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Variations in Water and Deposited Sediment Qualities in the Tidal River Basins of Bangladesh and Their Implications for TRM Success

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Abstract: The tidal river management (TRM) in coastal areas of Bangladesh has been successful in varying degrees. Though there are many studies on the social, institutional, hydrological and hydraulic factors in relation to TRM, there is no study that investigated the relationship between the water and soil qualities and the TRM success. This paper investigates the variations of water and deposited sediment qualities vis-à-vis the TRM success in selected tidal basins in the southwest coastal delta of Bangladesh. The basins were selected based on the level of success in TRM operation: Beel Bhaina (a successful TRM), East Beel Khuksia (a partially successful TRM), and Beel Pakhimara (an unsuccessful TRM). The level of success in TRM was decided from the local community's perception and how the TRM operation reduced the drainage congestion and increased the sedimentation depth inside a tidal basin. Fifteen water quality parameters with seven indices and eight soil quality parameters were analyzed to evaluate their suitability for agricultural purposes. The analysis reveals that the water of Beel Bhaina and East Beel Khuksia has high salinity, TDS, TSS, SAR and Na% than that of Beel Pakhimara due to the presence of an active tidal current. The most dominant cation is Na^+ in almost all the water samples due to the seawater influence. The most dominant anion is Cl^- in Beel Bhaina and East Beel Khuksia, and HCO_3^- in Beel Pakhimara. The deposited sediment quality parameters are worse in the dry season than in the monsoon, except for organic matter. The soil EC of Beel Bhaina and East Beel Khuksia is low, which may be one of the reasons for good yield in these basins. The average yields of *boro* rice were 7.2, 7.7 and 6.4 ton/ha in Beel Bhaina, East Beel Khuksia and Beel Pakhimara, respectively, which might be related to the quality of the deposited sediment in the tidal basins and also to the level of TRM success.

Keywords: tidal basin; tidal river management; sedimentation; water quality; deposited sediment quality; Bangladesh coast

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Citation: Hafiz, N.; Biswas, S.; Mondal, M.S.; Islam, M.A.; Khan, M.S.A. Variations in Water and Deposited Sediment Qualities in the Tidal River Basins of Bangladesh and Their Implications for TRM Success. *Sustainability* **2023**, *15*, 13855. https://doi.org/10.3390/su151813855

Academic Editor: Giuseppe Barbaro

Received: 4 August 2023
Revised: 1 September 2023
Accepted: 13 September 2023
Published: 18 September 2023

1. Introduction

Bangladesh, a major part of the world's largest delta—the Ganges–Brahmaputra–Meghna delta—is adorned with hundreds of rivers, *khals*, canals, swamps, *haors*, *baors*, lakes, and tidal basins [1,2]. This enormous river system transports a huge amount of sediment, which settles from the sediment-laden water onto the deltaic plain [3–6]. The alluvial deposits, rich in nutrients, shape almost the entire delta, approximately 80% of Bangladesh [5,7], within which the southwestern coastal region is located. The region is climate-vulnerable [8] and depends mainly on land and water resources for livelihoods and food and water security [9–11]. Due to the diverse and complex physiographical setting, the region faces multiple threats, such as land subsidence, tidal flood, extreme cyclonic event, storm surge, saline-water intrusion and submergence from sea level rise [5,12–16]. These make life dreadful for the local people as they depend entirely on natural resources.

To protect the arable lands from saline-water intrusion, they developed an indigenous knowledge system of water and river basin management by constructing temporary earthen embankments, low dikes and wooden sluice gates around their areas [17,18]. In the rainy season, the farming communities exchanged the saline water of their fields with the river water when it became almost sweet and thus minimized the salinity of the lands. This process allowed the sediment carried by the tidal flow to deposit on the floodplains and wetland basins. The deposited sediment, rich in nutrients, raised the land level and allowed the farmers to cultivate crops on fertile lands. Due to this traditional indigenous knowledge-based community practice, there was a balance between sedimentation, land formation and agricultural activities in the coastal areas.

The morphodynamic balance of coastal Bangladesh was hampered due to the inundation by several cyclonic storm surges and rising sea level induced by climate change [5,19]. The coastal people suffered a lot because of the saline-water inundation by the storm surges, which caused prolonged waterlogging to many crop fields [15,20]. Waterlogging and salinity were identified to be serious threats to agricultural activities in the coastal areas [21–23]. The lands remained fallow due to high soil and water salinity and lack of good-quality irrigation water. Agricultural production remained low, and this brought extensive pressure on food security, as more than 30% of the cultivable lands of Bangladesh are situated in the coastal zone [24,25]. Eventually, the water master plan of 1964 was prepared to introduce the polder system in the coastal tidal areas to reduce the people's suffering [19]. The government also implemented the coastal embankment project (CEP) with funding from donor agencies like the United States Agency for International Development to transform the brackish water zone into a freshwater zone in order to cultivate more crops [20,26,27]. Thus, the coastal polders have been constructed since the mid-1960s to protect the land from floods and salinity intrusion as well as to intensify agricultural production [5,28,29].

A polder is a tract of land, surrounded and enclosed by dikes, in which the discharge and supply of surface water are artificially controlled [30,31]. Polder is a Dutch term that refers to the reclaimed landmass with engineering interventions to grow more food by protecting the coastal land from saline-water intrusion caused by tidal flooding. During the 1960s and 1970s, about 139 polders were constructed on around 1.2 million ha of agricultural land in the coastal zone of Bangladesh [32]. There were about 1566 km of embankments and 282 sluice gates in the area to prevent the intrusion of saline water from the sea and recover more land for cultivation of the high-yielding variety (HYV) crops. These coastal polders also acted as a protection against climate change-induced sea level rises and storm surges [33], but the polderization ensued good crop production only until the 1980s, and thereafter eventually resulted in adverse impacts on agriculture and livelihood due to the continued waterlogging [34,35]. The CEP did not allow the areas to be flooded by tidal water, which carried a large amount of silt from the sea with high tide, so instead of accumulating on the floodplains, the silt was filling the rivers and killing them [36]. The drainage congestion and waterlogging problems resulted from the reduced drainage capacity of the rivers by sedimentation of active channels [29,37]. Gradually, this problem spread to more polders and led to waterlogging of an area of more than 100,000 ha in the Khulna, Jashore, and Satkhira districts of southwestern coastal Bangladesh [5].

As the polders altered the sensitive river–floodplain sediment balance and resulted in river siltation, drainage congestion, and waterlogging [28,37], tidal river management (TRM) was introduced to solve the problems ensuring sedimentation in the low-lying tidal basins [38,39]. TRM was considered an effective approach for addressing and managing the complex problems of siltation, salinity, drainage congestion and waterlogging [35,40,41]. TRM allows the sediment-laden flow to enter the tidal basin (a low-lying polder area) during high flood tide, and with time, the area fills up with settled sediment due to the reduction in flow velocity. During low ebb tide, water drains out containing a very low sediment load and eroding downstream of the riverbed [42]. Thus, the flood and ebb tides along the river and tidal basin prevent sediment deposition on the riverbed and ensure proper drainage of the tidal basin [28,38,43,44]. The width of the river also increases by two to three times within only two to three years of TRM operation and the depth increases by about 10–12 m [5,43]. The deposited sediment rich in nutrients improves the soil fertility and increases the potential for crop production [38,45,46], but in some areas, salinization affects the metabolism of the organisms present in the soil and drastically reduces the soil fertility [47]. Widespread nutrient deficiencies in N, P, Zn, and Cu were also observed in many areas of the coastal regions [25,48].

