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Current and Future Salinity Intrusion in the South-Western Coastal Region of Bangladesh

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The southwestern coastal regions of Bangladesh (SWCRB) are highly exposed to saltwater intrusions brought about through cyclones and storm surges. These salinity intrusions are contributing to soil and water salinity in the coastal areas. This study aimed to determine the impact of these salinity intrusions on the quality of water and soil in three vulnerable coastal areas. In this investigation, water and soil samples were collected and analysed for pH, electrical conductivity (EC) and other trace elements. The analysis found many of the parameters to be higher than the recommended values. The study found that in soil samples there was a significant correlation between OM and ECe dS/m, as well as K and TN; and a highly significant correlation between TN and OM. This study further examined the historical salinity data at low and high tides to determine any patterns occurring alongside storm surges and cyclones. Water salinity statistics were obtained from the three locations of the Bangladesh Water Development Board (BWDB), which neighbours the study area. A Digital Evaluation Model (DEM) predicts the salinity induced by storm gushes in the corresponding impacted zones. Lastly, the study compared projections for future storm surges at current and predicted sea levels. Potential storm gushes circumstances from 1 to 9 m can impact up to 33% of the nation and 97% of the Shyamnagar Upazila. The occurrence of cyclone-related storms will increase and make cultivation and settlement in the region difficult. The predicted sea-level rises and saltwater contamination will intensify the adverse effects of salinity.

Keywords: sea level rise, storm surges, Geochemical of salinity, Soil and water salinity, SWCRB

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INTRODUCTION

Bangladesh is a country that is highly susceptible to soil and water salinization due to its geographical location. The reason for Bangladesh's susceptibility to salinization is due to the ever-present occurrence of cyclones and storm surges annually across the country. Storm surges are disturbances on the sea surface caused by extreme events such as cyclones where wind drag occurs and pressure drops (Alam et al., 2017; Cochran et al., 2019; Kim et al., 2019). These storm surges can last from several hours up to several days and can encroach up to 10 m inland, bringing with them salinization through saltwater intrusions (Dasgupta et al., 2015a; ibid). Saltwater intrusions in the southwestern coastal region of Bangladesh are having devastating consequences on water resources, agriculture and human health. Soil and water resources are essential to life on Earth, having a serious bearing on food and water security, biodiversity, climate, and human well-being (McBratney et al., 2014; Bannari and Al-Ali, 2020). Saline soils are mainly found in arid and semi-arid regions, where evapotranspiration surpasses rainfall. However, they are also found in coastal districts due to seawater infiltration and inundation by coastal tides (Karmakar et al., 2016). Bangladesh is especially vulnerable to saltwater intrusions, as the country has a vast area of low altitude near the coast and is often subject to tropical cyclones (Brammer 2014; Faneca et al., 2015). Saltwater intrusions have detrimental impacts on land, by increasing the soil and surface water salinity (Rahman et al., 2011). Salt-affected soils also harm the bioavailability of plant nutrients such as N, P, K, Ca, or Mg (Fageria et al., 2011; Daliakopoulos et al., 2016; Alam et al., 2017). Also, the growth potential of legume crops is hampered by saline soil (SRDI, 2012; Alam et al., 2017). The high salt content in soil roots is the main obstacle to the intensification of crop production.

The southwestern coastal area of Bangladesh, in the Bay of Bengal, experiences frequent tropical cyclones and their associated storm surges; that flood areas with saline water (Dasgupta et al., 2010). Bangladesh was hit by 154 cyclones between the years 1877 and 1995, many of them included storm surges that went more than 7 m inland (Dasgupta et al., 2014). More recently between the years 2000–2020, there have been eight major cyclones, including Cyclone Sidr in 2007 and its associated storm surge, that affected around 3.45 million people (Hossain and Mullick 2020). Approximately 37% of arable seaside land is currently impacted by fluctuating degrees of soil salinity due to these surges (Dasgupta et al., 2014). Furthermore, 1.02 million hectares (about 70%) of this arable land on the coast is affected by varying degrees of soil salinity in general. The increase in soil and water salinity causes problems within the coastal ecological setting, affecting the cultivation of crops, thus decreasing food security and increasing the shortage of drinking water by significantly reducing the quality of freshwater (Brammer 2014). This situation can potentially subject more than 20 million people to the harmful effects of excess salt through food and water resources (Haldar et al., 2017). According to the Intergovernmental Panel on Climate Change (IPCC) report, saltwater intrusion in low-lying coastal areas, river deltas and estuaries has increased, leading to salinization of groundwater, surface water and soil resources (Oppenheimer et al., 2019). Excessive groundwater Mining has lowered the groundwater level, and rising sea levels have caused seawater to invade coastal aquifers from the ocean, leading to long-term salinization in southwestern Bangladesh (Salehin et al., 2018). During the dry season, the flow of the lower Ganges becomes low, and seawater pushes inland saltwater into rivers and canals, through vertical filtration or infiltration into nearby land, resulting in salinization of groundwater and soil, which lasts until the onset of the rainy season (Lam et al., 2021; Salehin et al., 2018). Floods and storm surges caused by severe tropical cyclones such as Sidr (2007) and Aila (2009) are also responsible for the long-term salinization of soil and surface water (Kabir et al., 2016; Salehin et al., 2018). This affects agricultural activities such as plant germination, biomass production and yield, and people's livelihoods (Lam et al., 2021).

On the Bangladesh Southwestern coast, shrimp and prawn farming has become widespread (Ahmed and Diana 2015). These farms can be for freshwater and saltwater shrimp with saltwater shrimp farming, increasing salinity, especially in the southern coastal areas (Rahman et al., 2013). Farmers raise shrimp on their land in saline aquaculture ponds that can contribute to groundwater and soil salinity. Freshwater shrimp farms are, on the other hand, at risk due to saltwater intrusions increasing gher salinity and poisoning the shrimp (Ahmed and Diana 2015). The total area of land affected by salinity in Bangladesh in 1973 was 83.3 million hectares; by 2000, it had risen to 102 million hectares, and by 2009, it reached 105.6 million hectares (Brammer 2014).

Another important driving factor increasing soil and water salinization over the previous half-century is climate change (Daliakopoulos et al., 2016; Gorji et al., 2019). This is because soil and water are closely associated with the atmospheric and climatic schemes through carbon, nitrogen and hydrological rotations. Therefore, the changing climate will impact soil and water processes. Low-lying semi-arid and arid areas are even further exposed to soil and water salinity due to declining groundwater quality and rainfall shortages (Kurylyk and MacQuarrie 2013). In these areas, irrigation-based cultivation is indispensable, despite causing the salinization of soil and water which can lead to land degradation (Baumhardt et al., 2015). Following rigorous irrigation, soil salinity affects around 40–45% of the Earth's land and leads to immense economic harm to a universal extent (Oo et al., 2013). One such example is in the Jaffna Peninsula in Sri Lanka where 32.8% of the land and 45% of paddy land have been impacted by salt (Gopalakrishnan and Kumar 2020). The global average surface temperature in the latter part of the current century (2081–2100) is forecasted to go beyond 1.5–2°C (IPCC, 2014; Talukder et al., 2018). Around 70% of the global coastal areas are predicted to undergo remarkable sea level rise. Climate change impacts would lead to the increased river and groundwater salinity in Bangladesh's Southwestern coastal regions by 2050 (Brammer 2014). At least 2.9 million poor people are affected by a drinking and irrigation water deficit in the region (Bannari and Al-Ali, 2020).

Due to the threat of increasing salinity, there is a need to study the effects of soil and water salinity in the southwestern coastal region of Bangladesh in the Shyamnagar Upazila, Shatkhira district, where it has caused significant negative effects on crops, fish and livestock production. This study area is adjacent to the low-lying plains at the confluence of the Ganges, Brahmaputra and Meghna (GBM) rivers which cover over 80% of Bangladesh (Yu et al., 2016). These regions at the coast usually have a mean elevation ranging between one and 4 m above mean sea level (MSL) (Rashid 1977). Slight variations in the tidal levels can cause sea water to travel far inland, depending on the tidal conditions and freshwater upstream flows (Dasgupta et al., 2015b). These low lying areas make the country vulnerable to sea level rises and saline intrusions, as well as other potential extreme weather events (Karim and Mimura 2008).

The main goal of this research is to analyse the geochemical properties of saltwater and its related compounds, the response to saltwater intrusion in river systems, and the possible areas affected by storm surges in the present and the hypothetical 2100 conditions.

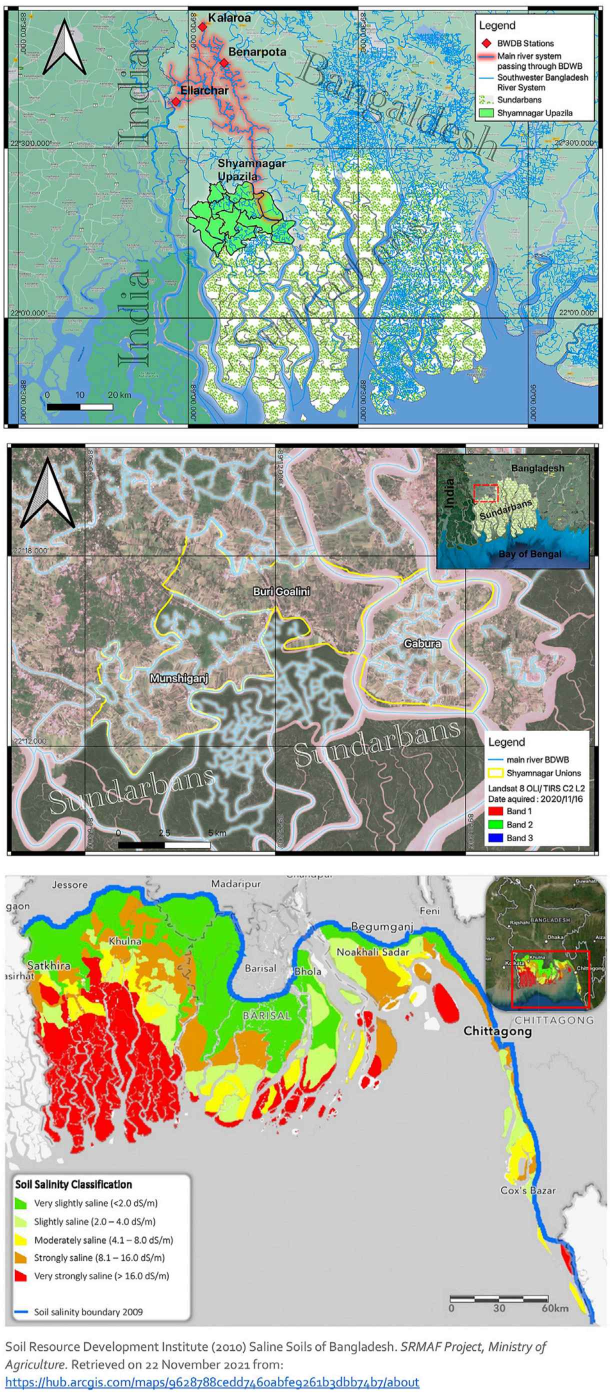

FIGURE 1 | (A) The geographical location of the river delta salinity stations in the southwestern coastal area of the Bay of Bengal, [Humanitarian Open Street Map Team (2021) HOTOSM Bangladesh (southwest) Waterways. Volunteered geographic information. Retrieved on November 22, 2021 from: https://data.humdata.org/dataset/hotosm_bgd_southwest_waterways]. **(B)** Along with the three Unions from where the data was collected. [Landsat-8 image courtesy of the U.S. Geological Survey; OCHA ROAP (2020) Bangladesh—Subnational Administrative Boundaries. Bangladesh Bureau of Statistics (BBS). Retrieved on November 22, 2021 from: https://data.humdata.org/dataset/administrative-boundaries-of-
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FIGURE 1 | bangladesh-as-of-2015]. **(C)** Soil Salinity Bangladesh [Soil Resource Development Institute (2010) Saline Soils of Bangladesh. SRMAF Project, Ministry of Agriculture. Retrieved on November 22, 2021 from: https://hub.arcgis.com/maps/9628788cedd7460abfe9261b3dbb74b7/about].

