Spatiotemporal Change in Groundwater Sustainability of Bangladesh for the Period 1995-2019

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Abstract

Groundwater is gradually becoming scarce in Bangladesh like many other countries around the globe due to various climatic, hydrological, and socio-economic changes. This study aimed to assess the spatiotemporal changes in groundwater availability and sustainability in Bangladesh. The study employed weekly groundwater table (GWT) data from 844 groundwater observation wells of the Bangladesh Water Development Board (BWDB) from 1995 to 2019. Mann-Kendall (M-K) test at 95% significance level and the Sen's slope estimator were used to assess the spatiotemporal variations in GWT, and the reliability-resiliency-vulnerability (RRV) approach was applied for evaluating sustainability. In addition, the yearly trends in RRV indicators and sustainability were estimated. The results revealed the mean GWT is low in the northwest and central regions. The GWT is declining almost all over the country, particularly in the areas where it is already low by 0.548−1.398 m/year. The groundwater showed remarkably poor sustainability for most of the areas. It also showed a declining trend over a large area in the central north. The analysis of results through the scrutiny of irrigated land and population distribution of the country revealed higher abstraction of groundwater for irrigation and domestic supply are the major cause of declining GWT in the northwest and central regions of the country. The study provided an understanding of the changes in groundwater and its sustainability which can be used as a guide for sustainable management of groundwater and contribute to drawing up future groundwater policies.

Keywords: Groundwater level, trend analysis, sustainability, driving factors, Bangladesh.

1. Introduction

The depletion of freshwater, the most important natural resource on the planet, and the seemingly inevitable climate changes are threatening the World's food security and people's well-being by limiting the sufficient provision of quality water to meet the ever-growing demand of the developing economy and increasing population (Falkenmark, 2013; Wang et al., 2016; Li et al., 2021). The Intergovernmental Panel on Climate Change (IPCC) estimated 2 billion people will lack adequate drinking water supplies by 2050, twice as many as they do currently. It has also been projected that half of the World's population will face a shortage of clean water by 2080 due to temperature rise and precipitation shift (Morrison et al., 2009). Most of Asia will possibly be more afflicted by water shortage. The problem is likely worsened by groundwater depletion due to overexploitation and climate change (Ahmed et al., 2017a, 2016; Hadi Pour et al., 2019; Nashwan et al., 2019; Shahid et al., 2016; Wang et al., 2016, 2014). Reduced runoff (Hughes et al., 2012), changes in habitats (Stromberg et al., 1992), and vanishing riparian vegetation and forests (Cunningham et al., 2011; Kath et al., 2014) are all common consequences of groundwater depletion. Studying and properly monitoring the groundwater system is critical for minimizing water stress, safeguarding this valuable resource, and establishing long-term groundwater management policies (Famiglietti, 2014).

Globally, groundwater provides about 50% of the current availability of potable water, 40% of the industrial water, and 20% of irrigation needs (Molden, 2007). On average, approximately 32% population uses groundwater for drinking in the Asia-Pacific region (Morris et al., 2003). In Bangladesh, roughly 32 km^3 of groundwater is extracted annually, of which 90% is used for irrigation and the rest for domestic use, which equals ~ 4% of global groundwater abstraction (Hanasaki et al., 2018). However, hydrological and socio-economic factors like over-abstraction, weak governance, and climate change implications, which are not well known, endanger the sustainability of groundwater supplies in the country. Efficient groundwater management is crucial for meeting national and international agendas, improving public health and sustainable growth, and alleviating poverty (Conti et al., 2016).

Several studies have been conducted to evaluate groundwater changes in Bangladesh (Mojid et al., 2019; Purdy et al., 2019; Rahman et al., 2018; Shamsudduha et al., 2012, 2011). Most studies focused northwestern part of the country, considering it as the only groundwater stress region. Groundwater studies focusing on the entire country is still very limited. Besides, groundwater sustainability in the country has not been studied using reliable scientific approaches. This gap urges a need to study the spatiotemporal variability, trends, and the sustainability of the groundwater of the entire country.

Hydrological data are generally fit with linear regression to assess existing trends in the series (Ahmed et al., 2017b; Mayowa et al., 2015; Sa'adi et al., 2017; Salman et al., 2017). In the recent past, many nonparametric trend detection methods have been developed to overcome the drawbacks of the parametric regression approach (A.I. McLeod, 2015; Geary and Kendall, 1948; Hamed, 2008; Mann, 1945). Among them, the Mann-Kendall (M-K) test (Mann, 1945; Kendal, 1975) and different modified versions of M-K tests have been most widely used (Khan et al., 2019). These tests are independents of data distribution and insensitive to missing values (Shahid, 2010), which are very common to groundwater records. Therefore, the M-K test can provide a better understanding of the changing pattern of groundwater.

Assessment of sustainability in natural resources is a complex problem (Maqbool et al., 2021). In recent years, the Resiliency-Reliability-Vulnerability (RRV) (Hashimoto et al., 1982) concept has been used to evaluate sustainability in resources against hazard risk (Hazbavi et al., 2019; Maity et al., 2013; Sung et al., 2018). In hydrology, it has been used to assess sustainability in the integrated ground and surface water irrigation (Onta et al., 1991), reservoir operation (Kwon et al., 2018), water resources management (Ashofteh et al., 2017; Sarzaeim et al., 2017), water supply system (Karamouz et al., 2017), water distribution system (Aydin et al., 2015), and flood protection systems (Simonovic and Li, 2004). Besides, it has been used for assessing urban flood risk (Ahmad and Simonovic, 2013) and future water deficit (Mondal et al., 2010). The RRV concept has also been used for sustainability assessment in water resources in recent years (Asefa et al., 2014; Butler et al., 2017; Goharian et al., 2018; Zhang et al., 2017).

