quality variables. PCA was applied by considering 13 variables containing pH, EC, TDS, Ca^{2+} , Mg^{2+} , Na^+ , K^+ , Cl^- , CO_3^{2-} , HCO_3^- , NO_3^- , SO_4^{2-} and PO_4^{3-} . For wet monsoon season PCA on the combined datasets provided three factors **with eigen value** >1 that can explain approximately 67.84% of the variability of the data (PC 1 variance of 42.11% and PC 2 variance of 15.37%) (Table 4). From the biplot analysis of PCA, when two variables are far from the centre and close to each other, then the variables are said to be significantly and positively correlated ($r=1$). In the wet-monsoon season coefficients of PC1 which were related to the salinity of the river water closely related to EC, TDS, Cl^- , K^+ and SO_4^{2-} (Figure 4a). PC 2 which might be related to the inorganic carbon content of the river HCO_3^- and CO_3^{2-} in a weak relation to Na^+ , Mg^{2+} and Ca^{2+} . On the other hand, for dry-

monsoon season PCA on the combined datasets provided four factors with eigenvalue >1 that could explain approximately 54.97% of the variability of the data (PC 1 variance of 38.40% and PC 2 variance of 16.58%) (Table 4). From the biplot analysis of PCA in dry-monsoon season, coefficients of PC1 was related to the salinity of the river water unlike wet-monsoon season. The closely related variables of EC and TDS to Cl^- and K^+ are shown in Figure 4(b). However, unlike PCA of wet-monsoon season it was challenging to find out the second set of component (PC 2) as there was not any strong relationship among the variables to support the assumptions.

4.2. Seasonal hydrochemistry of the coastal rivers of Bangladesh

The concentrations of major ions measured in the surface water samples are presented in the Piper Trilinear plot (Figure 5a-b). The high variability in major ion chemistry and their seasonal variations are shown in the analysis of two seasons. For the study area in the wet-monsoon season approximately 66 % of samples were Ca-Mg- HCO_3 and occupied the section of the diamond shape in the Piper diagram and their chemical properties dominated by alkaline earths and weak acids (Figure 5a). Second dominant category was Na-Cl type occupying 17.70% of the sample clustered near the right corner of the central diamond. These waters were from the contribution of seawater (Figure 5a). 5.20% sample fell in the category of Ca-Cl type water while 9.3% fell in mixed Na-Ca-Mg- HCO_3 -Cl type water probably evolved from silicate weathering or ion exchange process due to mixing of upstream water discharge and seawater (Karanth 1994). In the wet-monsoon season Ca-Mg- HCO_3 dominated in river water due to the discharge being dominated from upstream pushing off the Na-Cl type seawater towards south (Figure 5a).

Major river water in the dry-monsoon season fell into the category of Na-Cl type (52.27%) followed by Ca-Mg- HCO_3 type (31.81%) (Figure 5b). A small fraction of sample fell in the

category of Ca-Cl and mixed type. In the dry-monsoon season Na-Cl type sea-water dominates over Ca-Mg-HCO₃ type due to limited river water discharge from upstream and pushing the salinity front towards north.

4.3. Analysis of molar ratio to identify seawater intrusion

Constant records of pre and dry-monsoon hydrochemistry are important to study the coastal river water salinity and its fluctuation trends. Moreover ionic ratios reveal information about processes in water bodies more visibly than concentrations (Siebert et al. 2014). In this paper Cl/Br molar ratio, Na/Cl molar ratio, K/Cl molar ratio, Mg/Ca molar ratio were used to distinguish seawater intrusion. The Cl/Br molar ratio can be obtained by multiplying mass ratio by 2.254. The variation in Cl/Br molar ratio in sea water is about 290 ± 4 (Katz et al. 2011). A Cl/Br molar ratio vs. Cl (mg/L) depicts the sample affected by seawater intrusion (Figure 6). Approximately 77% sample in the dry-monsoon had crossed the Cl/Br molar ratio of sea water at 290 compared to the wet-monsoon season affected by approximately 34% sample. From Figure 6 it is clear that seawater was affecting the salinity trend of the river water more in dry-monsoon compared to the wet-monsoon season. In the wet-monsoon season Na/Cl molar ratio varied from minimum value of 0 to 39.42 with average value 1.28 ± 4.09 . On the other hand, dry-monsoon season it varied from 0.01 to 3.83 with average value 0.76 ± 0.75 (Table 5). Approximately 23% sample collected in the wet-monsoon season and 40% sample collected in the dry-monsoon had Na/Cl ratio above 0.86 indicating seawater intrusions. The spatial distribution of Na/Cl ratio for both seasons is depicted in Figures 7a-b by utilizing ordinary kriging (OK) method. It was clear from the spatial distribution map that dry-monsoon season was highly saline affected in the common sampling points in the sapling point areas. Moreover, from Br/Cl molar ratio, it was found that in the wet-monsoon season approximately 62% and in dry-monsoon approximately 90% sample had molar

ratio above >0.0015 (Table 5). In wet-monsoon season Mg/Ca molar ratio varied from minimum value of 0.001 to 32.36 with an average value of 1.69 while in dry-monsoon season it varied from 0.08 to 93.66 with an average value of 4.37. However, only 3 samples in wet-monsoon and dry-monsoon seasons had shown Mg/Ca molar ratio >5 . Therefore, from the above data analysis it was perceived that the existence of seasonal variation in anions and cations over time in respect to salinity occurrences due to seawater intrusion and low upstream water flow in the river.

4.4. Fluctuation of salinity trends in the coastal rivers of Bangladesh

Understanding the dynamics of salinity gives a useful instrument for environmental monitoring in an estuarine zone (Loitzenbauer and Mendes 2012). Therefore, it is also very important to understand annual trends of time-series data of salinity in the rivers. In this context, trends of salinity variation are very important for the surface water quality of coastal Bangladesh which was investigated by traditional hydrochemistry parameter electrical conductivity (EC) data of different rivers using Mann–Kendall and Sen’s slope test statistics. The results obtained from the Mann-Kendall test was used to establish the trends in time series of annual salinity trends in the 13 river stations belonging to the Gorai River network of south-west zone of Bangladesh whether they were increasing, decreasing, stable or trendless over time. Sen’s slope test was also used to identify the significant level of increasing or decreasing trend and a comparison of their value is presented in Table 6.

Findings from Mann-Kendall test also obtained the annual trend of salinity rising in the Madhumati River significantly (confidence factor 98.9%). Other rivers which showed increasing trend of salinity are Rupsa River, Khulna; Kakshiali River, Satkhira; Morichan River, Satkhira;

and Shibsha River, Khulna with confidence factor 96.9– 99.9%. The result is also in agreement with the spatial analysis of EC (Figure 2). Similar result of increasing salinity trend has been found in the MAKESENS tool kit for Madhumati River at 0.1 level of significance; Kakshiali River, Satkhira at 0.001 level of significance; Morichan River, Satkhira at 0.01 level of significance and Shibsha river, Khulna at 0.05 level of significance (Table 6). However, one river Panguchi River, Bagerhat found to be decreasing in salinity trend in both tool kit analyses at 0.1 level of significance in MAKESENS and 98.9% confidence factor in GSI toolkit analysis. Two rivers Pasur River, Bagerhat and Vadra River, Khulna showed “Probably increasing” trend with confidence interval 91.1% and 94.6%, respectively in GSI tool kit analysis. Although seasonal variations in the EC was found higher during trend analysis, overall annual analysis of the salinity trend was found to be “stable” over time for Kapotaksha River, Satkhira. Moreover, five rivers showed “no trend” in the analysis. The rivers are Daratana River, Bagerhat; Shailmari River, Khulna; Betna River, Satkhira; Kazibachha River, Khulna and Shibsha Rivers, Khulna. The causes of the variability in salinity trends in the above mentioned rivers are likely related to the local hydrogeologic condition, tidal effects from the Bay of Bengal, local rainfall-runoff condition, and climatic events. Besides these extreme western parts of rivers are actually parts of the moribund Ganges Delta.