Similar studies have been conducted to investigate the effect of cyclones and storm water surges on disaster-prone areas. One such study was conducted in the same Shyamnager Upazila district in Bangladesh (Shaibur et al., 2019). In the above-mentioned study, water samples were collected from ponds, pond sand filters and deep tube wells in the Buri Goalini and Gabura unions. The authors found that water from the pond sand filters was fit for drinking purposes according to the World Health Organisation (WHO), but water from the ponds and deep tubes were saline and not suitable for drinking purposes. The study by Shaibur et al. (2019) reflects the impacts that extreme weather events have had on the freshwater supplies in the coastal regions of Bangladesh. It is no surprise that years of saltwater intrusions have harmed the country however little is still known about the impacts on the region's soil and the long-term response to these events. It is important to consider the impact on the soil as well as on the water as these 2 are highly linked and influenced by each other in natural systems. Furthermore, assessing the response to these salinization events over the past decades can assist in pattern identification in how water and soil responds. Recognising these patterns can help the people and governments of disaster-prone areas to better prepare for the after-effects of such extreme weather events, particularly in the agricultural sectors.

Therefore, the objectives of this study are: 1) to assess the primary water and soil parameter results through laboratory tests; 2) to assess the geochemical composition, abundance and effects of saltwater related compounds in soil and water samples in Shyamnagar Upazila; 3) to analyse the relationship of the response to saltwater intrusion at three stations along the Betna-Kholpetua River using historical data and 4) to create a map of the areas commonly affected by storm surges under current conditions and predicted 2100 conditions for Bangladesh and the Shyamnagar Upazila regions.

METHODOLOGY

Study Area

The investigation was carried out at the Buri Goalini, Munshigonj and Gabura Unions under the Shyamnagar Upazila of Satkhira District, situated between 22°36′ and 22°24′ north latitudes and between 89°00′ and 89°19′ east longitudes (BBS, 2011). The 2011 Bangladesh census identifies a population base of 318,254 in Shyamnagar alone whilst 10% of the nationwide population, 14 million people, reside in the South-western coast (Szabo et al., 2016; Efretuei 2016; ibid). The main rivers of the region are the Kobadak, Sonai, Kholpatua, Morischap, Raimangal, Hariabhanga, Ichamati, Betrabati, Kalindi and Jamuna. Usual rainfall is 1, 68 mm with a day-to-day temperature fluctuating from 21 to 30°C. The yearly comparative moisture fluctuates between 7 and 80%. The standard deviation of annual precipitation around this expanse differs from 334.0 to 586.3 mm, (Kabir and Golder 2017) previously reported average maximum and minimum temperatures of 27.7 and 15.6°C during the dry season (November–February), 33.2 and 23.3°C during pre-monsoon season (March–May), and 31.7 and 25.5°C during monsoon season (June–October) for the South-western region of Bangladesh (Mukul et al., 2019).

The investigated region displays even topography, where the maximum expanse remains within 1 m from sea level. The soils are classified as histosols and are described as having grey, slightly calcareous, loamy soils on river banks and grey or dark grey, non-calcareous clays, mainly containing silts, in the extensive land area across the water bodies (Islam et al., 2012; Gorji et al., 2019; ibid). Histosols form when organic matter is generated fast than it is decomposed, this often occurs in areas prone to flooding, but not freezing, where there is poor drainage (Brady and Weil 2008a). Saline and exceedingly saline zones enclose approximately 3336.67 and 241.4 ha, corresponding to 41.46 and 36.6% of all the land of the study region (SRDI, 2012). The pH level usually varies from 5.4 to 7.44 (Islam et al., 2017; Shaibur et al., 2017).

Generally, Shyamnagar Upazila soils are highly dominated by silty clay and silty-clay loam texture (fine-textured and plastic in nature) where the presence of clay particles is much (Shaibur et al., 2017). Clay particles are mainly negatively charged which attract and adsorb positively charged particles to their surface (ibid) Also, lateral movement of water occurs in clay textured soil and that's why waterlogging conditions develop. When these waterlogging conditions are saline, soil salinity develops (Naher et al., 2011). Cations responsible for salt production, such as Ca^{2+}, K^{+}, Na^{+}, and Mg^{2+}, in the soil, get adsorbed by clay particles. Islam et al. (2012) stated that the salinity level of the soil in Shyamnagar Upazila varies from moderate to high. Cation exchange capacity (CEC) of clay or clay loam type soils lie within 15–30 meq/100 g soil or above (Penn and Camberato 2019).

Naher et al. (2011) found that the cation exchange capacity (CEC) of the Shyamnagar Upazila soil varies from 12.0 to 27.6 meq/100 g soil. Also, Shaibur et al. depicted that the status of bicarbonate (HCO^{3-}), sodium (Na), magnesium (Mg) and sulfur (S) were within 366–793 ppm, 7.50–13.50 ppm, 5.11–6.01 meq/100 g soil and 264–431 ppm respectively (Shaibur et al., 2017). Bangladesh's coastal zones have undergone key alterations around the previous five decades, mainly due to recurrent and varied natural catastrophes with direct and indirect bearings on land assets and their various uses (Rasel et al., 2013). The land is despoiled and disappearing due to the impact of increasing salinity, flooding of low-lying swampy land, deluges, and land attrition due to involuntary and chaotic land exploitation by the inhabitants. This intense variation in land exploitation and alteration of the agricultural system has impeded normal crop production during the year (ibid).

The three most vulnerable unions, Gabura, Burigoalini and Munshiganj located in the Shyamnagar Upazila were the focus areas of this study (**Figure 1B**). A total of 18 soil samples and 29 water samples were collected in these areas. Data was collected during rainy season in Bangladesh besides the rainy season in Bangladesh coincides with the summer monsoon season (June to

TABLE 1 | Areas where soil samples were collected and GPS coordinates with land use coded according to sampling source.

Union	Sample no.	Land use	Geographical location	
			Latitude	Longitude
Gabura	G-1	A_f	22.2833°	89.2833°
	G-2	P_s	22.3021°	89.7143°
	G-3	SG_s	22.2812°	89.2791°
	G-4	P_s	22.2849°	89.2852°
	G-5	A_f	22.2742°	89.2764°
	G-6	P_s	22.2736°	89.2751°
	G-7	P_s	22.2824°	89.2798°
Burigoalini	B-1	R_b	22.2453°	89.2467°
	B-2	A_f	22.2458°	89.2463°
	B-3	P_s	22.2443°	89.2454°
	B-4	SG_s	22.2439°	89.2460°
	B-5	P_s	22.2478°	89.2403°
	B-6	SG_s	22.2475°	89.2416°
	B-7	A_f	22.2478°	89.2403°
	B-8	P_s	22.2430°	89.2452°
Munshiganj	M-1	A_f	23.7053°	88.8527°
	M-2	A_f	23.7167°	88.9167°
	M-3	A_f	23.7182°	88.9132°

A_f, Agricultural field soil; P_s, Pond soil; SG_s, Shrimp gher soil; R_b, River-bank soil.

TABLE 2 | Water sample collection areas and GPS location with land use coded according to sampling source.

Union	Sample no.	Land use	Geographical location	
			Latitude	Longitude
Gabura	G-1	P_w	22.2736°	89.2751°
	G-2	SG_w	22.2742°	89.2764°
	G-3	SG_w	22.2812°	89.2791°
	G-4	R_{w1}	22.2915°	89.2702°
	G-5	P_w	22.2824°	89.2798°
	G-6	P_w	22.3021°	89.7143°
	G-7	HT_w	22.2833°	89.2833°
	G-8	P_w	22.2849°	89.2852°
Burigoalini	B-1	P_w	22.2758°	89.2463°
	B-2	S_w	22.2439°	89.2460°
	B-3	R_{w2}	22.2453°	89.2467°
	B-4	RH_w	22.2717°	89.2439°
	B-5	RH_w	22.2719°	89.2436°
	B-6	P_w	22.2478°	89.2403°
	B-7	P_w	22.2443°	89.2454°
	B-8	PSF_w	22.2471°	89.2412°
	B-9	P_w	22.2713°	89.2440°
	B-10	SG_w	22.2726°	89.2430°
	B-11	P_w	22.2478°	89.2403°
	B-12	SG_w	22.2475°	89.2416°
	B-13	HT_w	22.2478°	89.2403°
	B-14	RH_w	22.2478°	89.2403°
	B-15	P_w	22.2430°	89.2452°
Munshiganj	M-1	RH_w	23.7053°	88.8527°
	M-2	S_w	23.7150°	89.8241°
	M-3	SG_w	23.7053°	88.8527°
	M-4	P_w	23.7411°	89.7853°
	M-5	P_w	23.6923°	89.2725°
	M-6	PSF_w	23.7167°	88.9167°

RHw, Rain harvested water; PSFw, Pond sand filter water; SGw, Shrimp gher water; Rw1, Kholpatua River water; Rw2, Chuna River water; Sw, Supply water; Pw, Pond water; HTw, Hand pumped tube well water.