As such, not all TRM operations are able to produce the expected outcomes for many reasons, and these were analyzed by many researchers from different perspectives. Gain et al. [5] analyzed the TRM approach with a transdisciplinary framework. Mutahara et al. [49] examined TRM from a social perspective. Rezaie et al. [50] analyzed the institutional aspects and socioeconomic obstacles that limited the TRM success in the Bhabodaho Beel of the Jashore district. Parvin et al. [51] studied the land-use changes in the southwestern coastal areas due to human activity and examined the impacts of coastal land-use changes, including the impact on agricultural production. Islam et al. [52] studied the effectiveness of TRM to identify the best operation schemes to effectively trap sediment and raise the floodplain.

Successful TRM increases the elevation of the tidal basins and reduces the waterlogging problems in the coastal regions. However, operational disparities in different TRM projects cause different sediment distributions, and hence varied impacts on land raising, waterlogging and ultimately crop production [44]. Moreover, the sediments carried by the rivers inside the tidal basins are full of nutrients and crucial for crop production, so the analysis of nutrient contents of the deposited sediments, as well as water quality, is also necessary for the proper evaluation of a TRM operation. Though soil and water qualities were assessed in different studies, such assessment in connection with TRM operation is still absent. Morshed [53] studied the physicochemical characteristics of soils from different agroecological zones of Bangladesh. Mahtab and Zahid [54] investigated the overall quality of coastal surface waters. Shaha et al. [55] assessed the soil, sediment and water quality of a tidal river (Mayur River). Roy et al. [56] studied the spatial and temporal variations in water quality parameters of tidal rivers and the associated land uses in climate change-vulnerable areas of southwestern coastal Bangladesh. Sarkar et al. [57] analyzed the impacts of groundwater salinity intrusion on irrigation and agriculture in the coastal region of West Bengal, India. Ghosh et al. [58] investigated the hydrochemical properties of the surface and groundwater in the pre- and post-monsoon seasons of the lower Mayurakshi River Basin in West Bengal, India to assess their irrigation suitability. However, no studies have analyzed the water quality or qualities of the deposited sediment in relation to TRM operations.

It is important to understand how the sediment and nutrient distributions vary in different tidal basins, and how they are related to TRM operation and crop yield. The cultivable lands in the coastal areas are not effectively utilized for crop production due to morphological change, waterlogging, soil and water salinity, decreasing nutrients, lack of suitable irrigation water, etc. [11]. Therefore, water quality analysis in addition to deposited sediment quality analysis is important in evaluating the potential of the tidal river basins in the enhancement of agricultural prosperity [59]. A comparison of laboratory data with the standard nutrient values can reveal the potential problems with the water quality and deposited sediment. Thus, this study helps in understanding the effect of TRM operations on the deposition of sediment and the associated implications for crop production. The findings of this study would be significant for coastal communities and farmers who rely on crop production for their livelihoods. These would also help identify whether any potential measure needs to be taken in operating TRM and using the water for irrigation. As there is no significant information regarding the water and sediment qualities of the tidal basins, this study will be helpful for the government and non-government agencies, policymakers, funding agencies and farmers to plan their work. Furthermore, this study contributes to the development of effective policies and strategies for the sustainable management of soil and water resources in the coastal areas in Bangladesh and elsewhere.

2. Materials and Methods

For assessing the quality of the water and deposited sediment, three tidal basins in the southwest coastal region were selected. Different physical and physicochemical properties of water and deposited sediment for the dry and monsoon seasons were measured and evaluated for their suitability for agricultural purposes.

2.1. Selection of the Tidal River Basins

A tidal basin, locally known as a *beel*, is a natural depression in a floodplain that generally contains water throughout the year [60]. There are about 35 such basins in southwest coastal Bangladesh, among which 12 basins have been under TRM operation [5,28]. From these 12 TRM basins, three basins were selected to investigate the water and deposited sediment qualities. Figure 1 shows the locations of the selected basins. The basins were selected based on the level of success of TRM operations, namely, Beel Bhaina (a successful TRM basin), East Beel Khuksia (a partially successful TRM basin), and Beel Pakhimara (an unsuccessful TRM basin). Various socioeconomic, technical, operational, and financial factors were considered to determine the success level of TRM operation. Local farmers and relevant government and non-government officials were consulted through a number of field visits to decide on the level of success of TRM. If the people of a basin were satisfied with the level of siltation in the basin, improvement in waterlogging, and increase in crop yield, the TRM operation in the basin was considered successful. The success level of TRM was linked with the location and length of the link canal, duration of TRM operation, operation and maintenance of related structures, incorporation of local knowledge in planning and implementation, land acquisition and requisition, conflicts among local users and government agencies, and payment of compensation for land.

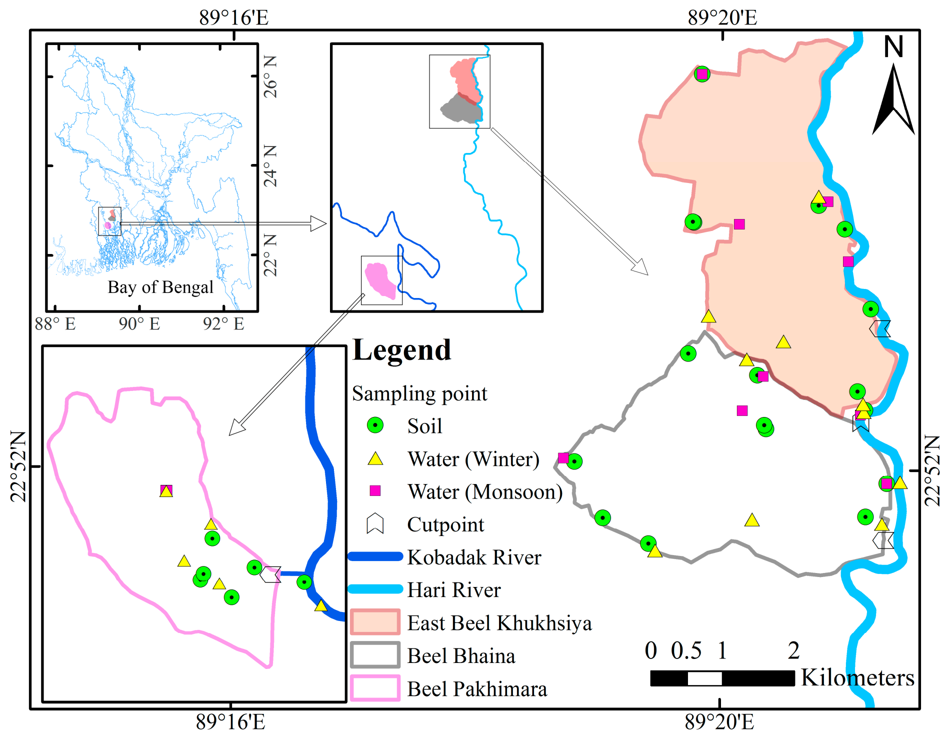

Figure 1. Locations of the tidal basins studied and the sampling points.

The topography, hydrology, climate, and socioeconomic contexts of the study areas are similar. The socioeconomics are determined by long-term poverty, malnutrition, illiteracy and vulnerability [61]. In this region, the crop production is mainly rice based and the cropping patterns are Fallow–T. Aman (Local)–Fallow, Fallow–Fallow–Boro (HYV), Fallow–T. Aman (Local)–Boro (HYV), and Fallow–T. Aman (HYV)–Boro (HYV) [27,62]. The available cultivable lands mostly remain fallow due to waterlogging, unsuitable soil and water conditions, excessive salinity, scarcity of irrigation water, etc.