5. Discussions

It is evident from our result that there is a marked seasonal variation exists in the hydrochemistry of coastal rivers in Bangladesh. There is a significant variation in anions and cations contributing to the salinity variation may be associated to at the Ganges-Brahmaputra-Meghna (GBM) River discharge as well as inland rainfall-runoff. Seasonal variation of anions and cations were significantly marked from the results. It was particularly evident in the nitrate variation in the

surface water. In Bangladesh the [rainfed aman](#) rice cultivation is widespread along the coastal areas ([Shelley et al. 2016](#)). It was apparent that wet-monsoon season NO_3^- indicated agricultural source and fertilizers application of transplanted aman (t. aman) production. NO_3^- containing fertilizer such as urea is applied 24 kg/3330m² in t. aman production (FAO 2017). Seeding time of aman rice is between March and April and transplanted between July and August during wet-monsoon period. The crop is harvested from November through December ([Shelley et al. 2016](#)) during the start of dry-monsoon period.

The up scaled monthly discharge of GBM river mouths produced for oceanographic investigations exhibited a marked seasonal and inter annual variability ([Papa et al. 2012](#)). The impact of Farakka Dam on the Lower Ganges River flow was calculated by comparing threshold parameters for the pre-Farakka period (from 1934 to 1974) and the post-Farakka period (1975–2005). In a normal hydrological cycle, rivers in Bangladesh suffer from low flow conditions when there is no appreciable rainfall runoff. The discharge of river is 80,684 m³/s during the flood or wet-monsoon season while during the dry-monsoon season when the inflow is very low, discharge can be as low as 6041 m³/s ([Ahmed and Alam 1999](#)). The results demonstrate that due to water diversion by the Farakka Dam, various threshold parameters, including the monthly mean of the dry season (December–May) and yearly minimum flows have been altered significantly. The ecological consequences of such hydrologic alterations include the increase of salinity in the southwest coastal region of Bangladesh ([Gain and Giupponi 2014](#)).

This further validates the seasonal shifting of Na-Cl dominated salinity front and molar ratio of Na/Cl, Br/Cl Mg/Ca. Seawater has distinct ionic and isotopic ratios such as Na/Cl=0.86, Br/Cl=0.0015, Mg/Ca=5.2 ([Vengosh et al. 1999](#); [Vengosh and Rosenthal 1994](#)). A Na/Cl ratio of 0.86 was thought to indicate sea water intrusion ([Bear et al. 1999](#)). The Na/Cl molar ratio could

reach unity due to the mixing of seawater and freshwater, which had a Na/Cl ratio greater than unity (Vengosh and Rosenthal 1994). Mg/Ca molar ratio greater than 5 is a direct indicator of seawater intrusion (Vengosh and Ben-Zvi 1994). Significant variation was observed during wet-monsoon season and dry-monsoon season from the molar ratio study of Na/Cl, Br/Cl Mg/Ca indicating seawater intrusion. Chloride and bromide ions have been used to differentiate among various sources of anthropogenic and naturally occurring contaminants in groundwater (Katz et al. 2011). The elements in the estuaries are typically assessed by making plots of their dissolved concentrations vs. salinity. Several elements are removed from the dissolved phase whereas some elements are also released from the suspended particles (Samanta and Dalai 2016). In the present study significant changes in the values of Cl/Br molar ratio, Na/Cl molar ratio, K/Cl molar ratio, Mg/Ca molar ratio in the dry-monsoon compared to the wet-monsoon season indicate saline water intrusion in the coastal rivers. To support the scenario a similar seasonal changes in $\delta^{18}\text{O}$ from Hooghly Estuary (India) was observed. The study had identified low salinity and depleted $\delta^{18}\text{O}$ during monsoon was consistent with increased river discharge as well as high rainfall. This was driven by composition of the freshwater source which was dominated by rainwater during monsoon and rivers during non-monsoon months (Ghosh et al. 2013). Furthermore, presence of seawater was found maximum (31–37%) during February till July and lowest (less than or equal to 6%) from September till November. A temporal offset between Ganges River discharge farther upstream at Farakka and salinity variation at the Hooghly Estuary was observed (Ghosh et al. 2013). Similar situation has been observed from the seasonal changes in hydrochemistry of anions, cations, Na-Cl dominated salinity front and molar ratio study of different anions and cations.

507 The results obtained from the Mann-Kendall and Sen's slope test (Table 4) along with spatial
508 analysis of EC (Figure 2) established the trends in time series of annual trend of salinity rising in
509 the Gorai-Madhumati River network. These results are in agreement with the previous
510 hydrodynamic modelling studies of Bhuiyan and Dutta (2012) and temporal and spatial analysis
511 of salinity occurrences in Kumar-Madhumati River by the study of Shammi et al. (2012).
512 Madhumati River is actually within the network of Gorai-Madhumati. Dry-season flow in the
513 Gorai-Madhumati, the main river carrying fresh water into western parts of the region, has
514 decreased over time. That was mainly due to reduced flow from the Ganges river into the Gorai
515 following construction of the Farakka barrage across the Ganges in India in 1975, but abstraction
516 of river water and groundwater for dry-season irrigation on the Ganges River Floodplain (Region
517 D) through which the Gorai-Madhumati passes has also reduced river flow ([Brammer 2014a](#)).
518 Due to the reduced flow of the rivers in this area in dry season, salinity intrudes into the river
519 systems ([Bhuiyan and Dutta 2012](#)).

520 According to Brammer ([2014b](#)), in the moribund Ganges delta, rivers have been cut off from the
521 Ganges for several centuries, making conditions in the extreme south-west region of Bangladesh
522 naturally saline in the dry season. Similar scenario has been observed from spatial distribution of
523 EC analysis from Figure 2 which is in agreement with the time series analysis. Immediately
524 adjacent to the Meghna River estuary and the Ganges Tidal Floodplain are five low-lying
525 regions/subregions (Ganges River floodplain, Gopalganj Bils, lower Meghna River floodplain,
526 and two sub regions of Meghna Estuarine floodplains in low and western outliers) might be
527 affected by a rising sea-level as early as the coastal regions. These regions/subregions include a
528 wide diversity of environmental conditions that need to be taken into account in assessing
529 potential impacts of sea-level rise and in considering appropriate mitigation measures (Brammer

2014b). A salinity flux model integrated with an existing hydrodynamic model was applied in order to simulate flood and salinity in the complex waterways in the coastal zone of Gorai river basin with sea level rise (SLR) scenario (Bhuiyan and Dutta 2012). The results of salinity model obtained had indicated the risk and changes in salinity due to sea level rise with increased river salinity as well as the salinity intrusion length in the river. Sea level rise of 59 cm produced a change of 0.9 ppt at a distance of 80 km upstream of river mouth, corresponding to a climatic effect of 1.5 ppt per meter SLR (Bhuiyan and Dutta 2012). The SLR depends not only on changes in the mass and volume of sea water but also on other factors, such as local subsidence, river discharge, sediment and the effects of vegetation (Lee 2013). Moreover, the SLR trend obtained from ensemble empirical mode decomposition (EEMD) was 4.46 mm/yr over April 1990 to March 2009, which was larger than the recent altimetry-based global rate of 3.360.4 mm/yr over the period from 1993 to 2007 (Lee 2013). It is, therefore, important to determine the impacts of SLR on salinity to devise suitable adaptation and mitigation measures and reduce impacts of salinity intrusion in coastal cities (Bhuiyan and Dutta 2012).

