Prediction of groundwater trends for irrigation in Northern Bangladesh
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ABSTRACT

Groundwater trends affect the domestic, agricultural, and industrial prospects of a region. The study area is Bogura, a northern region of Bangladesh, located on the Pleistocene terrace of the Bengal Basin. The aquifer consists of medium-to-coarse sand, located at a depth of 4.66–42.68 m; groundwater is scarce during dry seasons. The water table (WT) time-series data for 2007–2019 were used for forecasting and characterizing present and future groundwater conditions using existing numerical simulations. The annual groundwater budget for discharge and storage was 2,772 and 2,442 Mm³, respectively. Thus, the annual scarcity of groundwater was 330.4 Mm³ (13.5%), excluding the surface water contribution of 10 Mm³ (0.4%). The present spacing of deep tube wells (DTWs) and shallow tube wells (STWs) was 744 and 372 m, respectively. Currently, the DTW spacing ranged 744–800 m; however, the STW spacing of 250–372 m is higher than the set distance. Hence, further installations of STWs were strictly disallowed for irrigation. WT declined by 1.0 m in the last 13 years, i.e., 0.07 m or 1.2% decline rate per annum, causing water scarcity in the region during the peak period in the dry season (June–February), thus affecting irrigation and limiting agricultural production.

Key words | discharge, groundwater monitoring, groundwater storage, recharge, water table fluctuation, well spacing

HIGHLIGHTS

● In the study, highest priority was given on groundwater use for irrigation.
● The study emphasized the recharge-discharge and storage phenomenon as hydrological components.
● The study forecasts and predicts the present and future threats of groundwater resources.

INTRODUCTION

Groundwater is one of the leading sources of water in Bangladesh. Owing to the inadequate availability of surface water during dry seasons, it functions as a vital, innocuous, and reliable source of water for irrigation, domestic, and industrial purposes. Groundwater is attained using various types of lifting device, such as hand tube wells (HTWs), shallow tube wells (STWs), deep tube well (DTWs), deep-set shallow tube wells (DSSTWs), and force mode tube wells (FMTWs). Moreover, the main sources of surface water in the study area are canals and the rivers of Nagar, Bengali, Ichamoti, Karatoa, Bhadrabati, Jamuna, and Tulsiganga. In the study area, a part of the surface water is obtained from low lift pumps (LLPs); however, most of the canal and rivers cannot bring water during the rainy season because of the lack of mining not only in the study area but all over the country. Furthermore, the static water
tables (WTs) of subsurface water are decreasing in shallow aquifers in Asian mega deltas such as the Ganges–Brahmaputra–Meghna (GBM) basin owing to the large seasonal variation in the monsoon rainfall in Bangladesh. The penetration rates of the high Barind soil were 0.0015 m/d for wet land and 0.0075 m/d for dry land (MacDonald & Partners 1985). The WT is as much as 15 m below the ground surface, and groundwater fluctuation differs from 1.25 to 16.15 m (Asaduzzaman 1987). In 1990, the total amount of groundwater withdrawn was 8,806 Mm³ against a reserve of 21,088 Mm³ for several agricultural inputs in Bangladesh (MPO 1991). The irrigation coverage was 1.52 x 10⁶ ha during 1982–1983, and it increased to 3.79 x 10⁶ ha in 1996–1997 (BBS 1998). Groundwater also contributes 70% of the water used for irrigation and 90% of the drinking water in the country (Matin et al. 2000). The current available geological subsurface information indicates that most of the aquifers occur between depths of 30 to 130 m, and the country has heterogeneous aquifer systems (Zahid & Ahmed 2006). Further, alluvial aquifers are the proven sources of groundwater in Bangladesh, and the groundwater is annually refilled via rainfall and flooding and through the systematic recycling of water nationwide, except in Dhaka Megacity, where there is an imbalance between the asymmetrical recharge−discharge. Approximately 80% of the agricultural land is irrigated using groundwater after the start of the crop season in Bangladesh, and groundwater scarcity arose 42% each year during the operation of STWs in the dry season in northwest Bangladesh (Shahid & Hazarika 2010). In Barind Tract of Bangladesh, prospective groundwater recharge decreased by 85%, whereas the rest was moderate. In this region, only 8.6% of the total average annual rainfall (1,685 mm) infiltrates into the subsurface and ultimately contributes to the recharge of groundwater (Adham et al. 2010). Net recharge was increased approximately 0.005–0.015 m/year in many region of Bangladesh during 1985–2007 for increased groundwater withdrawal for irrigation as well as consumptive use, but net recharge marginally decreased from −0.0005 to −0.001 m/year, where groundwater irrigation was low; that is, <30% of total irrigation at the same period (Shamsudduha et al. 2011). Since the commencement of groundwater irrigation in the mid-1980s, a positive impact was observed in cropping patterns, cropping intensity, and national intensity, crop selection, and cultivation yields.
the availability of groundwater resources. Although research on groundwater in northern Bogura of Bangladesh is scanty, most focus on groundwater assessments (Abdullah 2014; Hasanuzzaman et al. 2017).

The main objective of the study is of interest to the hydrological community, particularly the Water Users Association (WUA) involved with groundwater resources, especially for irrigation. First, the aquifer is mapped using lithological data of boreholes. Second, the balance between groundwater recharge–discharge and storage is estimated. Third, the safe well spacing for installing the boreholes is determined.

