Chapter 7

Sustainable Groundwater Management in Context of Climate Change in Northwest Bangladesh

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Additional information is available at the end of the chapter

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Abstract

The objectives of the study are to understand the variability and changes in hydro-climatic variables in space and time dimensions, and to evaluate the performance of managed aquifer recharge (MAR) for sustainable water resources management in northwest Bangladesh. The study reveals that groundwater resource in the northwest Bangladesh is under stress. The stress has developed and it increases over the years, as a result, shallow groundwater resource has already become scarce. The people of the area are not getting even drinking water using their hand tube wells (HTWs) during the dry season and facing trouble with irrigation water. These problems are becoming acute as a result of uncontrolled and unplanned groundwater abstraction for irrigation. Moreover, rainfall in the study area decreases and dryness increases. Higher values of the seasonality index ($\overline{SI} = 0.87$) and precipitation concentration index (PCI = 19.8) are indicators of frequent dry spells. The area suffered from 12 moderate-extreme droughts during 1971–2011, and moderate to high drought risk (B) prevails in the area. The frequent drought, decreasing trend in rainfall, transboundary river flow, and thick clay surface lithology along with the uncontrolled irrigation are also responsible for rapid depletion of groundwater. As the annual surplus of water (average = 594 mm) is higher than groundwater recharge (330 mm), an experimental study on managed aquifer recharge (MAR) has been conducted to enhance the groundwater recharge. It shows good performance for restoring the groundwater without creating any sorts of hazards. Moreover, almost 5% of irrigated land can be irrigated from surface water sources by re-excavating the rivers, *Kharis* (small channels). It is necessary to prepare an integrated water resource management plan (IWRMP) considering the impacts of climate change, drought risk, driving factors of the groundwater resource depletion, and rainwater as a resource for achieving the sustainability.

Keywords: climate change, drought prone area, managed aquifer recharge, sustainable groundwater management

1. Introduction

Water is a vital natural resource and is a key requisite for sustainable development. Groundwater depletion has been recognized as a global problem. The estimated global groundwater depletion during 1900–2008 is about 4500 km^3, and rapid depletion of groundwater has occurred during 2000–2008 [1]. Groundwater withdrawal for irrigation has intensified around the world over the past few decades. This withdrawal has largely occurred without hydrological planning, as a result, a high groundwater depletion has occurred. Therefore, the sustainable management approach has attracted attention to the hydrological community and some concepts have developed. However, Unver [2] pointed out that sustainable development is a concept still in the making as most of the traditional concepts fail to ensure the use of water resources in a sustainable manner. The groundwater footprint concept focuses on groundwater recharge as an index of sustainability [3]. Groundwater recharge rates alone cannot serve to address the core policy question regarding the sustainable aquifer conditions [4]. Studies [4, 5] stated that groundwater management plans based on traditional concepts like safe yield, assured water supply, and groundwater footprints are not clear indicators of groundwater sustainability mainly due to ignoring the impact of climate change and drought. However, water resource is at the core of sustainable development recognized in the Rio World Summit in 1992. United Nation (UN) Sustainable Development Goals Report [6] has emphasized on sustainable management of water resources (Goal-6) and combating climate change impact (Goal-13). Hence, the present study has given the main attention to the sustainability of groundwater resource by integrating drought characteristics, and climate change effects and status of the groundwater resource. Our previous studies [7–9] investigated the groundwater level scenario, drought characteristics, and dynamics of drought in the northwest Bangladesh. However, the impact of climate change on rainfall pattern which is the main source of groundwater recharge and potentiality of surface water resource have not been investigated comprehensively yet. In the present study, rainfall climatology, reanalysis of long-term groundwater level data (1971–2011), driving forces of groundwater depletion, groundwater recharge, and potentiality of surface water resource have been investigated comprehensively. Beside these, an experimental study on managed aquifer recharge (MAR) has been conducted and performance of MAR has been assessed. Therefore, it is expected that the study will contribute to the development of the concepts of sustainable water resources management and understand the phenomena groundwater sustainability in the context of climate change in drought prone areas.

2. Study area

The study area includes Chapai Nawabganj, Naogaon, and Rajshahi districts and covers 25 Upazilas (sub-district) in the northwest Bangladesh (**Figure 1**). The area is popularly known as Barind area and the area covers approximately 7545.25 km^2. Geographically, the area extends from 24^{o}08′ to 25^{o}13′N latitudes and from 88^{o}01′ to 89^{o}10′E longitudes. The map of the study area, including the locations of rain gauge stations, meteorological stations, groundwater observation wells, vertical electrical sounding (VES) stations, and managed aquifer recharge