The progressive inland movement of the dry-season salt-water limit in south-western rivers has had adverse impacts on soil salinity, crop production and availability of potable domestic water supplies in affected areas (Brammer 2014b). Increased salinity possesses a risk of secondary soil salinization. Secondary soil salinization occurs when surface soil salinity has increased from non-saline to a saline level as a consequence of irrigation or other agricultural practices (Peck and Hatton 2003). The seasonal variation of using drinking water sources in the study area is influenced by the monsoonal precipitation and the success of tube well installation factors (Sarkar and Vogt 2015). Increased salinity of drinking water is likely to have a range of health effects, including increased hypertension rates. Large numbers of pregnant women in the coastal

553 areas are being diagnosed with pre-eclampsia, eclampsia, and hyper tension ([Khan et al. 2008](#)).

554 The main drinking water sources used in the study area are the tube well, with an average depth

555 of 200 m, and pond, with or without the adjacent filtration facility known as PSF (pond sand

556 filter) ([Sarkar and Vogt 2015](#)).

557 Nevertheless, the coastal area of the country is known as one of the highly productive areas of

558 the world ([Afroz and Alam 2013](#)). With increasing levels of salinity in the land and freshwater

559 resources, the brackish water aquaculture flourished rapidly on agricultural land. The change in

560 land-use from agriculture to brackish water shrimp aquaculture has further increased the soil and

561 water salinization across the landscape ([Shameem et al. 2014](#)). Salinity increases may affect

562 survival of some mangroves and wetland plants, especially in dry season ([Suen and Lai 2013](#)).

563 Integrated Coastal Zone Management (ICZM) involves an integrated planning process to address

564 the complex management issues in the coastal area of Bangladesh ([Afroz and Alam 2013](#)). It is a

565 blueprint for sustainable coastal development ([Afroz and Alam 2013](#)) which is made up of three

566 broad categories of integration: (i) policy integration, (ii) functional integration and (iii) system

567 integration ([Thia-Eng 1993](#)). Despite increasing recognition of the need for ICZM strategies, the

568 initiation of the Coastal Zone Policy and ICZM has not contributed any significant improvement

569 in the coastal areas ([Rahman and Rahman 2015](#)) of Bangladesh. Introduction of advanced coastal

570 protection models must incorporate the complexity of natural environmental variation, including

571 the influence of both the biotic and abiotic ecosystem ([Spalding et al. 2014](#)). A model should be

572 synthesized to optimize conjunctive uses of the water in the affected area based on two questions:

573 “Which water resources to use?” and “When to use which water source?” for the best

574 management of water resources. Introducing water resources information system aims to build a

575 data-bank of water resources and factors influencing their management ([Loitzenbauer and](#)

[Mendes 2012](#)). This data bank will provide information of existing and potential water resources for optimum uses of water without compromising the quality of water.

The salinity balance of each coastal river basins, including that of the Ganges, Gorai-Madhumati, Meghna, Karnafuli and other river networks should form part of this data-bank, together with the results from modeling the salinity distribution which requires regular trend analysis to combat not only salinity intrusion in the coastal areas but may help to combat other problems including, agricultural-non-point nutrient pollution, hypoxia, eutrophication, sewage pollution, industrial pollution and other problems. It is important to understand and communicate the economic, environmental and social costs of river salinization in order to guide management and restoration efforts. Impacts need to be anticipated and mitigated, and future scenarios of climate change and increasing water demand have to be integrated into the ecological impact assessment ([Canedo-Arguelles et al. 2013](#)). Consequently, for sustaining the ecosystem integrity of coastal rivers and estuaries, it is very important to restore and maintain minimum environmental flow assessment (EFA) of the major shared rivers with India. In the “Bangladesh: National Programme of Action for Protection of the Coastal and Marine Environment from Land-Based Activities” (DoE/MOEF/GOB 2006) strategy 5 clearly stated assessment of environmental flow requirement and salinity intrusion in the Integrated Coastal Zone Management Plan (ICZMP). In this regard a complete regional water management plan for the Ganges-Brahmaputra-Meghna catchment area is needed along with minimum EFA in the lower estuarine and coastal regions of Bangladesh to maintain ecological integrity of the region. However, to-date, India has not prepared any EFA of the joint rivers to support such a plan or to share hydrological data with Bangladesh ([Brammer 2004](#)). Moreover, this plan should be carried out with other countries of shared river including Nepal and China.

6. Conclusions and remarks

Trend analysis is one of the most important issues in any regional hydrological variables taking into account the spatial and temporal variable and providing result for present conditions and future scenario from past data analysis. In this context, spatial records of wet- and dry-monsoon salinity levels in the southern coastal rivers and estuary are important to study the level of salinity fluctuation trends of coastal areas of Bangladesh. The differences between wet- and dry-monsoon salinity levels, represents the combined effect of salinity scenario in the southern region. The results obtained from the historical trend analysis by Mann-Kendall test and Sen's slope was used to establish the trends in time series. In this framework, the conclusions and remarks, which can be significant from this study, are:

- a) EC and TDS is the principal component of salinity along with K^+ , Cl^- and SO_4^{2-} as observed from both wet-monsoon and dry-monsoon seasonal analysis in relation to the other anions and cations. Moreover, on a spatial basis the distribution of the EC values showed variable trends over the south regions. The most saline intruded areas in the wet-monsoon season is
- (i) Extreme south-west coastal zone of Bangladesh comprising the districts of Khulna, Satkhira, Bagerhat, Jessore and Gopalganj;
 - (ii) Lower Meghna River floodplain and Meghna estuarine floodplain comprising the districts of Bhola, Noakhali and Feni;
 - (iii) South-east part of Chittagong coastal plains containing the districts of Chittagong and Cox's Bazar near Bay of Bengal;
 - (iv) The little affected mid-south zone particularly Barisal, Jhalkathi, Patuakhali and Barguna which are also being affected in the dry-monsoon season

- b) From the hydrochemistry analysis of piper diagram in the wet-monsoon season approximately 66% of samples were Ca–Mg–HCO₃ type and second prevailing category was Na–Cl type subjugating 17.70% samples. In the dry-monsoon season foremost water type fell into the category of Na-Cl type (52.27%) followed by Ca–Mg–HCO₃ type (31.81%).
- c) Seawater intrusion was also confirmed by calculated ionic ratios. It was found from Cl/Br molar ratio vs. Cl⁻ that about 42.7% of the collected sample water was affected by salinity in wet-monsoon season compared to the 27% collected in dry-monsoon. Moreover roughly 33.33% sample collected in the wet-monsoon season and 38.63% sample collected in the dry-monsoon had Na/Cl ratio above 0.86 indicating sea-water-intrusion.
- d) From Mann-Kendall and Sen's slope test analysis it was prevalent that among the 13 river time series analysis of salinity trend, four rivers had shown significantly increasing trend of salinity in the extreme south-west zone of Bangladesh. This also signify the future work analysis of other major rivers affected by salinity particularly in other major rivers particularly in Meghna river estuary and eastern Chittagong coastal plains zones. These outcomes deliver the following perceptions for future mechanisms.