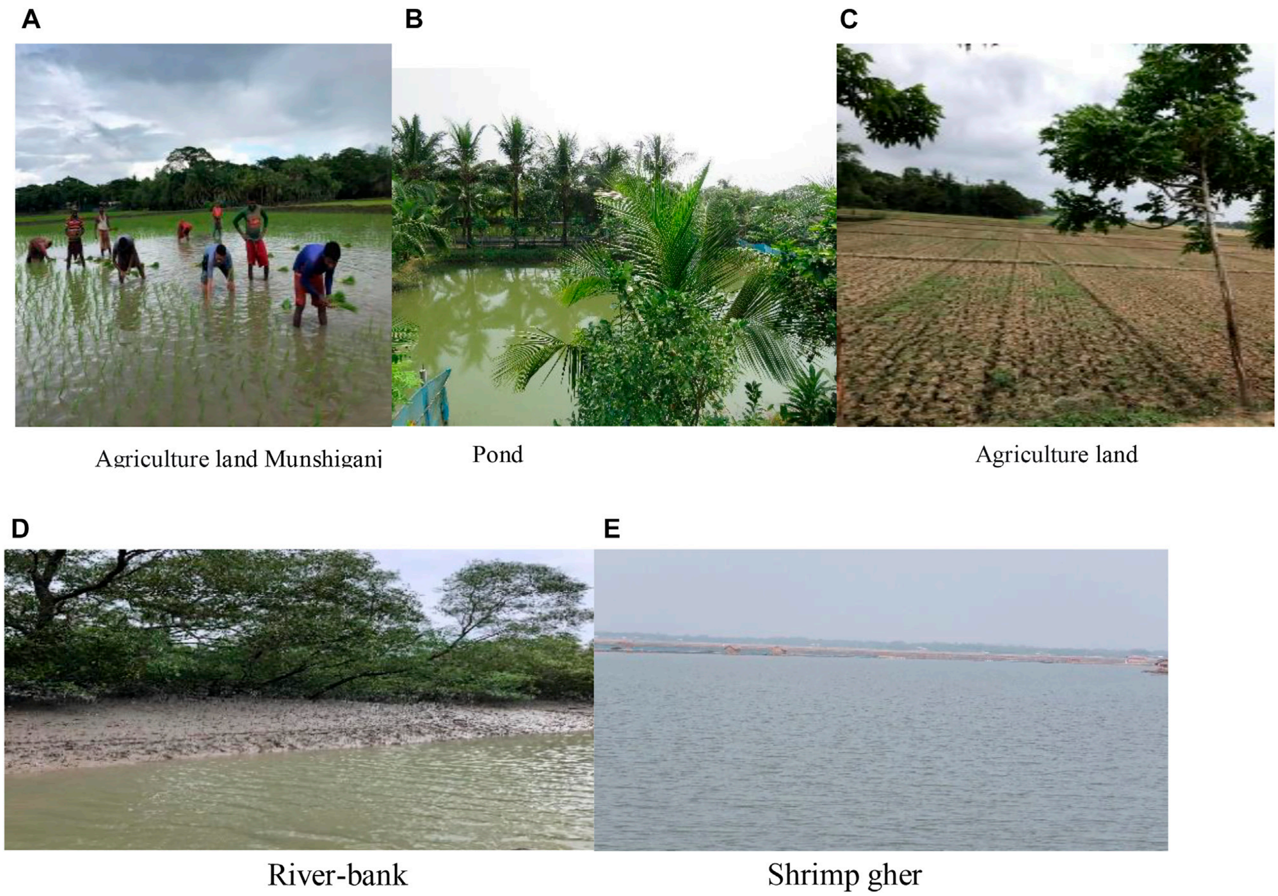


FIGURE 2 | Sample of soil collection areas.

mid-October), this season's rainfall accounts for 75–80% of the total rainfall the country's annual rainfall (Ahmed and Kim 2003).

Soil and Water Sampling

Soil and water samples were collected between the 10th and 13th of July 2019 at the three unions. Samples were collected in bottles that were shaken overnight with 20% nitric acid and rinsed with deionized water to remove internal and external contaminants. Soil samples were collected using a manual auger at a depth of 10–15 cm deep (Soil Survey Staff, 2014).

Eighteen soil samples were collected within these areas from agricultural fields, ponds, riverbanks, and shrimp ghers. The coordinates and land use information for the soil samples are displayed in **Table 1** and the water samples are displayed in **Table 2**. Photographs of the sites are also shown in **Figures 2**, **3** for soil and water samples respectively.

After the samples were collected, all samples were sent to the laboratory of the Soil Resources Development Institute (SRDI) within 21 h and kept in a refrigerator at a temperature below four degrees Celsius (Soil Survey Staff, 2014). Analysis of the soil and water samples was conducted from July 14 to August 21, 2019, at the SRDI. Soil samples were analyzed for pH, electrical conductivity (EC), calcium (Ca), organic matter (OM), total nitrogen (TN), potassium (K) and phosphorous (P). Water samples were analyzed for pH, EC, total dissolved solids (TDS), sodium (Na), bicarbonate (HCO_3) and chloride (Cl).

Twenty-nine water samples were also collected in these areas from tube wells, pond sand filters, and rainwater harvesting tanks. The coordinates and land use information for the soil samples are displayed in **Table 2** and photographs of the collection sites are shown in **Figure 3** below.

Soil and Water Sample Analysis

The major chemical constituents of soil and water and their quality factors were analysed using standard methodologies. Standard saturation paste method was used to determine the ECe where 350 g air-dried soil was taken for each sample to prepare the saturated paste, left it in room temperature for 24 h for equilibrium then the saturated paste extracts were collected by subsequently using Buchner funnel and applying suction (Rhoades, 1996; McBratney et al., 2014; Soil Survey Staff, 2014). In this research ECe soil sample was measured in saturated paste as ECe, dS/m at 25°C and for the EC water sample was measured as EC, dS/m at 25°C respectively. The EC was measured by means of the Jenway EC meter from the extracts (ibid). pH was measured using the Jenway pH metre as described by Tan (2005). The salt content (Total

FIGURE 3 | Water sample collection areas.

Dissolved Solids) was calculated using the following formula (Sparks 2003):

$$Total\ Dissolved\ Solids\ (TDS)\ \% = 0.064^{*}EC$$

The Olsen Sodium Bicarbonate test was used to determine soil phosphorus. Soil potassium and sodium were determined separately by flame emission spectrophotometer (Jenway Model: PEP-7), using potassium and sodium filters, respectively, as outlined by Jackson (1973). Chloride and bicarbonate contents were determined by the titrimetric method described by Jackson (1973). The sample was determined by the Kjeldahl method described by Bremner (2009) and organic carbon was analysed using Walkley and Black (1934) wet oxidation method (Ghosh et al., 1983; ibid).

Additionally, historical data for electrical conductivity (EC) and chloride concentration was obtained from the Bangladesh Water Development Board (BWDB) for the South-western coastal region with data ranging from 1968 to 2019. Data from the BWDB was available from 3 stations: Kalaroa (SW 23; 2001–2018), Elarchar (SW 254.5; 2001–2018), Benarpota (SW 24; 1980–2018). The EC and chloride data from the BWDB was averaged on yearly basis for low and high-water levels. This data was plotted in Microsoft Office Excel 16 as the levels of chloride and EC at high and low tide over time in years.

Statistical Analysis

The results of the soil and water samples were analysed using Pearson's correlation coefficient using the computer software IBM SPSS 25. Pearson's correlation coefficient is a linear correlation model using two sets of data that produces a value, *r*, by accounting for the covariance and standard deviations within the data sets. The *r* vale produced indicts how highly one dataset is correlated or influenced by another with high values being more significant. The standard Pearson's *r* is calculated as follows:

$$r = \frac{\Sigma(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\Sigma(x_i - \bar{x})^2 \Sigma(y_i - \bar{y})^2}}$$

Standard deviation and other general calculations were also conducted. A standard linear regression, using historical data, was created to determine the R^2 value for chloride and EC at low and high tide for the Kalaroa, Elarchar, and Benarpota stations. This was done to identify variables that correlate with each other to find statistical patterns that might reveal evidence of the physical mechanism underlying them. Most calculations were conducted in Microsoft Excel 16 unless otherwise stated.

Cyclonic Storm Surge Analysis

To calculate the areas affected by different seawater surges, three different storm surge heights were used, 1.5, 5.25, and 9 m as the minimum, mean and maximum surge height (Huq and Shoaib, 2013). A 90-m resolution Digital Terrain Model retrieved from (Jarvis et al., 2008) with a 1-m resolution altitude data were used. However, due to the 1-m altitude resolution of our data, the numbers were rounded to 1, 5, and 9 all of the areas within 1-m, 5-m and 9-m of mean sea level in the DEM were used to estimate the respective affected areas. The 1-m sea-level change was calculated using the same process, 1, 5, and 9-m surge 1-m above the current sea levels, similar to the methodology used in the study by Karim and Mimura

TABLE 3 | Some selected chemical properties and land use of soil samples collected from Gabura, Burigoalini and Munshiganj sites.

		Soil chemical parameters								
Location	**Sample ID**	**ECe (dS/m)**	**TDS (%)**	**pH**	**Ca (meq/100 g soil)**	**OM (%)**	**TN (%)**	**K (meq/100 g soil)**	**P (ppm)**	**Land use**
Gabura	G-1	4.3	0.28	7.8	29.5	2.2	0.15	2	4.2	P_w
	G-2	1	0.06	8.8	35.23	2.1	0.17	3	8.59	SG_w
	G-3	11	0.70	8.8	7.47	2.3	0.14	2	10.26	SG_w
	G-4	2.3	0.15	7.5	15.84	2.2	0.11	3	12.17	R_{w1}
	G-5	11.6	0.74	7.7	7.5	2.6	0.11	4	6.81	P_w
	G-6	32.7	2.09	7.3	15.12	4.8	0.24	5	7.52	P_w
	G-7	6.9	0.44	6.8	23.07	2	0.1	3	3.75	HT_w
Average		10.0	0.64	7.8	19.10	2.6	0.15	3.1	7.61	
SD		10.8	0.69	0.7	10.65	1.0	0.05	1.1	3.05	
Burigoalini	B-1	14.3	0.9152	8.4	28.45	2.9	0.14	4	7.47	R_b
	B-2	4.8	0.3072	6.5	25.64	2.4	0.12	2	6.63	A_f
	B-3	6.5	0.416	6.6	19.84	2.7	0.11	4	9.17	P_s
	B-4	17.5	1.12	7.8	33.7	2.4	0.12	3	13.39	SG_s
	B-5	7.9	0.5056	7.9	52.32	2.8	0.1	2	7.70	P_s
	B-6	10	0.64	6.6	81.03	3	0.14	3	8.42	SG_s
	B-7	24.2	1.5488	6.5	31.14	2.2	0.11	2	7.91	A_f
	B-8	6.7	0.4288	8.1	22.40	2.8	0.14	4	15.21	P_s
Average		11.5	0.74	7.3	36.82	2.7	0.12	3.0	9.49	
SD		6.7	0.43	0.8	20.45	0.3	0.02	0.9	3.10	
Munshiganj	M-1	13.6	0.8704	5.1	33.62	2	0.1	4	11.01	A_f
	M-2	20.2	1.2928	6.6	41.07	2.2	0.11	2	6.29	A_f
	M-3	5.2	0.3328	6.5	29.01	2.6	0.13	2	4.3	A_f
Average		13.0	0.83	6.1	34.57	2.3	0.11	2.7	7.20	
SD		6.1	0.39	0.7	4.97	0.2	0.01	0.9	2.81	

(2008). This 1-m sea-level rise projection were taken from (ibid) where a study puts the sea-level change in 2100 between 30 and 100 cm, as well as the IPCC's RCP8.5 estimating a rise of 52–98 cm in sea level by 2100, based on Mukul et al. (2019). Due to the constrained nature of the data resolution, a 1-m sea-level rise was used. Then, each affected area was counted by converting the raster DEM pixels into a vectorised matrix and selecting the pixels with the desired elevation values of 1 m, the sum of pixels from 1 to 5-m for the 5-m surge, and the sum of the pixels from 1 to 9 for the 9-m surge scenarios (Jarvis et al., 2008). This same technique was used with the 1-m sea-level rise scenario but taking the values from 1 m above, so by taking the pixel count from 2 m for the 1-m surge, the sum of 2–6 pixels for the 5-m surge, and the sum of 2–10 pixels for the 9-m surge. The pixel count then was multiplied by 8100 to calculate the area in square metres, and then divided by 1,000,000 to get the square kilometres (Huq and Shoaib, 2013; ibid).

