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A Resilient and Nature-Based Drinking Water Supply Source for Saline and Arsenic Prone Coastal Aquifers of the Bengal Delta

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Abstract: Salinity causes a hostile environmental impact throughout the year in the coastal region of Bangladesh, and its severity increases day by day. Because of upstream freshwater flow reduction and massive groundwater extraction, salinity has increased substantially over the last three decades. Moreover, arsenic contamination in shallow groundwater makes the groundwater unsuitable for potable use. Consequently, the coastal area suffers from acute storage of safe water supply. Salinity also negatively impacts human activities, livelihood, agricultural production, and the aquatic ecosystem. Though the shallow aquifer contains high salinity and a small amount of Arsenic (As), the very shallow aquifer (within 3m to 8m) contains fresh water in many areas in the rainy season due to the direct recharge of rainwater. However, rainfall recharge varies significantly depending on the geological and hydrogeological settings. Specifically, up to 50% of annual rainfall is stored in shallow aquifers of Quaternary sands through direct infiltration. The research's principal objective is to identify the safe and sustainable drinking water source in the arsenic and saline-prone coastal region. Groundwater samples were collected from the different locations of the study area during both dry and wet seasons and examined seasonal variations in groundwater table and salinity levels. The chemical analyses and Physico-chemical parameters indicate that the groundwater samples are suitable for drinking. Except for some groundwater samples from the wet season, the salinity of all samples was under the allowable limit for Bangladesh (<2000 µS/cm), and the targeted aquifer was almost arsenic (50 µg/l) free. Therefore, a comprehensive analysis has been made to accomplish the study goals. Particularly, the groundwater's electrical conductivity (EC) values of most samples were measured within the limit of fresh or brackish water (<2000 µS/cm). Overall, the results indicate the prospect of a very shallow aquifer as a source of freshwater for drinking purposes throughout the year, considering both arsenic and salinity, which effectively solve the freshwater shortage, especially in the saline-arsenic prone area.

Keywords: coastal area; salinity; arsenic contamination; very shallow groundwater; sustainable use

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Citation: Jahan, K.; Zahid, A.; Bhuiyan, M.A.E.; Ali, I. A Resilient and Nature-Based Drinking Water Supply Source for Saline and Arsenic Prone Coastal Aquifers of the Bengal Delta. *Sustainability* **2022**, *14*, 6703. https://doi.org/10.3390/su14116703

Academic Editor: Abel Silva Vieira

Received: 9 April 2022
Accepted: 27 May 2022
Published: 30 May 2022

1. Introduction

The present trend of groundwater use in Bangladesh is often not sustainable due to unplanned development and management, wasteful use, and inadequate governance actions [1–5]. This also hampers socioeconomic and agricultural development, causes widespread public health problems, and disturbs a wide range of ecosystems [6,7]. Besides that, Bangladesh experiences devastating extreme natural events such as tropical cyclones, storm surges, coastal erosion, floods, droughts, and saline water encroachment on the coast almost every year [8–10]. Geographically Bangladesh is a low-lying country. Generally, the land surface of the Ganges-Brahmaputra delta is located only 3 m above mean sea level [11–14] in the deltaic coastal plain. Salinity has increased significantly over the last three decades due to upland freshwater flow reduction and massive groundwater extraction [15]. The groundwater is unacceptable for potable use because of Arsenic contamination [15]. Despite the development of public and private tubewells, arsenic and salts contamination in groundwater limits the drinking water security. While there are no methodical records of private tubewells, the quantity of private tubewells is considered to be multiple times higher than public ones [16]. Specifically, 6.7 individuals per tubewell in regions with shallow freshwater springs are more than 12.4 individuals per tubewell in the coastal areas (high groundwater salinity) [17].

Consequently, the coastal belt suffers from acute storage of safe water supply. It also negatively impacts human activities, livelihood, agricultural production, the aquatic ecosystem, etc. Agriculture, fishing in rivers and bays, aquaculture, livestock rearing, tourism based on the Sundarban, and the mangrove forest are the principal occupations of the population for their livelihood in this coastal part. However, people consistently experience the adverse effects of natural hazards such as cyclones, storm surges, tidal inundation, drought, riverbank erosion, water and soil salinity, waterlogging, and unplanned shrimp farming. To build a resilient community, both traditional and indigenous practices and scientific and technical knowledge must be considered simultaneously. Under individual and project initiatives, the vulnerable community has adapted to become climate-resilient, i.e., rainwater harvesting for freshwater supply, homestead gardening on the modified bed for vegetables, plantation on embankments, and various activities to face the challenges of disaster risks. Studies indicate that these adaptation methods and techniques have brought positive income and employment changes [18]. However, freshwater availability, mainly during the dry period, is still a significant threat to ensuring a safe freshwater supply for all living in the coastal belt.

Freshwater resources are treated as essential resources in the coastal zone [5]. Bangladesh's coastal zone include about 20% of the land area and over 30% of the net cultivable area [19]. The area lies on an active and tidal delta. Due to its complex lithologic, hydrogeological, and geochemical characteristics, the coastal area is different from the rest of the country. Pumping fresh groundwater in the coastal aquifers accelerates saltwater intrusion and decreases water quality along horizontal and vertical salinization paths. The upper shallow and main aquifers [20] can yield large quantities of water. However, it is not entirely suitable for development because of quality issues, especially where arsenic contamination in shallow groundwater and saline water intrusion makes the water unusable for human consumption [21–26] in the coastal belt. The current coastal groundwater situation is strongly impacted by historical sea-level rise (SLR) and proximity to the sea, particularly in the low-elevation central part of the delta [27,28]. The massive groundwater withdrawal during dry irrigation is the primary cause of saline water encroachment on the coast. Inland salinization also occurs due to paleo-brackish water entrapped in small areas during rapid regressive events between 12,000 and 10,000 years after the transgression period between 18,000 and 12,000 years [29]. In addition, anticipated sea-level rise due to global warming could accelerate the rate of seawater intrusion [30–34]. As a result, 19 coastal districts of Bangladesh face an extreme salinity problem [35,36].

Therefore, investigating the source of the freshwater aquifer in the saline and arsenic-prone coastal aquifers is vital for mitigating drinking water scarcity. In the coastal zone, the salinity of the upper and principal aquifers is exceptionally variable and changes abruptly over short distances [37]. Therefore, shallow groundwater is unsuitable for domestic and irrigation purpose in most areas due to either connate salts or seawater intrusion. Except for high concentrations of salinity and arsenic, coastal groundwater also experienced high content of some trace metals, for example, manganese (Mn) and Iron (Fe) [38]. Several researchers found the source of trace metals by analyzing the coastal sediment core over the Bengal basin [39,40]. The study found that trace elements originated from the adsorption and desorption reactions processes.

Adaptation and mitigation are two possibilities for Bangladesh to meet the freshwater scarcity challenge. Adaptation is country-specific or even local, but the mitigation requires collective endeavors of global communities. Therefore, the development of adaptation policies for different sectors, for example, local and regional, will help to deal with the crucial hazards of freshwater scarcity in the coastal region of Bangladesh. However, if the probable impacts are not addressed and integrated into the development plans, it will fail to attain sustainability in Bangladesh's economy, environment, and security. Thus, this study can help find out the freshwater aquifers during the rainy season with potential recommendations for the coastal areas that could be coordinated with the adaptation activities of the country. Furthermore, this study aims to identify the prospect of a shallow aquifer as a source of fresh drinking water for the vulnerable local people in Paikgacha and Tala Upazila and provide potential recommendations to solve the issue.

2. Study Area

Paikgacha Upazila of Khulna district and Tala Upazila of Satkhira district (areal extension 89°5′0″ E to 89°25′0″ E and 22°27′0″ N to 22°55′0″ N) were selected as the study areas (Figure 1). These study regions are widely recognized for their severe groundwater salinity problem. The salinity ranges showed different concentrations in different seasons, i.e., in the dry season (November to March), salinity showed high intensity. On the other hand, during the wet season (April to October), salinity showed low ranges (<700 µg/L) [5]. A recent study by the Bangladesh Water Development Board [35] (BWDB, 2013) showed that the shallow and main aquifer was fully affected by salinity.