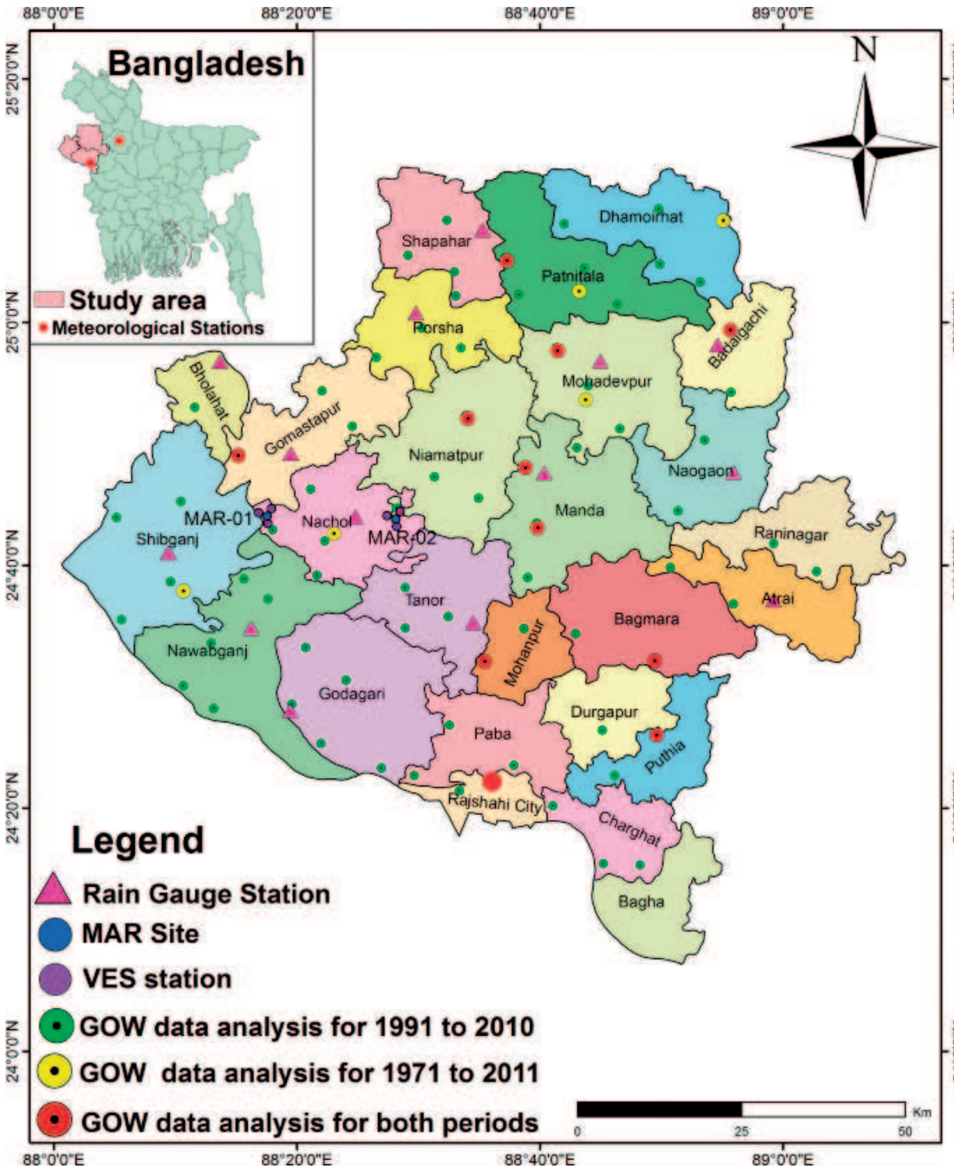

Figure 1. Study area with locations of meteorological, rain gauge, and VES stations, groundwater observation wells (GOW) and MAR sites.

(MAR) sites, is shown in **Figure 1**. Groundwater is the main source of irrigation in the agro-based northwest Bangladesh and Barind Multipurpose Development Authority (BMDA) is responsible for irrigation water management. Groundwater resource exploration is ongoing on the basis of one-third rainfall recharge hypothesis of BMDA that is beyond the sustainable yield [10]. About 75% of the land in the study area is used for agricultural practices. High yield variety (HYV) *Boro* rice, which cultivates during the dry season completely depends on groundwater irrigation, shares almost 81.2% of the total cultivable area.

2.1. Geology and hydrogeology

The physiographic features of the area are mainly two types. These are (1) Floodplains which include Tista, Lower Purnabhaba, Mahananda and Ganges flood plains; and (2) Barind Tract

(BT). There exists a significant lithological variation in the BT and the adjacent floodplain areas. BT is comprised of thick clay surface lithology which is underlined by thick coarser sediments of Early Pleistocene to Late Paleocene. The materials are dense and compact, and the hydraulic conductivity of the surface clay layer is low [11]. Two different aquifer units have been identified based on hydro-stratigraphic data in the area [11]. The upper-shallow aquifer exists just beneath thick surface silty clay layer. The thickness of this aquifer ranges from 10 to 35 m and it consists of very fine-to-fine sand with lenses of fine to medium sand and occasionally clay, silt, and trace mica lenses. Below the upper-shallow aquifer, there is a lower-shallow aquifer. The thickness of this unit ranges from 20 to 70 m, and it is composed of medium to coarse grain sand with occasional fine sediment lenses.

3. Data and methods

3.1. Data

There are 18 rain gauge stations, including one meteorological station in Rajshahi in the study area. However, 15 stations have long-term (1971–2011) good records (**Figure 1**). Rahman et al. [8] collected rainfall data from the Bangladesh Water Development Board (BWDB) and meteorological data from the Bangladesh Meteorological Department (BMD). The study prepared a complete rainfall dataset by estimating missing values by Multiple Imputations Method. Moreover, data of Bogra meteorological station have also been analyzed as it is located very close to the study area. Details regarding the rainfall data can be found in Rahman et al. [8]. There are about 150 groundwater monitoring wells in the study area. However, only 15 wells have long-term (1971–2011) good records and 73 monitoring stations have good records for the period of 1991–2011 (**Figure 1**). These data have also been collected from the BWDB. Details of groundwater level monitoring data can be found in Rahman et al. [7, 9].

3.2. Methods

Rainfall climatological characteristics, such as rainfall seasonality index, (SI) has been calculated by Walsh and Lawer [12] formula. Time series of seasonality index ($\overline{SI}_k$) and precipitation concentration index (PCI) have been estimated by Pryor and Schoof [13] and Oliver [14] formulas, respectively.

3.2.1. Trend analysis

In the present study, trends have been detected by non-parametric Mann–Kendall [15, 16] (MK) test. MK test shows a good performance for identifying trends in hydrological variable [7–9]. If there is a significant serial correlation at lag-1 in the climatic data, MK test cannot calculate the exact value of test statistic [17]. In the study, lag-1 serial correlation has been evaluated before analyzing the trends. If there is a significant serial correlation at lag-1, the trend free pre-whitening method [17] has been applied to eliminate the influence of serial correlation before estimating the test statistic (Z). Moreover, the sequential values of the MK test have been used [18] to find out the change point. The rate of change has been calculated by Sen's slope estimator [19]. The details of the methods can be found in [7–9, 15–19].

3.2.2. Drought risk ranking

Our previous study characterized the drought in the study area [8] using the standardized precipitation index (SPI) [20]. Drought risk ranking is necessary to prepare the viable adaptation measures of an area. This study has ranked the risk of drought using the drought risk ranking diagram [21] to know the risk condition of the area.

3.2.3. Groundwater recharge and abstraction

The groundwater budget of an area can be written as [22]:

$$R = \Delta S^{gw} + Q^{bf} + ET^{gw} + \left(Q^{gw}_{out} - Q^{gw}_{in}\right) \tag{1}$$

Here, R = recharge; ΔS^{gw} = change in groundwater storage; Q^{bf} = baseflow to river channel; ET^{gw} = evapotranspiration from groundwater, and $Q^{gw}_{out} - Q^{gw}_{in}$ = net subsurface flow from the area. The Q^{bf} and ET^{gw} are negligible for Bangladesh as river stage during the monsoon is higher than the groundwater level and land cover dominated by the shallow rooting depth crops [23]. Moreover, groundwater flow $(Q^{gw}_{out} - Q^{gw}_{in})$ is also negligible due to the absence of substantial hydraulic gradients in water level in shallow aquifer during monsoon [24]. Shamsudduha et al. [23] simplified Eq. (1) and calculated groundwater recharge (R) as:

$$R = \Delta S^{gw} = S_y \frac{\partial h}{\partial t} = S_y \frac{\Delta h}{\Delta t} \tag{2}$$

where, S_y is the specific yield, Δh is the water-level height between annual maxima and minima, and Δt is time period (a year). Eq. (2) is similar to water table fluctuation (WTF) method and recharge is referred as "net" recharge [25]. In WTF method, Δh is the difference between the peak water level and the theoretical lowest level [25]. However, Shamsudduha et al. [23] calculated Δh as an annual range between the annual maxima and minima from weekly measured data. Groundwater recharge calculation using Eq. (2) did not provide good results for recent periods (1985–2007 and 2002–2007) for some particular areas (Dhaka City and BT) as the seasonality in groundwater fluctuation suppressed by the long-term trend associated with intensive abstraction [23]. For these areas in Bangladesh, net groundwater recharge was calculated [23] as:

$$R = \Delta S^{gw} + Q^{P} \tag{3}$$

where Q^P is the annual groundwater abstraction. In the study, groundwater recharge has been calculated by Eq. (3) for the BT. However, Q^P is the groundwater abstraction for supplementary irrigation during the rainy season as a huge amount of groundwater withdrawn during the dry season for *Boro* rice cultivation about 1 m per square meter in Bangladesh [24, 26]. Therefore, adding the annual groundwater abstraction misleading the net recharge calculation.