This study aims to assess the trends and sustainability in groundwater resources of Bangladesh. Groundwater table (GWT) data for the period 1995–2019, collected from 844 locations covering the whole country, is used for this purpose. The robust nonparametric tests are used to estimate the changes in mean and variability of GWT and the significance of the changes. The RRV approach is employed to assess the spatiotemporal pattern of groundwater sustainability in the country. Besides, trends in RRV indicators and sustainability are estimated to understand spatiotemporal changes in groundwater sustainability. The study's novelty is assessing changing patterns of groundwater accessibility, vulnerability and sustainability in recent years and its drivers. The results produced in this study for understanding the changes in groundwater variability and sustainability can be used as a guide for sustainable management of groundwater of Bangladesh and contribute to drawing up the future groundwater policies.

2. Study Area

Bangladesh, located near the mouth of the Bay of Bengal (Figure. 2), occupies a substantial part of the Bengal Delta formed from the deposition of the Ganges-Brahmaputra-Meghna (GBM) river system (Kuehl et al., 2005). The GBM rivers have the World's greatest overall sediment load, originating mainly in the Himalayan and Indo-Burman mountains (Uddin and Lundberg, 1998) and the fourth-highest water discharges to the oceans (Coleman, 1969). Geographically, it extends from 20°34'N to 26°38'N latitude and from 88°01'E to 92°41'E longitude (BBS, 2019; CIA, 2021). The country's population till 2019 is 163,046,818 (UN DESA, 2019). Of the country's total land, 70.1% is used for agricultural purposes, 11.1% covers forest, and 18.8% is used for other purposes (CIA, 2021).

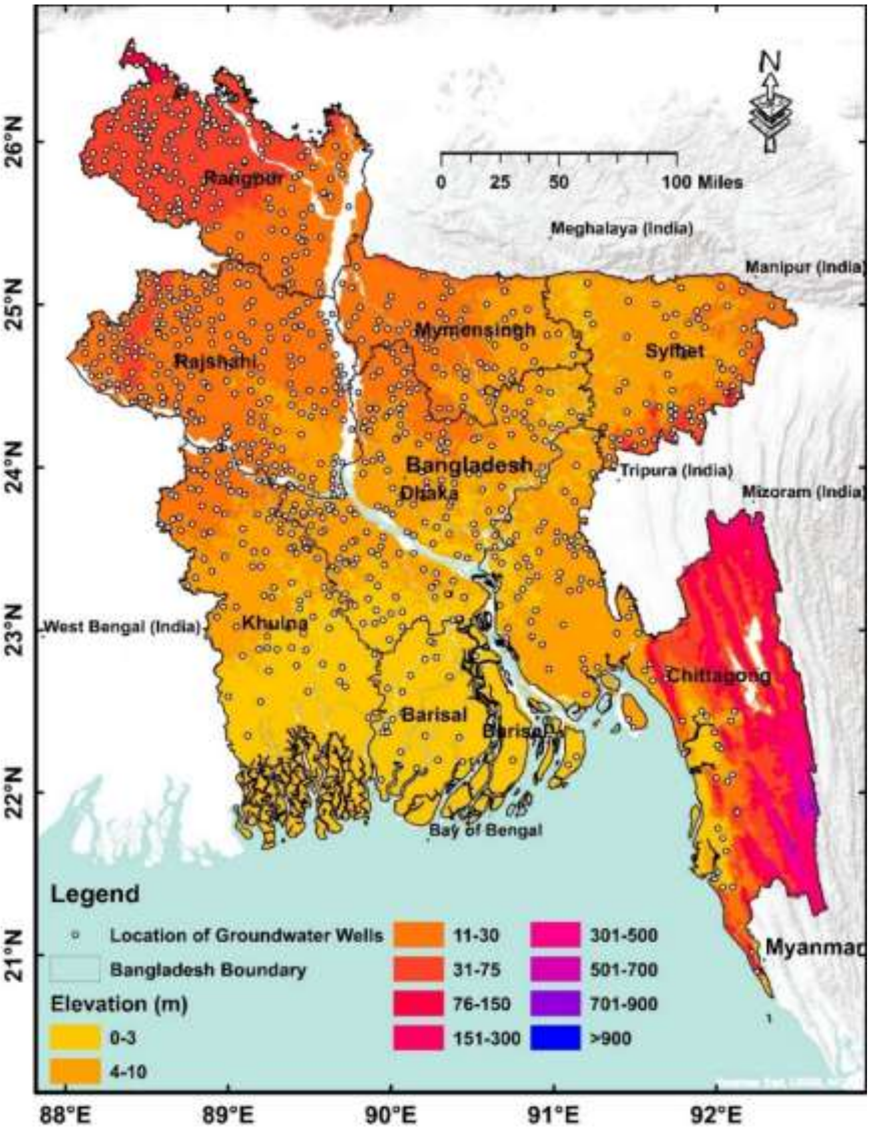


Figure 1 Location of BWDB groundwater observation wells with the elevation of Bangladesh in m.

The GBM Rivers cover the entire country and make it the World's largest delta (Ahmad et al., 2001). Approximately 80% land area of Bangladesh is low-lying and flat, crossed by many rivers. The strong rivers built up the delta and aquifer systems by depositing sediments in the GBM delta over the Pleistocene and Holocene periods. Many aquifers are formed by thick semi-consolidated to unconsolidated fluvial-deltaic sediments ranging in age from the Miocene to the Recent. However, most formations are too deep for groundwater abstraction, except Holocene and the Plio-Pleistocene Dupi Tila Sandstone formations. Most of the aquifers are located between 30 and 130 m deep. The primary water-bearing zone runs down to 250-350 meters and is mostly formed by fine to very fine sand, sometimes interbedded with clay lenses, and is normally interbedded with a silty clay bed (Coleman, 1969; Pradeep Aggarwal Head et al., 2000; Uddin and Lundberg, 1998; Zahid, 2015).