The result can provide insight into the need for digging or abstaining from digging new wells, selection of the device for extracting groundwater, and operability of different modes of the water-lifting equipment. Furthermore, the results will be a handy tool for decision-makers and planners working not only in the study area but also on national and global scales.

**METHODS**

In this study, the present and future groundwater tendencies were predicted using some recognized empirical equations. The focus was to obtain a clear understanding of groundwater resources, including the balance between recharge–discharge and storage. The methodological steps are described in the following flowchart:
This section provides a broad stepwise description based on appropriate simulation to rationalize the projected scenario of groundwater resources.

Study location

The target area of this study was Bogura in northern Bangladesh (Figure 1). Geographically, the study area lies between longitudes 89° 21 min, and 0 s east and from 24° 46 min to 48° north. It is called the gateway to north Bangladesh. It is approximately 200 km from the north of Dhaka, the capital of the nation.

Geology of the study area

Seven types of geological group formations are exposed across Bangladesh (Figure 1). Of these, two types of geological formations were found in the study area. These formations include the Pleistocene terrace (Madhupur Clay) and alluvium, flood plain deposits, delta plain deposits, and stream deposits. The mappable body of rock of the Pleistocene terrace is part of the Dihing formation. This enormous formation has aquifer characteristics. The formation contains clays of various colors, such as medium-grain molted clay and yellow and gray clays, and occasional pebbly sandstone. The rock formations are partly associated in most of the locations, and similarly, alluviums are loosened materials deposited on the flood plains, delta basins, river beds, lakes, or estuaries. Alluviums comprise sand, silt, gravel, cobbles, and boulders along with organic materials that are converted into fertile soil. Generally, the term ‘alluvium’ is constrained to size-sorted fine sediments (sand, silt, and clay) and un lithified riverine deposits. In addition, coarse-grained and very coarse-grained sand (brown and gray) is found most of the alluvium in the study area. The color of sand is transformed from yellowish and brownish to gray.

Sample size

Lithologies for 145 boreholes were analyzed for mapping aquifers and to prepare a groundwater lithological inventory to identify the soil formation types. Precisely, 11 stations were selected for monitoring the wells (Figure 2) (one from each station or subunit), and the time-series primary data of WT were collected for the last 15 years (2007-2019). The location of the selected monitoring wells is listed in Table 1.

Rockworks software

Rockworks software allow computer modeling based on the end-user specifications. The basic strategies of the software are the creation of a borehole database using the analytical results for various physical and chemical properties as a function of the depth. The database also generates images, such as block diagrams, cross sections, and fence diagrams, to check the legitimacy and geological reasonability of the modeling. It uses two-dimensional (2-D) and three-dimensional (3-D) images with three feature levels – basic, standard, and advanced. It is often difficult to determine the capabilities, operational features, and limitations of a particular groundwater modeling code from the documentation, or even without accurately running the code for situations relevant to the region for which a code is to be selected owing to the incompleteness, poor organization, or incorrectness of code documentation. Thus, this software was used in the study to map the aquifer using lithological data.

Estimation of annual groundwater storage

Groundwater refers to the water present in the pore spaces of soil. That part of the rock or unconsolidated deposit formation is called an aquifer when it can harness an effective quantity of water. Groundwater storage is the product of the area of the aquifer, depth or thickness of the WT fluctuation, and specific yield (Raghunath 1987):

\[ \Delta S = A \times \Theta H \times S_y, \]  

where \( \Delta S \) is the groundwater storage, \( A \) is the area of aquifer in the study area (m\(^2\)), \( \Theta H \) is the depth or thickness of the WT fluctuation (m), and \( S_y \) is the specific yield (%). The depth of the WT fluctuation is the difference between its maximum and minimum levels in the WT throughout the year in the given region. In this study, groundwater...
Figure 1 | Geological group formation of Bangladesh and soil formation of the study area (https://bdmaps.blogspot.com/2011/12/geological-group-formation-bangladesh.html).
fluctuations were measured at 11 monitoring wells. They were not constant at every location, and hence, a vertical aquifer was expected. Further, the specific yield ($S_y$) is the

ratio of the thickness of an equivalent layer of water of infinite spatial extent that is required to produce the measured change in gravity (in other words, it is the change in groundwater volume per unit area) by the change in WT elevation. The Equation can easily assess groundwater discharge by comparing storage, shortage, or steadiness of groundwater.

**Groundwater recharge**

Groundwater recharge is a hydrological process where water passes downward from the surface deeper into the ground. It is the amount of water that enters the saturated zone; that is, the enduring WT in an aquifer. The main source of recharge is rainfall, which may enter the soil directly to reach the groundwater zone. Aquifer recharge refers to the amount of water that may be available in the long term for extraction. Groundwater recharge, also referred to as deep drainage or deep percolation, is calculated for areas that receive abundant rainfall. The data of fluctuations were measured at 11 monitoring wells. They were not constant at every location, and hence, a vertical aquifer was expected. Further, the specific yield ($S_y$) is the
groundwater recharge is then used for calculating the well spacing in the study. Annual groundwater recharge estimated using the following formula:

(a) Chaturvedi’s formula (Chaturvedi 1973):

\[
R = 13.93 \left( \frac{P}{381} \right)^{0.4}
\]  

where \( R \) is the groundwater recharge (mm) and \( P \) is the annual rainfall (mm).