The groundwater abstraction for irrigation in Bangladesh estimated from the irrigated proportion of the surface area and the amount of water applied to an irrigated field during the growing season [24, 26]. The time series data of the total irrigated area of the greater Rajshahi district, which includes the study area and Natore district, have been collected from the book published by Bangladesh Bureau of Statistics (BBS) for the period of 1993–2010. The groundwater abstraction has been calculated as the irrigated area is multiplied by an estimated 1.0 m [24] of abstraction per pumping season per square meter of irrigated area.

3.2.4. Vertical electric soundings (VES)

Vertical electric soundings (VES) survey following the Schlumberger electrode configuration using a direct current resistivity meter has been carried out in six areas in Nachole Upazila (**Figure 1**) in Chapai Nawabganj district. The VES data has been analyzed using resistivity meter compatible software IGIS 2.0 which follows the inverse slope method for analyzing the resistivity data. Inversion is a mathematical iterative process and study [27] showed that the inverse method is quite a powerful scheme to interpret the resistivity data. Two bore holes have also been done and bore logs data have been used for validation of the lithology interpreted from resistivity data. These bore holes later have been used as MAR wells (**Figure 1**).

4. Results and discussion

4.1. Rainfall climatology

4.1.1. Exploratory statistics

The annual average rainfall in the area during the period 1971–2011 varies from 1326 to 1650 mm with an average of 1505 mm, which is about 39% less than the national average of Bangladesh (2456 mm) [28]. There is a sharp gradient in an increase in rainfall from southwest to northeast (**Figure 2a**). The winter season is very dry and only 2.5% of annual rainfall occurs during this season. After the winter, rainfall starts to increase due to thunderstorms or nor'wester during summer season. During summer, rainfall varies from 192 to 282 mm with an average of 220 mm which is 14.6% of annual rainfall. The rainfall during rainy season varies from 1001 in the southwest to 1370 mm in the northeast. Almost 83% of annual rainfall occurs during this season due to the tropical depressions which enter the country from the Bay of Bengal [29].

4.1.2. Trends in rainfall

4.1.2.1. Annual rainfall

The annual rainfall of the study area during the period of 1971–2011 shows an insignificant decreasing trend ($Z = -0.75$) at a rate of −2.76 mm/year. Trend analysis results of 15 stations indicate both decreasing (53.3%) and increasing (43.7%) trends. However, most of the trends (about 80%) are statistically insignificant. Two significant decreasing trends at 90 and 95%

confidence levels are found in Rajshahi (−8.02 mm/year) and Mohadevpur (−10.82 mm/year) stations, respectively. On the other hand, a significant increasing (+11.17 mm/year) trend is found in Nawabganj at 99% confidence level. The plots of sequential MK test statistics of u(d) and u′(d) (**Figure 3a–c**) indicate downward trends started in 1981 and 1988 in Rajshahi and Mohadevpur, respectively, and significant upward trend in Nawabganj starts in 1991. The spatial distribution of the Z statistic reveals that the declining trend mostly occurred in the eastern part of the area (**Figure 2b**) and magnitude (slope Q) varies from −0.25 to −10.82 mm/year (**Figure 2c**). Significant negative trends are detected in the northeast and southeast. However, the majority of the stations located in the BT shows insignificant positive trends. The projected rainfall of Bangladesh at different emission scenarios shows an increase in rainfall, but the study found decreasing rainfall in Rajshahi [21].

4.1.2.2. Seasonal rainfall

Trend analysis of seasonal rainfall shows a declining trend in rainfall for all seasons. The estimated Z statistics are −0.94, −0.12, and −2.13 for winter, summer, and rainy seasons, respectively. The declining trend in rainy season rainfall in the area is significant at 95% confidence

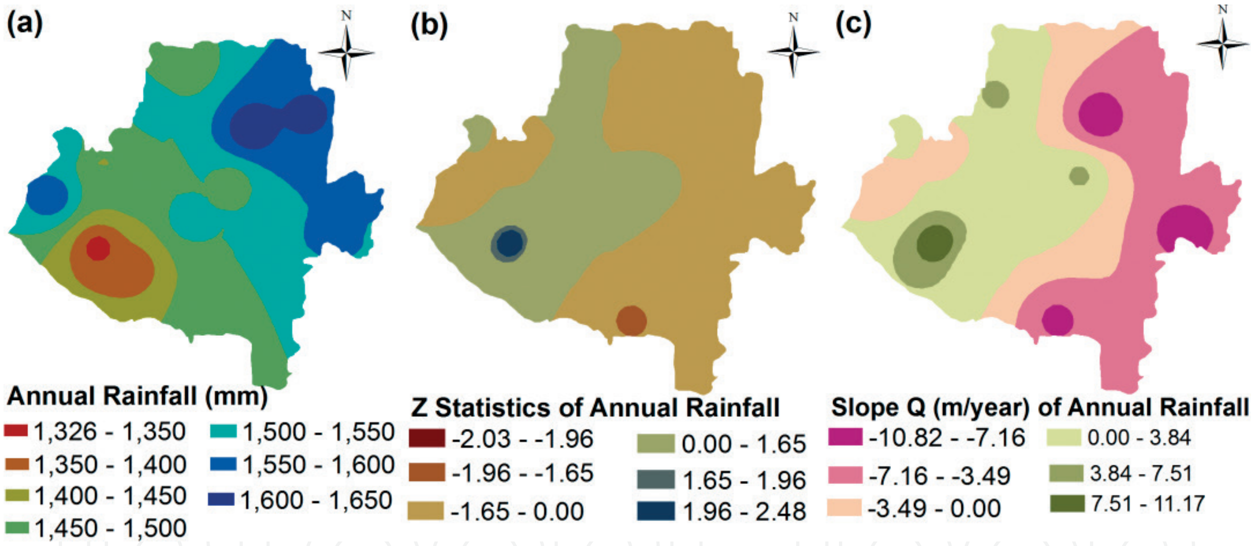

Figure 2. Distribution of (a) annual rainfall, (b) Z statistic of annual rainfall, and (c) Sen's slope (*Q*) of annual rainfall.

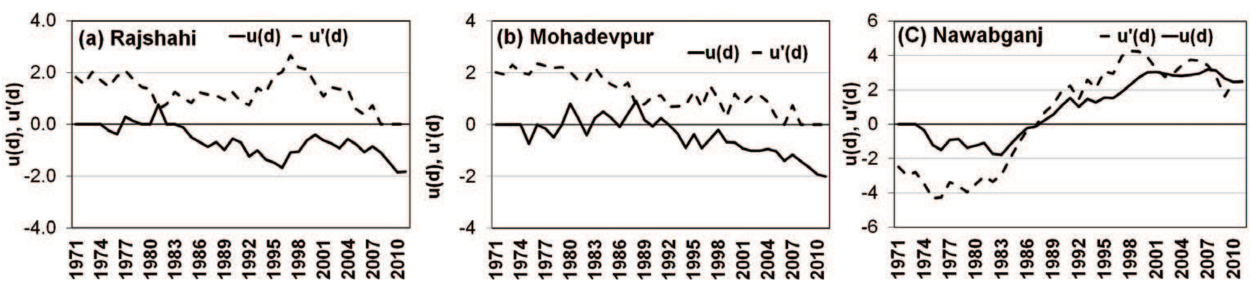

Figure 3. Sequential MK statistic u(d) and u′(d) of annual rainfall (a) Rajshahi, (b) Mohadevpur, and (c) Chapai Nawabganj.

interval. Station wise analysis reveals that most of the trends are insignificant decreasing and accounting for 73.3, 46.67, and 67% of the stations for winter, summer, and rainy season, respectively. The entire study area except the southwestern corner shows a declining trend in winter season rainfall (**Figure 4a** and **b**). In the summer season, insignificant negative trends are found in the eastern part of the area, however, insignificant positive trends are found in the western part (**Figure 4c** and **d**). Insignificant decreasing trends in rainy season rainfall are found in the eastern part, but insignificant rising trends are found in the BT (**Figure 4e**). The slopes of summer and winter seasons are very low (**Figure 4b** and **d**). Rainfall in the BT increases over the years at a rate of less than 3 mm/year (**Figure 4f**) during the rainy season.