Straddling in the Tropic of Cancer, Bangladesh is characterized by a humid tropical/subtropical climate with moderately warm temperature, high humidity, and a wide range of seasonal variations in rainfall patterns (Rashid, 1991). The climate zones of the country are three, according to Köppen-Geiger climate classification (Beck et al., 2018): Temperate, dry winter, hot summer (Cwa) (Zone 1), Tropical monsoon (Am) (Zone 2), Tropical savannah (Aw) (Zone 3) (Figure. 2). The average rainfall ranges from 1,500 mm in the west to over 4,000 mm in the northeast, with an average annual rainfall of 2300 mm (Chowdhury, 2010). The mean temperature ranges 18–22ºC in winter and 23–30ºC in summer. Climate models revealed an increase in temperature of Bangladesh by 2.4°C and rainfall by 9.7% at the end of this century (Alamgir et al., 2020; Pour et al., 2018).

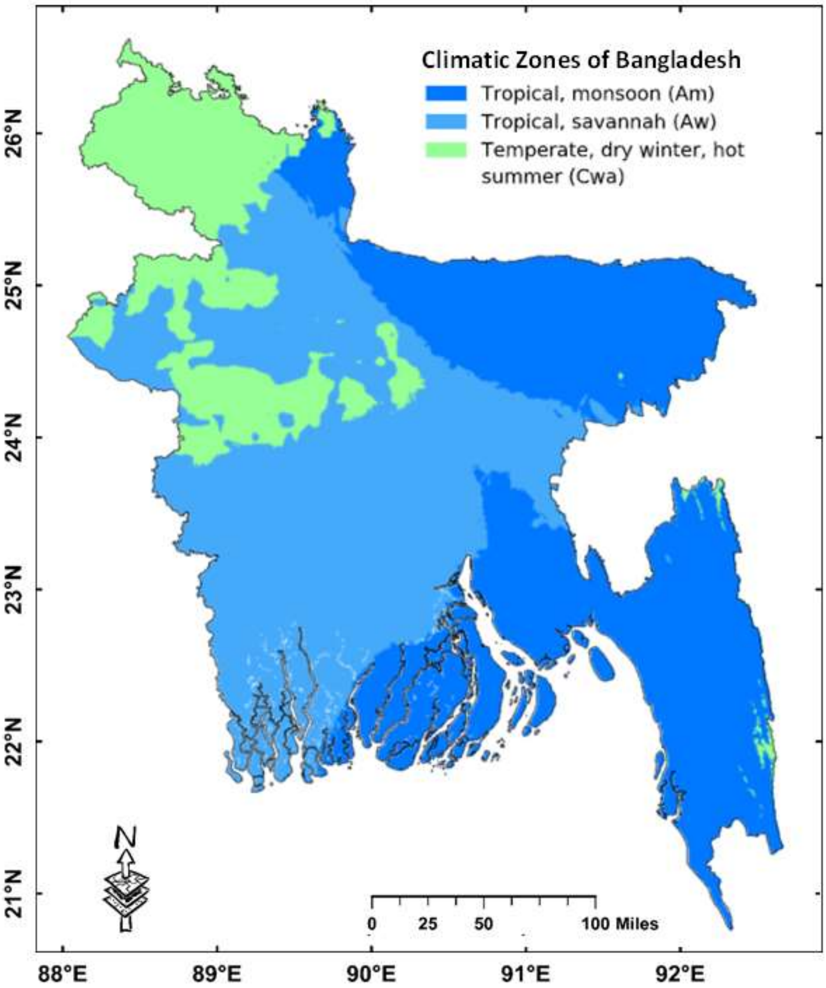


Figure 2 Climatic zones of Bangladesh according to Köppen-Geiger climate classification (Beck et al., 2018).

3. Research materials and methodology

3.1 Data and sources

The weekly GWT data of selected wells were collected from the Bangladesh water development board (BWDB). The organization has a permanent monitoring well network, consisting of more than 1327 groundwater observation wells, largely constructed at shallow depths (less than 50 m). BWDB collects GWT data from 1965 to the present. The data request was made online from the official website of Processing and Flood Forecasting Circle, BWDB (http://www.hydrology.bwdb.gov.bd/). Grided data of rainfall and potential evapotranspiration (PET) having a spatial resolution of $0.5^{o} \times 0.5^{o}$ were collected from Climate Research Unit (CRU) from 1995 to 2019 to show the coherence of GWT with climatic variables in different zones.

3.2 Methods

The study followed the four steps to attain the objectives of this study: (a) collection and processing of GWT data, (b) preparation of annual time series of GWT to assess trends in GWT, (c) assessment of the spatial distribution of groundwater sustainability using the RRV indicators (Hashimoto et al., 1982), and (d) assessment of trends in RRV indicators to evaluate changes in groundwater sustainability.

3.2.1 Data processing

BWDB GWT data from all the wells were carefully checked to assess their quality. The preliminary inspection showed that data from most wells are available only from 1995 to 2019. Therefore, the study period was selected between 1995 and 2019. Time series, histogram and boxplot of the data at each location were prepared to check the missing data, irregular variability, abnormal distribution and outliers. The station contains data with an abrupt change, large irregular variability, and outliers higher than 1% of the total sample was discarded. Finally, the stations with less than 10% missing data were selected. This procedure identified data of 844 monitoring wells having sufficient quality to conduct the study. The location of the monitoring wells is presented in Figure 1. The spatial distribution of the wells indicates that they cover the whole of Bangladesh, except the hill tracts in the southeast and forest in the southeast.