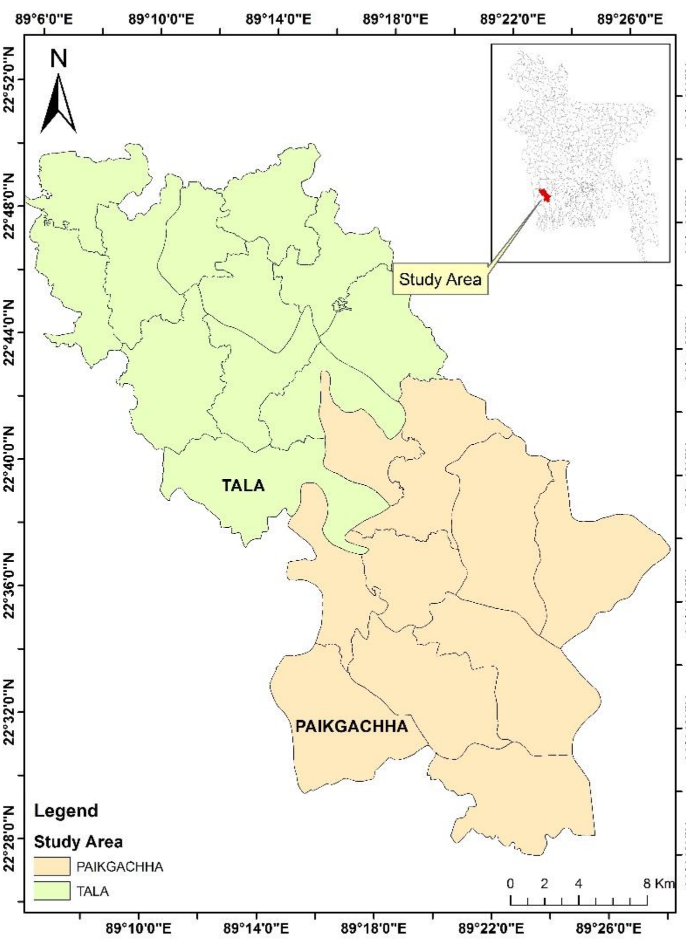


Figure 1. Location Map of Paikgacha and Tala Upazila, Khulna and Satkhira District.

In contrast, the deep aquifer was not affected by the salinity problem. Low concentrated arsenic was also found in this region in the shallow aquifer. Though the shallow aquifer contains high salinity and a small amount of arsenic, the very shallow aquifer (within 5 to 10 m) contains fresh water in many areas in the wet season due to the direct recharge of rainwater. Therefore, people could use this freshwater for their drinking purpose during this wet season. A comprehensive analysis of aquifers' hydrological and hydrogeological settings is essential for improved management and consumption of usable groundwater.

Our study area is characterized by a tropical monsoon climate where the mean annual rainfall is high (1800 mm). Therefore, in the wet season (April to October) there is expected to be more rainfall (80%) [41–43]. The rivers represent an overall dendritic pattern regulating the study area's hydrological system. The geology of the coastal area is dominantly characterized by the general Quaternary geology of the Bengal Basin [44,45]. During the Pleistocene period, sediments from early Ganges-Brahmaputra-Meghna (GBM) delta river systems accumulated over the basin's northern and eastern parts. However, tectonic movements and sea-level changes between Pleistocene and recent periods have granted deep erosion and deposition on the Pleistocene surface. As a result, a fluvial sedimentation environment formed overlapping deltaic arcs of GBM river systems in recent times in the southern downward area of the Bengal Basin. Moreover, sediments are susceptible to conserving high concentrations of arsenic, especially within the depths of 30–150 m (optimum well depth) [46]. Groundwater arsenic was officially recognized by the government and media in 1993. The arsenic concentrations were above 50 µg/L for 29% of the shallow tubewells and 2% of the deep tubewells [47].

Hydrogeologic Settings of the Study Area

Hydrogeology and the distribution of aquifer sediments are very complex in the coastal region of Bangladesh [37]. Aquifer-aquitard alteration is highly varying, even within a very short distance. The coastal area is dominated mainly by the Meghna Flood Plain, Chittagong-Cox's Bazar Coastal Plain, and the GBM Delta Complex. There are several numbers of small depressions (beels/haors) in the flood plain. Acquired data from several thousands of boreholes define the extent of aquifer-aquitard formations. The aquifers have been partitioned based on the depth and thickness of the sediment formation.

However, the sedimentation rate and subsidence of the entire Bengal Basin were not uniform throughout the Quaternary. About three hundred tube wells have been installed for water supply under the Department of Public Health and Engineering (DPHE) projects in the study area. Borelog shows no regular or sequential succession in the area. It actually displays a heterogeneous mixture of clay, silt, and sand. Lately, in 19 coastal districts, some wells installed under a Climate Change Trust Fund Project of the Bangladesh Water Development Board (BWDB) up to 350 m in depth. Those logs also supported previous borelog behavior in those areas [36]. Each sedimentary unit's geometry is inevitably complex and unique, having a general lack of horizontal continuity on a scale. Additionally, there is an upward fining of the sequence observed while the degree of sorting declines with depth.

The topmost zone is a predominantly clay layer having a considerable thickness variation. It is followed by a complex mixture of medium and fine sands, silts, and clay which is a characteristic of a semi-confined aquifer. This shallow aquifer comprises sand lenses at various levels interbedded with silts and clays. However, one hydraulic unit is considered sufficient overlap and convergence of sand lenses over large areas. In addition, there is substantial lateral variation in these sediments' thickness, characteristic of the deltaic deposits.

The borehole lithologic log analyses reveal that a thick composite (shallow and main) aquifer with a thickness of ~130 m, predominantly fine to very fine sand, is encountered below the Paikgacha area's surface overlain discontinuous clay aquitard of 3 to 5 m thick (Figure 2a). The deep aquifer is discovered below 200–250 m, which is made discontinuous because of clay. According to the lithologic section of Tala Upazila, an excellent composite aquifer with a thickness of ~80 m is encountered overlain by upper clay layer of 5-10 m thick (Figure 2b). The lower aquifer is about 100–120 m thick, separated by clay with variable thickness from the upper aquifer.

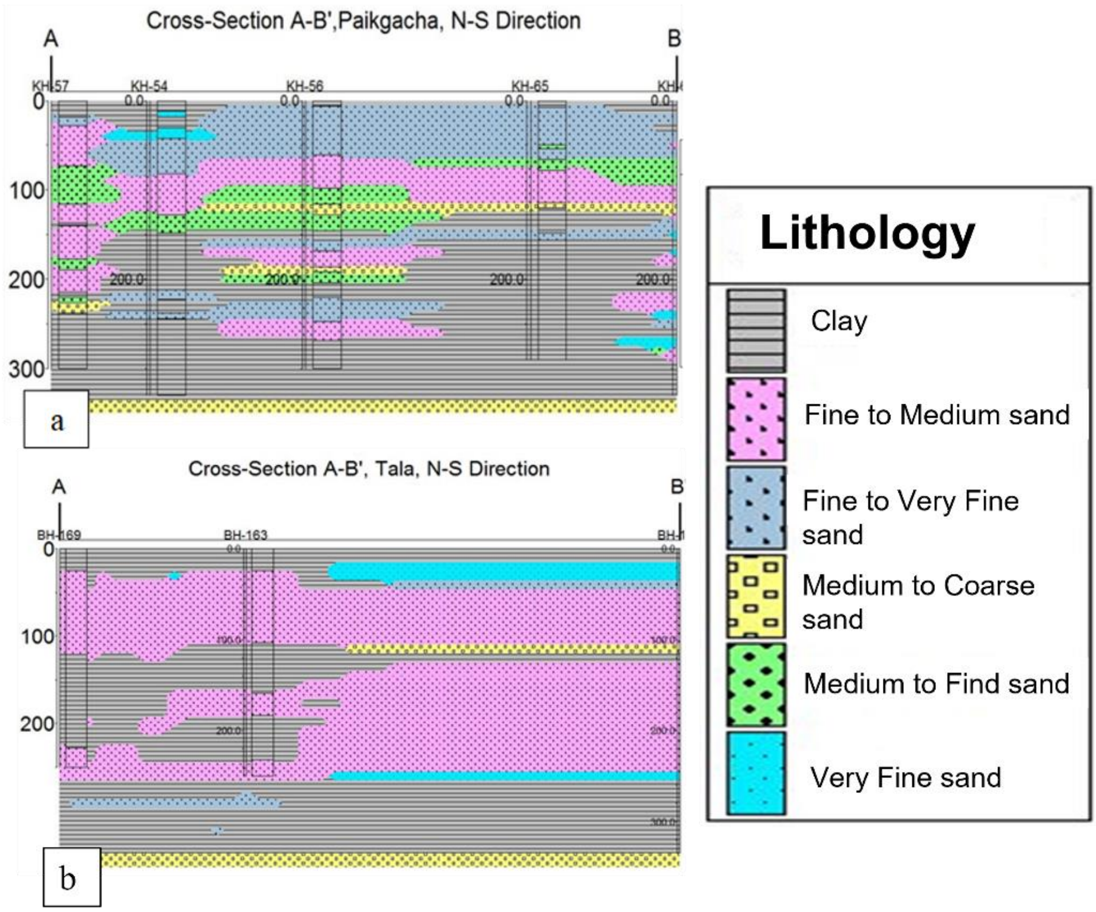


Figure 2. Lithologic sections of (**a**) Paikgacha and (**b**) Tala Upazila area.