4.1.2.3. Monthly rainfall

Monthly rainfall time series indicates the magnitude of change is close to zero for the months of Nov–Feb. All stations, except Sapahar, show increasing trends in rainfall for the month

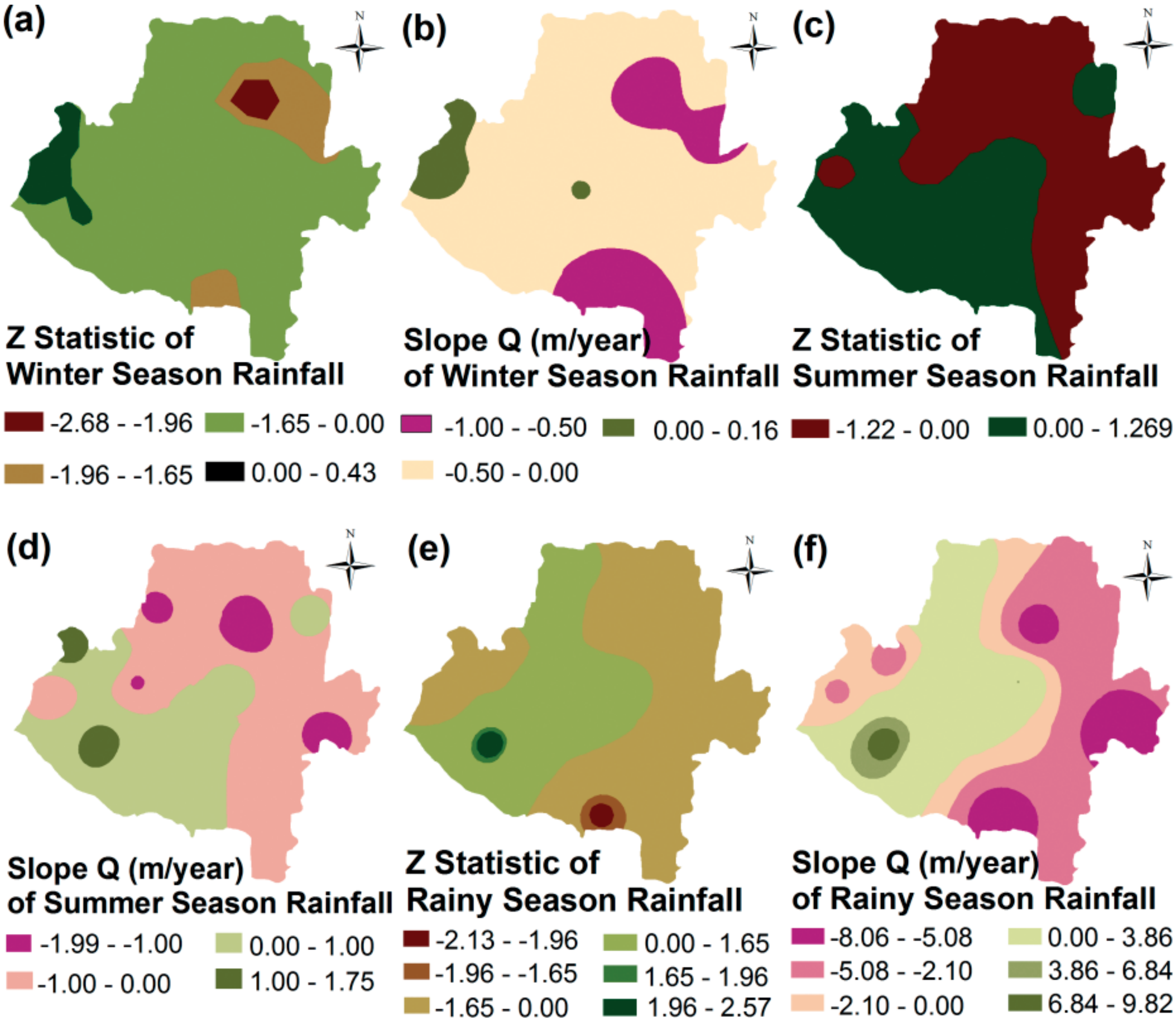

Figure 4. Distribution of Z statistic and slope (*Q*, mm/year) of seasonal rainfall.

of March and Nachole shows a significant increasing trend. There are no significant trends in rainfall for the months of April and May. Insignificant increasing trends except Atrai are found in rainfall in June. However, the decreasing trends except Nawabganj are found in July rainfall and significant trends found in Rohonpur, Badalgachi, Mohadevpur, and Sapahar. The magnitudes of changes of the significant trends range from −3.90 mm/year in Badalgachi to −5.76 mm/year in Sapahar. Insignificant decreasing trends are found in rainfall of 11 stations in August and September. The decreasing trends also dominate over the area in October rainfall. The overall findings show rainfall in the middle of the monsoon decreases.

4.1.3. Seasonality index (SI) and precipitation concentration index

SI value in the study area varies from 0.84 to 0.89 (**Figure 5a**) with an average of 0.87, which indicates rainfall is markedly seasonal with a long dry season. The Z statistic of seasonality index (SIk) time series (**Figure 5b**) indicates an insignificant trend dominated over the area. The PCI calculated on an annual scale varies from 18.26 in Rajshahi to 20.42 in Bholahat with an average of 19.84 (**Figure 5c**). In general, lower values are found in the BT, whereas higher