The present study employed cubic spline interpolation (CSI) (Peng-zhu et al., 2015) for filling gaps in the groundwater hyrographs. CSI considers all available data to fill the gaps in series. It fits a piecewise continuous curve passing through all points of a series. A separate cubic polynomial represents the different parts of the curve. Thus, it can fill the gaps in a series efficiently. Literature suggests CSI is an effective way to fill missing data in groundwater series (Chen et al., 2020; Huang et al., 2021).

3.2.2 Trend analysis

Different parametric, nonparametric, and mixed trend identification and/or quantification methods are available for trend analysis (Helsel and Hirsch, 1992). The nonparametric methods are typically employed in hydrological and climatic studies due to their robustness to the absent and tied values, serial dependency, non-linearity, non-normality, and seasonality (Helsel and Hirsch, 2002). The nonparametric M-K test and Sen's slope were used in this study. These two trend identification techniques are widely used in environmental, financial, hydrological, and climatological time series analysis.

The null hypothesis of the M-K test, H_0, states that there is no monotonic trend. H_0 is rejected if a trend exists in series at a predefined significance level. The M-K test statistics *(S)* for a time series is computed as:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \operatorname{sgn}(x_j - x_k) \tag{1}$$

where *n* is the number of time series observational points, x_k and x_j are from *k* =1, 2, …, *n*-1 and *j*=*k*+1, …, *n*. The $\operatorname{sgn}(x_j - x_k)$ is the sign function (Karpouzos, 2010):

$$\operatorname{sgn}(x_j - x_k) = \begin{Bmatrix} +1 \;\; if \; (x_j - x_k) > 0 \\ 0 \;\; if \; (x_j - x_k) = 0 \\ -1 \;\; if \; (x_j - x_k) < 0 \end{Bmatrix} \tag{2}$$

The variance can be computed as:

$$var(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{m} t_i(t_i-1)(2t_i+5)}{18} \tag{3}$$

where m is the number of tied groups (a set of sample data having the same value) and t_i is the number of ties (Gocic and Trajkovic, 2013). When the sample size is bigger than 8, then the standard normal test statistics Z_s is calculated as:

$$Z_s = \begin{Bmatrix} \frac{S-1}{\sqrt{var(S)}}, if \; S > 0 \\ 0 \;\; if \; S = 0 \\ \frac{S+1}{\sqrt{var(S)}}, if \; S < 0 \end{Bmatrix} \tag{4}$$

The positive and negative values of Z_s denote upward and downward trends, respectively. In a two-sided test for trend, H_0 is rejected if $|Z| \geq Z_{\alpha/2}$. This study considered $\alpha \leq 0.05$.

Sen's slope estimator is mainly used for depicting the quantification of change per unit time (Sen, 1968):

$$Q_i = \frac{x_j - x_k}{j-k} \quad for \; i = 1, \ldots, N, \tag{5}$$

where x_j and x_k are the data values at times *j* and *k* (*j* > *k*), respectively. The N values of Q_i are ranked from smallest to largest, and the Sen's slope (the median of the slope) is calculated as (Sen, 1968):

$$Q_{med} = \begin{cases} Q_{[(N+1)/2]} & if \; N \; is \; odd \\ \frac{Q_{[N/2]} + Q_{[(N+2)/2]}}{2} & if \; N \; is \; even \end{cases} \tag{6}$$

The sign of Q_{med} refers to the trend direction, while its values reflect the trend steepness.

3.2.3 Sustainability in groundwater resource

In this analysis, the sustainability of water supply is considered to be a function of the RRV of GWT, as per the following equation (Sediqi et al., 2019):

$$S = [Reliability \times Resiliency \times (1 - Dimnesion\ Vulnerability)]^{0.333} \quad (7)$$

The RRV indicators assess many aspects of the water system's performance and provide one of the most comprehensive approaches to analyzing the system's likelihood of success or failure, the rate of recovery from a failure state, and the expected effects of a failure over time (Asefa et al., 2014). Reliability indicates the likelihood of a water system to fail, whereas resiliency measures how fast a system is likely to recover or rebound after a failure, and vulnerability is an indicator of the magnitude of a failure if one happens. Even if the chances of failure are low, the potential implications of failure should be considered in measuring the vulnerability (Hashimoto et al., 1982).

The RRV concept is pictorially presented in Figure 3. In this study, one standard deviation (SD) less than the mean GWT for a 10-year base period, 1995–2004, was considered the threshold level for estimating RRV. Shahid and Hazarika (2011) defined GWT below 30-percentile as groundwater drought that causes water scarcity. One SD below mean GWT is nearly the 30-percentile level of GWT. The system performance indicators are defined as (Fowler et al., 2003; Hashimoto et al., 1982):

$$Reliability = 1 - \frac{\sum_{j=1}^{M} d(j)}{T} \quad (8)$$

$$Resiliency = \left(\frac{1}{M}\sum_{j=1}^{M} d(j)\right)^{-1} \quad (9)$$

$$Vulnerability = \frac{1}{M}\sum_{j=1}^{M} v(j) \quad (10)$$

$$Dimensionless\ Vulnerability = Vulnerability/Demand \quad (11)$$

where, $d(j)$ is the duration of the j^{th} failure event, M is the number of failure events, T is the total number of time intervals, and v is the vulnerability. The demand will be considered -1 in this study (Sediqi et al., 2019).