2.1.1. Beel Bhaina

Beel Bhaina is situated inside polder 24, near the Hari River in the Jashore district, and comprises an area of about 600 ha. In October 1997, the embankment of the polder was cut by the local people to connect the basin with the Hari River. Two cuts were made on the embankment along the Hari River, one at Agarhati village and another at 1.5 km north of Agarhati. The initiative was led by a local water management organization and a non-governmental organization (NGO) without any effective government support. The TRM operation ended on 8 December 2001. The land level inside the basin was raised by about 1 m around almost the entire area. However, there was still some waterlogging in the northwestern part of the basin [5], and the main reason was the non-uniform sedimentation inside the tidal basin [17]. The effectiveness of TRM in this basin is evident from the fact that the bed of the Hari River rose by more than 6 m within 8 months of closing the TRM operation [4]. It was considered a successful attempt because the waterlogging problem was mostly solved and the people could use their lands for crop production and fish farming.

The main river system in the area is the Mukteshwari-Hari, which provides drainage for the polder through numerous creeks and canals and experiences a semi-diurnal tide. Due to saltwater inundation, the soil condition of Beel Bhaina ranges from very slightly saline to moderately saline around the year [63]. The dominant cropping pattern is fish–fish–*boro* rice. Also, saline water shrimp (*bagda*), freshwater shrimp (*golda*), and other fish are cultivated in the basin.

The climatic condition of the area can be described as a typical southwest monsoon (June–September) with a hot and humid pre-monsoon (March–May), and a cool and dry winter (December–February). Almost 70–80% of the annual rainfall occurs in the monsoon season, with the highest monthly average normal rainfall of more than 300 mm in July. The monthly normal maximum temperature varies from 25.6 °C to 35.6 °C and humidity from 69% to 87%. The maximum normal wind speed is 6.25 m/s in May.

2.1.2. East Beel Khuksia

East Beel Khuksia is also situated in polder 24 beside the Hari River in the Jashore district and the area is about 1100 ha. After the successful TRM operation in Beel Bhaina, the government came forward and the Bangladesh Water Development Board (BWDB) started the TRM operation in East Beel Khuksia in April 2006. The TRM operation continued till 2013. Though it was expected to be completed by 2008, the operation was extended to 2013 due to compensation-related issues and conflicts among the different user groups. During the 5 months (December 2006–April 2007) of operation, about 0.9 million m^3 of siltation took place in the basin [5]. The measurement in November 2012 showed that the ground level was raised by about 2.0 m near the basin cut point and 0.5–1.5 m farther away from the point [2,4,5]. It was also noticed that the siltation occurred mainly near the cut point. The reason behind this was the presence of *gher* (infrastructure for fish cultivation) inside the basin. In May 2007, during TRM in East Beel Khuksia, the tidal volume of the Hari River was over 5 Mm^3. In 2012, the tidal volume became about 16 Mm^3 [11]. Some people claimed that the TRM operation in East Beel Khuksia was unsuccessful, as the waterlogging problem was not solved and they were not satisfied with the compensation by BWDB or the entire operation process. However, most people were satisfied with the raised lands, which contained good-quality sediments and increased crop production. Therefore, the TRM operation in East Beel Khuksia is considered partially successful.

Due to saltwater inundation, the soil condition of East Beel Khuksia ranges from very slightly saline (non-saline at some points) in monsoon to moderately saline in pre-monsoon [63]. The dominant cropping pattern is fish–fish–*boro* rice. Saline water shrimp, freshwater shrimp, and other fish are also cultivated in the basin. The topography, climate, hydrology, and socioeconomic contexts of East Beel Khuksia are similar to those of Beel Bhaina as they are located adjacent to each other.

2.1.3. Beel Pakhimara

Beel Pakhimara is located inside polders 6–8 beside the Kobadak River in Tala Upazila of Satkhira district, with a total size of about 700 ha. The TRM project in Beel Pakhimara was planned to be implemented in 2011, but due to conflicts between the local people and the government land office, the TRM operation could not be started. Initially, the local people breached the embankment to connect the basin with the Kobadak River. Later BWDB engaged with the process and started the TRM operation formally in 2015, which ended in 2021. Uneven siltation took place in the basin due to the TRM operation. The sedimentation was only about 1.0–1.5 m near the cut point in 2018 and very low at the farther points. Waterlogging was prevalent in the basin, which hampered the crop cultivation in the basin. The local people perceived the TRM operation unsuccessful in the basin.

The main river system of Beel Pakhimara is the Kobadak River, characterized by a semi-diurnal tide. The river system including *khals* and canals provides the drainage for the polders. However, the siltation of the system hinders the tidal effect [64]. Due to saltwater inundation, the soil condition of Beel Pakhimara ranges from moderately saline in monsoon to strongly saline in pre-monsoon [63]. As Satkhira is a neighboring district of Jashore, the climate in Beel Pakhimara is similar to the other two basins. The highest monthly normal rainfall is about 375 mm, which occurs in July. The monthly normal maximum temperature varies from 26.0 °C to 35.2 °C and humidity from 69% to 86%. The maximum normal wind speed is 3.75 m/s in April.

2.2. Analysis of Water Quality

Water samples from the river, basin, and groundwater were collected for each tidal basin in both dry and monsoon seasons. The dry season samples were collected in January, 2018 and the monsoon season samples in July–August, 2018. A total of 28 water samples (5 from rivers, 14 from basins and 9 from groundwater) were collected from the three tidal basins, with 14 samples each in the dry season (3 from rivers, 7 from *beels* and 4 from groundwater) and monsoon season. The groundwater samples were collected from shallow tube wells (STWs) with strainers at 25–30 m below the ground surface in Beel Bhaina and East Beel Khuksia. There was no tube well in Beel Pakhimara; therefore, no groundwater sample was collected for this basin. The basins either remained connected to or became disconnected from the tidal rivers depending on the status of the TRM operation. Water samples were collected in 500 mL plastic bottles. Water samples from the rivers and basins were taken from around 0.3 m depth below the water surface. The opening of the bottle, allowing water to flow in, and the closing of the bottle mouth with the cap were done underwater [65]. Groundwater samples were collected after pumping the STWs for a few minutes. Immediately after sampling, the sample bottles were labeled, and the temperature and pH of the water were recorded at the sites. The samples were then stored in an ice box and carried to the laboratory for analysis. For understanding the water quality, pH, electrical conductivity (EC), total dissolved solids (TDSs), total suspended solids (TSSs), Na^+, K^+, Ca^{2+}, Mg^{2+}, total Fe, $PO_4{}^{3-}$, $NO_3{}^-$, $NO_2{}^-$, $SO_4{}^{2-}$, $HCO_3{}^-$ and Cl^- were measured during the dry and monsoon seasons. Table 1 shows the water quality parameters analyzed and their methods of analysis. The suitability class of each parameter was determined considering the use of water for crop irrigation.

Table 1. Methods for determination of different water quality parameters.

Parameter	Determination Method
pH	HANNA Instrument, pH 211 [66]
EC	HANNA Instrument, pH 211 [66]
TDS	HANNA Instrument, pH 211 [66]
TSS	HANNA Instrument, pH 211 [66]
Na^+, K^+	Flame photometric method [66]
Ca^{2+}, Mg^{2+}	Titrimetric method [66]
$HCO_3{}^-$	Titration method [66]
Cl^-	Titration by silver nitrate [66]
$NO_3{}^-$, $NO_2{}^-$, $PO_4{}^{3-}$, $SO_4{}^{2-}$, total Fe	Turbidimetric method (Thermo Spectronic, UV-visible spectrophotometer) [66]

2.3. Assessment of Suitability of Water for Irrigation Purpose

Sodium adsorption ratio (SAR), sodium percentage (Na%), potential salinity (PS), permeability index (PI), Kelly's index (KI), and magnesium ratio (MR) were calculated to evaluate the suitability of the water samples for irrigation purposes.