On equilibrium, the result of this study proves the extent of seawater intrusion in the coastal rivers by using an interdisciplinary approach. Moreover, the hydrochemical data in conjunction with the remote sensing and GIS and statistical methods identified the spatial extent of salinity occurrences in a seasonal basis. With the application of Mann-Kendall and Sen's slope this research further assessed salinity rising trend in south-west coastal zones of Bangladesh. In order to predict future trends in other rivers, the same method can be utilized to predict future trends of seawater intrusion. This method can be further applied to study other environmental processes to

645 assess. The results of this study can also provide important information and a priori assessment
646 to water resource managers, engineers, practitioners and policy makers and environmental
647 scientists of the country to implement structures for the management of important water
648 resources. This study could further help to comprehend seasonal trends in the hydrochemistry
649 and water quality of the coastal and estuarine rivers, and help policy makers to obligate some
650 important implications for the future initiatives taken for the management of land, water, fishery,
651 agriculture and environment of coastal rivers and estuaries of Bangladesh.

653 **Conflicts of Interest**

654 All authors have read the manuscript and declared no conflict of interests. All authors discussed
655 the results and implications and commented on the manuscript at all stages.

657 **Acknowledgements**

658 This work has been supported by the project entitled “Establishment of monitoring network and
659 mathematical model study to assess salinity intrusion in groundwater in the coastal area of
660 Bangladesh due to climate change” implemented by Bangladesh Water Development Board and
661 sponsored by Bangladesh Climate Change Trust Fund, Ministry of Environment and Forest.

663 **References**

- 664 Afroz T, Alam S (2013) Sustainable shrimp farming in Bangladesh: A quest for an Integrated
665 Coastal Zone Management. *Ocean Coast Manage* 71: 275-283
- 666 Ahamed AU, Alam M (1999) Development of Climate Change Scenarios with General
667 Circulation Models. in: Saleemul Huq, Z. Karim, M. Asaduzzaman, and F. Mahtab (eds.)

668 Vulnerability and Adaptation to Climate Change for Bangladesh. Kluwer Academic
669 Publishers, Dordrecht, the Netherlands. pp. 13-20.

670 Aziz JJ, Ling M, Rifai HS, Newell CJ, Gonzales JR (2003) MAROS: A decision support system
671 for optimizing monitoring plans. *Ground Water* 41(3): 355-367

672 Bahar MM, Reza MS (2010) Hydrochemical characteristics and quality assessment of shallow
673 groundwater in a coastal area of Southwest Bangladesh. *Environ Earth Sci* 61(5): 1065-
674 1073

675 Bear J (1999) *Seawater intrusion in coastal aquifers: concepts, methods and practices*. Boston.
676 Mass: Kluwer Academic.

677 Bhuiyan MJAN, Dutta D (2012) Assessing impacts of sea level rise on river salinity in the Gorai
678 river network, Bangladesh. *Estuar Coast Shelf Sci* 96: 219-227

679 Brammer H (2004) *Can Bangladesh be Protected from Floods?* University Press Ltd, Dhaka.

680 Brammer H (2014a) *Climate Change, Sea-level Rise and Development in Bangladesh*,
681 University Press Ltd, Dhaka.

682 Brammer H (2014b) Bangladesh's dynamic coastal regions and sea-level rise. *Climate Risk*
683 *Manage* 1: 51-62

684 Canedo-Arguelles M, Kefford BJ, Piscart C, Prat N, Schafer RB, Schulz CJ (2013) Salinisation
685 of rivers: an urgent ecological issue. *Environ Pollut* 173: 157-67

686 DoE/MOEF/GOB (2006) Bangladesh, national programme of action for protection of the coastal
687 and marine environment from land-based activities. Department of Environment,
688 Ministry of Environment and Forests, Government of the People's Republic of
689 Bangladesh, Dhaka.

690 Da Lio C, Carol E, Kruse E, Teatini P, Tosi L (2015) Saltwater contamination in the man aged
691 low-lying farmland of the Venice coast, Italy: An assessment of vulnerability. *Sci Total*
692 *Environ* 533: 356-69

693 FAO (1985) FAO report on tidal area study. Fisheries resources survey system. FAO/UNDP-
694 BGD/79/015.<http://www.fao.org/docrep/field/003/ac352e/AC352E00.htm#TOC>.
695 Accessed on 15th March 2016

696 FAO (2017) Applying flexible cropping schedules for rice (t. aman) production in
697 Bangladesh. <http://teca.fao.org/read/6853>. Accessed 30th January 2017

698 Ghabayen SMS, McKee M, Kemblowski M (2006) Ionic and isotopic ratios for identification of
699 salinity sources and missing data in the Gaza aquifer. *J Hydrol* 318(1-4): 360-373

700 Gain A, Giupponi C (2014) Impact of the Farakka Dam on thresholds of the hydrologic flow
701 regime in the lower Ganges River basin (Bangladesh). *Water* 6(8): 2501-2518

702 Ghosh P, Chakrabarti R, Bhattacharya SK (2013) Short- and long-term temporal variations in
703 salinity and the oxygen, carbon and hydrogen isotopic compositions of the Hooghly
704 Estuary water, India. *Chem Geol* 335: 118-127

705 Halim MA, Majumder RK, Nessa SA, Hiroshiro Y, Sasaki K, Saha BB, Saepuloh A, Jinno K
706 (2010) Evaluation of processes controlling the geochemical constituents in deep
707 groundwater in Bangladesh: spatial variability on arsenic and boron enrichment. *J Hazard*
708 *Mater* 180(1-3): 50-62

709 Islam MA, Zahid A, Rahman MM, Rahman MS, Islam MJ, Akter Y, Shammi M, Bodrud-Doza
710 M, Roy B (2016) Investigation of Groundwater Quality and Its Suitability for Drinking
711 and Agricultural Use in the South Central Part of the Coastal Region in Bangladesh.
712 *Expo Health*. Doi: 10.1007/s12403-016-0220-z

713 Jiang Y, Guo H, Jia Y, Cao Y, Hu C (2015) Principal component analysis and hierarchical
 714 cluster analyses of arsenic groundwater geochemistry in the Hetao basin, Inner Mongolia.
 715 Chem Erde Geochem 75(2): 197-205

716 Karanth KR (1994) Groundwater Assessment Development and Management, Tata McGraw-
 717 Hill Publishing Company Limited, New Delhi, (third reprint).

718 Katz BG, Eberts SM, Kauffman LJ (2011) Using Cl/Br ratios and other indicators to assess
 719 potential impacts on groundwater quality from septic systems: A review and examples
 720 from principal aquifers in the United States. J Hydrol 397(3-4): 151-166

721 Kendall MG (1975) Rank correlation methods. Griffin, London

722 Khan A, Mojumder SK, Kovats S, Vineis P (2008) Saline contamination of drinking water in
 723 Bangladesh. Lancet 371(9610): 385

724 Kisi O, Ay M (2014) Comparison of Mann–Kendall and innovative trend method for water
 725 quality parameters of the Kizilirmak River, Turkey. J Hydrol 513: 362-375

726 Lee HS (2013) Estimation of extreme sea levels along the Bangladesh coast due to storm surge
 727 and sea level rise using EEMD and EVA. J Geophys Res: Oceans 118(9): 4273-4285

728 Loitzenbauer E, Mendes CAB (2012) Salinity dynamics as a tool for water resources
 729 management in coastal zones: An application in the Tramandaí River basin, southern
 730 Brazil. Ocean Coast Manage 55: 52-62