(b) Sehgal’s formula (Sehgal 1973):

\[
R = 12.6 \left( \frac{P}{406.4} \right)^{0.5}
\]  

where \( R \) is the groundwater recharge (mm) and \( P \) is the annual rainfall (mm).

(c) Datta’s formula (Datta et al. 1980):

\[
R = 0.11 \left( \frac{P}{41.8} \right)
\]  

where \( R \) is the groundwater recharge (cm) and \( P \) is the annual rainfall (cm).

**Groundwater discharge and surface water contribution**

Groundwater discharge is the term used to describe the movement of groundwater from the subsurface to the surface. Again, surface water contribution is the sense used to the water coming from the surface (canals or rivers). Annual discharge and surface water contribution can be easily determined to ascertain the number of wells (DTWs, STWs, and LLPs), average pumping capacity, and time period of operation. The annual discharge and surface water contribution of groundwater for irrigation in the study area is estimated using the following equation (Asaduzzaman 1987):

\[
V_a = N \times Q \times t
\]  

where \( V_a \) is the annual groundwater discharge (Mm³), \( N \) is the number of tube wells operated in the area, \( Q \) is the pumping capacity of a well (m³ h⁻¹), and \( t \) is the operation period (h/year).

**Safe well spacing**

This is generally defined as the maximum area of the resource basin that can be drained efficiently and economically by a well. The prevailing spacing between wells was determined for the study area by considering a uniform areal distribution of wells and entire utilization of the safe yield of the groundwater basin on the basis of the available groundwater recharge. Safe yield is defined as the amount of water that can be withdrawn from the groundwater basin without producing an undesired effect. The annual recharge must not exceed the total groundwater extracted. The well spacing clearly indicates the distribution of water-lifting devices installed in an irrigation field. The relation of well spacing to recharge, discharge, and pumping period is described by the following equation (Chowdhury & Wardlaw 1978):

\[
S = 60 \sqrt{\frac{QtN}{R_b}}
\]  

where \( S \) is the well spacing (m), \( Q \) is the well discharge in (L/S), \( t \) is the pumping period in (days/year), \( R_b \) is the groundwater recharge in (mm/year), and \( N \) is the number of operating well (h/day).

**Growth rate and WT trends**

For computing the WT growth rates, the following exponential trend line formula is used.

\[
Y = ae^{bt}
\]  

\[
\ln Y = \ln a + bt
\]  

where \( Y \) is the dependent variable (WT; m); \( t \) is the independent variable (month-year); \( a \) is the intercept, and \( b \) is the absolute growth rate. Thus, \( b \) is the growth with a ratio scale multiplied by 100 and expressed as a percentage of decrease. To verify the significance of the estimated regression, the following equation for the F-test, where null hypothesis \( H_0: b = 0 \) was used (Gujarati 1995):

\[
F = \frac{R^2}{(1 - R^2)}
\]  

where \( R^2 \) is the coefficient of determination.
where $R^2$ is the explained sum of squares and $(1 - R^2)$ is the unexplained sum of squares.

**Direct field supervision**

Some data were collected through direct field supervision with consent from end users, beneficiaries, and managers handling groundwater resources in the study area.

**RESULTS AND DISCUSSION**

The study results are clearly systematically stated and described in this section considering the applied methods.

**Aquifer mapping**

A total of 145 boreholes from various locations in 11 stations of the Bogura region were considered along with the lithologies and latitudinal–longitudinal coordinates. Those borehole data were analyzed using Rockworks software. A location map of boreholes was plotted (Figure 3), and panel diagrams of groundwater resources in the north–south (N–S) direction (Figure 4(a)) and west–east (W–E) direction (Figure 4(b)) were obtained. The location map shows the borehole sites in the study area, and the panel diagrams show the aquifer formation. In addition, the panel diagrams show 25 types of soil formations using various colors for the easy identification of the present groundwater inventory of water logs. For example, subsurface layers are classified as sandy, clay,
sticky, rock, plastic, stone, etc. Mostly, sandy soil remains in the water in the subsurface withdrawn using various lifting devices, such as HTWs, STWs, and DTWs, for drinking, irrigation, and industrial purposes.

Moreover, screen or strainers were settled on wells, where the sandy layer was located along the depth or thickness, using the water logs. This result was compared with the findings of earlier studies. The comparison showed that the thick layer of sticky and plastic clay hampered the recharge in WT; further, land collapse risk is low, but this layer acts as an aquitard that hampers groundwater recharging. The increased surface runoff has led to a severe decrease in the groundwater level. This area faces the risk of several adverse effects such as land subsidence and biodiversity loss. In addition, the aquifer was oriented west–east in the northwest region of Bangladesh (Rahman & Mahbub 2022).

Lithology

Borehole inventory is plotted in Figure 5 using both the borehole and aquifer thickness of 145 lithologies. From this figure, the maximum, minimum, and average borehole thickness were found as 72, 27, and 44.54 m, respectively. In addition, the maximum, minimum, and average aquifer
thicknesses were 42.68, 4.66, and 19.48 m, respectively. The aquifer in the study area was composed of medium sand (MS) to coarse sand (CS). This result is in agreement with the result of a recent study reporting that the highest thickness of the clay layer is 27.43 m and the lowest value is 6.09 m and that the thickness gradually increases from the east to the west; finally, the aquifer depth was 6.09–27.43 m from the surface (Rahman & Mahbub 2012).