RESULTS

Soil Analysis

The results of the soil analysis are displayed in **Table 3** above.

ECe values of the soil samples are shown in **Table 3**, where the electrical conductivity of the soil samples varies between 1 and 32.7 dS/m. Again, the above results show high salinity statuses for all three respective sampling areas with more than 95% of the samples havilo1ng an ECe dS/m value higher than 8 dS/m across all the sampling areas. Soil salinity is often based on the direct measure of the electrical conductivity, soils with an ECe above 4 dS/m of which most of the samples were; furthermore some scientists have recommended that soils with an ECe above 2 dS/m be classified as saline as most crops will be harmed by salinity above ECe 2 dS/m (Ghosh et al., 1983; Sparks 2003; Brady and Weil 2008b). This will also have a large impact on agricultural production as only some salt-tolerant varieties of crops may produce a satisfactory yield in these areas (Alam et al., 2017; Van Tan and Thanh, 2021).

The highest pH values found for Gabura, Burigoalini and Munshiganj were 8.8, 6.8, and 8.4 whilst the lowest pH values were 6.5, 6.6, and 5.1, respectively. The results indicate that most of the areas of Gabura and Burigoalini have higher soil pH levels (mildly to strongly alkaline) as opposed to the neutral range (Ahmad and Rahman 2010). However, lower pH values were found in the Munshiganj site soils. The results confirm that agricultural and livestock production in Gabura and Burigaolini has been seriously affected due to the high pH levels (Alam et al., 2017). Salinity is known to have an impact on the pH of a soil, as salinity increases, pH decreases, in other words, the soil becomes more acidic. This serves to explain the

TABLE 4 | Pearson correlation coefficient of soil nutrients with soil pH, ECe and organic matter (SOM).

	Correlations						
	pH	**ECe (dS/m)**	**OM (%)**	**TN (%)**	**Ca (m_{eq}/100 g soil)**	**K (m_{eq}/100 g soil)**	**P (ppm)**
pH	1						
ECe (dS/m)	–0.189	1					
OM (%)	0.101	0.555*	1				
TN (%)	0.351	0.375	0.752**	1			
Ca (m_{eq}/100 g soil)	–0.243	–0.040	–0.021	–0.114	1		
K (m_{eq}/100 g soil)	–0.006	0.299	0.560*	0.395	–0.263	1	
P (ppm)	0.199	0.016	0.006	–0.029	–0.076	0.339	1

*Correlation is significant at the 0.05 level (2-tailed).
**Correlation is significant at the 0.01 level (2-tailed).

lower pH soils having high salinity or TDS (Ghosh et al., 1983, Sparks, 2003).

Organic Matter (OM), nitrogen (N) and potassium (K) showed statistical significance in their sample abundance (**Table 4**). Most of the samples displayed a potassium concentration that exceeded the recommended 2.0 m_{eq}/100 g range and could be detrimental to certain species. The reason for this high levels of K could be due to the alternating wetting and drying of the soils that can be brought about during extreme weather events, it is known that alternating wetting and drying periods enhances the K fixation in the soil, making it more available (Weil and Brady, 2017). Above this threshold, luxurious potassium intake in plants, retains elevated levels causing slow plant growth, furthermore excess K is toxic for human and animal consumption (He and Chen 2013; Alam et al., 2017). The abundance in total nitrogen (TN) and organic matter was observed for all the samples in all study areas (Xue and An 2018). Inundated soil is rich in organic matter and nitrogen content, which explains the proportionally higher rates of these two variables, especially in water-filled soils such as ponds and ghers (Fulton et al., 2011). External organic and non-organic additions may change the ratio of total nitrogen and available nitrogen, as nitrogen may be unavailable to plants in certain compounds (Bingham and Cotrufo 2015). The deficiency of phosphorous (P) in the soil samples is visible in all of the study areas, this is to be expected as high organic matter in soils leads to lower levels of phosphate fixation (Weil and Brady, 2017). However, there is a higher concentration of phosphorous in shrimp ghers as compared to agricultural lands, likely due to biological excretions by the shrimp. This is a problem, as the phosphorous concentrations are too low for agricultural production, which has the potential to lead to phosphorus deficiency in plants, resulting in the need to use phosphorous fertilizers (Lawlor et al., 2004; Sharma et al., 2013). The low phosphorous in these soils is likely due to the high level of organic matter in the soil which has likely arisen due to the nature of heavy flooding in the area, soils that are not aerated tend to have higher OM contents as less decomposition occurs, this in turn also reduces the soils P fixation capacity (Weil and Brady, 2017). Similarly, calcium (Ca) concentrations in all the samples are way above the recommended 5–10 m_{eq}/100 g soil (Van Tan and Thanh, 2021). This excess of calcium inhibits seed germination and reduces growth rates dramatically (Lawlor et al., 2004). A statistical correlation was conducted between the soil nutrients with soil pH, electrical conductivity (EC) and organic matter (OM) was conducted and the results are shown in **Table 4**.

The Pearson's correlation coefficient study in **Table 4** showed a significant positive correlation between ECe dS/m and OM (0.555*), OM and TN (0.752**) and OM and K (0.560*). Other correlations were found to be nonsignificant, indicating no influence between the parameters. This correlation study illustrated that organic matter concentration is positively correlated with electrical conductivity (EC), total nitrogen (TN) and potassium (K) and vice versa. The correlation with TN is expected as OM is essentially dead plant and animal material which tend to be mainly made of carbon, nitrogen, phosphorous, and hydrogen. Similarly the correlation between OM and K is expected as an increase in OM increase the CEC of soils, making K fixation higher (Weil and Brady, 2017). The correlation between OM and ECe dS/m is interesting as an increase in ECe dS/m directly reduces the decomposition of OM in the soil (Iranmanesh and Sadeghi 2019). A decrease in OM decomposition will also result in a decrease of available P which further explains the results in **Table 3**. In summary, the soils in the area are high in OM due to the nature of flooding in the area; the flooding in the area also increases the overall TDS and in turn ECe dS/m of the soil. The increase in ECe dS/m in the soil will decrease OM decomposition which will further decrease P availability (Ghosh et al., 1983). This will continue in cycles with every extreme weather event.

Further comparisons were conducted between pH and phosphorous (P) and are graphically displayed in **Figure 4** below.

Comparing phosphorous content with pH shows that at a pH of 7.0–8.3, samples had P content greater than 12 ppm (Jackson, 1973). At higher and lower pH values (pH > 8.3; pH < 7.0) the P content of the samples was mostly below 10 ppm. However, no significant correlation exists between these two variables, indicating either the absence of coupled physical processes. In soil, both acidic and alkaline conditions increase phosphorus concentrations, which explains their relatively low abundance outside the neutral pH range. Thus, maximum P availability occurs at near-neutral pH, confirming the findings of Penn and Camberato (2019). However, the input of synthetic phosphorous in agriculture and shrimp farms may skew the results, so no statistically significant relationship can be found. This means that

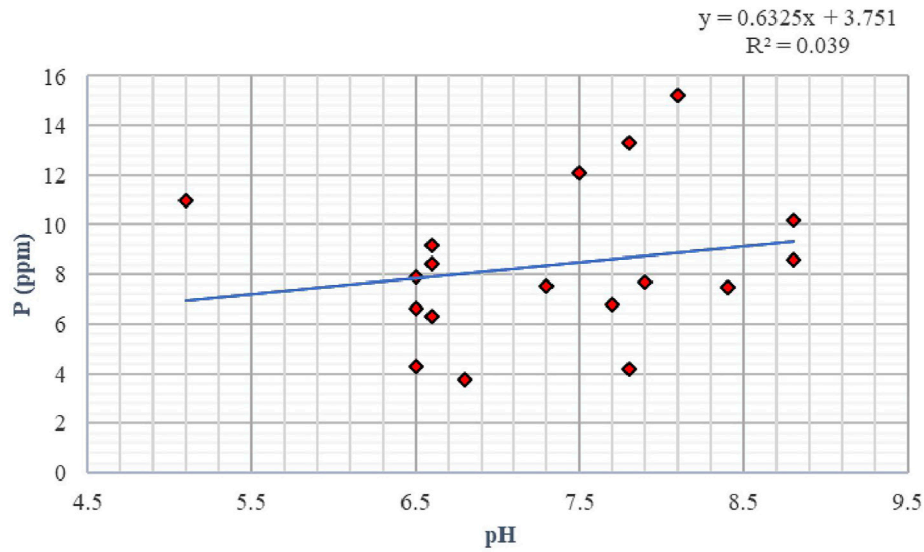


FIGURE 4 | Statistical relationship between Phosphorous (ppm) and pH. The abundance of Phosphorous is greater within the neutral area of pH despite not having any correlation (R^2 = 0.039).

if pH was to fluctuate above or below a neutral pH, it will rapidly be threatened phosphorous levels.

Water Analysis

The results of the water analysis are displayed in **Table 5** below where the EC values varies from 0.1 to 41.3 dS/m. The results show that most of the samples have exceeded the permissible limit of salinity in the sampling areas, particularly in river water (>30 dS/m) (Alam et al., 2017). Increased shrimp production using brackish water causes artificial salinity in the water and affects adjacent agricultural fields and drinking water reservoirs (Mahmuduzzaman et al., 2014; World Health Organization, 2017). Continuous use of saline water can be a great threat to human consumption and irrigation.

As seen above, G1–G4 had much higher Na values than compared to the other soil samples in the area. Furthermore, six samples from the Buri Goalini area and one from the Munshigani union had similar high Na concentrations. This is a concern as high Na levels can cause sodicity in soil which makes soil less permeable and more prone to being flooded (Sparks 2003). In turn, the soil in these flooded areas will develop higher organic matter concentrations (histosol formation).

Approximately 93% of the water samples showed a sodium (Na) concentration beyond the recommendation of 200 mg/L as well as chloride above 250 mg/L, these concentrations are unsuitable for drinking water (World Health Organization, 2017). As these two elements are associated with salt, the samples containing NaCl are much higher in TDS than the standard values (Tavakkoli et al., 2011; ibid). The results furthermore represent a direct connection between pH and bicarbonate (HCO^{3-}). The higher the bicarbonate, the higher the pH (alkaline condition) (ibid). Most of the water samples from the Gabura and Burigoalini sites showed moderately to highly alkaline conditions exceeding the permissible limit for human consumption (Islam et al., 2017). Saline water can also corrode metal pipes of supply water and increase metal concentration in drinking water which can pose a further threat to human health. Among the water samples, the concentration of bicarbonate (HCO^{3-}) was highest at 384.3 mg/L for sample B-15 and lowest at 30.5 mg/L for sample B-11; despite this, none of the samples was above the standard limit of 600 mg/L (World Health Organization, 2017). This trend follows a similar relationship with pH, which was verified by the very strong statistical correlation in **Table 6**.