3.2.4 Spatial mapping

The maps were generated by interpolating point data using the Empirical Bayesian Kriging (EBK) method. EBK is a probabilistic interpolation method that automates the most timeconsuming components of creating a credible kriging model (Al-Abadi and Al-Najar, 2019). The model parameters are manually modified in conventional kriging approaches to produce an accurate result. In this study, the EBK parameters were determined automatically through sub-setting and simulation (Krivoruchko and Krause, 2011).

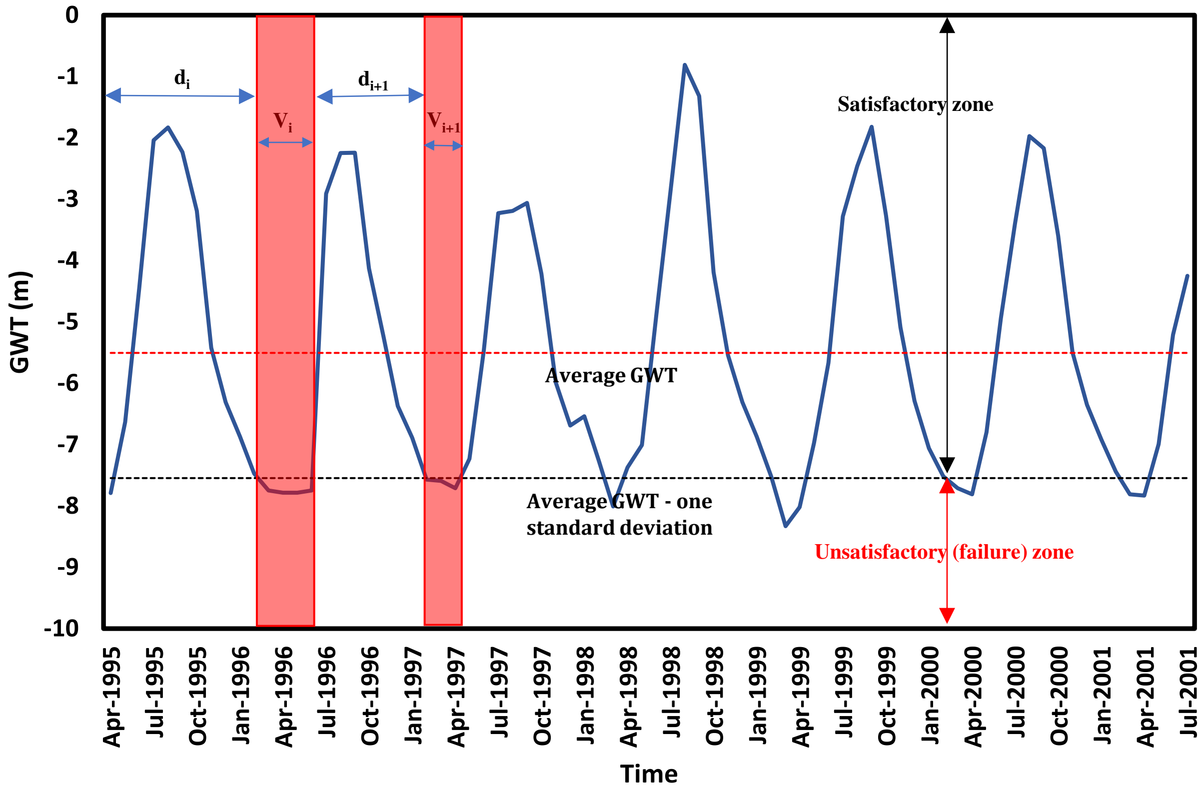


Figure 3 Time series of GWT for a well in the central region used as a depiction for explaining the equations used for estimating reliability, resiliency, and vulnerability.

4. Data Analysis and Results

4.1 Changes in monthly GWT

The monthly mean of GWT data for three climatic zones is averaged and presented in Figure 4 as level plots, where the x-axis represents the year, and the y-axis shows the GWT data of each month of a year. Therefore, the plots represent the monthly GWT data for the whole study period in an area. The blue color in the plot represents high GWT (low depth from the surface), and the red color represents low GWT. The results show a relatively higher depth in GWT in Zone 2, followed by Zone 1 and 3. The seasonal variability of GWT in different climatic zones is also very clear from the figure. The GWT comes near the surface in late monsoon and post-monsoon months due to recharge from monsoon rainfall, and it goes down in premonsoon irrigation months due to large abstraction for irrigation. The gradual decrease in GWT in all zones, particularly Zone 1 and 3, is clear. However, higher GWT is observed throughout July to December and lower from February to June in all three zones. GWT also shows a decreasing trend in yearly patterns in all three zones, where the decline is most severe in Zone 1 and 3. The average GWT in Zone 1 seldomly went below 16 m before 2005, but it has become common in recent years. The increased yellow color band indicates GWT drop below 16 m for a longer period in recent years. In Zone 3, GWT below 16 m has become permanent in recent years though it never occurred in any month before 2005. The GWT even goes below 30 m during premonsoon months when groundwater is most needed due to scarcity of surface water.