2.3.1. SAR

Irrigation water containing excessive sodium compared with calcium and magnesium promotes soil dispersion as well as structural breakdown. When sodium concentration is high in water, it results in an infiltration problem and supplies less water to the crop. SAR is used to indicate sodium toxicity and is calculated as [67]:

$$SAR = \frac{Na^+}{\sqrt{\frac{Ca^{2+} + Mg^{2+}}{2}}} \quad (1)$$

where Na^+, Ca^{2+} and Mg^{2+} are in meq/L.

2.3.2. Na%

Alkaline hazard occurs when Na^+ concentration is high, and is mainly related to the relative concentration of cations in irrigation water. If the proportions of Ca^{2+} and Mg^{2+} are high, the alkaline hazard is low, and conversely, if Na^+ is predominant, the hazard is high [68]. Na% is calculated as:

$$Na\% = \frac{(Na^+ + K^+)}{(Ca^{2+} + Mg^{2+} + Na^+ + K^+)} \times 100 \quad (2)$$

where Na^+, K^+, Ca^{2+} and Mg^{2+} are in meq/L.

2.3.3. PS

The suitability of irrigation water is not dependent on the quantity of soluble salts, because salts with low solubility precipitate in the soil and accumulate with successive irrigations, while the concentrations of highly soluble salts increase the salinity of the soil [69,70]. PS is calculated as:

$$PS = Cl^- + \frac{1}{2}SO_4^{2-} \quad (3)$$

where Cl^-, SO_4^{2-} and PS are in meq/L.

2.3.4. PI

The long-term use of irrigation water can affect the soil permeability where the concentrations of Na^+, Ca^{2+}, Mg^{2+} and HCO_3^- influence it [71]. PI is a vital parameter to assess the quality of irrigation water in relation to soil for improvement in the agricultural sector [71,72]. PI is calculated as:

$$PI = \frac{Na^+ + \sqrt{HCO_3^-}}{(Ca^{2+} + Mg^{2+} + Na^+)} \times 100 \quad (4)$$

where the concentrations of cations and anions are in meq/L. Water can be classified into three classes based on PI, where Class I and II are considered good for irrigation with 50–75% or more of maximum PI, and Class III unsuitable with 25% or less of maximum PI [69].

2.3.5. KI

The hazardous effect of sodium in water for irrigation is determined by KI [70,73]. Water with KI > 1 indicates excessive sodium in water and is unsuitable for irrigation use. Water with KI < 1 is suitable for irrigation use. KI is calculated as:

$$KI = \frac{Na^+}{(Ca^{2+} + Mg^{2+})} \quad (5)$$

where all concentrations are in meq/L.

2.3.6. MR

Generally, calcium and magnesium maintain an equilibrium state in most water bodies. In equilibrium, more magnesium in water may adversely affect crop yield [68]. MR is calculated by the following formula [74]:

$$MR = \frac{Mg^{2+}}{Mg^{2+} + Ca^{2+}} \times 100 \quad (6)$$

where concentrations of cations are in meq/L. If the MR value is more than 50%, the soil would become more alkaline and it would affect the crop yield. MR less than 50% is considered satisfactory for agricultural production.

2.3.7. Ca:Mg

A ratio of Ca and Mg above 1 indicates that the water is calcium-dominant. If the ratio is below 1, the water is considered rich in exchangeable Mg, which may cause infiltration problems in the soil [75].

2.4. Analysis of Deposited Sediment Quality

As the land formation in the study areas occurs through sediment deposition, the term “deposited sediment” is used for both soil and sediment. The sediment samples were collected from the riverbed, basin bed and cropland. The samples were collected from different sites in both dry and monsoon seasons for understanding the spatial and temporal variations of the sediment qualities according to the guidelines of the Bangladesh Agricultural Research Council [76]. About 550–600 g composite sediment sample was collected from each sampling site and each sampling depth of 0–0.15 m or 0.16–0.30 m and was kept in a zipper plastic bag labeled with an identification number. The numbers of sampling points were 9, 8 and 6 in Beel Bhaina, East Beel Khuksia and Beel Pakhimara, respectively, and the corresponding numbers of samples were 36, 32 and 24, respectively. Samples were collected from the locations where sedimentation occurred after TRM operation and were less disturbed. The locations of the sampling sites in the basins are shown in Figure 1. The samples were kept in a cool and dry place and taken to the laboratory for analysis. All soil samples were homogenized and dried in the air. The air-dried soil samples were broken and ground by a wooden hammer and sieved through a 2 mm sieve. Then, a number of physical and physicochemical properties of the samples, e.g., soil texture, organic matter (OM), pH, EC, and available nutrient elements (Ca^{2+}, Mg^{2+}, total Fe, total P, S and Cl^{-}), were determined for assessing the deposited sediment quality. Table 2 shows the soil parameters analyzed and the methods of analysis at the laboratory.

Table 2. Methods for determination of different soil parameters.

Parameter	Determination Method
Soil texture	Hydrometer [77]
Organic matter	Loss by ignition [78]
pH	HANNA Instrument, pH 211 [66]
Salinity	HANNA Instrument, pH 211 [66]
Ca^{2+}, Mg^{2+}	Titrimetric method [66]
Total Fe, total P, S	Turbidimetric method (Thermo Spectronic, UV-visible spectrophotometer) [66]
Cl^{-}	Titration by silver nitrate [66]

In addition, to understand the vertical variations of soil properties, one site each from Beel Bhaina and East Beel Khuksia and two sites from Beel Pakhimara were selected. Since the TRM operation in Beel Pakhimara is recent and sedimentation has not been uniform, more soil samples were collected from this basin. The sites for vertical profiling were selected such that they represented the soil formation through the tidal processes and were relatively less disturbed by human activities. Soil samples were collected from three to four vertical levels at each site. Soil texture and OM were analyzed for each sample.

2.5. Collection of Agricultural and Socioeconomic Data

Data on agricultural practices and socioeconomic aspects, such as cropping pattern, irrigation practice, crop yield, profitability of crop cultivation, local conflicts and TRM success, were collected through semi-structured interviews with the farmers in the three tidal basins. The numbers of farmers interviewed were 40, 35 and 40 in Beel Bhaina, East Beel Khuksia and Beel Pakhimara, respectively. In addition, key-person interviews were conducted with Upazila agriculture officers, Upazila fisheries officers, officials of the Department of Agriculture Extension, chairmen/secretaries of the local water management committees, and officials of a few local NGOs. A number of field visits were made to the study tidal basins in 2018, 2021 and 2022 for data collection purposes.

3. Results

3.1. Water Quality in the Tidal Basins

3.1.1. pH

Tables 3–5 show the values of pH and other water quality parameters analyzed for the three tidal basins. The detailed site-specific results are provided in Supplementary Material S1. All pH values were within the tolerance range (6.5–8.5) for irrigation in Bangladesh [79]. Among the three sources, the river water had the lowest pH and the groundwater had the highest pH.

Table 3. Average values of the water quality parameters from different sources in Beel Bhaina.