731 Mann HB (1945) Nonparametric tests against trend. Econometrica 13:245–259

732 MoWR (2005) Coastal Zone Policy (CZPo), Ministry of Water Resources (MoWR)

733 Niazi F, Mofid H, Modares FN (2014) Trend analysis of temporal changes of discharge and
 734 water quality parameters of Ajichay River in four recent decades. Water Qual Exp Health
 735 6(1-2): 89-95

736 Otache M, Bakir M, Zhijia L (2008) Analysis of stochastic characteristics of the Benue River
 737 flow process. *Chin J Oceanol Limn* 26(2): 142-151
 738 Papa F, Bala SK, Pandey RK, Durand F, Gopalakrishna VV, Rahman A, Rossow WB (2012)
 739 Ganga-Brahmaputra river discharge from Jason-2 radar altimetry: An update to the long-
 740 term satellite-derived estimates of continental freshwater forcing flux into the Bay of
 741 Bengal. *J Geophys Res: Oceans* 117: C11021
 742 Peck AJ, Hatton T (2003) Salinity and the discharge of salts from catchments in Australia. *J*
 743 *Hydrol* 272: 191-202.
 744 Piper AM (1944) A graphic procedure in the geochemical interpretation of water analyses. *Am*
 745 *Geoph Union Trans* 25: 914-923
 746 Rahman AM, Rahman S (2015) Natural and traditional defense mechanisms to reduce climate
 747 risks in coastal zones of Bangladesh. *Weather Climate Extremes* 7: 84-95
 748 Salmi T, Maata A, Antilla P, Ruoho-Airola T, Amnell T (2002) Detecting trends of annual
 749 values of atmospheric pollutants by the Mann–Kendall test and Sen’s slope estimates-the
 750 Excel template application MAKESENS. Finnish Meteorological Institute, Helsinki,
 751 Finland.
 752 Samanta S, Dalai T (2016) Dissolved and particulate Barium in the Ganga (Hooghly) River
 753 estuary, India: solute-particle interactions and the enhanced dissolved flux to the oceans.
 754 *Geochim Cosmochim Acta* 195: 1-28
 755 Sarkar R, Vogt J (2015) Drinking water vulnerability in rural coastal areas of Bangladesh during
 756 and after natural extreme events. *Int J Disaster Risk Reduct* 14: 411-423
 757 Sen PK (1968) Estimates of the regression coefficient based on Kendall’s tau. *J Am Stat Assoc*
 758 63:1379–1389

759 Shahid S (2010) Trends in extreme rainfall events of Bangladesh. *Theor Appl Climatol* 104(3-4):
760 489-499

761 Shameem MIM, Momtaz S, Rauscher R (2014) Vulnerability of rural livelihoods to multiple
762 stressors: A case study from the southwest coastal region of Bangladesh. *Ocean Coast*
763 *Manage* 102: 79-87.

764 Shammi M, Bhuiya G, Ibne Kamal A, Rahman M, Rahman M, Uddin M (2012) Investigation of
765 Salinity Occurrences in Kumar-Madhumati River of Gopalganj District, Bangladesh. *J*
766 *Nature Sci Sustainable Technol* 6(4): 299-313

767 Shammi M, Karmakar B, Rahman M, Islam M, Rahman R, Uddin M (2016) Assessment of
768 salinity hazard of irrigation water quality in monsoon season of Batiaghata Upazila,
769 Khulna District, Bangladesh and adaptation strategies. *Pollution* 2: 183-197

770 Shelley I, Takahashi-Nosaka M, Kano-Nakata M, Haque M, Inukai Y (2016) Rice cultivation in
771 Bangladesh: present scenario, problems, and prospects. *J Intl Cooper Agric Dev* 14: 20-
772 29

773 Siebert C, Möller P, Geyer S, Kraushaar S, Dulski P, Guttman J, Subah A, Rödiger T (2014)
774 Thermal waters in the Lower Yarmouk Gorge and their relation to surrounding aquifers.
775 *Chem. Erde Geochem.* 74(3): 425-441

776 Spalding MD, Ruffo S, Lacambra C, Meliane I, Hale LZ, Shepard CC, Beck MW (2014) The
777 role of ecosystems in coastal protection: Adapting to climate change and coastal hazards.
778 *Ocean Coast Manage* 90: 50-57

779 Suen J-P, Lai H-N (2013) A salinity projection model for determining impacts of climate change
780 on river ecosystems in Taiwan. *J Hydrol* 493: 124-131

781 Takeuchi K, Xu ZX, Ishidiaira H (2003) Monitoring trend step changes in precipitation in
782 Japanese precipitation. *J Hydro* 279:144–150

783 Trabelsi N, Triki I, Hentati I, Zairi M (2016) Aquifer vulnerability and seawater intrusion risk
784 using GALDIT, GQISWI and GIS: case of a coastal aquifer in Tunisia. *Environ Earth Sci*
785 75(8): 1-19

786 Thia-Eng C (1993) Essential elements of integrated coastal zone management. *Ocean Coast*
787 *Manage* 21: 81-108

788 Vengosh A, Heumann KG, Juraski S, Kasher R (1994) Boron isotope application for tracing
789 sources of contamination in groundwater. *Environ Sci Technol* 28 (11): 1968–1974

790 Vengosh A, Spivack AJ, Artzi Y, Ayalon A (1999) Geochemical and Boron, Strontium, and
791 Oxygen isotopic constraints on the origin of the salinity in groundwater from the
792 Mediterranean coast of Israel. *Water Resour Res* 35(6): 1877–1894

793 Vengosh A, Ben-Zvi A (1994) Formation of a salt plume in the coastal plain aquifer of Israel: the
794 Be’erToviyya region. *J Hydrol* 160: 21–52

795 Vengosh A, Rosenthal E (1994) Saline groundwater in Israel: Its bearing on the water crisis in
796 the country. *J Hydrol* 156: 389–430

797 Webster R, Oliver M (2001) *Geostatistics for environmental scientists*. John Wiley & Sons, Ltd,
798 Chichester, Sussex.

799 Werner AD, Bakker M, Post VEA, Vandenbohede A, Lu C, Ataie-Ashtiani B, Simmons CT,
800 Barry DA (2013) Seawater intrusion processes, investigation and management: Recent
801 advances and future challenges. *Adv Water Resour* 51: 3-26

802 Williams WD (1987) Salinization of Rivers and streams: an important environmental hazard.
803 *Ambio* 16: 181-185

804 Williams WD, Sherwood J (1994) Definition and measurement of salinity in salt lakes. Int J Salt
805 Lake Res 3(1): 53-63
806