The Pearson's correlation coefficient study of water parameters in **Table 6** illustrated a highly significant and positive correlation between pH and bicarbonate (0.79**), EC and Na (0.99**), EC and Cl^- (0.91**) and Na and Cl^- (0.89**) (Tavakkoli et al., 2011). Other correlations were found to be non-significant. Overall, the correlation study of the study areas showed that in most cases, the concentrations of EC, Na, and Cl^- were highly and positively correlated with each other (Tavakkoli et al., 2011; Alam et al., 2017; Islam et al., 2017). On the other hand, pH showed a weak and negative correlation with EC and other parameter concentrations besides bicarbonate. The pH and bicarbonate show strong positive correlations, which are related to the bicarbonate buffer system (Rhoades, 1996). A Pearson correlation was conducted between different soil and water parameters.

The Pearson correlation coefficient study between the soil and water parameters depicted a significant negative correlation between the ECe dS/m of soil and the EC of water (−0.47*); the ECe dS/m of soil and the Na of water (−0.50*) and a positive correlation between the OM of soil and the Na of water (0.50*) (Akter et al., 2016; Alam et al., 2017). Other correlations, both positive and negative were found to be non-significant. Surprisingly, a negative but significant correlation is visible between the ECe dS/m of soil and the EC of water (−0.47*). This indicates that if water salinity

TABLE 5 | Some of the selected chemical properties and land use of water samples collected from the Gabura, Burigoalini and Munshiganj sites.

		Water chemical parameters						
Location	**Sample ID**	**EC (dS/m)**	**TDS (%)**	**pH**	**Na (mg/L)**	**Bicarbonate (mg/L)**	**Chloride (mg/L)**	**Land use**
Gabura	G-1	32.8	2.10	8.1	5520	219.6	12420	P_w
	G-2	38.2	2.44	8.4	6900	122	15019	SG_w
	G-3	41.3	2.64	8.2	7360	91.5	64005	SG_w
	G-4	39	2.50	8.3	6440	128.1	62928	R_{w1}
	G-5	2.3	0.15	8.9	920	256.2	2208	P_w
	G-6	0.8	0.05	8.4	50.6	109.8	552	P_w
	G-7	1.9	0.12	8.4	460	128.1	4554	HT_w
	G-8	5.4	0.35	8.7	460	262.3	6072	P_w
Average		20.2	1.29	8.4	3513.83	164.7	20969.8	
SD		19.0	1.22	0.3	3299.8	69.5	26676.2	
Burigoalini	B-1	6.1	0.39	8.9	1380	311.1	7603	P_w
	B-2	0.2	0.01	7.7	23	18.3	276	S_w
	B-3	39.6	2.53	8.1	6900	122	63480	R_{w2}
	B-4	0.7	0.04	8.1	460	54.9	690	RH_w
	B-5	0.1	0.01	7.2	460	36.6	138	RH_w
	B-6	0.6	0.04	8.5	460	128.1	690	P_w
	B-7	1.4	0.09	8.2	460	73.2	1794	P_w
	B-8	0.7	0.04	8.6	55.2	109.8	690	PSF_w
	B-9	3.7	0.24	8.3	460	91.5	4830	P_w
	B-10	39.6	2.53	8.2	5980	128.1	60720	SG_w
	B-11	0.1	0.01	7.9	460	30.5	690	P_w
	B-12	38.3	2.45	8.2	5980	146.4	62100	SG_w
	B-13	1.2	0.08	8.2	115	115.9	1104	HT_w
	B-14	39	2.50	8.3	5980	140.3	68034	RH_w
	B-15	16.7	1.07	8.7	2760	384.3	24978	P_w
Average		12.5	0.80	8.2	2128.88	126.1	19854.5	
SD		17.1	1.10	0.4	2641.9	99.9	28030.8	
Munshiganj	M-1	0.3	0.02	8	920	61	414	RH_w
	M-2	2.9	0.19	8.4	460	280.6	3594	S_w
	M-3	35.5	2.27	7.9	5980	54.9	57408	SG_w
	M-4	2.8	0.18	8.7	920	195.2	2760	P_w
	M-5	0.6	0.04	7.9	920	61	414	P_w
	M-6	1.1	0.07	8.7	96.6	244	1242	PSF_w
Average		7.2	0.46	8.3	1549.43	149.5	10972.0	
SD		13.9	0.89	0.4	2196.2	102.8	22785.0	

TABLE 6 | Pearson correlation coefficient of water nutrients with pH and EC.

	Correlations				
	pH	**EC (dS/m)**	**Na (mg/L)**	**Bicarbonate (mg/L)**	**Chloride (mg/L)**
pH	1				
EC (dS/m)	−0.084	1			
Na (mg/L)	−0.116	0.992**	1		
Bicarbonate (mg/L)	0.790**	0.024	−0.007	1	
Chloride (mg/L)	−0.094	0.914**	0.892**	−0.028	1

**Correlation is significant at the 0.05 level (2-tailed).*
***Correlation is significant at the 0.01 level (2-tailed).*

increases, soil salinity decreases. This can be explained by the dissolution of salts from the soil into the water when it is waterlogged (Islam et al., 2017). Other nonsignificant correlations are visible between chloride, calcium and potassium, which are all responsible for the increase of the salinity in soil and water by producing calcium chloride ($CaCl_2$)

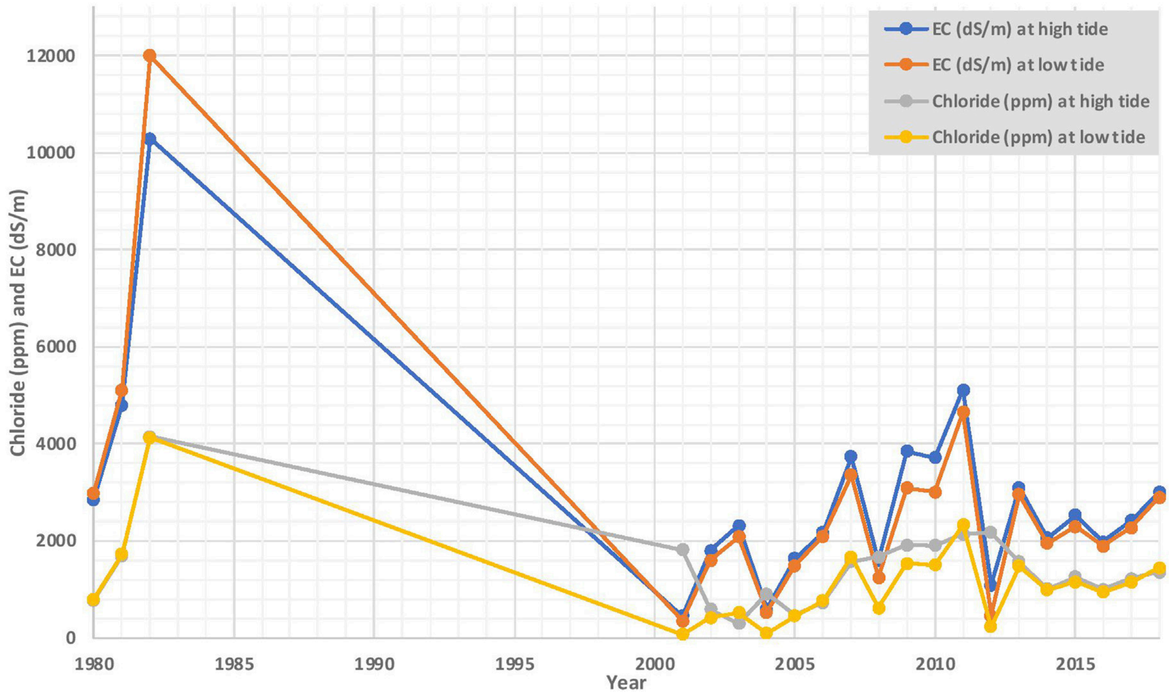


FIGURE 5 | Chloride concentrations (ppm) and electric conductivity (dS/m) at high and low tides in the Betna-Kholpetua river at Benarpota from 1980 to 2018. This graph shows a large increase in salinity and chloride concentrations in 1982, a smaller one in 2007, and another one from 2009 to 2011.

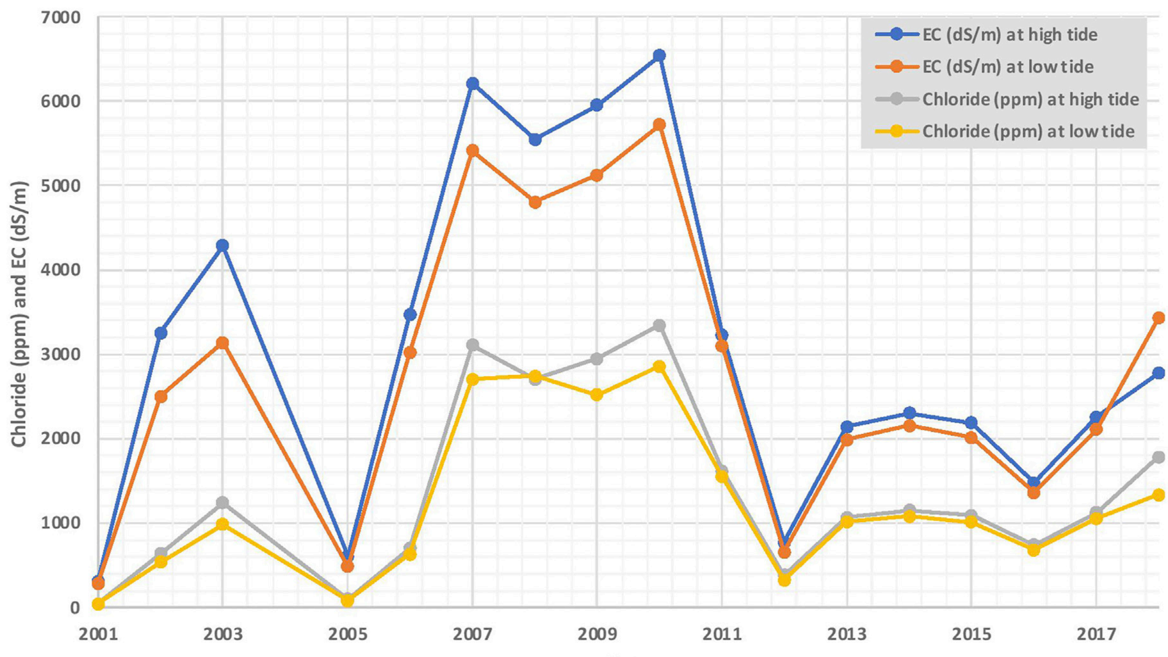


FIGURE 6 | Chloride concentrations (ppm) and electric conductivity (dS/m) at high and low tides in the Betna-Kholpetua River at Kalaroa from 2001 to 2018. This graph shows an increase of both chloride and EC from 2001 to 2003, followed by a more prolonged increase from 2006 to 2011, finally with a slight increase from 2013 to 2015.