Hydrograph

A hydrograph is a graph showing the rate of flow past a specific point such as a river, channel, or conduit. In this study, the hydrographs show the monthly rainfall and WT data from 2007 to 2019 (Figure 6). The x-axis denotes the month–year, and the y-axis represents monthly rainfall and groundwater table reflected in the hydrographs as well as in the two recognized limbs, particularly seen in the one-year water curve of Bogura Sadar upazila. The two limbs of the hydrograph show groundwater level fluctuations; one, the rising limb or crest or peaks representing the recharge phenomena, and the other, the recession limb or trough representing the discharge phenomena. The hydrographs are compared and classified with groups of identical classes. The form of the annual hydrograph in a specific well remains nearly unchanged over consequent years in spite of the deviations in its magnitude with the variation of the annual recharge or discharge to the aquifer.

Groundwater condition

The groundwater conditions shown in Figure 7 are plotted using monthly groundwater table (GWT) data for the last 13 years (2007–2019). From these figures, the maximum, minimum, and average GWT, groundwater fluctuation, and standard deviation values are obtained as listed in Table 2.

From the data in Table 2, the maximum, minimum, and average WT are 8.95, 2.95, and 6.40 m, respectively; the maximum, minimum, and average groundwater fluctuations are 4.73, 2.22, and 3.37 m, respectively; the maximum, minimum, and average standard deviation are 1.44, 0.70, and 1.03 m, respectively. Finally, the average WT and groundwater fluctuation are 6.40 and 3.37 m, respectively, in the study area. These findings were associated with earlier research on cropping patterns, cropping intensity, national intensity, crop selection, and yields practices of cultivation after groundwater irrigation commenced in the mid-1980s. WT has decreased continuously at rates of 0.4 m and 0.22 m/year in the wet and dry seasons, respectively (Rahman & Mahbub 2012).

Groundwater pressure

Generally, the suction mode of centrifugal pumps (a shallow aquifer) is employed in the case of STWs, and the force mode of submersible pumps (a deep aquifer) is employed in the case of DTWs. Using the suction mode, water can be lifted at not more than 10.33 m by exerting a pressure of 1.03 (kg cm⁻²). The maximum WT in Sherpur, Dupchachia, and Adamdhigi stations (Table 2) are 10.95, 11.52, and 10.47 m; these values exceed the limit of 10.33 m, beyond which the suction mode is inoperable. In other words, the centrifugal pumps of STWs failed in the dry seasons. The remaining eight stations (Bogura Sadar, Sariakandi, Dhunat, Gabtali, Nandigram, Kahalo, Shibganj, and Sonatola) are safe zones for pumping up groundwater throughout the year because the WTs in these stations are within 10.33 m.

Annual groundwater storage

The analysis of the lithology and aquifer type in Bogura district revealed the presence of MS-to-CS. The specific yield ($S_y$) for MS and CS was 15–30% and 20–35%, respectively, for this soil formation (Walton 1996). The aquifer area of Bogura, $A$, is 2,898.25 km²; average depth of the WT
fluctuation, $\Delta H$, is 3.37 m (from Table 2). These values were substituted in Equation (1). Then, for a specific yield, $S_y$, of 22.5% (average for MS), the groundwater storage was estimated to be $2,898.25 \text{ km}^2 \times 3.37 \text{ m} \times 0.225$ or $2,197.59 \text{ Mm}^3$. Now, for a specific yield of 27.5% (average for CS), the same equation yielded an estimate of

Figure 6 | Typical hydrograph of monthly rainfall and water table data along with time-series data during 2007–2019 in wells from 11 stations in the study area.
2,898.25 km² × 3.37 m × 0.275 or 2,685.95 Mm³ as the groundwater storage. The annual groundwater storage was taken as the average of these two values; that is, 2,441.77 Mm³. Corresponding study findings reacted with these results that the annual groundwater recharge and discharge were estimated to be 106.41–244 Mm³ and
93.77–291 Mm³, respectively, in Naogaon in northwest Bangladesh. The annual recharge and withdrawal remained balanced up to 1993, but the discharge has exceeded the recharge since then. In addition, 23.99–42.08 Mm³ of groundwater was discharged using STWs and DTWs, and the rest of groundwater was discharged by natural seepage (Reza et al. 2016).

Groundwater recharge

Groundwater recharge was calculated using Equations (2)–(4), as listed in Table 3.

The average groundwater recharge in Table 3 is 261.82 mm. This is close to the values of 234.97 mm calculated using Chaturvedi’s formulas (Chaturvedi 1973). Hence, in this study, the groundwater recharge is considered to be 261.82 mm. These results were compared with the outcomes of an alternative study, and the prospective groundwater recharge decreased by 85% and rest (15%) was moderate in the Barind Tract of Bangladesh, where only 8.6% of the total average annual rainfall (1,685 mm) infiltrates into the subsurface and ultimately contributes to groundwater recharge (Adham et al. 2010).