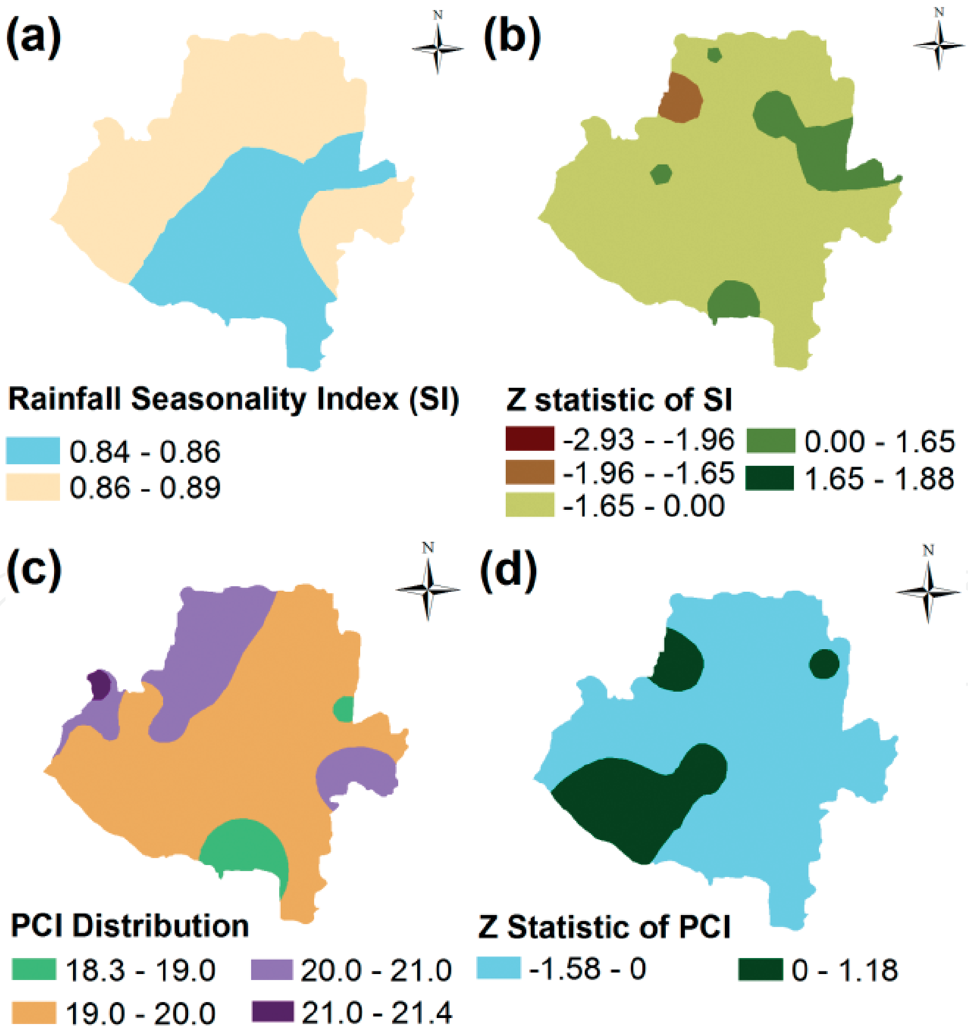

Figure 5. Distribution of (a) rainfall seasonality index (SI), (b) Z statistic of SI, (c) PCI, and (d) Z statistic of PCI.

values are found in the northwestern part (**Figure 5c**). The PCI value indicates irregular to strong irregular distribution of rainfall over the area. High PCI value also indicates a higher percentage of annual total rainfall occurs within a few rainy days, as a result, the area suffers from frequent drought. The distribution of the Z statistic (−1.58 to 1.18) of the MK test of PCI indicates an insignificant negative trend dominates over the study area (**Figure 5d**).

4.1.4. Drought characteristics

The details of drought characteristics of the area have been discussed in Rahman et al. [8]. The area suffered from 12 moderate to extreme droughts during the period of 1971–2011. Almost 75% of drought events in the area associated with El Niño. Southern and central parts of the area frequently suffer from severe to extreme hydrological droughts, whereas the northern part suffers from agricultural drought. The trend analysis of the SPI indicates dryness in the area increases [8]. The drought risk ranking diagram has been prepared to know the risk condition of the area. In the risk ranking diagram, the frequency has been plotted on the vertical axis and classified into four classes as high (one event in 3 years); moderate (one in 3–5 years); low (one in 5–10 years); and very low (one after 10 years) [21]. SPI drought classification [20] has been used to classify the drought and plotted on the horizontal axis. Risk is classified as A (high), B (moderate to high), C (sufficiently high), and D (low) [21]. Agricultural, meteorological, and hydrological drought risks conditions of the area have been presented in **Figure 6**. The severity of mild drought is the lowest among the four categories, but frequency is high. Hence, risk associated with mild drought is sufficiently high (Class C). The risk associated with moderate agricultural and meteorological droughts is low (Class D), however, it is sufficiently high (Class C) for hydrological drought. The drought risk condition is moderate to high (Class B) for severe drought in the study area. It is also moderate to high (Class B) for extreme hydrological and agricultural droughts. The rain feed *Aman* paddy cultivates over the area; the frequent mild and moderate droughts cause damage to the crop production. Severe drought can cause more than 40% damage to rice production [21]. Our field study reveals that during the last drought period (2008–2010), farmers of the area frequently irrigated the paddy field to minimize the loss of rice production as a result rapid depletion of groundwater occurred.

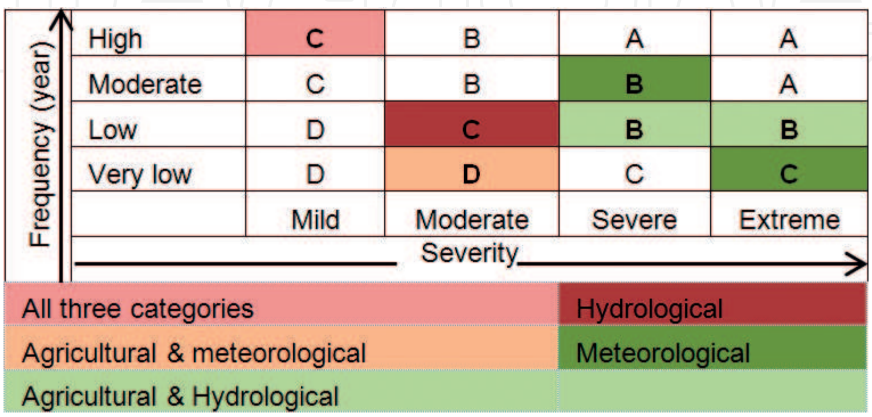

Figure 6. Drought risk ranking based on frequency and severity.

4.1.5. Water balance

PET has been calculated by Penman-Monteith equation [30]. The concept of water balance in the unsaturated zone [31] has been applied to calculate actual evapotranspiration (AET), annual deficit and annual surplus of water. This combination produced better results for the water balance study of Bangladesh [32]. PET has been calculated for two meteorological stations like Rajshahi (1378 mm) and Bogra (1327 mm). The AET varies from 875 to 955 mm with an average of 914 mm which is about 62% of annual rainfall. Annual surplus amount of water varies from 448 to 759 mm (**Figure 7a**) with an average of 594 mm (39% of annual rainfall). Soil moisture deficit in the area varies from 375 to 503 mm (**Figure 7b**) and higher values are found in the BT. The monthly water balance study reveals that water deficit starts in December and continues until May in the western part, while it starts in December and continues until April in the eastern part of the area.