Season	Source	pH	EC µS/cm	TDS mg/L	TSS mg/L	Total Fe mg/L	Na^+ mg/L	K^+ mg/L	Ca^{2+} mg/L	Mg^{2+} mg/L	PO_4^{3-} mg/L	NO_3^- mg/L	NO_2^- mg/L	SO_4^{2-} mg/L	HCO_3^- mg/L	Cl^- mg/L
Dry	Hari River	6.8	19,210	9600	2099	0.005	5014	114	168	442	0.7	2.8	0.004	2519	159	3722
	Basin	7.2	18,245	9130	1378	0.005	4328	112	128	433	0.8	6.0	0.004	1942	180	4271
	GW	7.7	3010	1486	310	0.005	609	9	111	58	0.8	1.7	0.004	287	375	540
Monsoon	Basin	7.1	1613	815	59	0.005	357	2	42	29	0.2	1.3	0.006	142	220	390
	GW	7.6	1852	925	195	0.005	399	2	61	32	0.4	2.7	0.005	86	498	390
Permissible Limit *		6.5–8.5	2250	1000	50	2	920	2	400	61	2	5	1	960	610	600

* Note: The sources of permissible limits for pH, EC, TDS, PO_4^{3-} and NO_3^- are MoEFCC [80], for NO_2^- are EPA [81], for total Fe and Cl^- are BADC [79], for Na^+, K^+, Ca^+, Mg^{2+}, SO_4^{2-} and HCO_3^- are Ayers and Westcot [75], and for TSS are Holmes [82].

Table 4. Average values of the water quality parameters from different sources in East Beel Khuksia.

Season	Source	pH	EC µS/cm	TDS mg/L	TSS mg/L	Total Fe mg/L	Na^+ mg/L	K^+ mg/L	Ca^{2+} mg/L	Mg^{2+} mg/L	PO_4^{3-} mg/L	NO_3^- mg/L	NO_2^- mg/L	SO_4^{2-} mg/L	HCO_3^- mg/L	Cl^- mg/L
Dry	Hari River	7.3	18,900	9450	8679	0.005	4709	108	168	369	0.4	5.9	0.004	3010	171	4360
	Basin	7.7	9800	4900	923	0.005	3453	57	136	168	0.4	4.2	0.004	1979	159	2411
	GW	7.3	1385	690	221	0.005	237	2	55	35	0.4	0.4	0.004	113	519	239
Monsoon	Hari River	6.9	844	422	349	0.005	145	4	36	23	1.6	0.8	0.003	122	214	177
	Basin	7.0	2135	1075	721	0.005	421	13	41	34	0.9	8.0	0.004	217	189	471
	GW	7.7	666	334	59	0.005	106	2	56	22	0.2	0.5	0.004	506	302	157

Table 5. Average values of the water quality parameters from different sources in Beel Pakhimara.

Season	Source	pH	EC µS/cm	TDS mg/L	TSS mg/L	Total Fe mg/L	Na^+ mg/L	K^+ mg/L	Ca^{2+} mg/L	Mg^{2+} mg/L	PO_4^{3-} mg/L	NO_3^- mg/L	NO_2^- mg/L	SO_4^{2-} mg/L	HCO_3^- mg/L	Cl^- mg/L
Dry	Kobadak River	7.1	977	489	358	0.005	258	9	32	24	0.3	0.6	0.004	142	153	142
	Basin	7.4	1149	575	379	0.005	106	10	67	31	0.4	0.9	0.005	149	336	263
Monsoon	Kobadak River	6.9	806	406	1395	0.005	71	5	52	21	1.5	1.4	0.004	34	378	145
	Basin	7.0	711	356	367	0.005	65	5	47	16	0.4	1.7	0.005	91	223	115

3.1.2. EC

The average EC was higher in the dry season than in the monsoon. The highest EC (19,210 µS/cm) was found for the Hari River in the dry season and the lowest (666 µS/cm) for the groundwater in East Beel Khuksia in the monsoon. The basin water samples from Beel Bhaina and East Beel Khuksia showed higher EC, as these basins are connected to the Hari River and have tidal influences. Beel Pakhimara had EC values within the permissible range for irrigation.

3.1.3. TDS and TSS

The TDS and TSS values were higher in the dry season than in the monsoon at all the sites. In the dry season, only the groundwater of Beel Bhaina and East Beel Khuksia was permissible for irrigation. In the monsoon, the water from all the sources was good or permissible for irrigation. The highest TDS (9600 mg/L) and TSS (8679 mg/L) were found in the Hari River in the dry season, whereas the lowest TDS (334 mg/L) and TSS (58.9 mg/L) were found in the groundwater of East Beel Khuksia in the monsoon.

3.1.4. Cations

The cations, namely, Na^+, K^+, Ca^{2+}, Mg^{2+} and total Fe, were measured to understand the suitability of water for irrigation. The most dominant cation was Na^+ at all the sampling sites irrespective of the seasons and tidal basins. The water samples from the Hari River and the tidal basins of Beel Bhaina and East Beel Khuksia fell outside the permissible limit (0–920 mg/L), indicating that the water is unsuitable for irrigation in the dry season in terms of sodium toxicity. The seawater influences due to the presence of an active tidal current and the lack of local rainfall as well as freshwater flow from the upstream could be the reasons for sodium toxicity. The permissible K^+ concentration in irrigation water ranges from 0 to 2 mg/L, but higher values were found at most of the sites except for groundwater in the monsoon. The usual range for Ca^{2+} concentration in irrigation water is 0–400 mg/L. The available Ca^{2+} at all the sites was within the suitable range for crop production in both the seasons. Mg^{2+} concentration showed a similar pattern. Total Fe concentration was found to be within the permissible limit (2 mg/L) at all the sites in both the seasons. Thus, the values of Na^+, K^+, Ca^{2+}, and Mg^{2+} concentrations in water from the river, basin, and underground sources were higher in the dry season than in the monsoon. The groundwater in the monsoon season was found to contain lower quantities of cations than the water from other sources.

3.1.5. Anions

The most dominant anion was Cl^- in most of the water sources. Only groundwater showed HCO_3^- dominance in Beel Bhaina and SO_4^{2-} dominance in East Beel Khuksia. The water samples from the Hari River and the tidal basins of Beel Bhaina and East Beel Khuksia were unsuitable for irrigation in terms of Cl^- and SO_4^{2-} in the dry season. The SO_4^{2-} concentration was within the permissible limit (0–20 meq/L) in the monsoon season. Alkalinity in water occurs due to the dissolved HCO_3^- and CO_3^-. The usual range of HCO_3^- in irrigation water is 0–10 meq/L. The average concentration of HCO_3^- was lower in the dry season (4.16 meq/L) than in the monsoon (7.03 meq/L). The values of HCO_3^-, PO_4^{3-} and NO_3^- at all the sites were found to be satisfactory and fell under the "no problem" or "moderate" class, indicating that the water from the sources was suitable for irrigation. A very low concentration of NO_3^-, NO_2^- and PO_4^{3-} was found in the water samples compared to the other available anions.

3.2. Agricultural Suitability Indices

Water quality indices, such as SAR, Na%, PS, PI, KI, MR and Ca:Mg, were calculated to evaluate the suitability of the water from different sources for irrigation purposes. The spatial and seasonal variations in the indices for the three tidal basins are presented in Tables 6–8.

Table 6. Variations in the water quality indices in Beel Bhaina.

Season	Source	SAR	Na%	PS meq/L	PI	KI	MR	Ca:Mg
Dry	Hari River	46.05	83.13	131.39	83.56	4.86	81.22	0.23
	Basin	41.41	81.77	140.89	82.28	4.57	84.51	0.18
	GW	13.42	71.51	18.26	78.14	3.57	45.23	1.22
Monsoon	*Beel*	10.35	77.56	12.49	86.99	3.45	53.28	0.88
	GW	10.30	75.20	11.91	87.52	3.06	47.12	1.17

Table 7. Variations in the water quality indices in East Beel Khuksia.

Season	Source	SAR	Na%	PS meq/L	PI	KI	MR	Ca:Mg
Dry	Hari River	46.47	84.24	3.93	84.75	5.27	78.32	0.28
	Basin	44.80	87.45	2.87	88.63	6.99	61.95	0.68
	GW	6.12	64.12	5.74	82.14	1.82	50.69	0.99
Monsoon	Hari River	4.63	63.38	3.95	81.70	1.70	51.28	0.95
	Basin	11.77	79.46	5.97	86.84	3.81	58.47	0.72
	GW	3.03	50.35	1.24	74.64	1.01	37.98	1.76

Table 8. Variations in the water quality indices in Beel Pakhimara.