3. Methodology

A questionnaire survey was carried out amongst people in the Paikgachha and Tala areas to understand their perception and response to disasters and salinity problems and gather information on socioeconomic conditions. Furthermore, the shallow tubewells (>10–15 m) located area produce saline and arsenic-contaminated water. In our study, very shallow tubewells were considered (<15 m) for sampling to determine groundwater chemistry by analyzing essential parameters. The details of the sampling procedure and the name of the methods and instruments are listed in Table 1. The entire study was carried out in two stages. One is hydrogeological settings, and the other is hydrogeochemical analysis.

Table 1. Sampling procedure and list of instruments and the applied methods for each of the physical and chemical parameters for this study.

Sampling Procedure	
Groundwater samples were collected in 500-mL polystyrene bottles, and chemical analyses followed standard guidelines (APHA 2005). After pumping the wells for 15–20 min, samples were collected and filtered through 0.45-lm membranes to avoid debris. To preserve the samples for trace metal analysis, they were acidified with concentrated HNO3 (AR grade: 60–61% and density:1.38 kg/L) and stored at 4 °C.	
Physical Parameter	
Parameter	*Instrument*
Temperature (°C) pH Electrical conductivity (EC) Total dissolved solids (TDS	Portable Multi-Meter Hach, Sens ION, MM150

Table 1. *Cont.*

Chemical Parameter			
Parameters		***Instrument***	***Method***
Cations	Sodium (Na^+), Potassium (K^+), Magnesium (Mg^{2+}), Calcium (Ca^{2+})	Atomic Absorption Spectrophotometer (Varian AAS, 680FS), USA	Default AAS Method
Anions	Nitrate (NO_3) Sulfate ($SO_4{}^{2-}$) Phosphate ($PO_4{}^{3-}$) Fluoride (F^-)	UV-VIS spectrophotometer, USA	Default Method
	Chloride (Cl^-)	Hach digital titrator, USA	HACH method 8207
	Bicarbonate ($HCO_3{}^-$)	Manual Titration	HCL titration
Trace Metals	Manganese (Mn)	Spectrophotometer at 560 nm (DR 2800, HACH USA	1-(2-pyridylazo)-2-naphthol method (0.006–0.7 mg/L)
	Iron (Fe)	Spectrophotometer (DR 2800, HACH USA) at 562 nm	FerroZine iron reagent method (0.009–1.4 mg/L)
Halogen Group	Iodine (I)	Spectrophotometer (DR 2800, HACH USA) at 530 nm	*N*,*N*-diethyl-p-phenylenediamine method (0.07–7.00 mg/L)
	Bromine (Br)	Spectrophotometer (DR 2800, HACH USA)	*N*,*N*-diethyl-p-phenylenediamine method (0.05–4.50 mg/L) at 530 nm

3.1. Assessment of Socioeconomic Status

A questionnaire survey was performed to compile primary data to assess the socioeconomic status of Paikgacha and Tala Upazila's people. The conducted research is a quantitative cross-sectional study that is generally conducted in a population at a time or over a short period. Moreover, cross-sectional studies were typically quick (snap-shotsnapshot) and economical, where cause and effect were analyzed at the same time [20]. A detailed questionnaire was developed for this study. The target group of this questionnaire was the local stakeholders of Paikgacha and Tala Upazila. The major sections of the questionnaire were developed based on general information about the households, socioeconomic status of households, source of drinking water, water collection procedure, drinking water quality, educational status, health issues, and willingness to pay for drinking water. A socioeconomic vulnerability analysis was carried out based on three major indicators: employment, economic status (income level), and economic facilities of the stakeholders. The socioeconomic status was determined based on 30 household surveys (Figure 3).

3.2. Analysis of the Hydrogeological Settings

A total of 4 observation wells (Figure 4) were installed down (depth: 8 and 12 m) under the study to monitor seasonal trends of groundwater table and water salinity at 3 h intervals using Solinist Level-Temperature-Conductivity (LTC) data logger. After completing the study, these newly installed tubewells were handed over to the local community.

The hydraulic properties of aquifers were estimated by applying the slug test, which was a cost-effective and time-consuming method. Slug testing was performed by lowering a slug (a cylinder of known volume, constructed of MS pipe capped at both ends tied to a rope or cable) down in a borehole to replace the stagnant water with an equivalent fluid volume. Next, a pressure transducer was placed below the slug level to examine the water level responses. The data were recorded in a data logger. The slug remained in place until the water level equilibrated to the static water level. Finally, during the equilibrium stage, the data logger was stopped. Bouwer and Rice's (1976) [48] method was used to calculate the hydraulic conductivity of aquifer materials in a single well. The detailed hydrogeological settings methodology is explained in the flow chart (Figure 5).

Figure 3. Few Glimpses of the questionnaire Survey with the focused or targeted group.

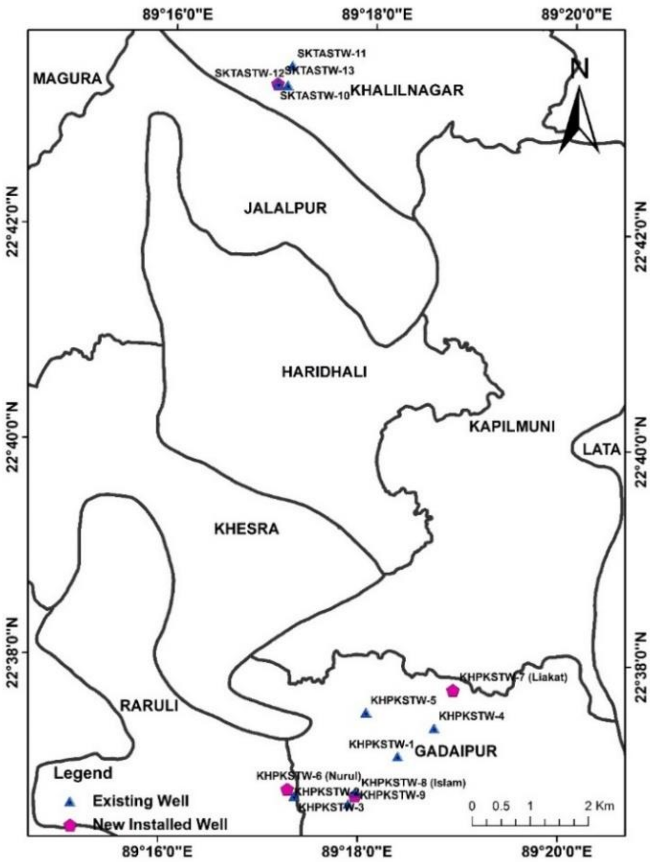


Figure 4. Location of the existing and newly installed observation wells in Tala and Paikgacha Upazila.

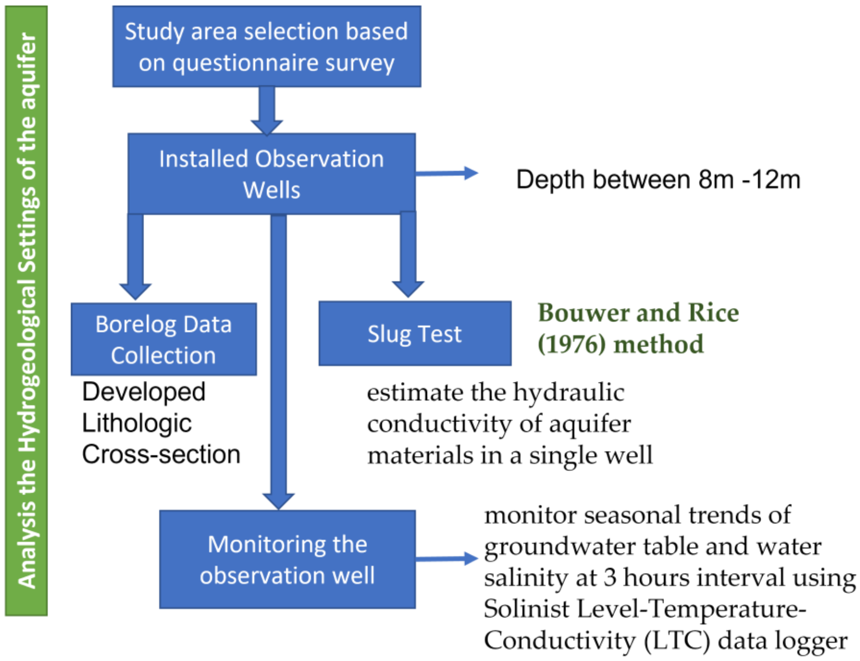


Figure 5. Flow chart of the hydrological settings.