Figure file

Figure 1

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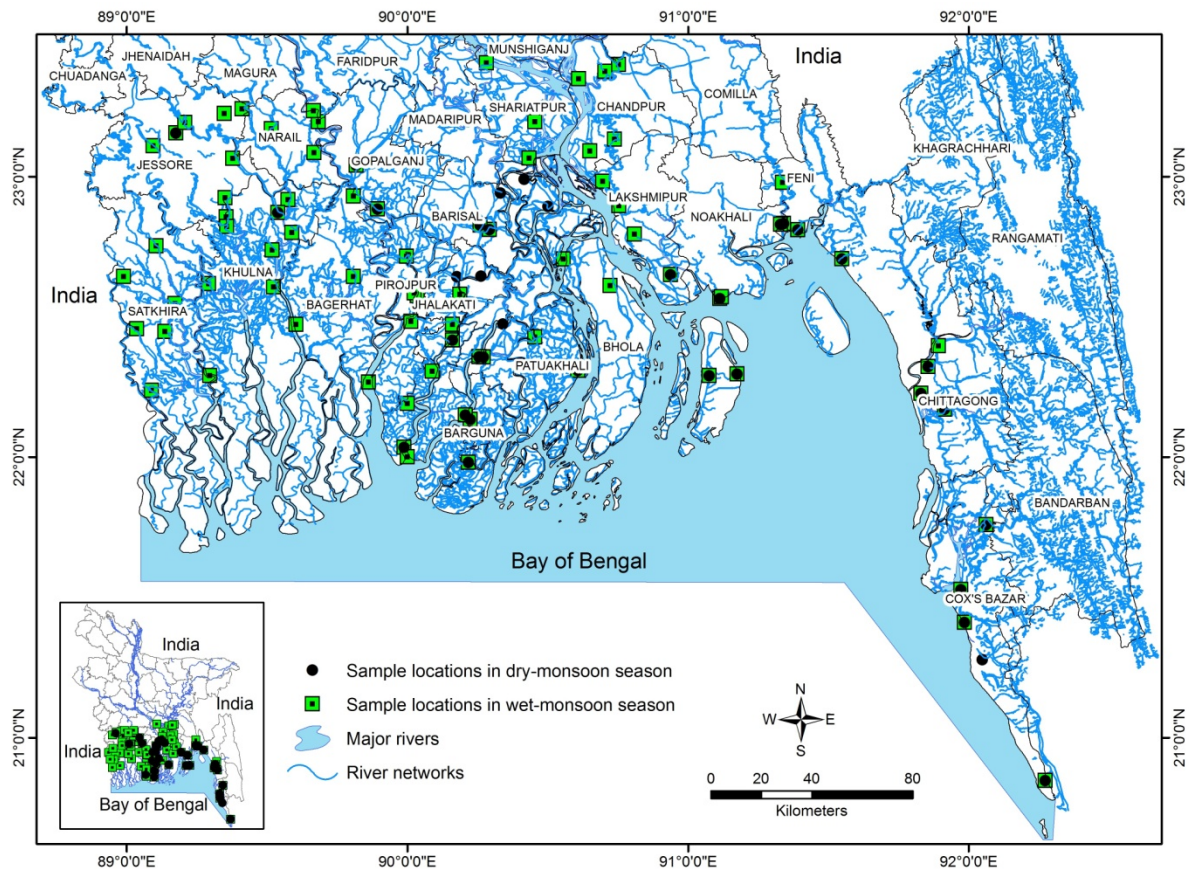


Figure 1. Location map of surface water sampling points in wet-monsoon season and dry-monsoon season along with river networks in the study area

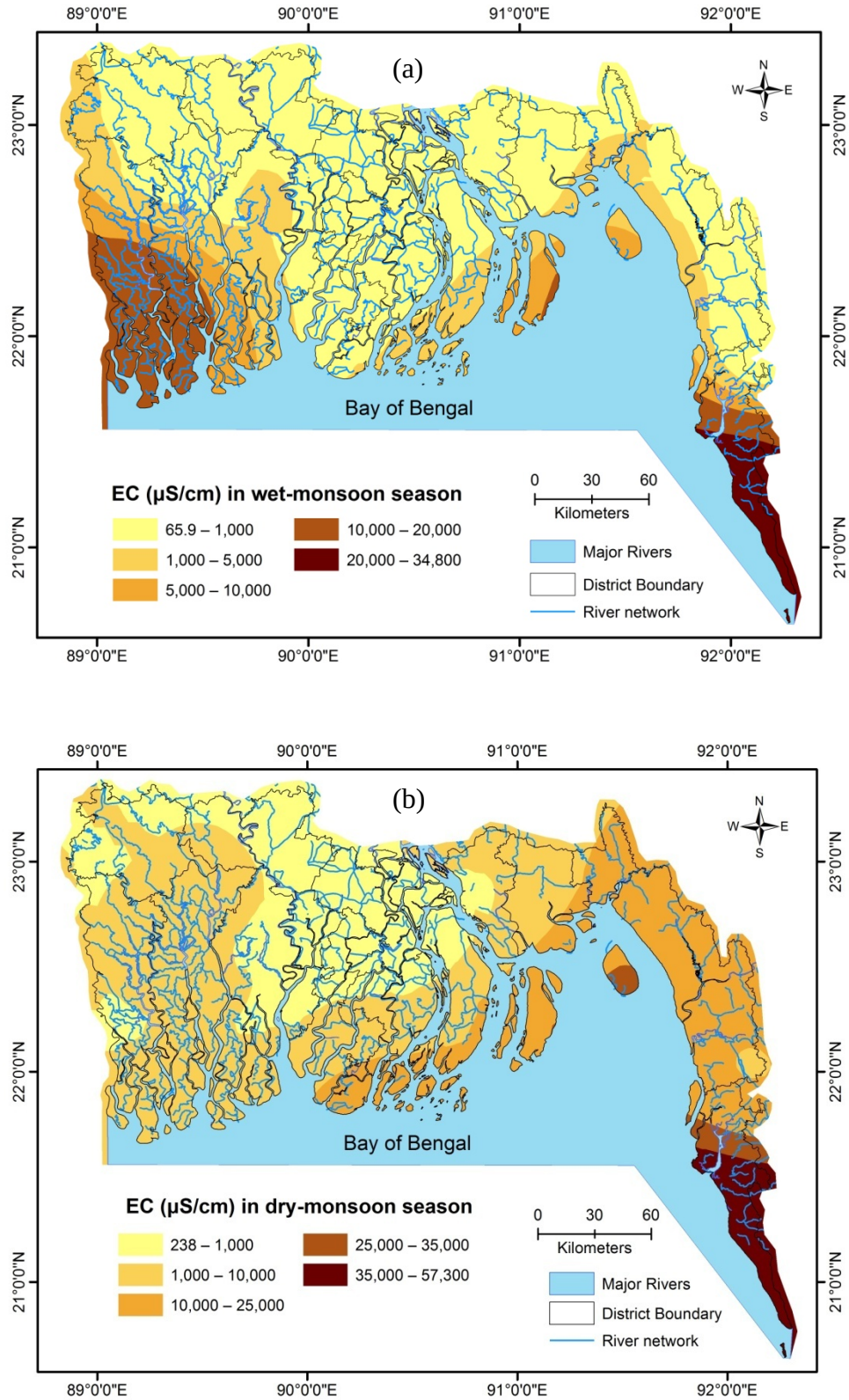


Figure 2. Spatial distribution of salinity occurrences as EC ($\mu\text{S/cm}$) in wet-monsoon season and dry-monsoon season in the coastal rivers and estuaries of Bangladesh. Sampling points in wet-monsoon ($n=96$) (a) and dry-monsoon ($n=44$) (b).