4.2. Groundwater scenario

4.2.1. Trends in groundwater depth

Our previous studies [7, 9] evaluated the spatio-temporal scenario of groundwater level of the study area. To confirm about the trends obtained in the most recent (1991–2010) groundwater level, we have reanalyzed the long-term (1971–2011) data. The plots of long-term average groundwater level data of the study area, linear trend, and Sen's Slope have been shown in **Figure 8**. Similar to the results of recent period data [7, 9], statistically significant increasing trends have been found in 86.67% dry season long-term groundwater depths time series data. Moreover, trend analysis of wet season groundwater depth also shows almost similar result. Significant increasing trends in groundwater depth with high magnitude of changes are found in the BT. The

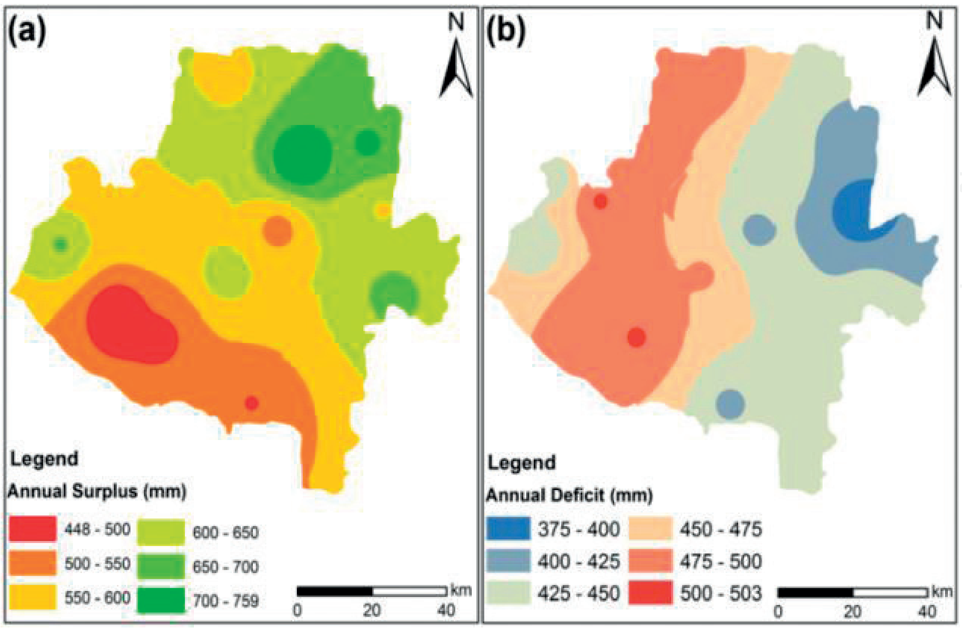

Figure 7. Annual surplus and deficit of water found from the water balance study over the study area.

increasing depth of groundwater during the wet season indicates that groundwater withdrawal of the area is unsustainable, and aquifers of the area are not fully recharging during the wet season. During the period of 1991–2010, on an average 9–14 m groundwater level depletion occurred in the area. People are not getting drinking water during the dry season using HTWs as the water runs far below the suction mode of the pump [7]. Farmers of the area have also mentioned that they are not getting water with a full swing from DTWs during the dry season.

4.2.2. Groundwater recharge

To calculate groundwater recharge of the study area, groundwater level data of 73 (**Figure 1**) monitoring wells for the period of 1991–2010 have been used. The average net groundwater recharge in the area varies from 153 mm in Patnitala to 580 mm in Godagari with an average of 325 mm. The previous study [33] showed that groundwater recharge ranges from 109 to 572 mm (**Figure 9**) with an average of 330 mm. There is no notable difference between the estimated average net groundwater recharge and previously estimated groundwater recharge [33]. However, there are notable variations in some Upazilas. Groundwater recharge in some Upazilas in the study area has been increased in comparison to the previous study.

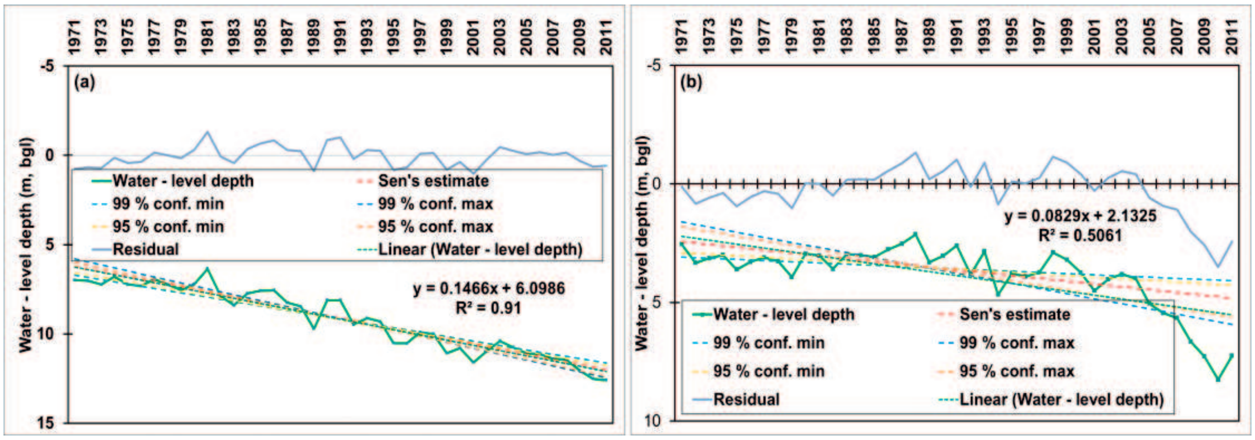

Figure 8. Linear trend in groundwater depth in the study area and Sen's slope at different confidence levels (a) dry season and (b) wet season.

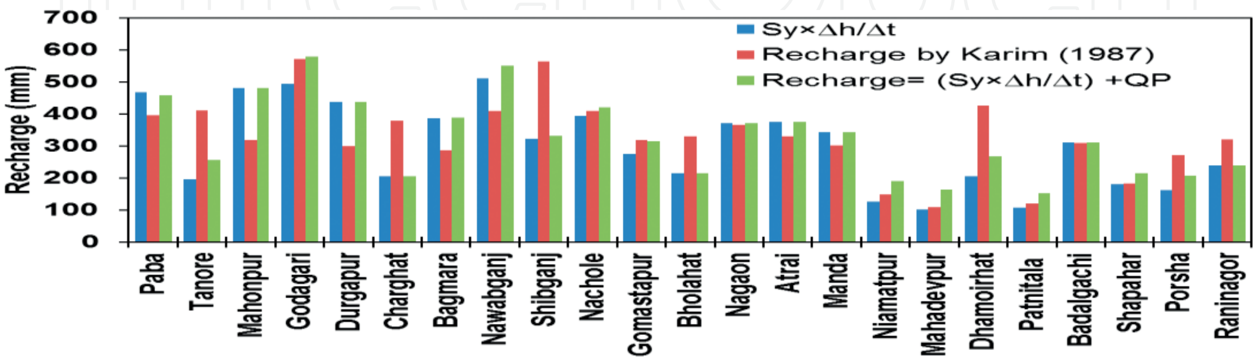

Figure 9. Upazila wise calculated values of $S_y \times \Delta h/\Delta t$ (mm), groundwater recharge (mm) calculated by Karim [33], values of groundwater recharge (mm) considering groundwater abstraction during rainy season.

The increasing amount of groundwater recharge may relate to the favorable recharge structures created by BMDA such as re-excavation of *Kharis*, rivers, etc. Groundwater recharge in some places of BT increases, but declining trends in wet-season groundwater level indicates recent groundwater storage depletion [23].