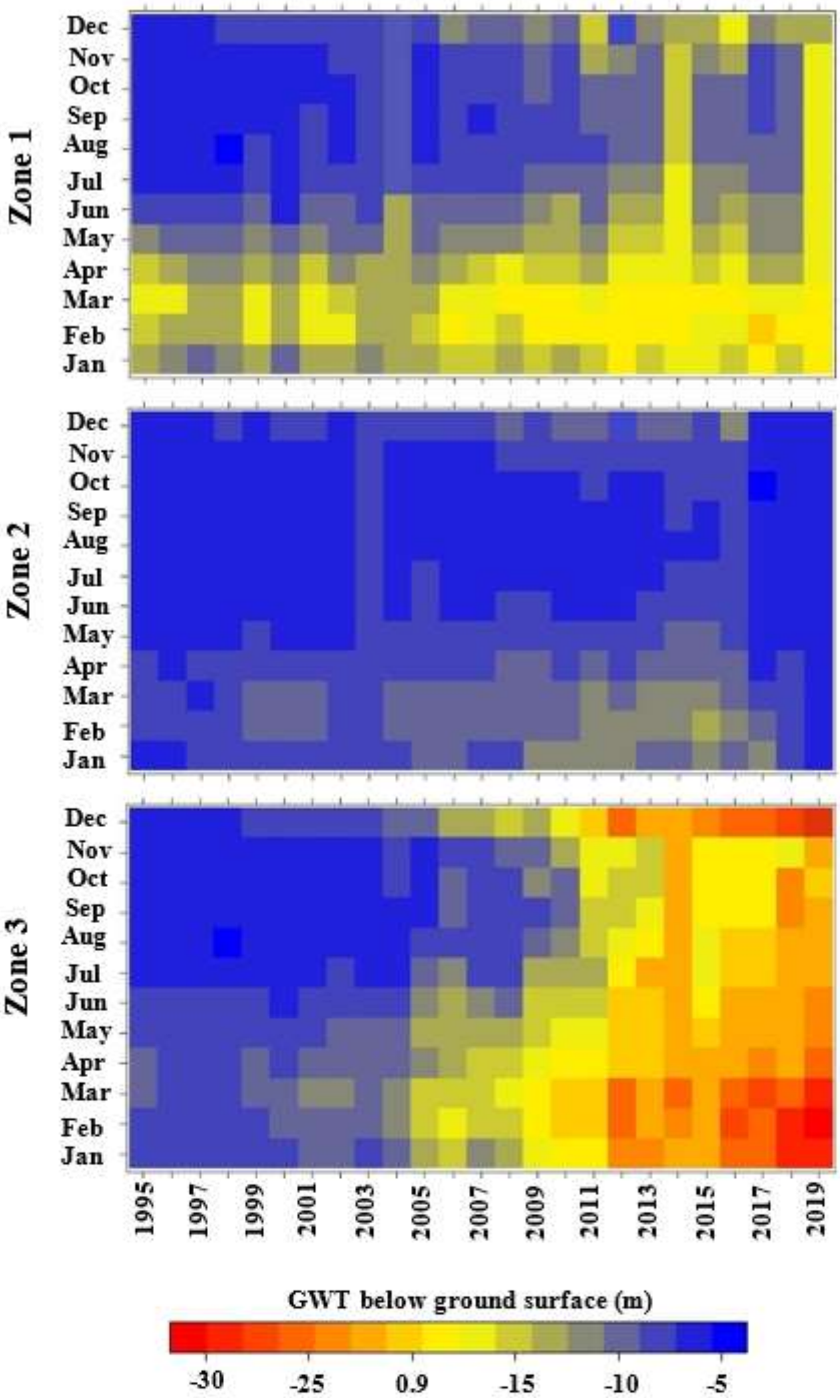


Figure 4 Level plot of the monthly mean GWT in the different climatic zones of Bangladesh.

The monthly gridded rainfall and PET data for three climatic zones are averaged and presented in Figure 5 as level plots. These plots are prepared to reveal the coherence of GWT with climatic variables. Rainfall is high in monsoon months, July to October, and low between November and February. Zone 2 receives the most rain, while Zone 3 receives the least. The PET is higher from February to June and lower in December and January in all three zones.

The seasonal pattern of GWT indicates a good coherence with the seasonal climatic pattern of the country. GWT goes down during low rainfall and high PET months, while it comes near to surface after monsoon when PET is less.