3.3. Analysis of the Geochemical Parameters

Both wet (September 2013) and dry (March 2014) seasons were considered for groundwater sample collection. Moreover,13 groundwater samples were collected for the wet season, as shown in Figure 1. Similarly, 14 samples were collected in the dry season. Among the 14 tubewells, 4 were newly installed. Some of the parameters of water samples, such as temperature, hydrogen ion (pH), electrical conductivity (EC), total dissolved solids (TDS), salinity, and arsenic were measured in the field. In addition, the major constituents (Na^+, K^+, Ca^{2+}, Mg^{2+}, SO_4^{2-}, NO_3^-, Cl^-, HCO_3^-) and the trace components (Fe, Mn, Br, I, and F) had been analyzed in the laboratory by adopting standard methods such as Atomic Absorption Spectrophotometry (AAS), UV-VIS Spectrophotometry and titration. The framework of the conducted research scheme is shown in Figure 6. A total of 13 drinking water elements were considered to analyze the water quality (Table 2). Additionally, a detailed comparison is shown for each of the parameters for both wet and dry seasons in the result section.

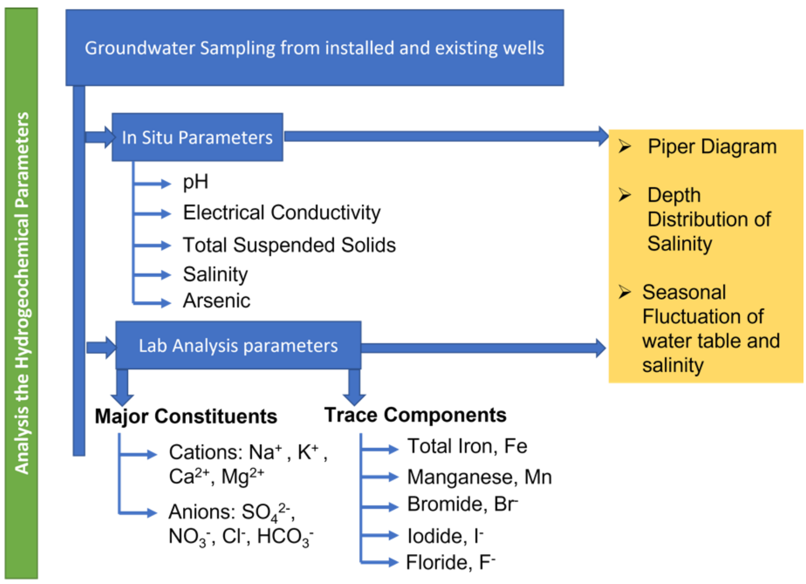


Figure 6. Flow chart of the hydrogeochemical analysis procedure.

Table 2. WHO (2011) [49] and Bangladesh Drinking Water Standards [50] for the analyzed parameters.

Elements	WHO (2011) Standards (mg/L)	Bangladesh (BD) Standards (mg/L)
Magnesium (Mg)	50	50
Calcium (Ca)	75	75
Manganese (Mn)	0.5	0.5
Bromide (Br)	<6	-
Iodide (I)	0.02	-
Bi-carbonate (HCO_3^-)	200	-
Sulfate (SO_4^{2-})	250	400
Fluoride (F)	1.5	4.0
Nitrate (NO_3^-)	50	10
Chloride (Cl)	250	150–600
Iron (Fe)	0.3	1.0
Sodium (Na)	200	600
Potassium (K)	12	12

4. Results and Discussion

4.1. Assessment of Social Challenges through Questionnaire Survey

In this study, socioeconomic status was analyzed based on the small size (n = 30) of household surveys for Paikgacha and Tala Upazila. A total of seven indicators were considered for this analysis (Table 3).

Table 3. Socioeconomic status of the households based on the questionnaire survey.

Indicator	Weightage	Percentage (%)
Education	3	
Literate		30
Illiterate		70
Main Occupation	2	
Farming		45
Labor		35
Business		15
Service		5
Household Income	1	
Ultra-poor		65
Poor		25
Non-poor		10
Source of Drinking water	4	
Community Tubewell		70
Personal Tubewell		25
Other		5
Health Issue	1	90
Willingness to Pay	2	
Agreed		70
Not Agreed		30

Ultra-poor, poor, and non-poor were categorized according to the World 2016 study, which was defined based on a daily per capita income. ultra-poor 1.90 USD; poor 1.9–2.50 USD and non-poor over 2.50 USD.

4.2. Hydrogeologic Settings Analysis

The study area section discussed the hydrological settings of the entire Paikgacha and Tala upazilaUpazila areas based on 300 m lithological information, which was matched with newly installed four exploratory wells. The topmost layer was predominantly composed of clay with varying thicknesses from 0 to 9 m and was underlain by a composite mixture of medium and fine sands that was considered a semi-confined shallow aquifer in this study. The groundwater table was found from 0.5 m to 1.6 m, which was not too deep from the surface. So, the primary source of water was rainfall which was considered freshwater. The ranges of the total depth of all four installed monitoring wells were 8.5 m to 12.2 m, and the aquifers were available from 2.5 m to 9.2 m. All this information (Table 4) indicated that the freshwater zone was easily accessible from the shallow aquifer.

Table 4. Information on installed monitoring well and lithologic settings.

Well ID	Total Depth (m)	GWT from the Surface (m)	Installed Strainer	Thickness (m)	
				Top Zone	Aquifer
KHPKSTW-6	10.37	0.50	(8.7–9.8)	(0–4.8)	(4.9–10.4)
KHPKSTW-7	12.2	0.90	8–10.5	0–7.6	7.61–12.2
KHPKSTW-8	8.5	1.6	4.8–7.6	0–2.5	2.5–8.5
SKTASTW-13	12.2	0.65	4.5–9.15	0–9.15	9.2–12.2

4.3. Groundwater Chemistry

Silt, clay, and very fine sand dominate the shallow subsurface of the study area. Water infiltrates very slowly through pore spaces in fine-grained sediments. Silt, clay, and very fine sand allow long residents time for water that favors minerals' dissolution. On the other hand, soils and aquifers contain abundant materials that can sorb chemicals from water due to mass transfer among solution and solid. On the alluvial plains of southwestern Bangladesh, the shallow sub-surface faces continuous reduction conditions controlled by high groundwater table to repeating reduction and oxidation due to land submergence and seasonal fluctuations of the water table. Moreover, agricultural activity and shrimp farming increased significantly in this area over the past decades. These play an essential role in water chemistry, mainly in shallow groundwater.

Results of the major ions concentrations and trace elements of groundwater samples for both wet and dry seasons are presented in Figures 7–9. The samples were found to be neutral, with pH values ranging between 7 and 7.9 and 7.07 and 7.7 in wet and dry seasons, respectively. The temperature of groundwater was measured between 26.1 and 27.0 °C. The groundwater's electrical conductivity (EC) value varied from 360 to 4100 and from 803 to 4350 µS/cm for wet and dry seasons. EC values of most of the samples (except 5) were measured within the limit of fresh or brackish water (<2000 µS/cm). Generally, wet season EC values were detected lower than dry season EC values of groundwater samples. However, few samples showed the opposite trend because of saline or brackish water. Total Dissolved Solids (TDS) of water varied from 373 to 2160 and 402 to 2396 mg/L, respectively, for wet and dry season samples.

The concentrations of Na^+, K^+, Ca^{2+}, Mg^{2+} (Figure 7) were measured as 26.1 to 205.3 and 299 mg/L to 512 mg/L, 1.0 mg/L to 9.8 mg/L and 2.62 mg/L to 23.2 mg/L, 15.3 mg/L to 40.0 mg/L and 10.3 mg/L to 141 mg/L and 27.65 mg/L to 149.1 mg/L and 17.1 mg/L to 183.8 mg/L for wet and dry seasons, respectively. The average Na^+, K^+, Ca^{2+}, Mg^{2+} concentrations is 74.79 mg/L to 424.54 mg/L, 2.92 mg/L to 9.66 mg/L, 22.28 mg/L to 28.19 mg/L, and 76.34 mg/L to 68.38 mg/L, respectively for wet and dry seasons. Na^+ concentration of few samples showed substantial variation between wet and dry seasons. Na^+ concentration in most of the samples exceeds the WHO recommended limit of 200 mg/L for potable water [51]. Groundwater can contain a large amount of sodium due to saltwater intrusion [52]. It is noted that dietary intake of sodium is limited to between 1800 and 5000 mg/day. Discretionary sodium intake variability is very high [53]. The concentrations of Mg^{2+} in most water samples show little greater than the WHO 2011 [49] allowable limit of 50 mg/L for Bangladesh [50].