Groundwater discharge and surface water contribution

The annual discharge and surface water contribution are calculated from the total number of DTWs, STWs, and LLPs with their average pumping capacity and operating period. The study area has 2,700 DTWs, 65,607 STWs, and 273 LLPs with discharge capacities of 56 Ls⁻¹ (or 201.6 m³/h), 14 Ls⁻¹ (or 50.4 m³/h), and 14 Ls⁻¹ (or 50.4 m³/h), respectively (BADC 2019). Considering pump design, the actual pumping efficiency of each DTWs, STWs, and LLPs was regarded as approximately 25% less than the discharge capacity. Presently, the average irrigation period was considered as 960 h/year for DTWs, STWs, and LLPs (entire irrigation depends on the Rabi season, but

Table 3 | Annual groundwater recharge

| Sl. no. | Equation name | Rainfall unit | Average rainfall during 2007–2019 (mm) | Annual recharge, Rg (mm) |
|--------|---------------|--------------|--------------------------------------|-------------------------|
| 1      | $R = 13.95 \times (P - 381)^{0.4}$ Chaturvedi (1973) | $P = \text{mm}$ | 1,549.62 | 234.97 |
| 2      | $R = 12.6 \times (P - 406.4)^{0.3}$ Sehgal (1973) | $P = \text{mm}$ | 1,426.02 | 426.02 |
| 3      | $R = 0.11 \times (P - 41.8)$ Datta et al. (1980) | $P = \text{cm}$ | 1,247.47 | 124.47 |
| Average |               |              | 261.82                              |                         |
supplementary irrigation is performed for the seasons of Aus and Aman cultivation; that is, July–August and December–January, respectively, if needed).

From Equation (5), the number of wells, average pumping capacity, time period of operation, annual discharge, and surface water contribution are obtained as listed in Table 4.

The annual groundwater storage and annual groundwater discharge were 2,441.77 Mm$^3$ and 2,772.16 Mm$^3$, respectively. The annual shortage of groundwater was 330.39 Mm$^3$ (13.53%) of the total storage in the northwest region of Bogura. Therefore, the groundwater shortage occurs primarily in the dry season and affects the amount of water available for irrigation. This result agrees with the results of an earlier study that the annual groundwater recharge and discharge were 106.41–244 Mm$^3$ and 93.77–291 Mm$^3$, respectively, in northwest Bangladesh; these values revealed the existing balance between the annual recharge and withdrawal up to 1993; thereafter, the discharge has exceeded the recharge. Further, 23.99–42.08 Mm$^3$ of groundwater was discharged using STWs and DTWs, and the rest of the groundwater was discharged by natural seepage (Reza et al. 2013). Additional, the main sources of surface water are the canal and the rivers of Nagar, Bengali, Ichamoti, Karatoa, Bhadrabati, Jamuna, Tulshiganga etc. in the study area. From Table 4, a total of 273 LLPs are used for contributing surface water with an amount of 9.90 Mm$^3$ (0.41%).

Safe well spacing

To calculate the well spacing, the following parameters were considered: the pumping capacity of DTWs, $Q$, was 151.2 m$^3$/h or 42 Ls$^{-1}$; pumping period, $t$, was 60 d/year; operating hours, $N$, was 16 h/day; and groundwater recharge, $R_g$, was 261.82 mm/year (Table 3). Then, using Equation (6), the well spacing of the existing DTWs was calculated as 744 m. Further, for the pumping capacity of STWs, $Q$, 37.8 m$^3$/h or 10.5 Ls$^{-1}$ and all other parameters identical to those for the DTWs, the well spacing of existing STWs was calculated as 372 m using the same equation. However, the recommended spacing for DTWs (a well with a discharge capacity of 201.60 m$^3$/h or 2.01 cusec) and STWs (a well with a discharge capacity of 50.4 m$^3$/h or 0.50 cusec) are 800 and 250 m, respectively, in the study area in Bangladesh (MoA 2019). Thus, the results showed that although the spacing of DTWs is appropriate, that for STWs is inappropriate. Hence, further installation of STWs should be strictly disallowed in the district, and all STWs should be operated very carefully in the dry season to ensure they do not over lift groundwater. Further, the installation of DTWs is preferable for the proper management of groundwater in future. Besides, the annual shortage of groundwater due to the over-exploitation of groundwater for excess installation of STWs was 330.39 Mm$^3$ (13.53%); this shortage occurs in the dry period, when the WT declines slowly.

Period toward groundwater fluctuations

The list in Table 5 shows that the average WT fell by 1.02 m over the last 13 years in the period 2007–2019 in the study area. Meanwhile, the WT increased in March–May but fell during the nine months of June–February. This result is in agreement with the results of a previous study that the WT

### Table 4 | Annual groundwater discharge and surface water contribution

| Sl. no. | Name of devices | Total numbers of operation, nos. | Pumping capacity, $Q$ (m$^3$/h$^{-1}$) | Irrigation period (16 h day$^{-1}$) $\times$ 60 day year$^{-1}$, $T$ (h year$^{-1}$) | Annual discharge, $V_a = N \times Q \times T$ (Mm$^3$) |
|---|---|---|---|---|---|
| 1 | DTW | 2,700 | 151.2 | 960 | 391.91 |
| 2 | STW | 65,607 | 37.8 | 960 | 2,380.74 |
| **Total** | | | | | **2,772.16** |
| 1 | LLP | 273 | 37.8 | 960 | 9.90 |
suffers a yearly fall of 1.20 m in some northern parts of Bangladesh because of excessive withdrawal through tube wells along with low recharge, poor management, and land use changes (Khan & Islam 2018). Moreover, a previous study on Chapai–Nawabgonj in northwest Bangladesh in 2007–2011 on the effect of rainfall and WT fluctuation showed that the rainy season usually started in May and ended in September and that low or no rainfall occurred during the rest of the year. It also showed that the maximum rainfall occurred in June–August and the maximum WT is observed in July–September owing to rainwater infiltration. The minimum WT was observed in March–May during the irrigation period of the area, and the WT declined daily because of the over withdrawal of groundwater for irrigation (Hasan et al. 2013).