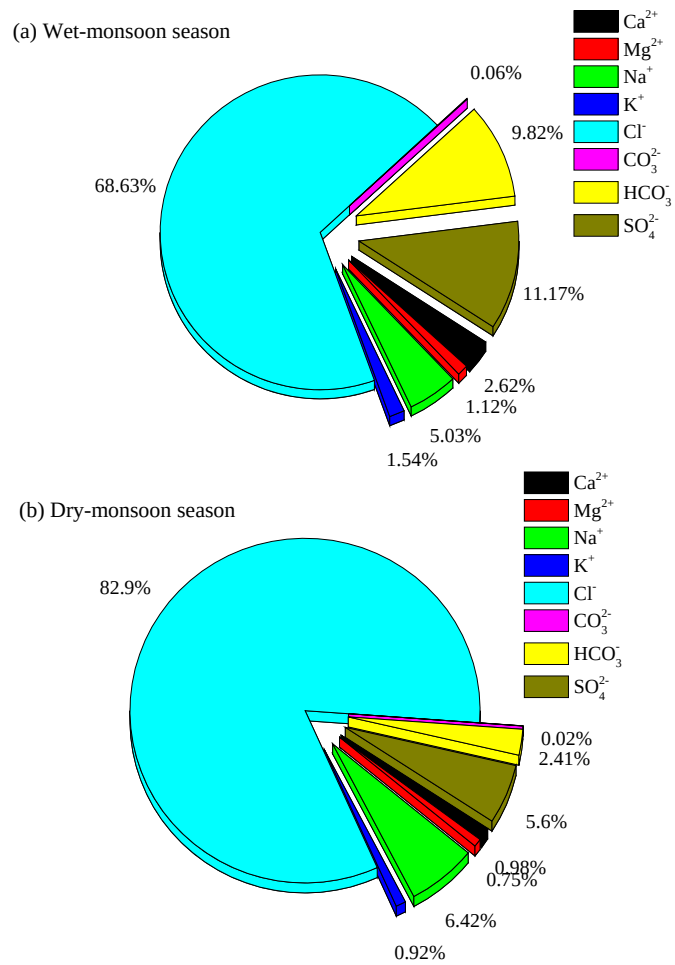


Figure 3. Seasonal variation of anions and cations contributing to salinity in the major coastal rivers and estuarine water based on average data (a) variation in wet-monsoon season (b) variation in dry-monsoon season

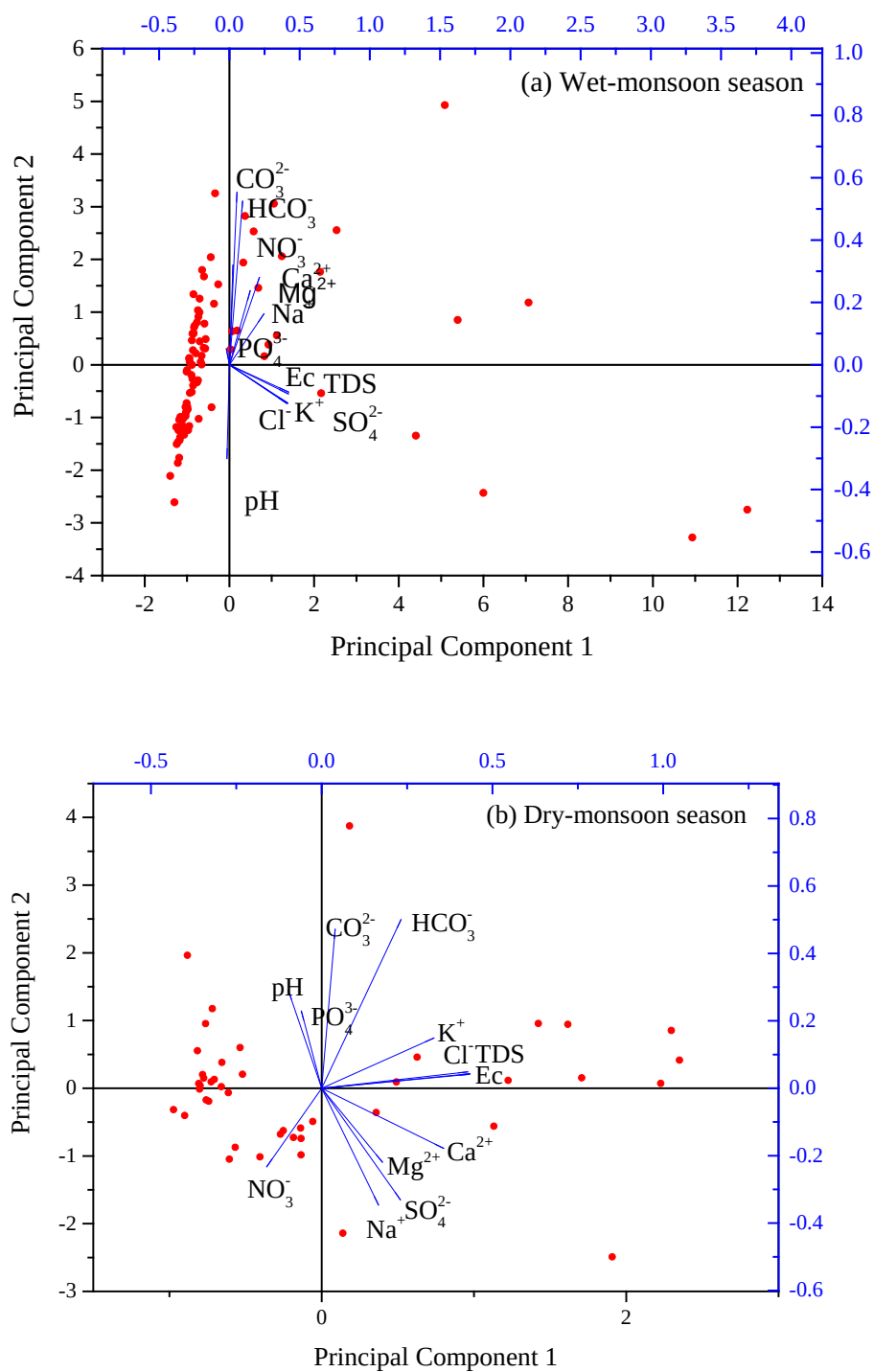


Figure 4. PCA on the combined data sets of anions and cations with other important water parameters to understand seasonal variations of river water (a) Wet-monsoon season and (b) Dry-monsoon season