SO_4^{2-} was (Figure 8) found between 0 and 91.0 mg/L and 0 and 100.0 mg/L with an average of 14.69 mg/L and 27.27 mg/L in wet and dry seasons. However, SO_4^{2-} of most of the samples was measured as very low. NO_3^- (Figure 8) concentrations range between 0.71 and 8.81 mg/L and 0.87 mg/L and 7.59 mg/L with an average of 3.43 mg/L and 2.5 mg/L, respectively, for wet and dry seasons. Enhancement of organic N mineralization in soil and oxidation due to land clearing, drainage, plowing, pit-latrines, and other agricultural applications provide extensive contents of leachable NO_3^-. The reduction in the only process for in situ nitrate removal from groundwater as NO_3^- does not form insoluble minerals that could precipitate, nor is adsorbed considerably under aquifer conditions [54].

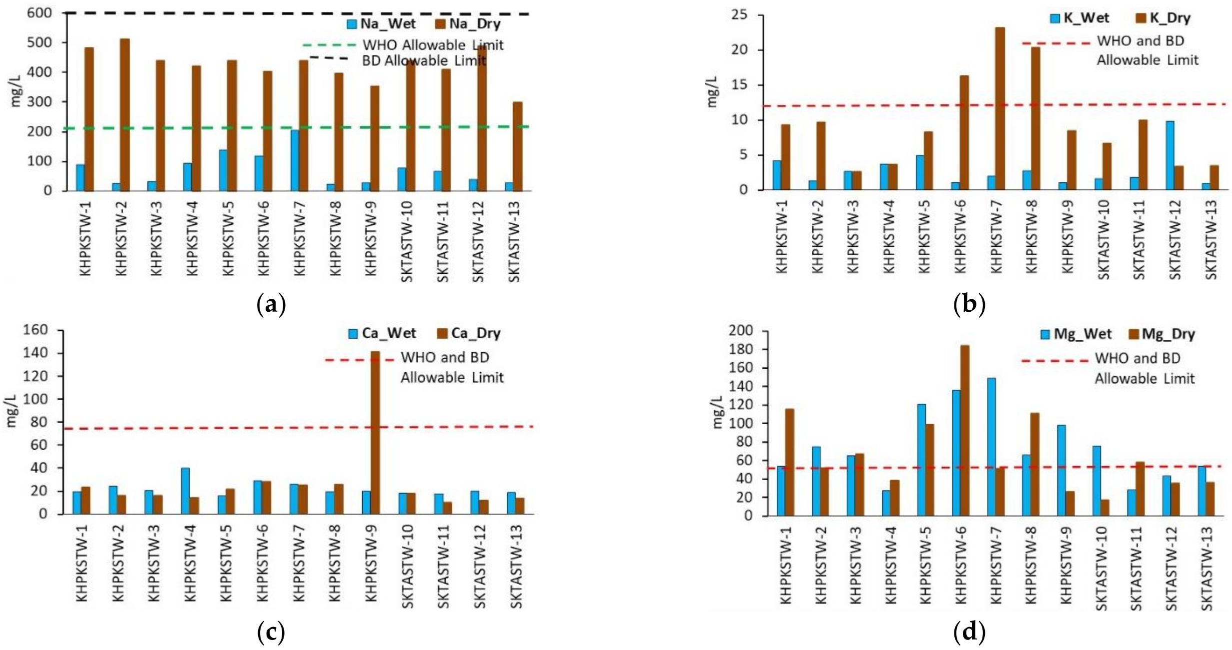


Figure 7. Comparison of both wet and dry seasons of cations in terms of WHO and BD allowable limit for drinking water (**a**) Sodium (Na^+); (**b**) Potassium (K^+); (**c**) Calcium (Ca^{2+}); and (**d**) Magnesium (Mg^{2+}). Except for Magnesium (Mg), all other parameters are mostly under the standard limit. Sodium (Na) does not meet the WHO limit for the dry season, but both dry and wet are under the BD limit.

In a few cases, reduction of NO_3^- to NH_4^+ could occur, but denitrification generally can be responsible for the significant decrease of NO_3^- in aquifers [55]. The shallow water tables and poor drainage during infiltration promote the microbial reduction of NO3- to N_2 gas or microbial oxidation of NH4+ to NO3 [56]. Recharging NO_3^-, sourced from agriculture fertilizer, moved down in the aquifer where denitrification is coupled with sulfide oxidation until encountering sulfide minerals and producing SO_4^{2-} [57]. Very low SO_4^{2-}/Cl^- ratios occasionally result from the reduction of SO_4^{2-}. Sorption retards the movement of SO_4^{2-} in the subsurface [58]. Br, I, and F concentrations were measured between 0.05 and 1.21 mg/L and 0.04 mg/L and 2.0 mg/L, 0.35 mg/L and 3.09 mg/L and 0.11 mg/L and 3.15 mg/L and 0.007 mg/L and 0.38 mg/L and 0.13 mg/L and 1.15 mg/L, respectively, for wet and dry seasons.

The variations of Cl^- (Figure 8) cause a wide range of total dissolved ions, is 15.0 mg/L to 830 mg/L and 150 mg/L to 867 mg/L for wet monsoon and dry irrigation seasons, respectively, and HCO_3^- also has a significant role with values ranging from 111.63 mg/L to 260.47 mg/L, 298.9 mg/L and 519.4 mg/L for wet and dry seasons, respectively. The average concentrations of Cl^- and HCO_3^- are 250.85 mg/L and 402.31 mg/L and 180.9 mg/L and 424.65 mg/L for wet and dry seasons, respectively. Cl^- concentration exceeds a brackish water level of 600 mg/L in a few samples, i.e., groundwater of most of the very shallow tubewells is found within the drinking water limit. However, HCO_3^- (Figure 8) concentration in many water samples exceeds the WHO recommended limit of 200 mg/L for drinking water. Freshwater is often dominated by Ca^{2+} and HCO_3^- ions due to calcite dissolution. The water softening reactions are the prominent exchange processes when groundwater flows through clay-rich layer Ca^{2+} and Mg^{2+} exchange with absorbed Na^+ in the groundwater [54]. The monovalent ions are generally replaced by divalent ions, which are more strongly bonded. However, the reversible reaction may also happen at high activities when the divalent ions are replaced by the monovalent ions [59].

Figure 8. Comparison of both wet and dry seasons of anions in terms of WHO and BD allowable limit for drinking water (**a**) Sulfate (SO_4^{2-}); (**b**) Nitrate (NO_3^-); (**c**) Bromide (Br^-); (**d**) Chloride (Cl^-); (**e**) Fluoride (F^-); (**f**) Iodide (I^-); and (**g**) Bi-carbonate (HCO_3^-). SO_4^{2-}; NO_3^-; F^- and Br^- meet the limit for both WHO and BD. The F analysis showed a significantly lower amount during the wet season than dry. Cl^- mostly meets the BD limit for the wet season except for one sample but three samples for the WHO limit. No allowable limit is available for Iodide for both WHO and BD.

The matter of groundwater-rock interaction and degradation of organic matter by an integrated microbial process is made noticeable in the concentrations of dissolved HCO_3^- [58]. Weathering and dissolution of carbonate, silicate or evaporate minerals releases elements into water [54]. The Na^+ and Ca^{2+} ratios are low in most samples, usually due to carbonate weathering unless many ion exchanges [60]. The alkalinity of water or

HCO_3^- influences the secondary mineral formation$^-$, sourced from weathered calcite or silicate by respired or atmospheric CO_2 [61]. Weathering processes further influence carbonate and silicate minerals to release Na^+, K^+, Ca^{2+}, and Mg^{2+} to the groundwater [58]. Contents of Ca^{2+} more than SO_4^{2-} indicate Ca^{2+} sourced from calcite/dolomite or silicates [60]. However, high Cl^- and higher proportions of Na^+ in comparison to K^+, Ca^{2+}, and Mg^{2+}, indicate the role of Na^+ and Cl^- [58] and intrusion of seawater, as well as percolation due to shrimp cultivation with brackish or saline water, are expected in this region of the coastal belt.

Excess heavy metal concentration is treated as harmful contaminants on biota due to their poisonous impacts [62]. However, except iron, trace metals in natural or contaminated groundwater, generally found at concentrations below 1.0 mg/L, controls by the solubility of amorphous substances or minerals and adsorption on surfaces of clay minerals or organic matter or hydrous oxides of Fe and Mn [63]. This study's Fe content of groundwater was measured as 0.2 mg/L to 13.7 mg/L and 0.01 mg/L to 0.85 mg/L in wet and dry seasons, respectively (Figure 9). The concentration of most wet season samples exceeds the WHO limit of 0.3 for drinking water [53], while almost all dry season samples show values within the allowable limit. Important Fe^{2+} bearing minerals commonly present in aquifer sediments comprise minerals such as magnetite, ilmenite, pyrite, siderite, silicates (e.g., amphiboles, pyroxenes, olivine, biotite), and clay minerals (e.g., smectites). Oxidative dissolution of pyrite as a source for Fe^{2+} in groundwater is a necessary process [54]. The concentration of Mn in groundwater was measured between 0 mg/L and 0.28 mg/L and 0.04 mg/L and 0.85 mg/L, respectively, for wet and dry seasons. Mn concentration of many of the sampled wells slightly exceeds the WHO recommended value of 0.1 mg/L.