WT trends

The annual exponential value was computed using the trend line for the 11 stations of the northern region of Bogura, Bangladesh, as listed in Table 6. The x-axis denotes the number of years, and the y-axis represents year; the WT is reflected in the exponential value $y$ and regression $R^2$. The trend lines shown in Figure 8 were computed using

### Table 5 | Monthly rise (−) or fall (+) in the groundwater table during the period 2007 to 2019 (in meters)

| Station name    | Jan  | Feb  | Mar  | Apr  | May  | Jun  | Jul  | Aug  | Sep  | Oct  | Nov  | Dec  | Avg. |
|-----------------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| Bogura Sadar    | −0.37| −0.63| −0.75| −1.70| −2.04| −1.34| 1.59 | 3.09 | 4.01 | 4.18 | 2.93 | 2.80 | 0.96 |
| Sherpur         | 0.90 | 3.27 | −0.11| −1.55| −1.21| −0.64| 0.95 | 2.25 | 2.32 | 2.25 | 2.38 | 2.20 | 1.08 |
| Sariakandi      | 1.10 | 0.77 | 0.52 | −0.25| 0.29 | 1.72 | 1.44 | 2.95 | 0.33 | 1.86 | 1.56 | 1.20 | 1.16 |
| Dhunat          | 1.80 | 1.81 | 2.18 | 1.28 | 1.51 | 2.46 | 2.29 | 4.79 | 4.78 | 3.20 | 3.59 | 2.61 | 2.69 |
| Gabtali         | 0.65 | −0.52| −0.31| −0.49| −0.36| 0.93 | 0.84 | 0.16 | 0.11 | 0.21 | −0.07| −0.05| 0.09 |
| Nandigram       | 2.00 | 0.42 | −0.05| −0.38| −0.60| −0.19| 2.02 | −0.75| 3.57 | 4.78 | 4.85 | 4.38 | 1.67 |
| Kalo            | 3.78 | 3.07 | 1.93 | 0.65 | 0.28 | 0.46 | 1.21 | 1.16 | 1.71 | 3.18 | 4.30 | 3.09 | 2.07 |
| Shibganj        | −1.92| −1.97| −1.51| −1.62| −1.59| −1.36| −1.20| −1.59| −1.39| −1.31| −1.30| −1.35| −1.51|
| Sonatola        | −0.80| −0.88| −2.75| −0.22| −0.80| 0.81 | 1.79 | 3.40 | 2.83 | 2.61 | 2.70 | 2.66 | 0.95 |
| Dupchachia      | 1.35 | 1.16 | 1.38 | 1.06 | 1.69 | 1.95 | 2.15 | 2.27 | 2.40 | 2.49 | 2.81 | 2.82 | 1.96 |
| Adamdighi       | 1.54 | −0.47| −1.42| −1.63| −1.42| −1.12| −0.75| −0.39| 0.51 | 0.87 | 2.59 | 2.14 | 0.12 |
| Average         | 0.91 | 0.55 | −0.08| −0.40| −0.39| 0.33 | 1.10 | 1.57 | 1.92 | 2.30 | 2.39 | 2.05 | 1.02 |

### Table 6 | Growth rate of the water table

| Upazila/sub unit | Y = ae^{bt} | \ln Y = \ln a + bt | Growth rate of WT = b \times 100 (% per annum) | \text{R}^2 | \text{F} = \frac{\text{R}^2}{1-\text{R}^2} |
|-----------------|-------------|-------------------|-----------------------------------------------|---------|----------------|
| Bogura Sadar    | Y = 5.3459e^{-0.0139x} | 1.6763 + 0.0139x  | 1.39                                           | 0.456   | 0.26352        |
| Sherpur         | Y = 6.1289e0.0187x   | 1.8130 + 0.0187x  | 1.87                                           | 0.1275  | 0.01752        |
| Sariakandi      | Y = 3.2934e0.0047x   | 1.19 + 0.0047x    | 0.47                                           | 0.0163  | 0.00037        |
| Dhunat          | Y = 3.578e0.0367x    | 1.2748 + 0.0367x  | 3.67                                           | 0.606   | 0.58047        |
| Gabtali         | Y = 4.2011e0.0013x   | 1.4353 + 0.0013x  | 0.13                                           | 0.0035  | 0.00001        |
| Nandigram       | Y = 5.904e0.0276x    | 1.7756 + 0.0276x  | 2.76                                           | 0.3675  | 0.15614        |
| Kalo            | Y = 7.4321e0.0162x   | 2.0058 + 0.0162x  | 1.62                                           | 0.3547  | 0.14392        |
| Shibganj        | Y = 8.8074e0.016x    | 2.1755 + (−)0.016x| −1.60                                          | 0.5474  | 0.42785        |
| Sonatola        | Y = 3.4654e0.0051x   | 1.2428 + 0.0051x  | 0.51                                           | 0.0153  | 0.00023        |
| Dupchachia      | Y = 7.9958e0.0224x   | 2.0789 + 0.0224x  | 2.24                                           | 0.6788  | 0.85449        |
| Adamdighi       | Y = 8.1311e0.0052x   | 2.0956 + 0.0052x  | 0.52                                           | 0.0158  | 0.00025        |
| Average         |               |                   |                                               | 1.22    |                 |

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Figure 8 | Trend lines of the annual water table in the 11 stations of the study area.
Equation (7) or Equations (8) and (9), which are presented in Table 6.