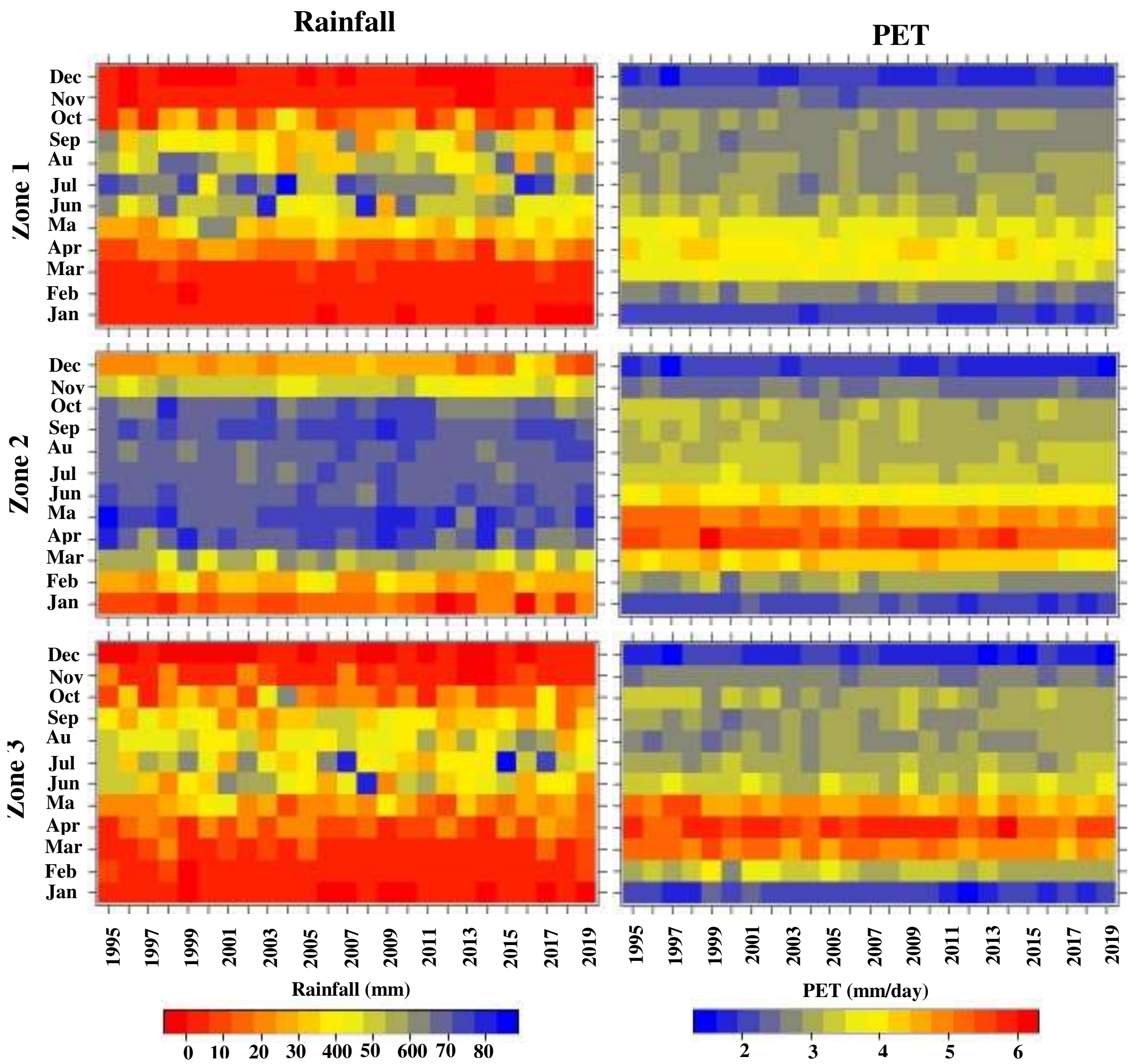


Figure 5 Level plot of the monthly mean of rainfall (left) and PET (right) in the different climatic zones of Bangladesh

4.2 Trends in mean and variability of GWT

Figure 6(a) shows that the mean GWT in Bangladesh ranged from 1.44 m to 48 m below the ground surface. The lowest GWT, ranging from 20 to 54 m below the ground surface, is found in the central and northwestern regions of the country. The highest levels of GWT (1.44 to 3 m) are observed mainly in the southern coastal region and some areas of the northeast and far northwest of the country. The GWT in the northeast part ranges from 2.5 to 10 m.

Trend analysis reveals decreasing GWT throughout the country, as shown in Figure 6(b). The declining rate is higher where the GWT is low. The GWT is decreasing at the highest rate in the central and northwestern parts of the country (0.548 to 1.398 m/year). In contrast, a significant increasing trend in GWT is noticed in the south and far north of the country.

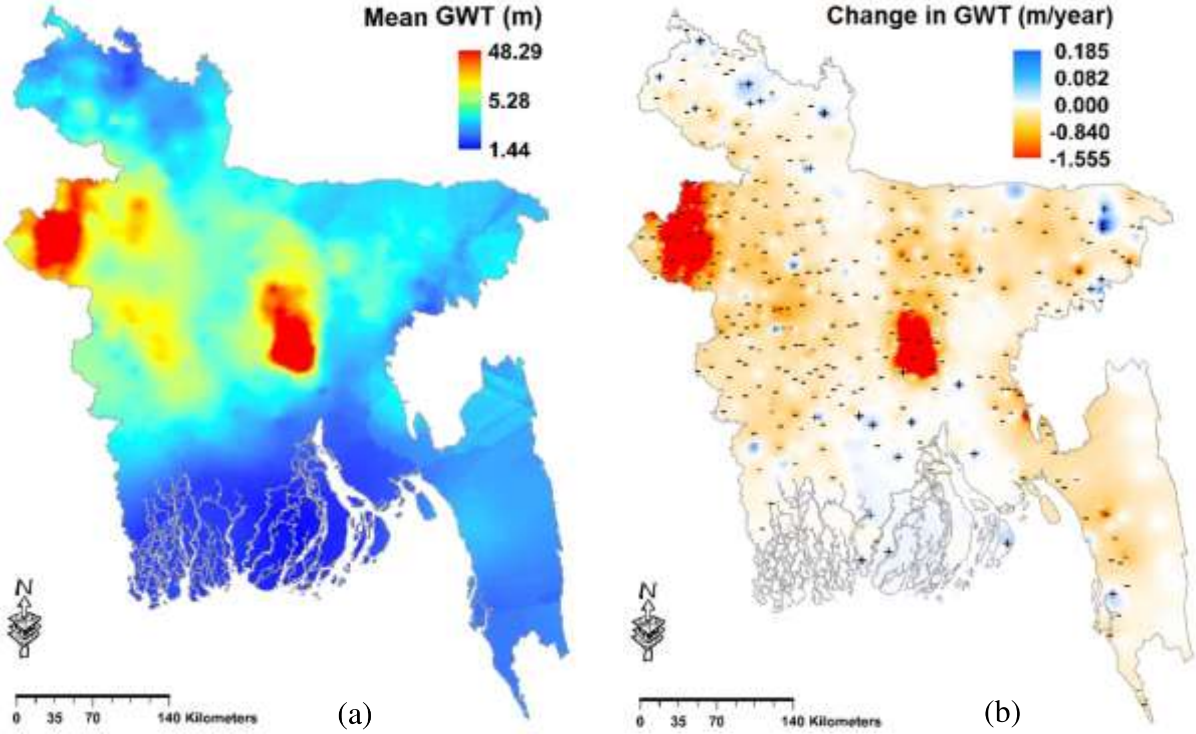


Figure 6 Spatial variability of (a) mean GWT (m); (b) the rate of change in GWT (right) in m/year, derived from BWDB GWT data for 1995–2019 using Sen's slope method. The color ramp represents change per year, whereas the sign '-' or '+' represent the significant decrease or increase in GWT derived using the M-K test.