Season	Source	SAR	Na%	PS meq/L	PI	KI	MR	Ca:Mg
Dry	Kobadak River	8.36	76.06	5.48	86.36	3.11	55.48	0.80
	Basin	2.91	47.35	8.99	66.32	0.96	43.58	1.39
Monsoon	Kobadak River	2.09	42.60	4.46	75.38	0.71	39.50	1.53
	Beel	2.12	42.88	4.20	72.50	0.81	34.28	2.48

3.2.1. SAR

Water samples are classified as "doubtful" if the SAR value is 18–26 and "unsuitable" if the value is greater than 26 [83]. In the monsoon season, all the water samples from the three tidal basins fell under the "good" or "excellent" class. However, in the dry season, the samples from the Hari River and the basin water from Beel Bhaina and East Beel Khuksia were unsuitable for crop production. The highest SAR value of 46.47 was found in the Hari River water in the dry season and the lowest of 2.09 in the Kobadak River water in the monsoon season. Groundwater had the lowest SAR value, and the water was used for growing vegetables. The water from the basin and river in Beel Pakhimara was suitable in both the seasons.

3.2.2. Na%

The highest Na% of 87.45 was found in the basin water of East Beel Khuksia in the dry season and the lowest of 42.60 in the Kobadak River water in the monsoon. The water of the Hari River, Beel Bhaina and East Beel Khuksia in the dry season was unsuitable for irrigation. The samples from all other sites were "doubtful" or "permissible" for irrigation. In Beel Bhaina and East Beel Khuksia, severe sodium toxicity was present in water, whilst there was no sodium toxicity in Beel Pakhimara.

3.2.3. PS

The PS of the water samples ranged from 11.91 to 140.89 meq/L in Beel Bhaina, 1.24 to 5.97 meq/L in East Beel Khuksia and 4.20 to 8.99 meq/L in Beel Pakhimara. Most of the PS values were higher in the dry season than in the monsoon. The PS values of all the samples from Beel Bhaina were high (>10) in both the seasons, making the water unsuitable for irrigation usage. However, the water from East Beel Khuksia and Beel Pakhimara showed acceptable PS values.

3.2.4. PI

The PI values of the water samples were 78.14–87.52% in Beel Bhaina, 74.64–88.63% in East Beel Khuksia and 66.32–86.36% in Beel Pakhimara. The water in both the seasons was under Classes I and II [69] and thus was good for irrigation purposes. The minimum PI value (66.32%) was found in the water of Beel Pakhimara and the maximum value (88.63%) in East Beel Khuksia in the dry season.

3.2.5. KI

KI > 1 indicates excessive sodium in water and unsuitability of water for irrigation use [73]. All the samples from Beel Bhaina and East Beel Khuksia were unsuitable for irrigation in both the seasons. The KI values were 3.06–4.86 in Beel Bhaina and 1.01–6.99 in East Beel Khuksia. In Beel Pakhimara, the water from the Kobadak River in the dry season was also found to be unsuitable for irrigation. However, the water from the river in the monsoon season and that from the basin in both the seasons were found to be suitable.

3.2.6. MR

The water from the Hari River, Beel Bhaina and East Beel Khuksia had MR values higher than 50% in both the seasons, making it unsuitable for irrigation. However, the groundwater in the two basins had a satisfactory MR value. The Kobadak River had a slightly higher MR value in the dry season, while the water sources of Beel Pakhimara were suitable for irrigation. The maximum value of 84.51% was found in Beel Bhaina in the dry season and the minimum value of 34.28% in Beel Pakhimara in the monsoon.

3.2.7. Ca:Mg

In Beel Bhaina and East Beel Khuksia, the Ca:Mg ratio was more than or near to 1 for groundwater and lower than 1 for the Hari River or basin water. In Beel Pakhimara, the Ca:Mg ratio was lower than 1 for the Kobadak River in the dry season, while the values were higher.

3.3. Quality of the Deposited Sediment in the Tidal Basins

3.3.1. pH

Table 9 shows the average values and standard deviations of pH and other soil parameters analyzed for the tidal basins. The detailed site-specific results are provided in Supplementary Material S2. All the soil samples were within the permissible pH range (6.5–8.4) and most of them were alkaline. The pH values were higher in the dry season than in the monsoon in Beel Bhaina and East Beel Khuksia; however, they were higher in the monsoon season than in the dry season in Beel Pakhimara.

Table 9. Variations in soil quality parameters (0–0.30 m below ground level) in the selected tidal river basins of southwest coastal Bangladesh.

Parameters	**Beel Bhaina**		**East Beel Khuksia**		**Beel Pakhimara**	
	Dry	**Monsoon**	**Dry**	**Monsoon**	**Dry**	**Monsoon**
pH	7.7 ± 0.2	7.6 ± 0.3	7.8 ± 0.2	7.3 ± 0.3	7.7 ± 0.1	7.9 ± 0.1
EC (dS/m)	9.2 ± 5.5	5.3 ± 4.3	6.2 ± 4.1	4.5 ± 1.7	11.0 ± 2.0	8.3 ± 2.1
Ca^{2+} (meq/100 g soil)	20.5 ± 3.9	23.0 ± 5.4	21.7 ± 3.6	24.0 ± 2.9	21.3 ± 2.7	23.5 ± 3.0
Mg^{2+} (meq/100 g soil)	8.2 ± 2.2	8.0 ± 2.6	6.0 ± 1.5	5.8 ± 2.9	6.7 ± 1.2	7.7 ± 2.6
Total Fe (ppm)	94.7 ± 91	7.0 ± 6.9	122.5 ± 106	22 ± 39	185.7 ± 96	13.4 ± 2.4
Total P (ppm)	39.6 ± 20	33.0 ± 11	44.0 ± 21	57.1 ± 38	37.0 ± 7.9	37.6 ± 5.1
S (ppm)	380 ± 355	79 ± 143	582 ± 199	113 ± 94	754 ± 81	258 ± 107
Cl^- (ppm)	1440 ± 1131	1300 ± 440	1214 ± 988	1131 ± 369	2015 ± 439	1452 ± 403

3.3.2. EC

The average EC values found in the three basins are given in Table 9. The soils were found to be non-saline to very saline in Beel Bhaina and East Beel Khuksia, and slightly saline to very saline in Beel Pakhimara, depending on the sampling locations. The average EC was higher in the dry season than in the monsoon in all the tidal basins. Beel Pakhimara is the most saline and East Beel Khuksia is the least saline. The highest EC (14 dS/m) was found in Beel Pakhimara in the dry season, and the lowest (0.60 dS/m) was found in Beel Bhaina in the monsoon.

3.3.3. Calcium

Available Ca^{2+} was higher in the monsoon season than in the dry season, and the average value was more than 20 meq/100 g soil. All the values were above 11 meq/100 g soil in Beel Bhaina, above 14 meq/100 g soil in East Beel Khuksia, and above 17 meq/100 g soil in Beel Pakhimara. The lowest and highest available Ca^{2+} values were about 11.6 meq/100 g and 30.8 meq/100 g soil, respectively, both in Beel Bhaina.

3.3.4. Magnesium

The lowest available Mg^{2+} was about 2.4 meq/100 g soil in the monsoon season in Beel Pakhimara, whereas the highest available Mg^{2+} was 12.8 meq/100 g soil in the monsoon season in Beel Bhaina. Like Ca^{2+} content, seasonal change in Mg^{2+} content was not apparent.