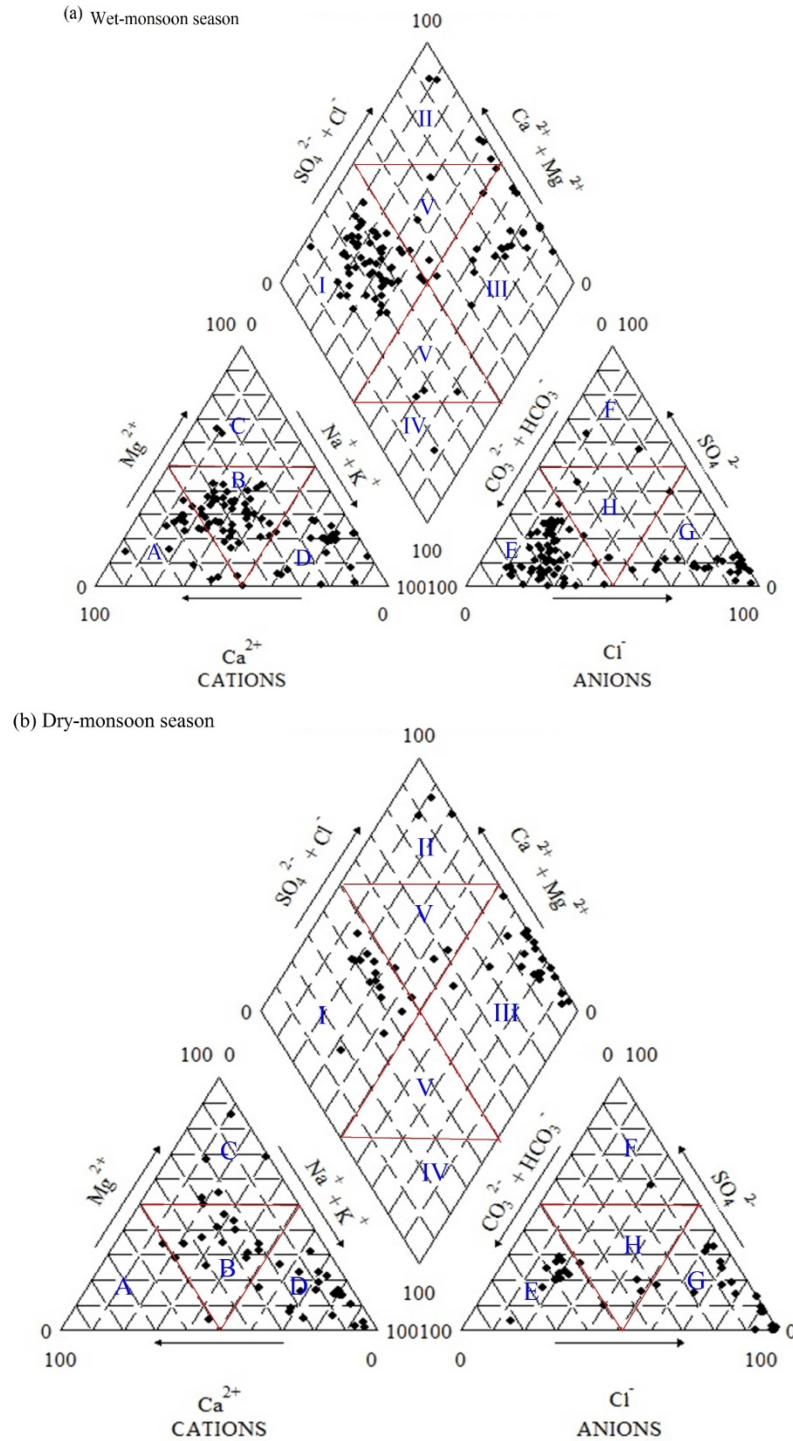


Figure 5. Piper diagram for major ion contents of surface waters of the study area to determine water types (a) wet-monsoon season and (b) dry-monsoon season. The surface waters are classified into three types; Type I: Ca-Mg-HCO₃, Type II: Ca-Cl type, Type III: Na-Cl type, Type IV: Na-HCO₃, Type V: mixed Na-Ca-Mg-HCO₃-Cl

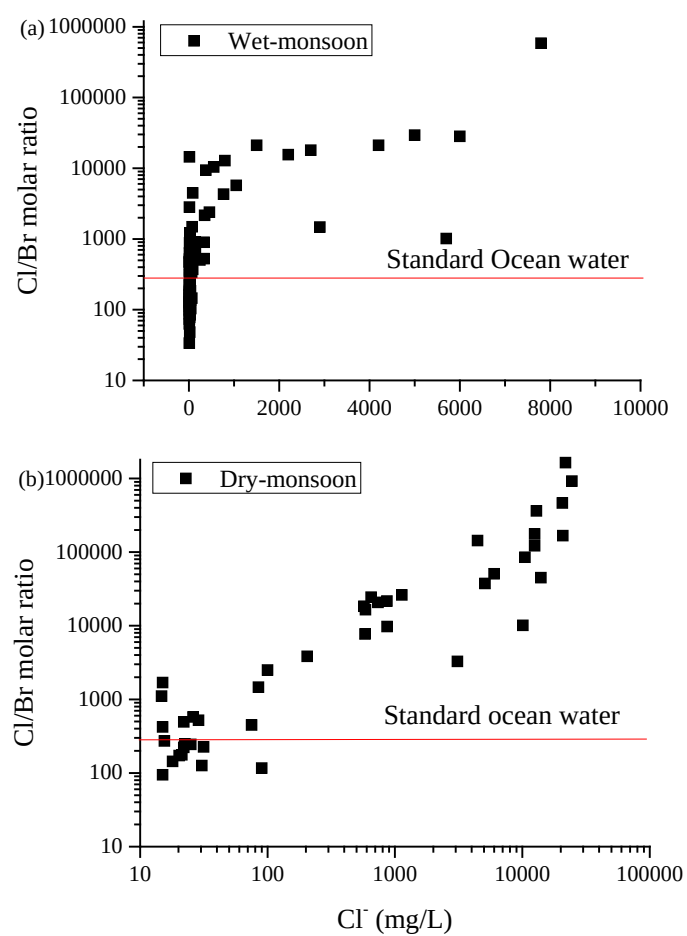


Figure 6. Cl/Br molar ratio vs. Cl^- (mg/L) for (a) Wet-monsoon and (b) Dry-monsoon season

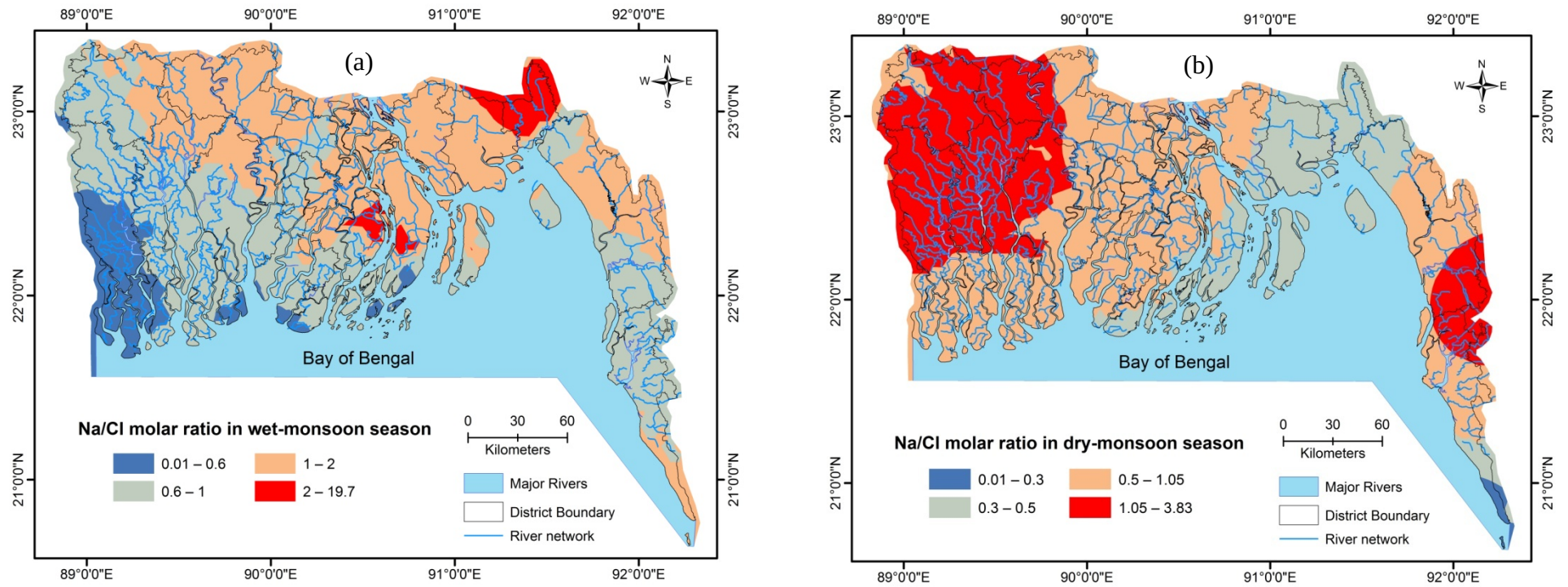


Figure 7. Spatial distribution of Na/Cl molar ratio in wet-monsoon season (a) and dry-monsoon season (b) in the coastal rivers and estuaries of Bangladesh as obtained by Ordinary Kriging method (OK). Sampling points in wet-monsoon (n=96) and dry-monsoon (n=44).