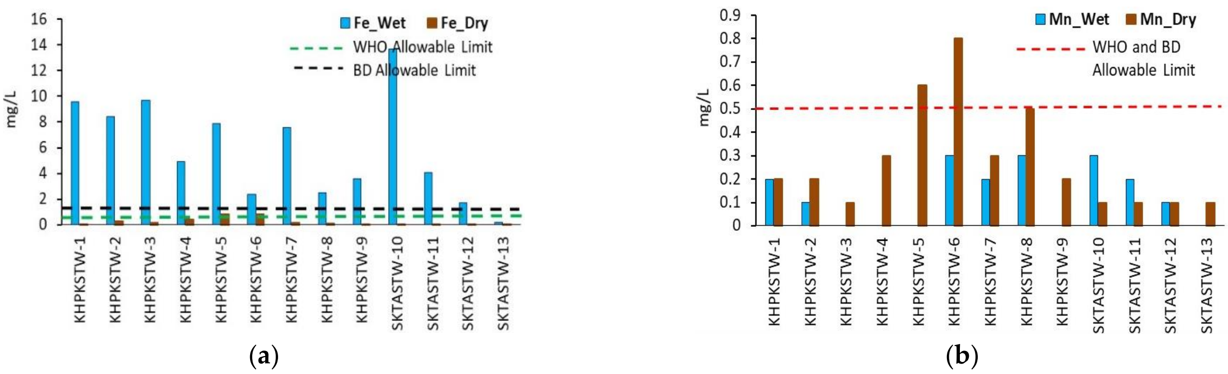
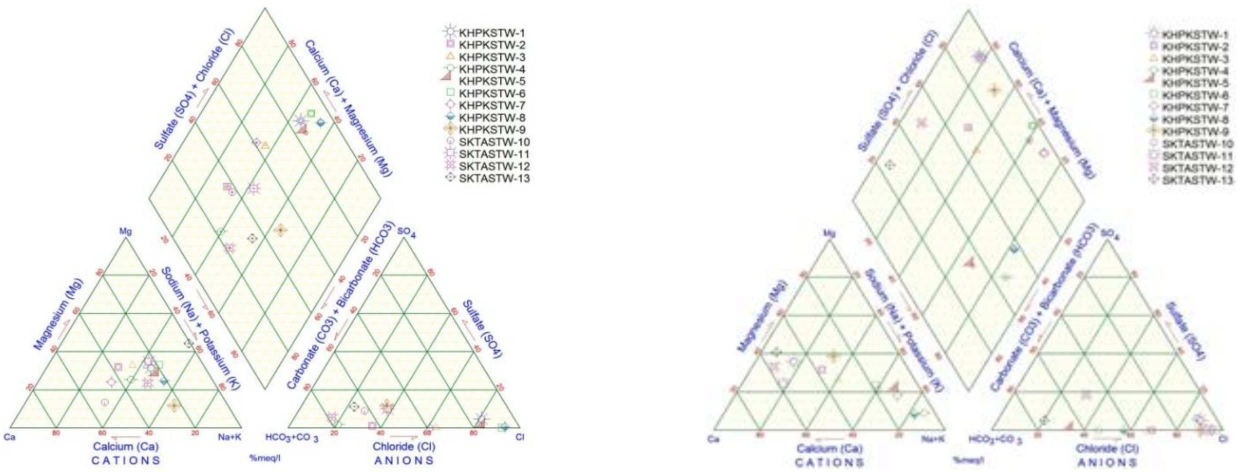


Figure 9. Comparison of both wet and dry seasons of trace elements in terms of WHO and BD allowable limit for drinking water (**a**) Iron (Fe^{2+}); (**b**) Manganese (Mn^{2+}). It seems Iron concentration is high during the wet season due to the presence of water. Therefore, a further adaptation step is needed to remove the iron from this layer. However, Mn^{2+} meets the expectation of the WHO limit during the wet season.

Changing land-use patterns, such as for paddy cultivation in Bangladesh, has a role in changing soil properties resulting availability of trace elements in groundwater [64]. During flooded irrigation for weeks, the redox potential of the topsoil may change from positive values to negative values of the order of −0.1 to −0.2 V [65]. The importance of redox potential may also rise from negative to positive (0.3–0.6 V) after water drainage and aeration, generally within a few days, which is usual for aerobic conditions. Reductive environments play an essential role in the mobility of metals [66]. In anoxic groundwater, Fe is a common element to occur. The weathering of minerals e.g., pyrite, biotite, amphiboles, and metamorphic carbonates in the Ganges-Brahmaputra-Meghna river system, enhanced the occurrence of Fe oxyhydroxide ($FeOOH_x$) and Mn oxide on the surfaces of sediment grains during transportation [67]. Additional Fe- and Mn- oxides are formed within unsaturated oxidized sediments. Partial reduction of $FeOOH_x$ and Mn oxides occurs in a reducing environment due to the isolation of this sediment from the atmosphere during the seasonal flood and extensive dry season irrigation [68–70]. Chemically reduced Fe and Mn that enter the solution may move downward with recharging water. The desorption of Fe by reducing $FeOOH_x$ is common with groundwater's high dissolved Fe contents in the Holocene aquifers in the country [21,37,71].

To classify major ions of groundwater and evaluate the hydrochemical processes between different water sources, the use of Piper diagrams is very significant [72]. Using the pattern on the piper plot (Figure 10a,b), the groundwater of the Paikgacha area is classified as the Na–Cl type in the dry season but turns to Ca^{2+}- Cl^- and Mixed Ca^{2+}-Mg^{2+}-HCO_3^- types in the wet season. $Na^+ > Ca^{2+} > Mg^{2+} > K^+$ and $Cl^- > HCO_3^- > SO_4^{2-}$ are the major ion trends of the Na–Cl type for almost all samples. In the Tala area, dry season groundwater is of Ca^{2+}- HCO_3^- and Mixed Ca^{2+}- types, and during the wet season, it turns to Ca^{2+}-Mg^{2+}-HCO_3^- and Ca^{2+}- Cl^- types. This type of water interacts with pit sediment, sand, and enriched carbonate layers. Both Ca^{2+}- HCO_3^- and Ca^{2+}- Na^+- HCO_3^- types of groundwater can be referred to as freshwater because freshwater originates from rainfall-derived recharge to the aquifer.



(**a**) (**b**)

Figure 10. Piper diagrams for (**a**) dry and (**b**) wet seasons.

4.4. Depth Distribution of Salinity

In many regions, the flushing of saltwater has developed freshwater pockets. At the shallow depths of the coastal aquifers, fresh groundwater (Cl < 300 mg/L; EC < 1000 µS/cm) is detected in areas of Satkhira, Narail, Jashore, Barishal and Patuakhali districts, while brackish water (Cl 300–600 mg/L; EC 1000–2000 µS/cm) occurs at Shariatpur, Chandpur and Gopalganj aquifers. Salinity (Cl > 600 mg/L) infiltrates the shallow aquifers of Chandpur, Shariatpur, Laksmipur, Feni, Noakhali, Cox's Bazar, Barishal, Barguna, Bhola, Jhalokathi and Pirojpur districts. Additionally, seasonal salinity inconsistency is observed, and dry season salinity is generally greater than wet season salinity in upper aquifers. In shallow groundwater, to depths of 100 m, the salinity is variable, overlain by shallow freshwater pockets recharged from recent precipitation, and rapidly changes over short distances. Pumping fresh water in the coastal aquifers can accelerate encroachment of saline water and deteriorate water quality both spatially and laterally. Therefore, a clear understanding of the groundwater system, characterization of aquifer sediments, safe yield of groundwater, hydro-geochemical processes of the coastal aquifer, and determining the impacts of climate change is essential. Generally, a deep aquifer (>250–300 m depth) stores fresh water in most areas, but the higher depth is not viable for low-income people to install household-level deep tubewells. Therefore, characterizing the potential of very shallow fresh groundwater is essential to ensure fresh and safe drinking water availability at the household level in the saline-prone and arsenic-affected coastal areas.