The data in Table 6 show that the WT fell by 1.22% annually in the northwest region of Bogura. The WT for 10 stations, excluding Shibganj station (−1.60%), declined. The decline in the annual WT varies from 0.13 to 3.67%, indicating a wide variation in the rate of decrease in different locations because of excessive withdrawal through tube wells along with low groundwater recharge and topographical changes in the study area. This result, along with related findings, indicates that the decline increased by approximately 4% of the country’s total during 1998–2002; however, it drastically increased to 11% in 2008 and 14% in 2012, and the WTs are declining gradually in the northwestern area but more slowly from 0.1 to 0.5 m year\(^{-1}\) because of the intensive use of STWs in the Boro season in March–May (Qureshi et al. 2014).

**CONCLUSIONS**

In this study, groundwater trends were studied by intensively focusing on hydrological properties such as borehole lithologies, groundwater storage, the groundwater discharge–recharge phenomenon, existing well spacing (DTWs and STWs), and WT fluctuations for driving advanced groundwater enrichment plans. The borehole and aquifer thickness were 27–72 m and 4.66–42.68 m, respectively; using 145 borehole lithologies, the most helpful ones for digging of water-lifting devices containing their appropriate design. Soil formation was demarcated as MS – to – CS, which can be easily grasped for calculating the volume of water in a borehole to covering a command area. The annual groundwater budget for discharge and storage were predicted to be 2,772.2 and 2,441.8 Mm\(^3\), respectively, and the annual scarcity of groundwater was 330.4 Mm\(^3\); that is, 13.5%. These results can support simple perception of the groundwater shortage, steadiness, or excess condition not only in the study area but on national or global scales. The existing spacing between DTWs and between STWs was 744 and 372 m, respectively; the results can convey a message for boring water-lifting devices in the future. Furthermore, the WT increased in March–May but fell during the nine months of June–February. Monitoring the change in WT in these periods can provide the alarm for assessing the relation of the pumping head with the discharge throughout the year. WT declined by 1.0 m in the last 13 years; that is, a decline of 0.07 m or 1.2% rate per year. This result can be considered in future groundwater user plans.

The study results can be significant for decision-makers, planners, and researchers involved in groundwater management at nationwide and worldwide scales.

The recommendations made on the basis of the results of this study are as follows. (i) If WT fluctuations are identified in a region, any borehole can be easily designed for ensuring sustainability; (ii) the crop planting seasons, most notably for rice, can be alternated considering the groundwater shortage (13.53%) during the dry season in the study area; (iii) water-saving technologies for rice production, such as the use of alternating wetting and drying (AWD) methods and the raised bed crop (RBC) technology approach, can be employed; (iv) the current well spacing for DTWs is appropriate (744–800 m); however, the spacing for STWs is inappropriate (250–372 m). Hence, further installations of STWs should be strictly disallowed in northern Bogura, Bangladesh; (v) future groundwater plans should be established to ensure a balance between groundwater recharge–discharge with a reserve; and (vi) the mathematical, physical, and analogue modeling of groundwater resources in this area will require further research.

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**CONFLICT OF INTEREST**

The authors declare no conflicts of interest.
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DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

REFERENCES

Abdullah, M. 2014 Assessment of Groundwater Resources in Bogra District Using Groundwater Model. A thesis for Master of Science in Department of Civil Engineering, Bangladesh University of Engineering and Technology (BUET), Bangladesh, October, 2014. Available from: https://www.researchgate.net/publication/342655878_assessment_of_groundwater_resources_in_Bogra_district_using_groundwater_model.

Adham, M. I., Jahan, C. S. J., Mazumder, Q. H., Hossain, M. M. A. & Haque, A. M. 2010 Study on groundwater recharge potentiality of Barind Tract, Rajshahi district, Bangladesh using GIS and remote sensing technique. Journal of the Geological Society of India 75 (2), 432–438. Available from: http://www.geoscindia.org/index.php/jgsi/article/view/57660.

Asaduzzaman, M. 1987 Development and utilization of water resources in Barind area. The Sangbad, June 8, Daily Newspaper, Bangladesh.

BADC (Bangladesh Agricultural Development Corporation) 2019 District Wise Irrigation Equipment used and Total Area Irrigated. Unpublished Report, Financial Year 2018–19, BADC Bogura region, Bangladesh.

BBS (Bangladesh Bureau of Statistics) 1998 Yearbook of Agricultural Statistics of Bangladesh. Bangladesh Bureau of Statistics, Dhaka, Bangladesh.