4.2.3. Driving forces of groundwater depletion

The areas irrigated by Shallow Tube Wells (STWs), DTWs, and Power Pumps (PPs) were 368, 180, and 81 thousand acres, respectively, in 1993, which increased to 978, 679, and 121 thousand acres, respectively, in 2010. The groundwater abstraction for irrigation in 1993–1994 pumping season was about 2543.3 million cubic meters (Mm^3) for greater Rajshahi district and it was 7195.3 Mm^3 in 2010. The groundwater abstraction for the irrigation pumping season 1993–1994 to 2009–2010 is shown in **Figure 10a**. The estimated Z (5.05) statistic indicates a statistically significant trend in groundwater abstraction at 99% confidence level. Hence, this significant trend is a significant responsible factor for groundwater depletion in the area. The Padma River, which is one the mighty river in Bangladesh, flows along the south of the study area. Aquifer feeds the river during the dry season (Nov–May) as the river water level goes below the groundwater level and river feeds the aquifer during the rainy season [34]. The trends in annual maximum and minimum discharge of the Padma River are shown in **Figure 10b**. It is seen that both the maximum and minimum discharge are decreasing over the years. However, the decreasing rate of minimum discharge (−132.45 m^3/s) is higher than that of maximum discharge (−22.27 m^3/s). This is one of the reasons for the rapidly increasing trend in groundwater depth during the dry season in the study area. The Padma river which originates in India is a transboundary river. India is controlling the flow of the river. Hence, transboundary river relation is also a driving factor of groundwater depletion in the study area. Moreover, decreasing rainfall and frequent droughts are also responsible factors for rapid depletion of groundwater level [7, 8]. Furthermore, the thick clay surface lithology (15–30 m) lies over the aquifer in the central part of the area is the inherent problem of groundwater recharge in the study area. It is also one of the driving forces of groundwater depletion.

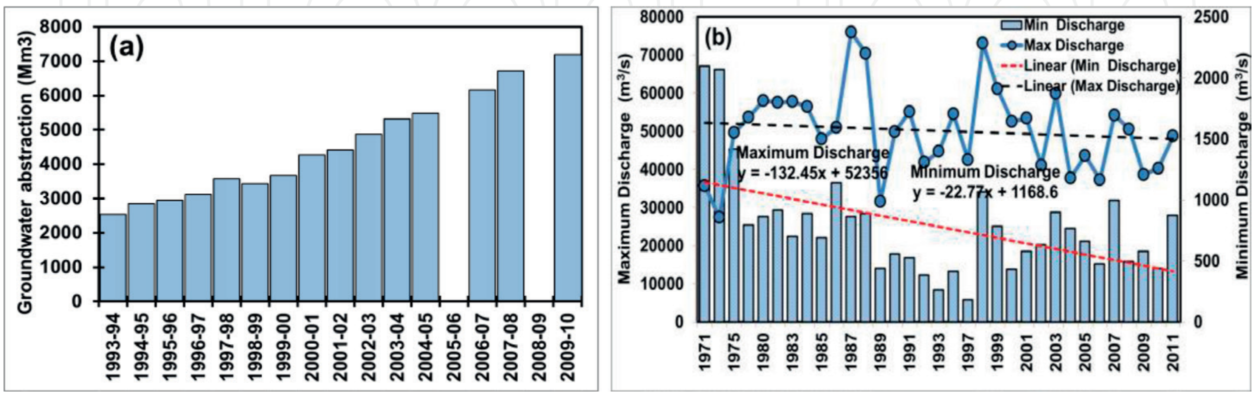

Figure 10. (a) Groundwater abstraction during 1993–1994 to 2009–2010, (b) annual minimum and maximum discharge of Padma river.

4.3. Alternatives for achieving sustainability in water resources management

4.3.1. Surface water potentiality

Surface water is the best alternatives of groundwater. BMDA [35] conducted a detailed survey on the surface water potentiality in the northwest Bangladesh. The survey data have been analyzed and presented in **Table 1**. There is a scope to irrigate 23,565 ha (hectares) of land using surface water from different sources in different Upazilas in the northwest Bangladesh. 9285 ha of land can be easily irrigated by surface water as the surface water always available over the years (A+). In addition, 4035 ha of land can be taken under surface water irrigation scheme by re-excavating the existing rivers and *Khals* in different Upazilas in northwest Bangladesh. Almost 5.08% of irrigated land can be irrigated from surface water sources (**Table 1**) in the northwest Bangladesh.

4.3.2. Managed aquifer recharge

MAR as a mechanism of storing water in underground is gaining popularity in the different parts of the world [36]. An experimental study on MAR in two villages (Mallickpur and Ganoir) in the study area has been done in Nachole Upazila in Chapai Nawabganj district (**Figure 1**). VES survey has been conducted in the selected sites to know the lithology and optimum depth of recharge wells. Two bore holes have been done to confirm about the interpreted lithology from VES and these bore holes later used as recharge well. The topmost layer (Zone-I) is characterized by clay lithology with thickness varies from 22 to 27.5 m. The resistivity value of Zone-1 ranges from 9 to 28 Ωm. There exists an aquifer (Zone-II) composed of fine to medium sand lithology with thickness varies from 8 to 20 m. The resistivity value of Zone–II ranges from 63 to 198 Ωm. This aquifer is treated as the main aquifer having potentiality for groundwater development for drinking purposes. The schematic diagram of MAR has been shown in **Figure 11**. Rainwater falls on the roof of the corrugated iron in household level. Rainwater is collected through a pipeline system and poured through into a storage system (**Figure 11**), which is a recharge box. The total catchment is used for rainwater harvesting is 200 m^2 with five recharge points in each village. Before injecting the rainwater through the recharge structure into the aquifer, it makes free from any sorts of silt and debris present. The recharge box (1.5 m × 1.5 m size) is filled with brick cheeps of 6, 10, and 20 mm sizes and coarse sands. The depth of the recharge box is 3 m in the top clay layer. The recharge well has been constructed at the bottom of the recharge box, so that water can enter in the recharge well after filtering in the recharge box. There is a strainer at the bottom of the recharge well where it meets the aquifer. Finally, the rainwater enters into the aquifer through the strainer. The groundwater level is monitored by observation wells in both villages. Rain-gauge stations have been set up to record it. Eighty percent of rainfall has been considered as effective rainfall for recharge as rainfall loss occurs during heavy rainfall events. To ensure the quality of groundwater, water quality of both sites has been analyzed before and after the implementation of MAR. The water is safe for drinking before and after the MAR [37]. The average maximum and minimum water-level depth was 14.6 (m, bgl) and 5.2 (m, bgl) during the period of 1991–1995 in Nachole Upazila, respectively. Average maximum and minimum water level