The Bengal delta's complex drainage and river network makes it unique among the more enormous deltas of the world. The entire delta is crisscrossed by numerous small and extensive channels, of which many are active, some are decaying, while many others are being drained by the tidal flow only. This drainage network also plays an integral part in saltwater encroachment both in groundwater and surface water environments. The southwestern part of the delta, comprising the Sundarbans, the largest mangrove forest in the world, is ultimately a maze of tidal channels and creeks. These surface water bodies carry a significant volume of water through distributaries, which connect these creeks and tidal channels. The continuous shifting of courses is another prominent characteristic of the delta-rivers. Rivers flow towards the south-east direction in a significant part of the western delta, while some eastern rivers flow towards the south-west. The Ganges-Padma main channel has long been hovering in the southeast direction. However, several significant streams also follow a straight channel that can be considered as channels controlled by tectonics. About 3 million cusecs of water flow through the delta during the summer monsoon, and it performs as a fluvial delta. In contrast, it behaves as a tide-dominated delta during the winter when water discharge through the delta reduces to 250,000 to 300,000 cusecs. These distinctive characteristics make this one the most complex delta in the world.

In the study areas of Tala and Paikgacha, very shallow groundwater samples (<8–10 m) have salinity values within the potable standard of 600 mg/L of Cl and 2000 μS/cm of EC (Figure 11a), both in wet and dry seasons. The arsenic level in this very shallow aquifer is within the WHO recommended limit of 10.0 μg/L for potable water (Figure 11b). Deeper samples (below 10–14 m depth) show higher salinity and arsenic values.

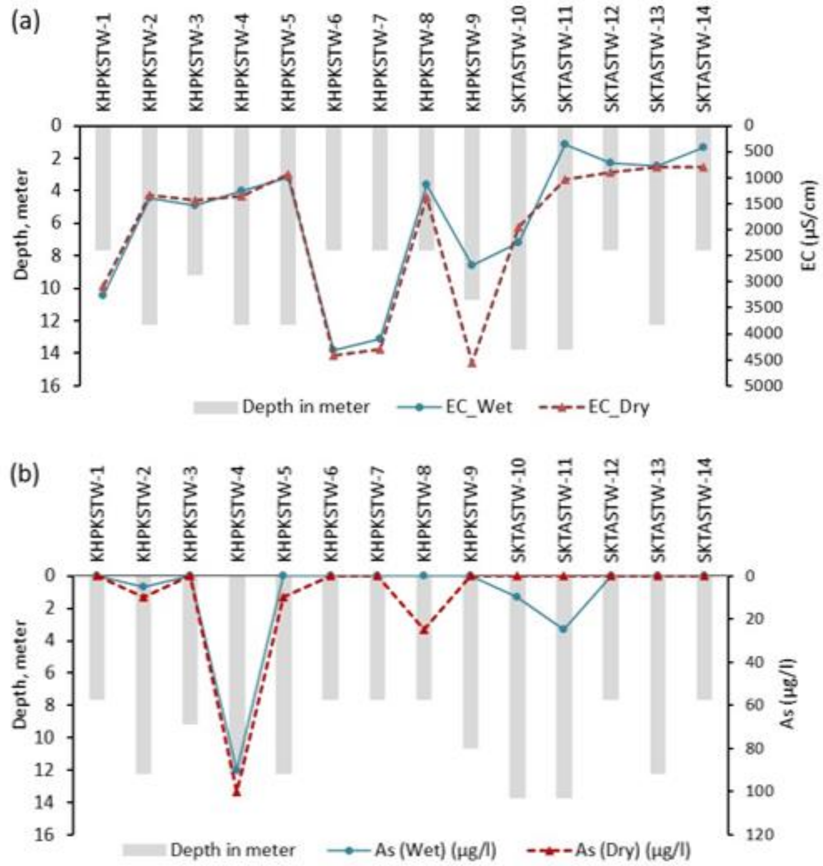


Figure 11. Depth distribution of (**a**) salinity and (**b**) arsenic at Paikgacha and Tala Upazila in the coastal belt. Except for four samples, the rest of the samples from the wet season are under the tolerable limit of As, that is 50 μg/L. Only one place in Khulna showed a higher concentration of arsenic during the wet season; the rest of the samples showed a lower concentration of arsenic in this shallow aquifer layer.

Generally, in the aquifer where clay aquitard above pumping aquifers is absent or leaky, vulnerability to vertical infiltration of saline water due to periodic storm surge flooding is remarkable [73]. Due to sea-level rise, susceptibility to lateral saltwater migration is influenced by the hydraulic properties of aquifer sediments. The more permeable section of the aquifer is generally more vulnerable than the low permeable portion, but the process of salinity intrusion is prolonged. Where groundwater abstraction occurs from freshwater pockets bounded by saline water, pumping-induced threats of mixing preexisting fresh and saline groundwater or increasing saline water mobility rates may be ubiquitous. The lower topographic relief (central delta) aquifers have a higher vulnerability to all three intrusion pathways than higher-relief (eastern delta) aquifers.

As the sea level rises near coastal areas, the associated impacts of regular inundation are likely to enhance the salinity. A direct effect of SLR would be salinity encroachment through the rivers and estuaries. It would be more severe in the dry season, mainly when freshwater moves from rivers diminish.

4.5. Seasonal Fluctuation of Water Table and Salinity

Both depths to groundwater table and groundwater salinity have a seasonal fluctuation, with a maximum during the dry season and a decreasing trend in the wet season during monsoon (Figure 12). It usually reflects that the groundwater table rises during the rainy season due to direct rainfall recharge and falls in the dry season. For example, at Paikgacha, the water table fluctuates about 1.0 to 1.5 m seasonally. At Tala Upazila, this fluctuation is about 2 m. Similarly, recent recharge during monsoon reduces salinity concentration that increases in the dry season. The seasonal differences in EC values are about 100 µS/cm to 200 µS/cm. EC values are about 100 µS/cm to 200 µS/cm.

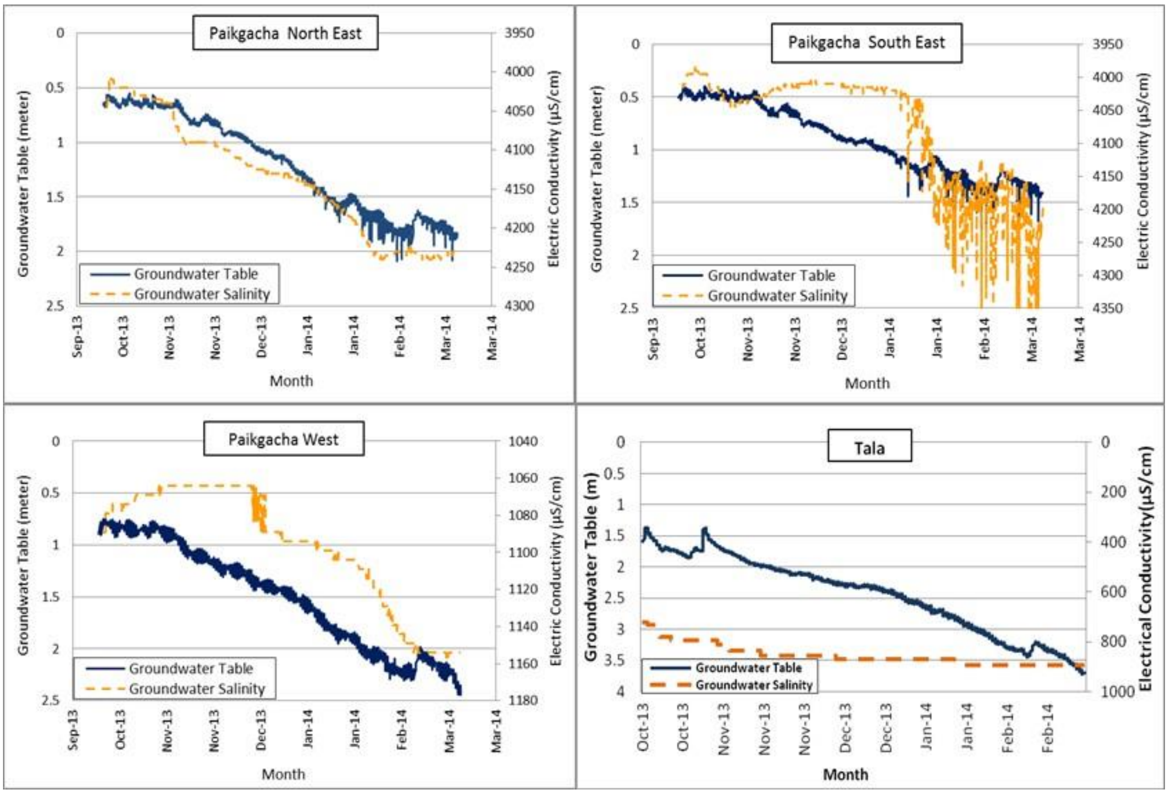


Figure 12. Seasonal trend of groundwater table and salinity in Paikgacha and Tala Upazila.