Chaturvedi, R. S. 1973 A Note on the Investigation of Ground Water Resources in Western Districts of Uttar Pradesh, Annual Report, UP Irrigation Research Institute, pp. 86–122.

Chowdhury, S. I. & Wardlaw, I. F. 1978 The effect of temperature on kernel development in cereals. Australian Journal of Agricultural Research 29 (2), 205–223. doi:10.1071/AR9780205.

Datta, A. K., Colby, B. M., Shaw, J. E. & Pagano, J. S. 1980 Acyclovir inhibition of Epstein-Barr virus replication. Proceedings of the National Academy of Sciences 77 (9), 5163–5166. Available from: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC350017/. doi:10.1073/pnas.77.9.5163.

Gujarati, D. N. 1995 Basic Econometrics, 3rd edn. McGraw-Hill Inc., New York, NY, USA. ISBN; 0070252149, pp. 540–583. Available from: https://www.worldcat.org/title/basic-econometrics/oclc/31075018.

Hasan, M. R., Mostafa, M. G. & Matin, I. 2013 Effect of rainfall on groundwater level fluctuations in Chapai-Nawabgonj district. International Journal of Engineering Research & Technology (IJERT) 2 (4). Available from: https://www.ijert.org/effect-of-rainfall-on-groundwater-level-fluctuations-in-chapainawabgonj-district.

Hasanuzzaman, M., Song, X., Han, D., Zhang, Y. & Shakir, H. S. 2017 Prediction of groundwater dynamics for sustainable water resource management in Bogra district, northwest Bangladesh. Water 9 (4), 238. Available from: https://www.mdpi.com/2073-4441/9/4/238. doi:10.3390/w9040238.

Khan, S. S. & Islam, A. R. M. T. 2015 Anthropogenic impact on morphology of Teesta River in northern Bangladesh: an exploratory study. Journal of Geosciences and Geomatics 3 (3), 50–55. Available from: https://www.researchgate.net/publication/276941795_Anthropogenic_Impact_on_Morphology_of_Teesta_River_in_Northern_Bangladesh_An_Exploratory_Study.

Matin, M. A., Khan, M. H. & Khan, N. I. 2000 RDA Developed Low-Cost DTW Technology for Multipurpose uses (Performance Evaluation). Director General, Rural Development Academy (RDA), Bogra, Bangladesh.

MacDonald, M. & Partners 1983 Water Balance Studies Bangladesh. Final Report, Report II Groundwater, Demter House, Station Road, Cambridge, Cambridge, p. 68.

MoA (Ministry of Agriculture) 2019 Notification of Groundwater Management Act for Agriculture in Bangladesh, 2018. S.R.O. no. 128-law/2019. Ministry of Agriculture, Government of Bangladesh (GoB), Dhaka.

MPO (Master Plan Organization) 1991 National Water Plan Phase II, Vol I & II. Ministry of Water Resources, Government of Bangladesh (GoB), Dhaka.

Qureshi, A. S., Ahmed, Z. & Krupnik, T. J. 2014 Groundwater Management in Bangladesh: an Analysis of Problems and Opportunities. Research Report No. 2, Cereal Systems Initiatives for South Asia-Mechanization and Irrigation (CSISA-MI). Available from: https://csisa.org/wp-content/uploads/sites/2/2014/01/Groundwater-management-in-Bangladesh-An-analysis-of-problems-and-opportunities.pdf.

Raghunath, H. M. 1987 Groundwater, 2nd edn. Wiley Eastern Limited, New Delhi, India, p. 6.

Rahman, M. M. & Mahbub, A. Q. M. 2012 Groundwater depletion with expansion of irrigation in Barind Tract: a case study of Tanore Upazila. Journal of Water Resource and Protection 4, 567–575. http://dx.doi.org/10.4236/jwarp.2012.48066.

Reza, A. H. M., Mazumder, Q. H. & Ahmed, M. 2013 Groundwater balance study in the high Barind, Bangladesh. Rajshahi University Journal of Science 39 (2011), 11–26. https://doi.org/10.3329/rujs.v39i0.16539.

Sehgal, S. R. 1973 Groundwater Resources of Punjab State. Third annual session, Central Board of Irrigation and Power, New Delhi, India.
Shahid, S. & Hazarika, M. K. 2010 Groundwater droughts in the north-western districts of Bangladesh. *Water Resources Management* 24 (10), 1989–2006. Available from: https://link.springer.com/article/10.1007/s11269-009-9534-y.

Shamsudduha, M., Taylor, R. G., Ahmed, K. M. & Zahid, A. 2011 The impact of intensive groundwater abstraction on recharge to a shallow regional aquifer system: evidence from Bangladesh. *Hydrogeology Journal* 19, 901–916. Available from: https://link.springer.com/article/10.1007/s10040-011-0723-4.

Walton, W. C. 1996 *Aquifer Test Analysis with Windows™ Software*, 1st edn. Lewis Publishers, USA.

Zahid, A. & Ahmed, S. R. U. 2006 *Groundwater Resources Development in Bangladesh: Contribution to Irrigation for Food Security and Constraints to Sustainability*. No H039306, IWM Institute. Reports from International Water Management Institute. Available from: https://econpapers.repec.org/scripts/redir.pl?u=https%3A%2F%2Fpublications.iwmi.org%2Fpdf%2FH039306.pdf;h=repec:iwt:bosers:h039306.

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