Upazila	Upazila area (km^2)	Irrigated area (%) of total area	Irrigated area (ha)	Potential surface water irrigation areas (ha)					
				A+	A	B	C	Total	Irrigated area (%)
Bagha	184	27	4975	—	270	—	—	270	5
Bagmara	363	59	21,417	—	—	2210	—	2210	10
Charghat	165	71	11,715	200	300	450	—	950	8
Mohanpur	163	72	11,736	—	390	700	—	1090	9
Paba	280	71	19,880	300	300	400	—	1000	5
Puthia	193	90	17,370		120	810	—	930	5
Bholahat	124	90	11,117	250	—	175	110	535	5
Gomastapur	318	39	12,407	2200	550	—	—	2750	22
Nachole	284	36	10,212	575	—	—	—	575	6
Nawabganj	452	52	23,494	3440	—	—	—	3440	15
Shibganj	525	45	23,644	750	—	—	225	975	4
Atrai	284	76	21,584	470	690	—	—	1160	5
Badalgachi	214	72	15,408	—	—	200		200	1
Dhamoirhat	301	90	27,090	—	—	1000	120	1120	4
Mohadevpur	398	83	33,034	980	685	110		1775	5
Naogaon	276	93	25,668	—	—	250	210	460	2
Niamatpur	449	55	24,695	—	—	—	200	200	1
Patnitala	382	61	23,302	120	280	—	—	400	2
Porsha	253	41	10,373	—	—	690	600	1290	12
Raninagar	258	92	23,766	—	450	450	320	1220	5
Sapahar	245	37	9065	—	—	315	700	1015	11

Note: A+: Potential surface water sources located in dry areas and water is available over the years; A: Surface water is available in some years during dry season; if re-excavated, water will be available over the years; B: Surface water is not available during dry seasons; if re-excavated, water will be available over the years; and C: Surface water is not available; if re-excavated, it is possible to conserve water for irrigation purposes.

Table 1. Potential surface water irrigation areas in different Upazilas (sub-district) in northwest Bangladesh (data source: BMDA [35]).

went down to 18.9 (m, bgl) and 12.2 (m, bgl) during 2006–2010, respectively. The regaining of GWL during the rainy season were 9.4, 12.4, and 11.7 m during 1991–1995, 1996–2000, and 2000–2005, respectively. However, it was only 6.5 m during the period 2006–2010. The regaining of GWL in the area was the lowest during 2006–2010 due to inadequate recharge and heavy withdrawal of groundwater for supplementary irrigation during rainy season. Artificial recharge structures in the two villages in Nachole Upazila ware installed in the month of November in 2013. The water-level depths of both villages show the regaining of GWL in

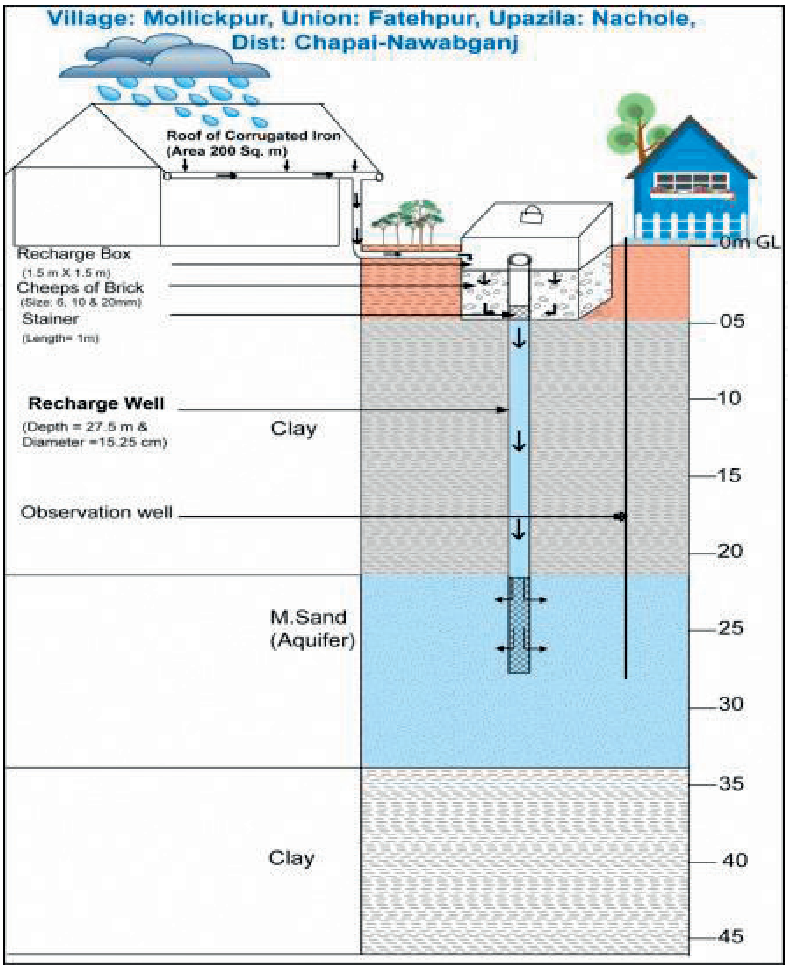

Figure 11. Schematic diagram of MAR technique implemented in Nachole Upazilla, Chapai Nawabganj district.

response to artificially augmented recharge over the last 2 years. The maximum water-level depth was 13.66 (m, bgl) in Mallickpur Village in May in 2014, but it was 09.88 (m, bgl) again in May in 2015. This result indicates that water-level depth was 3.78 m above than the previous year depth as the cumulative effective rainfall for the period of Jan–May was only 103 mm in 2014, but it was 448 mm in 2015 for the same period. The people of the area mentioned that they were not getting water using their HTWs during the months of Mar–May. However, now they are getting water using their HTWs during this period. Furthermore, in Ganoir Village the same kind of scenario has been observed and water-level depth was 1.47 m above in 2015 than in 2014. The amount of GWL restoration is not same for both villages. This difference is mainly due to the difference in rainfall and other factors like the elevation of the recharge point and rate of abstraction may also responsible.

5. Conclusions and recommendations

The compass of this chapter is to understand the long-term hydro-climatic characteristics and evaluate the performance of MAR for achieving the sustainability in groundwater management. Our intent was not to cover all the aspects related to the sustainability of water resources management. However, the findings of the study will contribute to understanding the phenomena related to sustainable groundwater management in drought prone areas. Our study demonstrates that unplanned irrigation for the dry season rice production is the significant responsible factor for groundwater depletion. Moreover, climate-related factors, like decreasing trend in rainfall, distribution of rainfall (SI and PCI), frequent drought, are also related to the groundwater depletion. In the study area, the thick clay surface lithology, which is the barrier of groundwater recharge, is also an important factor for groundwater depletion. The study also demonstrates that water resources management also related to the transboundary river relationship. To achieve sustainability in groundwater resource management particularly in the study area, water resource managers need to consider several factors along with the factors mentioned. First, it is time to take decision about the land use patterns as rice, which cultivates in about 81% cultivable area during the dry season, is the highest water consuming crop in the area. Though it is the staple food in the country, it is necessary to reduce this crop cultivation to protect rapid depletion of groundwater resource. Moreover, water-saving irrigation techniques such alternate drying and wetting, raised bed techniques need to promote for farming. Surface water irrigation where and when it is available need to facilitate to minimize the stress on groundwater. The present study also indicates that groundwater recharge in some Upazilas increases due to create favorable recharge structures like re-excavation of rivers and *Kharis* (small channel). However, the effort is not quite enough for protecting groundwater depletion. As annual surplus water is higher than the net groundwater recharge, groundwater recharge favorable structures for rainwater harvesting need to develop. An experimental study on MAR shows the potentiality of the technique for ensuring drinking water supply especially in the rural areas. An IWRMP considering the driving forces of groundwater depletion, potentiality of surface water, and MAR and land use pattern of the area need to prepare and execute the plan accordingly for achieving the sustainability in water resources management.

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