5. Recommended Solutions

Managed aquifer recharge (MAR) could be a long-term solution for mitigating or minimizing freshwater or safe drinking water scarcity. Alternatively, government or non-profit organizations can take the initiative to install tubewells in the shallow aquifer zone to provide safe drinking water for the entire community in exchange for payment.

5.1. Managed Aquifer Recharge (MAR)

Managed Aquifer Recharge (MAR) is a valuable groundwater management tool for stressed aquifers such as depleting water tables, encroachment of saline water, or land subsidence due to declining water levels [74,75]. In the study area, where very shallow groundwater is slightly saline, artificial recharge by rainwater harvesting can reduce the salt content and turn it into potable water. Furthermore, techniques of both direct recharge, i.e., by direct vertical infiltration through the unsaturated vadose zone, and indirect recharge, i.e., percolation through the beds of surface-water bodies to the water table [76], can be applied to reduce salt content by adding additional water storage in coastal aquifers. Considering this, the design of MAR, i.e., Recharge Tank and Recharge Pond, is proposed for the salinity and arsenic affected study area to enhance the freshwater discharge of very shallow wells (up to 5–8 m) (Figure 13a,b).

Time-variant meteorological events (e.g., precipitation and evapotranspiration) affect the various processes of groundwater recharge. Recharge is also influenced by other climate and surface and sub-surface conditions, including changing land-use and aquifer characteristics [77]. For example, increasing shrimp cultivation using saline and brackish water on the land surface in coastal landform can limit the availability of very shallow freshwater by introducing higher salt contents. Therefore, field investigations are required to assess the potential of area-specific recharge technologies by monitoring recharge processes. Specifically, a remarkably thick clay layer, i.e., aquitard, is encountered in the sub-surface (at least 3–5 m thick), which is less vulnerable to surface contamination. Recharge technologies such as Recharge Tank and Recharge Pond can be constructed by removing this surface clay and filling it with sand for additional water storage in the shallow aquifer.

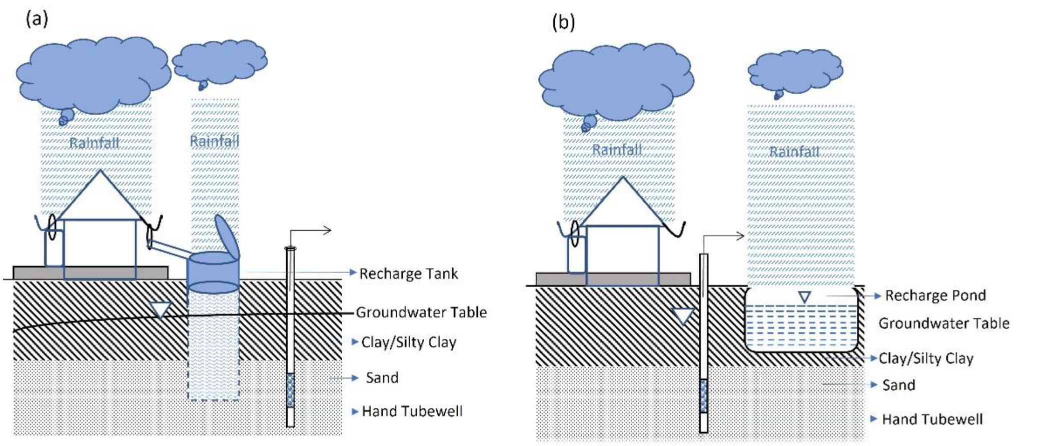


Figure 13. Diagrams of (**a**) Recharge Tank and (**b**) Recharge Pond to augment the freshwater discharge of very shallow wells (up to 5–8 m) for the salinity and arsenic-contaminated coastal areas of Bangladesh.

The Water Table Fluctuation (WTF) method can be applied to quantify the recharge and availability of freshwater storage. The technique is best suited for shallow water tables because of capturing sharp water-level fluctuations with high accuracy [78]. Recharge is calculated as [79,80]:

$$R = S_y \frac{dh}{dt}$$

where S_y is specific yield, t is time, and h is the height of the water table. All other factors, such as changes in subsurface storage, and evaporation are zero during recharge. Recharge for Paikgacha and Tala areas are computed at 60 mm and 100 mm, respectively, by considering seasonal groundwater table fluctuation of 1.5 and 2.0 m, respectively. Considering the average distance between two adjacent household tubewells as 50 m, available water for a very shallow hand tubewell may be estimated to be 150–250 m^3/year. This volume of water can be increased, and salinity concentration level can be reduced by providing artificial recharge technologies such as Recharge Tank and Recharge Pond. The average hydraulic conductivity of very shallow aquifer sediment (8–10 m depth) is measured as 9.45 and 5.45 m/day for Paikgacha and Tala areas, respectively, by conducting slug tests from the installed observation wells. Considering the thickness of the upper shallow aquifer at Paikgacha and Tala as 130 and 80 m, the transmissivity can be estimated as 1280 and 436 m^2/day, which is great potential for groundwater abstraction.

5.2. Willingness to Pay for Fresh and Safe Drinking Water

Even though the high percentage of the local people is ultra-poor and poor, they are still willing to pay for fresh and safe drinking water. So, government or non-profit organizations can take an enormous step to install the shallow aquifer tubewell to secure safe and fresh potable water for the community. And Government or non-profit organizations can take a minimum amount of payment from the local people based on their income. Moreover, few people can earn money providing their service for installation and monitoring activities through these initiatives. Most households are interested in ensuring access to sources of improved potable water. However, about 84% of households reported that they wanted new drinking water supply technology to ensure access to safe and fresh drinking water.

6. Conclusions

This study investigates the sustainable drinking water source for the arsenic and saline-prone coastal aquifers of the Bengal Delta. Groundwater abstraction from upper freshwater pockets and deep aquifers in the coastal areas can be done by manually operating small diameter (38–50 mm) tubewells. After doing all analyses for both seasons, it may be concluded that the very shallow groundwater (5–8 m) that is mainly recharged by direct rainfall is suitable for drinking purposes. This layer should be preserved only for drinking and cooking purposes. For other uses, water should be used from surface water bodies, precipitation during monsoon, and groundwater below this very shallow aquifer. In that case, the low-income population on the coast can get drinking water over the year, both in wet and dry seasons.

The study also recommends probable solutions to solve the problem of freshwater scarcity in the study area. To build a resilient community, both traditional and indigenous practices and scientific and technical knowledge must be considered simultaneously. In the study area, the salinity of selected samples was under the allowable limit (<2000 μS/cm), and the targeted aquifer was almost arsenic (50 μg/L) free. Moreover, the extensive range of total dissolved ions significantly varied over the study area for wet and dry seasons (e.g., Cl^-: 15.0 mg/L to 830 mg/L and 34.0 mg/L to 867 mg/L for wet and dry seasons, respectively). In addition, the average concentrations of Cl^- are 250.85 mg/L and 402.31 mg/L for wet and dry seasons, respectively. Cl^- concentration exceeds a brackish water level of 600 mg/L for the few samples. Therefore, additional recharge by artificial recharge mechanisms can dilute the concentration of Cl^- to some extent. The design of affordable recharge technologies such as the Recharge Tank and Pond is suggested to augment artificial recharge of rainwater to groundwater table to increase the freshwater availability of very shallow tubewells (up to 6–8 m). Groundwater in the upper shallow aquifer is less vulnerable to surface contamination when a remarkably thick clay layer overlays it (at least 3–5 m), i.e., aquitard, on the surface. Further investigation and comprehensive study are necessary to quantify the additional seasonal recharge by these artificial recharge technologies. In all cases, concern and maintenance must be taken to avoid threats of surface contamination, including salinity sourced from storm surges.

Author Contributions: For this research, K.J. and A.Z. developed and designed the research framework. K.J., carried out the analysis of results, and wrote the original paper. K.J. and A.Z. contributed to the interpretation of results, resources, supervision, project administration. M.A.E.B. involved with writing, review & editing and contributed to the development of the paper. I.A. project administration and funding acquisition. All authors have read and agreed to the published version of the manuscript.

Funding: The research was funded by DFID under Action Re-search for Community Adaptation in Bangladesh (ARCAB) project.

Institutional Review Board Statement: Not applicable.

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

Data Availability Statement: Not applicable.

Acknowledgments: The authors are grateful to DFID for sponsoring the study under Action Research for Community Adaptation in Bangladesh (ARCAB) project. Saleemul Huq, International Center for Climate Change and Development (ICCCAD), and Sumana Tanchangya, ARCAB, are acknowledged for their cooperation. In addition, M. Aminur Rahman and M. Rashidul Hassan are recognized for their valuable support during field and laboratory activities.

Conflicts of Interest: The authors declare no conflict of interest.

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