3.3.5. Iron

According to SRDI [84], in terms of Fe content, the soil is classified as low (<20 ppm), medium (21–40 ppm), high (41–200 ppm) and excessive (>200 ppm). In the monsoon season, the Fe content of all the samples fell under the low category, indicating suitable for agricultural purposes (Table 9). Samples fell under medium, high, and excessive categories in the dry season, and thus could hamper the yields of some crops. The Fe content was much higher in the dry season than in the monsoon in all the tidal basins. The average Fe content was higher in Beel Pakhimara than the other two basins.

3.3.6. Phosphorus

Available P shows a fluctuating pattern in both the seasons. According to SRDI [84], in terms of P content, the soil is classified as low (<12 ppm), medium (13–25 ppm), and high (26–75 ppm). The available P at all the sites was found to be medium to high in both the dry and monsoon seasons, while the average value fell under the high category in all the basins.

3.3.7. Sulphur

A large variation in the S concentration was noticed between the monsoon and dry seasons. The S content at all the sites was higher in the dry season than in the monsoon. According to SRDI [84], in terms of S content, the soil is classified as low (<12 ppm), medium (13–25 ppm), and high (26–75 ppm). An excessive amount of S was present in all the samples in the dry season.

3.3.8. Chloride

At all the sites, the available Cl^- was higher in the dry season than in the monsoon. The average available Cl^- was the highest in Beel Pakhimara and the lowest in East Beel Khuksia. The maximum available Cl^- was found to be 3195 ppm in Beel Pakhimara in the dry season and the minimum was 35.5 ppm in Beel Bhaina in the monsoon.

3.4. Deposited Sediment Composition in the Tidal Basins

The spatial and seasonal variations in the sediment composition (soil texture and OM) of the three tidal basins are described in this section.

3.4.1. Soil Texture

The vertical variations of soil texture in the three tidal basins are shown in Figure 2.

In Beel Bhaina, the soil inside the basin ranges from clay loam to silt loam at different depths. The soil has a medium texture (silt loam) at 0–0.20 m depth and a moderately fine texture (silty clay loam or clay loam) at 0.20–0.70 m depth, so the soil texture becomes finer with the increase in depth below the top surface. In East Beel Khuksia, the soil texture also varies from medium texture (silt loam) to fine texture (clay) with increasing depth from the top surface. Thus, there is also a gradual fining of soil texture with increasing depth from the surface. In Beel Pakhimara, the soil texture varies from moderately fine (silty clay loam) to fine (clay) at one site without any particular vertical pattern. However, at another site, the soil texture varies from moderately fine to moderately coarse with increasing depth from the top surface.

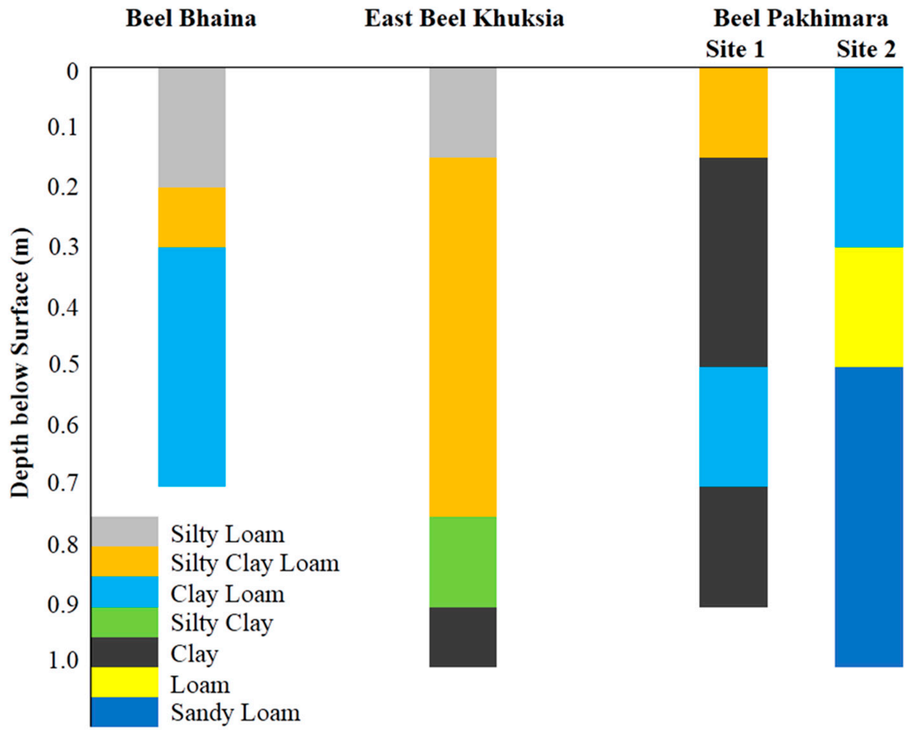

Figure 2. Vertical variations of soil texture in the three select tidal basins in southwest coastal Bangladesh.

In Beel Bhaina, the soil textures at 0.15–0.30 m depth remained unchanged between the dry and monsoon seasons at most of the sites, and thus there was no significant variation in soil texture with seasons. However, in East Beel Khuksia, a significant change in soil texture was found in all the samples taken from 0.15–0.30 m depth. In Beel Pakhimara, the soil textures at 0.15–0.30 m depth changed from the dry to the monsoon seasons. Though the soil texture at one site was found to be clay in both the seasons, the texture changed from silty clay loam to clay loam, or from clay to clay loam, at the other sites.

3.4.2. OM

The average OM contents of the soils were 2.09%, 2.42% and 2.35% in Beel Bhaina, East Beel Khuksia and Beel Pakhimara, respectively. The maximum OM contents of the soils were 3.63%, 3.63% and 3.90% in Beel Bhaina, East Beel Khuksia and Beel Pakhimara, respectively. At most of the sampling sites, OM was higher in the monsoon season than in the dry season.

4. Discussion

The water and soil quality parameters given in the preceding section indicate that there are large spatial and seasonal variations in the parameters. The EC, TDS, TSS, Na^+ and Cl^- values of basin water in the dry season have the highest values in Beel Bhaina and the lowest in Beel Pakhimara. The values are in between for East Beel Khuksia. Thus, there is a spatial pattern in the variation in basin water quality in the three tidal basins. During the monsoon season when there is rainfall, freshwater flow from upstream, and less tidal influence, the spatial pattern changes in that East Beel Khuksia shows the highest values in place of Beel Bhaina. Beel Pakhimara still has the lowest values. The variation in river water quality in the dry season follows almost a similar spatial pattern as the basin water in the same season. However, the difference in water quality of the Hari River between its upstream (Beel Bhaina) and downstream (East Beel Khuksia) areas gets reduced. The differences in water quality between the Hari River and the Kobadak River during the monsoon also become reduced. The variation in groundwater quality between Beel Bhaina and East Beel Khuksia follows the same spatial pattern in both the dry and monsoon seasons. Moreover, the groundwater quality gap between the two basins remains even in the monsoon.

The pattern of variation in soil quality in the three basins is different from that of water quality. The soil parameters, such as EC, Cl^- and total Fe, have the highest values in Beel Pakhimara and the lowest in East Beel Khuksia in the dry season. Thus, East Beel Khuksia in the dry season is in a more favorable condition in terms of soil parameters than the other two basins. Though the soil quality improves from the dry to the monsoon seasons due to rainfall in all the basins, the pattern of variation in the major parameters remains the same. The poor soil quality of Beel Pakhimara compared to its water quality could be due to a high proportion of clay particles in soils (Figure 2, Site 1), waterlogged conditions, fish cultivation, and use of basin water in irrigating the crops.