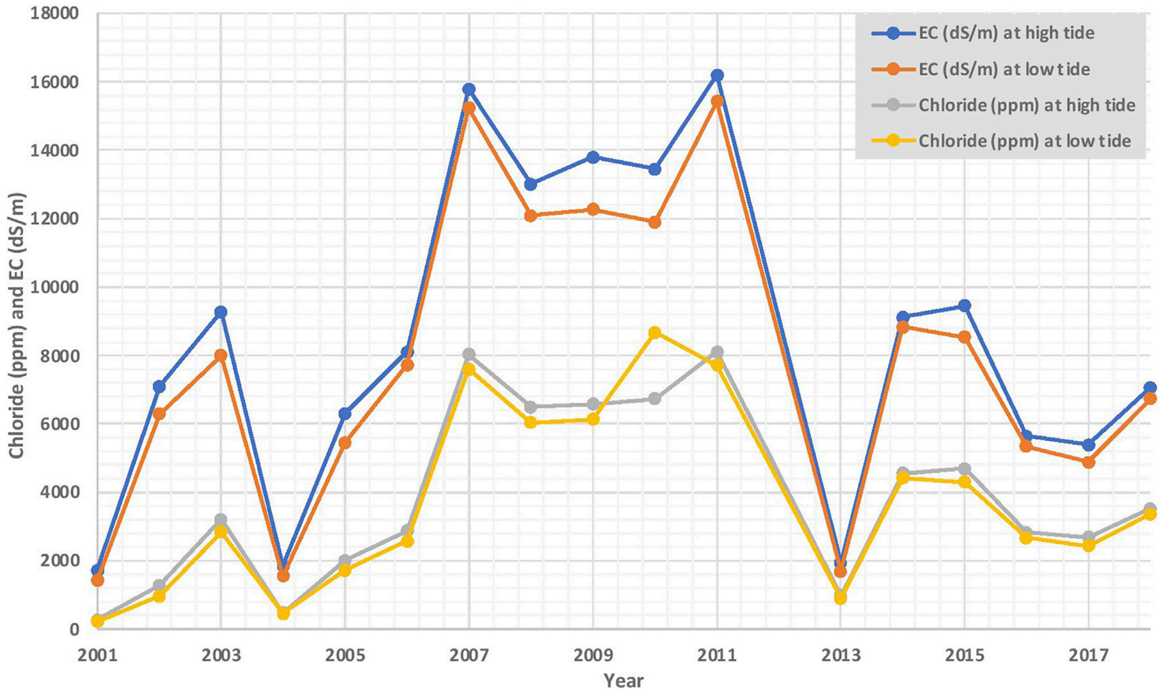


FIGURE 7 | Chloride concentrations (ppm) and electric conductivity (dS/m) at high and low tides in the Betna-Kholpetua River at Elarchar from 2001 to 2018. An increase of both chloride and EC from 2001 to 2003, followed by a more prolonged increase from 2006 to 2011, finally with a slight increase from 2013 to 2015.

and potassium chloride (KCl^-) salts. However, these correlations are too weak to draw any conclusions.

Historical Patterns of Water Salinity

Historical data was collected and analysed overtime to try to determine and/or predict future patterns and correlations. The relationship between chloride and EC at different tide levels at the Benaporta station is shown in **Figure 5**.

The Benaporta station shows a matching relationship between Cl^- and EC concentrations at low and hide tides, but Cl^- at high tide shows a more attenuated relationship (Ahmad and Rahman 2010). At the same time, there was a massive spike in chloride in 1982, with EC levels reaching over 10,000 (dS/m), a smaller spike is visible from 2006 to 2007 with salinity levels of >3,000 dS/m and chloride levels of >1,000 ppm, and another spike from 2009 to 2011. Thereafter, a more intense increase in both salinity levels of 3,000 to 4,000 dS/m and chloride concentrations of 1,000 to 2,000 ppm, from 2009 to 2011. This increase is followed by minor spikes from 2012 to 2018.

The relationship between chloride and EC at different tide levels at the Benaporta station is shown in **Figure 6**.

The Kalaroa station clearly shows a spike of both chloride and EC from 2001 to 2003, with a salinity level of >4,000 dS/m and a chloride concentration of >1,000 ppm at high tides. These levels are similar to the same spike at Benaporta station. From 2006 to 2011, there is a massive increase in salinity (Pal et al., 2016). The SIDR Disaster caused salinity intrusions in the south-western parts of Bangladesh–with levels fluctuating between 5,000 and 6,000 dS/m at high and low tides, and chlorine levels fluctuating between 2,000 and 3,000 ppm. These values are more than double the spike recorded between 2001 and 2005 and are higher than the same anomaly observed at Benaporta station. Finally, from 2013 to 2015 a minor spike can be seen, however, much weaker than the two others. Lastly, the relationship between chloride and EC at different tide levels at the Elarchar station is shown in **Figure 7**.

In **Figure 7**, a trend similar to that observed at the Kalaroa station is repeated at Elarchar, where an increase in chloride and EC is observed from 2001 to 2003 with a salinity level of >8,000 dS/m and a chloride concentration of >2,000 ppm at high tides. Surprisingly, these values are twice as high as those seen in Kalaroa. Along with this, a massive increase in salinity, with levels well above 12,000 dS/m at high and low tides, and chlorine levels above 6,000 ppm is recorded from 2007 to 2011 (SRDI, 2012; World Health Organization, 2017). These values are again twice as high as those recorded at the Kalaroa station. **Table 7** reflects the correlations between the chloride concentrations at high tide between the three stations.

Every correlation is higher than R^2 = 0.2 except for the Benarpotas high tide with the Kalaroa's high and low tide. This indicates that most data sets are affected quite similarly by the same environmental process. The same correlations were done using the EC data in **Table 8**.

TABLE 7 | Correlations between Chloride concentration at low and high tides from the Bearpota, Kalaroa and Elarchar stations.

		Correlations						
		Benarpota		Kalaroa		Elarchar		Legend
		Cl (ppm) HT	Cl (ppm) LT	Cl (ppm) HT	Cl (ppm) LT	Cl (ppm) HT	Cl (ppm) LT	
Benarpota	Cl (ppm) HT		0.5855	0.1763	0.1931	0.3049	0.3416	>0.7
	Cl (ppm) LT	0.5855		0.3789	0.3621	0.5297	0.5181	>0.2
Kalaroa	Cl (ppm) HT	0.1763	0.3789		0.982	0.6897	0.7467	<0.2
	Cl (ppm) LT	0.1931	0.3621	0.982		0.7172	0.7597	
Elarchar	Cl (ppm) HT	0.3049	0.5297	0.6897	0.7172		0.9574	
	Cl (ppm) LT	0.34	0.5181	0.7467	0.7597	0.9574		

TABLE 8 | Correlations between EC concentration at low and high tides from the Bearpota, Kalaroa and Elarchar stations.

		Correlations						
		Benarpota		Kalaroa		Elarchar		Legend
		EC HT	EC LT	EC HT	EC LT	EC HT	EC LT	
Benarpota	EC HT		0.9776	0.3407	0.4120	0.5268	0.5294	>0.7
	EC LT	0.9776		0.2592	0.3319	0.4389	0.4518	>0.2
Kalaroa	EC HT	0.3407	0.2592		0.9662	0.6274	0.5935	<0.2
	EC LT	0.4120	0.3319	0.9662		0.6345	0.6126	
Elarchar	EC HT	0.5268	0.4389	0.6274	0.6345		0.9939	
	EC LT	0.5294	0.4518	0.5935	0.6126	0.9939		

All the correlations had values greater than $R^2 = 0.2$, indicating that these data values respond in a similar way to the same environmental process.

The correlation analysis from **Table 7** shows the chloride concentrations of the three stations at low and high tide, except for the correlation between Benarpota's high tide and Kalaroa high and low tide data. Similarly, **Table 8** shows that all had a significant correlation above $R^2 = 0.2$. Both tables show correlations above $R^2 = 0.5$. The two most predominant spikes from 2001 to 2003 and 2006/7 to 2011 are therefore statistically supported by these correlations. This means that the physical and environmental processes behind these spikes are affecting trends in salinity levels of the Betna-Kholpetua River in a similar and fairly uniformly manner.

Storm Surges and Sea-Level Rises

Figure 8 below displays two maps with projected impacts of potential storm surges at different distances inland in the Bay of Bengal. **Figure 8A** is at current sea level and **Figure 8B** is with a 1-m rise in sea level.

These maps show that a potential storm surge of 9 m has the capacity, in both scenarios, to cover over a third of the country [Self-made with data retrieved from Jarvis et al. (2008)]. The results from the different storm surge flooding extents with current sea levels indicate that even a small cyclone that creates a 1-m surge (Dasgupta et al., 2014; Hossain and Mullick 2020) has the potential to affect 1,492 km^2 or about 1% of the area of Bangladesh and could reach the city of Khulna. However, a more severe cyclone creating a 5-m storm surge has the potential to flood 17,724 km^2 of the coastal area, or about 12% of the country's territory, reaching the outskirts of Chittagong and Dhaka. Lastly, as a worst-case scenario, a very extreme cyclone, with a 9-m storm surge could flood an area of 48,491 km^2 or about a third of the country (Karim and Mimura 2008; IPCC 2014), having a considerable impact on Dhaka and Chittagong.

Based on the maps above it is evident that the most vulnerable areas are the rivers. Many streams enter deep into Bangladesh's territory, which means that even a moderate cyclone (1-m surge), can affect river environments and freshwater supplies far from the coast. These results may explain the correlations between the Kalaroa, Benarpota and Elarchar stations in **Tables 7**, **8**, as these are within the range of a 1-m storm surge. Also, in **Figures 5–7**, these stations reflect an increase in salinity over the years, where cyclones have led to an intrusion of saltwater (IPCC 2014).

As seen in **Figure 8B**, the map indicates the same seawater surge scenario but based on the scenario of a projected 1-m rise of sea level, according to the IPCC's RCP8.5 from Mukul et al. (2019). This indicates that a 1-m surge can reach as far as the north-western border with India, because the surge can penetrate deep into the country through the channels of the rivers that run through it, covering 1.2%. A 5-m surge will cover a great part of the southwestern portion of Bangladesh and the surrounding floodplain areas of river systems with the potential to affect 17% of the country's area (IPCC 2014). An extreme 9-m surge event is predicted to cover more than one-third of the country and has the potential to affect the entire southern portion, having a considerable impact on all three major cities. Similarly, the Bangladeshi Sundarbans, will be highly affected, as the southwestern portion (Dasgupta et al., 2014), will be mostly inundated by a 9-m water surge.

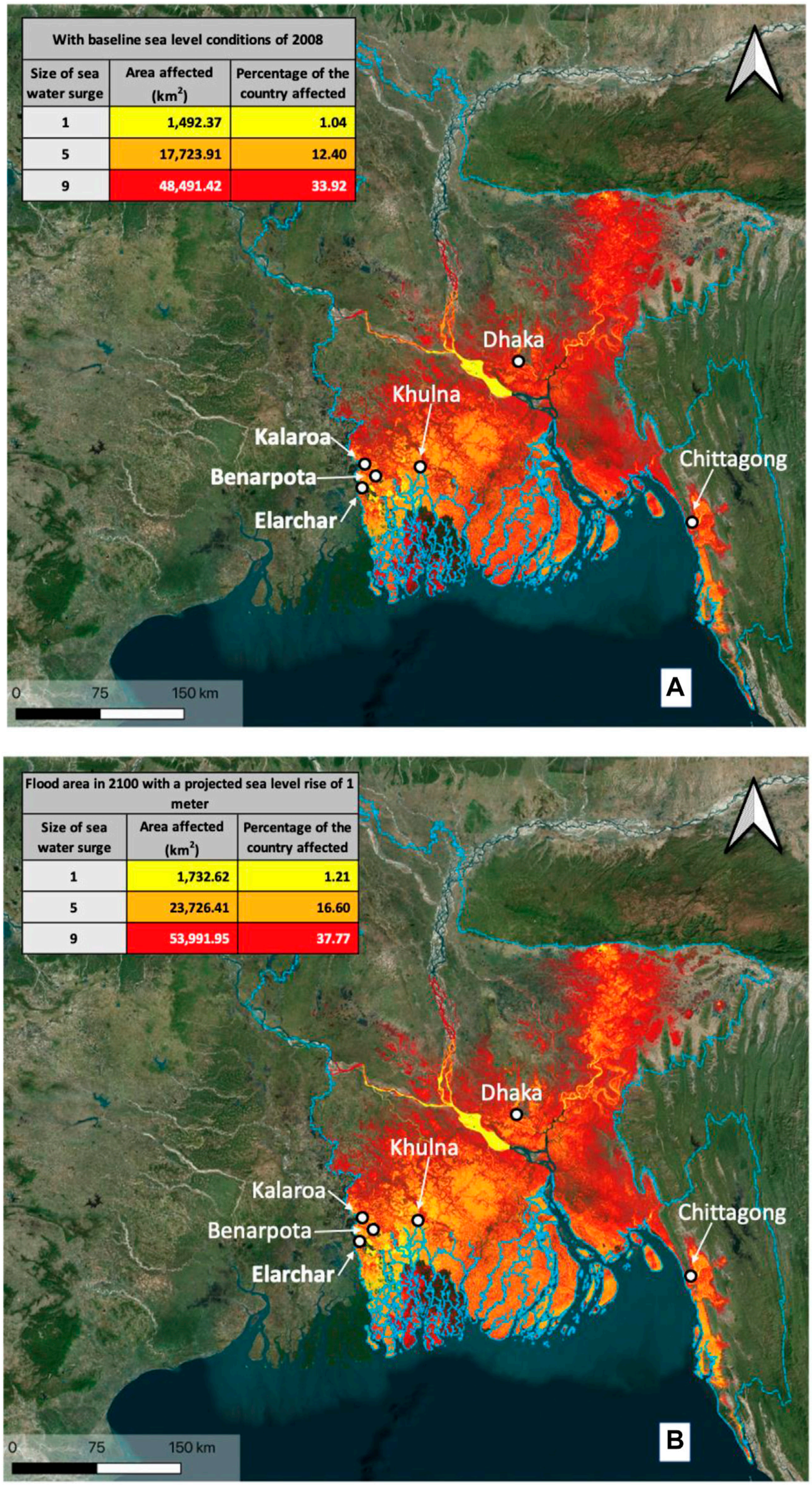
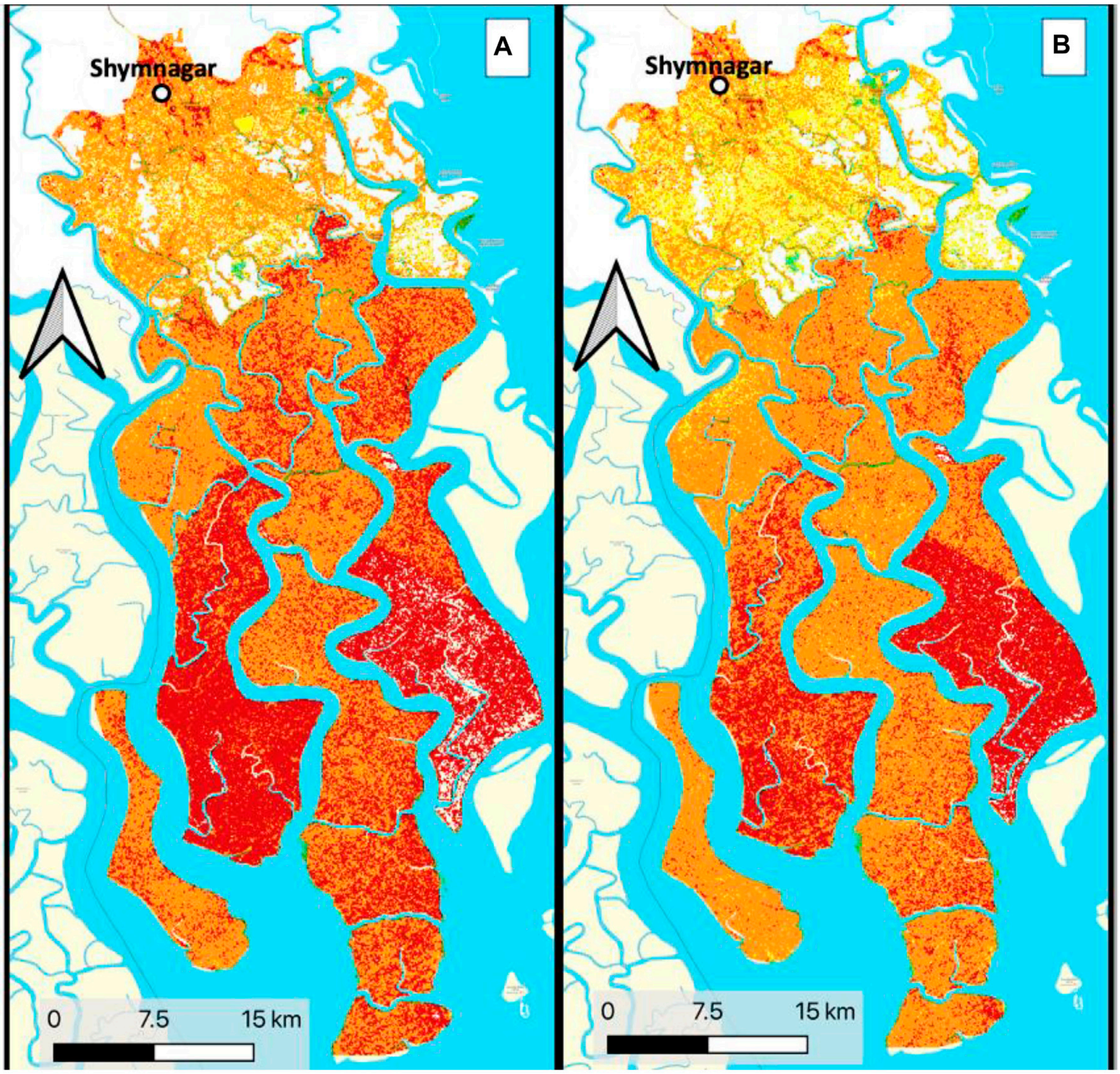


FIGURE 8 | Storm surge projections over the Bay of Bengal for areas affected by surges of 1, 5, and 9 m. **(A)** at current sea level. **(B)** at a 1 m rise in sea level.

Figure 9 displays the maps from two different storm surge scenarios for the Shyamnagar Upazila region. Map A is a projection of the area affected by surges of 1, 5, and 9 m due to a cyclone or a tropical storm, with current sea levels. Map B shows the same area but with a 1-m rise in sea level, similar to **Figure 8**.



A With baseline sea level conditions of 2008			**B** Flood area in 2100 with projected sea level		
Size of sea water surge	Area of Shyamnagar upazila affected (km^2)	Percentage of Shyamnagar upazila affected	Size of sea water surge	Area of Shyamnagar upazila affected (km^2)	Percentage of Shyamnagar upazila affected
1	79.04	5.59	1	124.46	8.81
5	867.78	61.41	5	1,010.77	71.53
9	1,374.81	97.30	9	1,321.73	93.54

FIGURE 9 | Results from two different storm surge scenarios for the Shyamnagar Upazila, map **(A)** is a projection of the area affected by surges of 1, 5, and 9 m due to a cyclone or a tropical storm, with current sea levels. Map **(B)** shows the same area but with a 1-m rise in sea level. This map shows that a 9-m storm surge can cover most of the area (>90%) in the Upazila. Self-made with data retrieved from Jarvis et al. (2008).

The maps above show that a 9-m storm surge can cover most of the area (>90%) in the Upazila [Self-made with data retrieved from Jarvis et al. (2008)]. The first scenario shows that a 1-m surge will affect 79 km^2 of the area or around 6% of the Upazila, however, a 5-m water surge can affect more than half of the area, and a potential 9-m surge scenario will flood almost the entire area or 97% of the Upazila.

Comparatively, **Figure 9B** shows the same scenario, but with a baseline of 1 m above sea level, indicating that 5.6% of the area or 79 km^2 will be submerged by 2100 (IPCC 2014). Here, the most significant change can be seen in the 1-m surge, as it will cover 9% of the area, mainly affecting a large part of the mainland around Shyamnagar town. The 5-m surge will now cover almost three-quarters of the Upazila, affecting areas in the southern Sundarbans that were only affected by a 9-m surge. Finally, a 9-m surge will cover less area compared to the current scenario but is expected to affect almost the entire Upazila.

DISCUSSION

Bangladesh is an extremely vulnerable nation due to its low topography, where half of the country lies within 5 m above sea level. Furthermore, Bangladesh is also extremely vulnerable to cyclonic and tropical storm activity, as displayed in the projection scenarios above. Based on several studies this research identifies that from 1891 to 2008, about 178 cyclones have hit the coast of Bangladesh (Karim and Mimura 2008; Dasgupta et al., 2010). The deadliest cyclones in recent years were in 1970, 1982, 1991, Sidr in 2007 and Ayla in 2009, with several other cyclones flooding vast areas of the Bangladeshi coast (Dasgupta et al., 2010; Dube 2012). Karim and Mimura (2008) indicated that about seven cyclones with surges of more than 4 m have occurred between 1970 and 2008. In summary, the Bangladeshi coast is affected by more than one cyclone each year and a cyclone with a moderate surge storm (>4 m) every 5.4 years. Based on this information, it is expected that more than 12% of the country is at a very high risk of saltwater flooding every 5.4 years, as well as 1–2% of the country being flooded by seawater every year. This also means that 64% of the total area of the Shyamnagar Upazila is expected to be flooded with saline water, and 5.6% annually.