EC is considered one of the most important parameters in determining the suitability of water for crops. Though the dry season EC values of the surface water of Beel Bhaina and East Beel Khuksia are higher compared to the values for soil and groundwater (Tables 3 and 4), the groundwater is relatively less saline and used for irrigation in the two basins. Similarly, the high Na^+, Cl^- and SO_4^{2-} concentrations in surface water do not impact the crop cultivation. Moreover, though the water of the Hari River and its two basins has a high SAR value and is unsuitable for irrigation, the groundwater is good to use.

EC is also a measure of the amount of salts present in the soil. In agriculture, EC is used as a measure of soil salinity and helps determine soil fertility. Soil is classified into five categories based on EC: non-saline (<2 dS/m), slightly saline (2–4 dS/m), moderately saline (4–8 dS/m), very saline (8–16 dS/m) and extremely saline (>16 dS/m). High soil EC and Cl^- have made Beel Pakhimara less favorable for crop production than Beel Bhaina and East Beel Khuksia.

OM is a major contributor to soil health. It holds the soil particles together and provides the soil structure. It also contains essential nutrients and retains moisture to make the soil conditions favorable for crop growth. Generally, the soil should contain about 5% of OM. Otherwise, nutrient toxicity could occur, leading to an unbalanced soil ecosystem. The soils containing 3–6% of OM are considered healthy and rich soils. Less than 3% of OM in soils indicates an unfavorable soil condition for crop production. The OM was found to be lower than that required for favorable soil conditions in all the basins.

The average TDS and TSS were found to be higher in the Hari River than in the Kobadak River. The success of TRM operation in Beel Bhaina and East Beel Khuksia and the failure in Beel Pakhimara can be linked to this variation in sediment concentration.

A significant increase in livelihood opportunities in agriculture and fisheries has occurred in Beel Bhaina after the successful TRM operation in the tidal basin, which has improved its drainage. An uneven sedimentation in the partially successful TRM in East Beel Khuksia has resulted in livelihood loss, human displacement, conflicts and social unrest [44,63,85]. The sediment deposition under the TRM scheme in Beel Pakhimara has also been uneven [86]. This has also resulted in a different nutrient distribution in this basin from the other tidal basins. The soil type of Beel Bhaina is peaty clay and sandy clay loam, which become more abundant in nutrient contents with time and contribute to increased crop productivity [18]. The soil type in East Beel Khuksia shows similarity with Beel Bhaina, as the two basins are adjacent to each other and receive the tidal flux from the same Hari River.

Soil quality determines the crop species and production in an area. The cropping practice and profitability of the farmers in the three basins are found to be linked to the level of success of TRM operation. The dominant cropping pattern in the basins is fallow–fish–*boro* rice. Saline water shrimp, freshwater prawn and other fish are cultivated in Beel Bhaina and East Beel Khuksia. In Beel Bhaina, mixed farming of rice and fish on main farms and cultivation of vegetables on dikes have increased significantly after the completion of the TRM operation. In East Beel Khuksia, rice and shrimp cultivation is practiced on the recently developed lands. In Beel Pakhimara, the local people are trying to cultivate *boro* rice during the dry season. However, there is no crop cultivation in the monsoon season. Moreover, about one-third of the basin is still under fish and shrimp cultivation. The yields of *boro* rice are about 7.2, 7.7 and 6.4 ton/ha in Beel Bhaina, East Beel Khuksia and Beel Pakhimara, respectively. The average profit margins for the farmers of Beel Bhaina, East Beel Khuksia and Beel Pakhimara are 53.6%, 50.0% and 43.7%, respectively. In addition to geophysical and hydrological factors such as land topography, drainage condition, and soil and water quality, socioeconomic factors such as land ownership and control, and local sociopolitical structure play important roles in land cultivation and crop choice in a tidal basin. It is not practical to cultivate rice in small plots surrounded by large aquaculture ponds due to different water management practices. Therefore, the small and marginal farmers are sometimes forced to lease out their lands to local influentials and large farmers who prefer to cultivate fish and shrimp in large areas. The prevalence of aquaculture in the tidal basins even after successful TRM operation is partially due to these socioeconomic factors.

5. Conclusions

This study assessed the spatial and seasonal variations in water and deposited sediment qualities to evaluate their suitability for agricultural purposes. A total of 28 water samples and 23 soil samples were collected from three selected tidal river basins of southwest coastal Bangladesh. The water qualities of Beel Bhaina and East Beel Khuksia, which are considered successful and partially successful TRMs, respectively, were worse in the dry season than Beel Pakhimara, an unsuccessful TRM, in terms of EC, TDS, TSS, Na^+ and Cl^-. However, the deposited soil qualities of the first two basins were better than the last one in terms of EC, Cl^- and total Fe. Though the surface water (both river and basin) qualities in the successful and partially successful tidal basins were poor, the groundwater qualities were better, and the groundwater was used for agriculture in both the basins. The use of groundwater for agriculture has resulted in better soil quality. The better soil quality along with the availability of suitable groundwater has increased the crop cultivation in the first two basins. In contrast, the poor soil quality coupled with the non-availability of suitable groundwater has discouraged the farmers of Beel Pakhimara in cultivating *boro* rice. The variations in the yields of *boro* rice (7.2, 7.7 and 6.4 tons/ha in Beel Bhaina, East Beel Khuksia and Beel Pakhimara, respectively) and the profit margins of the farmers (53.6%, 50.0% and 43.7%, respectively) also support these findings.

The surface water quality in the basins improves a lot in the monsoon season due to direct rainfall on the basins and increased freshwater inflows in the rivers from upstream. The values of almost all the water quality parameters are largely reduced during this season and fall within the permissible limits for some parameters, such as EC, TDS, K^+, Mg^{2+}, SO_4^{2-} and Cl^-. However, the changes in soil quality parameters of the basins from the dry to the monsoon seasons are not substantial, except for total Fe and S contents. Moreover, the soils of Beel Pakhimara remain unsuitable for crop production, even in the monsoon, in terms of S content.

The Hari River and its two connecting basins have much higher TSS and TDS than the Kobadak River and the connecting basin in the dry season. Since tidal influence in the rivers is more pronounced in the dry season, the sedimentation in Beel Bhaina and East Beel Khuksia and consequently the success of TRM operation in these basins can be linked to the dry season sediment concentrations. The availability of surface water for irrigation does not have any major role in the post-TRM crop cultivation due to the quality constraints. Moreover, the farmers do not practice *aman* rice cultivation in the monsoon season despite better surface water quality. Thus, the level of sedimentation and the soil quality in the basins are linked to the cultivation practices in the dry season. The findings of this study have implications as to why TRM succeeds and the role of water and soil quality in that. The insights gained will be useful in implementing TRM elsewhere in coastal areas.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/su151813855/s1, Supplementary Material S1: Values of water quality parameters from different tidal basins; Supplementary Material S2: Values of deposited sediment quality parameters from different tidal basins.

Author Contributions: Conceptualization, N.H., M.S.A.K. and M.S.M.; methodology, N.H. and M.A.I.; investigation, N.H.; laboratory analysis, M.A.I.; data curation, N.H., S.B. and M.S.M.; resources, M.S.A.K.; writing—original draft preparation, S.B.; writing—review and editing, M.S.M. and M.A.I.; visualization, N.H. and S.B.; supervision, M.S.M. and M.S.A.K.; project administration, M.S.A.K.; funding acquisition, M.S.A.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Netherlands Organization for Scientific Research under Living Polders: Dynamic Polder Management for Sustainable Livelihoods, Applied to Bangladesh.

Institutional Review Board Statement: Ethics review and approval were waived for this study as the study was not on human subject or linked to ethical matters such as race, religion, and gender.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Data can be made available upon request.

Acknowledgments: We thank the four anonymous reviewers for their valuable comments and useful suggestions, which helped improve the quality of the paper.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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