At extreme scenarios, the highest prediction of a 9-m surge will have a lower periodicity but will not be uncommon. Zaman (2011) indicates that storm surges of these proportions are common in the literature, and cyclones with storm surges of 15-m have also been reported. In 1876, a cyclone with an associated 13-m surge hit the coast of Bangladesh, and a 10-m storm surge hit the coast in 1970 (Dasgupta et al., 2010). Furthermore, a 10-m wave is expected to hit the coast every 20 years (Dasgupta et al., 2014). For the Shyamnagar Upazila, this means that most of the area will be flooded with saline water every 20 years.

The same parameters will apply for storm surges with an estimated 1-m rise in sea level. The increase in the area flooded by sea rise compared to the current conditions depends on the topography of the land, which allows more water to pass inland, rather than an increase in the intensity of cyclones. Karim and Mimura (2008) note that the frequency of cyclones in November is increasing for the coast of Bengal. There has also been a clear increase in global cyclone activity over the last 35 years (Dasgupta et al., 2010). Huq and Shoaib (2013) indicate that an intensification of wind speeds and cyclones is expected in the foreseeable future, due to increased ocean surface heat. This will increase the size and periodicity of associated seawater intrusion over Bangladeshi territory. This suggests that the above predictions for the area affected by cyclones underestimate the possible future predictions, which should be 1–3 m depending on the vulnerability of the area (Dasgupta et al., 2010).

Furthermore, evidence of these seawater surges is recorded in the chemical archives within the Kalaroa, Benarpota, and Elarchar stations of the Bangladesh Water Development Board as a pattern of spikes or increases of both salinity and chloride. These spikes reflect the Sidr, Aila, and Nargis storms in 2007, 2008, and 2009 respectively. First, the 1982 spike, with EC levels reaching over 10,000 (dS/m), can be attributed to a storm surge in the same year, which caused heavy loss of life (Dube 2012). Similarly, the 2007 to 2011 spikes can be attributed to storms Sidr in 2007 (Pal et al., 2016) and Ayla in 2009 (Rasheed et al., 2014; Haldar et al., 2017) that resulted in saltwater intrusion into the river system. Similarly, during 2008, (Fritz et al., 2009) storm Nargis primarily affected the Myanmar deltaic region, but also the coast of Bangladesh, which can be considered as a link between the two spikes in 2007 and 2009 in **Figures 5–7**.

The storm surges that create saltwater intrusion far into Bangladesh, permeate the soil and freshwater systems, such as rivers and ponds (Brindha et al., 2014; Zahid et al., 2018). This is seen in **Table 5**, as the river samples show a disproportionately high salinity value. The soil sample analysis shows very saline soils with high organic matter and low phosphate levels, this can lead to metal salt toxicity and phosphorous deficiency in plants, which will reduce agricultural yields. Shaibur et al. (2017) confirmed the salinity range of 4.21–8.02% in the Gabura and Burigoalini union soils and stated that these areas are in poor condition for crop and fish cultivation (Fulton et al., 2011; Shaibur et al., 2017). High soil salinity prevents plants from getting essential nutrients as sodium competes with other nutrients such as K^+, Ca^{2+} (Soil Survey Staff, 2014; Akladious and Mohamed, 2018). The water samples also revealed high levels of salinity, with most samples exceeding the recommended levels for human consumption. Not only did most of the water samples have a high level of salinity (TDS) they also had a high level of Na, this can lead to surrounding soils becoming not only saline but sodic as well (Ghosh et al., 1983; Tavakkoli et al., 2011). Sodic soils are less permeable and thus encourage waterlogging and flooding in the regions they occur. This is not a problem in semi-arid or arid regions which are often very saline. This is because in arid regions soil particles are generally large and thus do not allow flooding (Sparks 2003). The Bangladesh coastal regions are similar to the neighbouring Brahmaputa floodplain which consists mainly of smaller silt and clay particles. These soils are prone to flooding and an increase in solicit will worsen the problem. These Na levels also make water unsuitable for agricultural production and can also cause structural damage to people's homes (Tavakkoli et al., 2011; Shaibur et al., 2017).

TABLE 9 | Pearson correlation coefficient analysis between soil and water parameters.

Correlations								
		Soil						
		ECe (dS/m)	pH	OM (%)	TN (%)	P (ppm)	Ca (meq/100 g soil)	K (meq/100 g soil)
Water	EC (dS/m)	−0.47*	0.39	−0.12	0.01	−0.12	0.04	−0.19
	pH	−0.17	−0.17	0.26	0.13	−0.12	0.02	0.40
	Na (mg/L)	−0.50*	0.42	−0.15	0.03	−0.05	0.03	−0.19
	Bicarbonate (mg/L)	0.05	−0.13	0.50*	0.41	−0.32	−0.14	0.42
	Chloride (mg/L)	−0.31	0.22	−0.01	−0.14	−0.02	0.02	−0.13

** Correlation is significant at the 0.05 level (2-tailed).*
*** Correlation is significant at the 0.01 level (2-tailed).*

Not only is the water and soil unfavourable to crop-based agriculture, but it is also having a major effect on freshwater shrimp farmers as high salinity causes the death of shrimp (Ahmed and Diana 2015). This has prompted discussions of relocation of prawn farms to more inland regions that are less affected by extreme weather events and sea-level rises (ibid).

High concentrations of sodium in water reduces its quality, causing high blood pressure in humans and limiting the absorption of nutrients in plants (Kumar and Puri, 2012). Very high concentrations of chloride accelerate the corrosion rate of metal pipes, depending on the alkalinity of the water. This could lead to an increase in the concentration of metal in the water supply, posing further risks to human health (Radelyuk et al., 2021).

The general trend shows an increase in potassium in the soil with increasing water salinity (**Table 9**). This is in accordance with the findings by Alam et al. (2017) where salinity will increase the presence of certain ions within the soil, some of these beyond the scope of the study. This suggests that if salinity rises due to the rise in water surges, potassium levels will also rise, adding to the damage already done in agricultural areas (Rasel et al., 2013). Water and soil salinity also have a negative correlation, indicating that salt stored and concentrated in dry soils due to evaporation may dissolve with future monsoons (Sharma et al., 2013).

Eight water samples, all from pond water, as well as 2 soil samples, had pH values above 8.5. This water pH is unfit for human consumption and may have adverse effects on human health (Kumar and Puri 2012). It creates a corrosive environment for metal pipes, which increases the concentration of dissolved metals in drinking water. According to Akter et al. (2016), the mean pH in local drinking water in Bangladesh is slightly alkaline (pH of 7.4). Although our study reveals much more severe results, alkalinity did surpass the recommended level for human consumption.

Low levels of phosphorous in soil could be attributed to the precipitation of phosphorus in solution under alkaline conditions as well as the inability of organic matter to fix phosphates, in which the soils have a high organic matter content (Weil and Brady, 2017; Alam et al., 2017). This means that if there are more occurrences of saltwater intrusion into cultivated land, alkalinity is expected to rise, which will further decrease the availability of P for plant uptake. The data from **Table 3** shows that agricultural land is disproportionately depleted of P compared to other land uses, as this element acts as a plant fertilizer. On the other hand, shrimp ghers had the highest amount of phosphorus, which can be explained by the phosphorous leftover from fertilizers and food for shrimps (Tan 2005).

Low water levels of flooding can reach far into Bangladeshi territory according as seen in **Figure 8**. The hydraulic dynamics of the river system has a strong influence on surface and groundwater, exchanging the water mass between reservoirs (Alam et al., 2017). Based on the results in **Table 5**, saline water intrusions are canalized through rivers and channel systems. This suggests that salinity will be much more widespread than previously thought. There has been a 27% increase in salt-affected coastal areas and beaches between 1973 and 2009. This led to an increase in the amount of salt being added to the sea bed (Jarvis et al., 2008; Alam et al., 2017). Rising sea levels, increasing the intensity of water surges their frequency will have a significant impact on places further inland (Rahman et al., 2013; Dasgupta et al., 2014; Rasheed et al., 2014). In the next century, this rise in salinity, alkalinity, and related amounts of other geochemical chemicals may be predicted to be ubiquitous. Also, agriculture and permanent settlements may become unsuitable in the Shyamnagar Upazila region (IPCC 2014).

CONCLUSION

Through analysis of the primary data, this study revealed that most of the water samples and more than 50% of the soil samples have moderately alkaline conditions. Also, the concentration of calcium (Ca) and potassium (K) in the soil and sodium (Na) and chloride (Cl^-) in the water was very high compared to permit limits for human consumption and agricultural cultivation. This study further revealed the deficient status of phosphorus (P) and total nitrogen (TN) in the soil of the study area which is directly an impact of a high EC that reduces the decomposition of organic matter. Eventually, one large storm surge is predicted along the coast, covering 12% of the region every 5 years, and one third every 20 years. More than half of the Shyamnagar Upazila, on the other hand, is affected every 5 years and almost entirely every 20 years. In the Betna-Kholpetua river station, small surges of 1 m are indicated as cyclonic surges, resulting in increased EC and chloride. They greatly contribute to the salinization of soil and water of the Southwestern coast of Bangladesh, which explains the very serious levels of salinity observed in this report. For the Shyamnagar Upazila, the salinity of most water and soil samples was well above the permissible standards for human use and agriculture. Similarly, extremely alkaline environments would impact natural soil biogeochemical processes that already promote scattered phosphorus precipitation, corrode pipes, and pollute drinking water and decrease crop size and yield.

The salt content of the soil may also adversely affect the supply of other vital nutrients such as K, Ca, and P, and thus impede the optimum cultivation of crops (Fageria et al., 2011). In the short term, these problems are likely to be exacerbated by recurrent and significant saltwater intrusion, leading to an increase in salinity and alkalinity. In the near future, these problems are likely to worsen as climate change exacerbates the increase in storms in Bangladesh and increase the salinity and pH levels. It was found that not only do current conditions show that a third of the study area can be affected by major storms, but that this region will expand in the future as the frequency and periodicity of these events increase. The Shyamnagar Upazila is so affected that not only farming, but permanent human settlements could be inappropriate. This suggests a terrible future for Bangladesh, as increased salinity and alkalinity of water intakes and in soil for farming would directly impact millions of people through flooding.

The vision of sustainable climate and livelihood in Bangladesh can be achieved with saltwater supply through structural management such as coastal sluice schemes, barriers, sluices, and coastal areas, as well as non-structural management to change land use and other practices. Innovation and cultivation of different types of salt-tolerant crop varieties can also reduce food scarcity in the areas affected by salinity. Furthermore, a more detailed analysis is ultimately necessary to formulate the ambitious management model through various optional scenarios.

DATA AVAILABILITY STATEMENT

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found in the article/ **Supplementary Material**.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication. Conceptualization, MA; methodology, MA; software, MA and AC; validation, MA, AC, FDS, and SL; formal analysis, MA, and investigation, MA; resources, MA; FDS and SL; data curation, MA; writing—original draft preparation, MA writing—review and editing, MA, FDS, AC, and SL; visualization, MA and AC; supervision, FDS; AC and SL. All authors read and approved the final version of the manuscript.

CONFLICT OF INTEREST

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontierspartnerships.org/articles/10.3389/sjss.2022.10017/full#supplementary-material

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