The weekly variability of GWT in a year is estimated for all years between 1995 and 2019. The GWT variability time series at each location is then used to estimate the mean GWT variability and trends to prepare the corresponding maps. The results show higher variability in GWT in the northwest and upper central regions (Figure 7(a)). The GWT variability is as high as 5.51 m in the upper central region.

The trends in GWT variability indicate an increase all over the country (Figure 7(b)). The highest increase is noticed in some northwest and central regions. However, GWT variability is also decreasing at a few small patches, sporadically located in different regions.

The increased variability in GWT indicates a gradual increase in the lowest and the highest GWT within a year in most of Bangladesh.

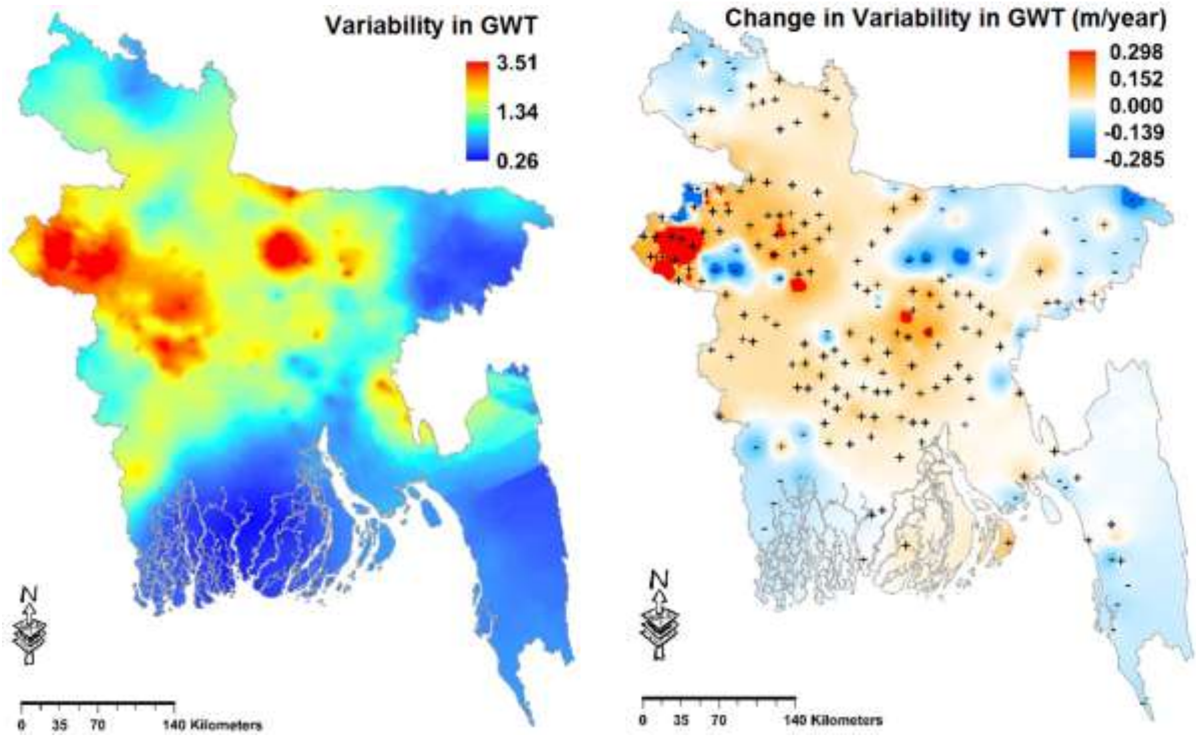


Figure 7 Same as Figure 8, but for GWT variability within a year

4.3 Groundwater sustainability

The RRV indicators and sustainability of GWT are calculated at each well of BWDB, interpolated using EBK method, and presented in Figure. 8. The GWT in Bangladesh varies from 0.178 to 0.810 (Figure 8(a)). Higher reliability in GWT is noticed in the country's north and centre-south regions, while the lower reliability is noticed at the patches in the northwest and central regions, where GWT is lowest, and over a major area in the northwest. The resiliency values are found relatively less (0.094-0.296) than reliability (Figure 8(b)). The highest resiliency is observed in the southern coastal region, which gradually decreases to the north, while the lowest resilience is noticed in the central and central north of the country. The GWT vulnerability in the country varies from 0.009 to 0.7 (Figure 8(c)). The vulnerability values are lowest in the northwest and central regions, particularly over the patches where GWT is the lowest. In the rest of the country, it is below 0.15. The lowest vulnerability (near zero) is noticed in the southern coastal belt.

The spatial distribution of GWT sustainability estimated from the aforementioned three indicators is shown in Figure 8(d). GWT sustainability in Bangladesh varies from 0.127 to 0.578. The spatial distribution of GWT sustainability indicates moderate to low sustainability (below 0.5) over the country. The highest sustainability is noticed in the southern coastal belt, where the lowest is in the central region, where GWT is the lowest, followed by some areas in the northwest and northeast.

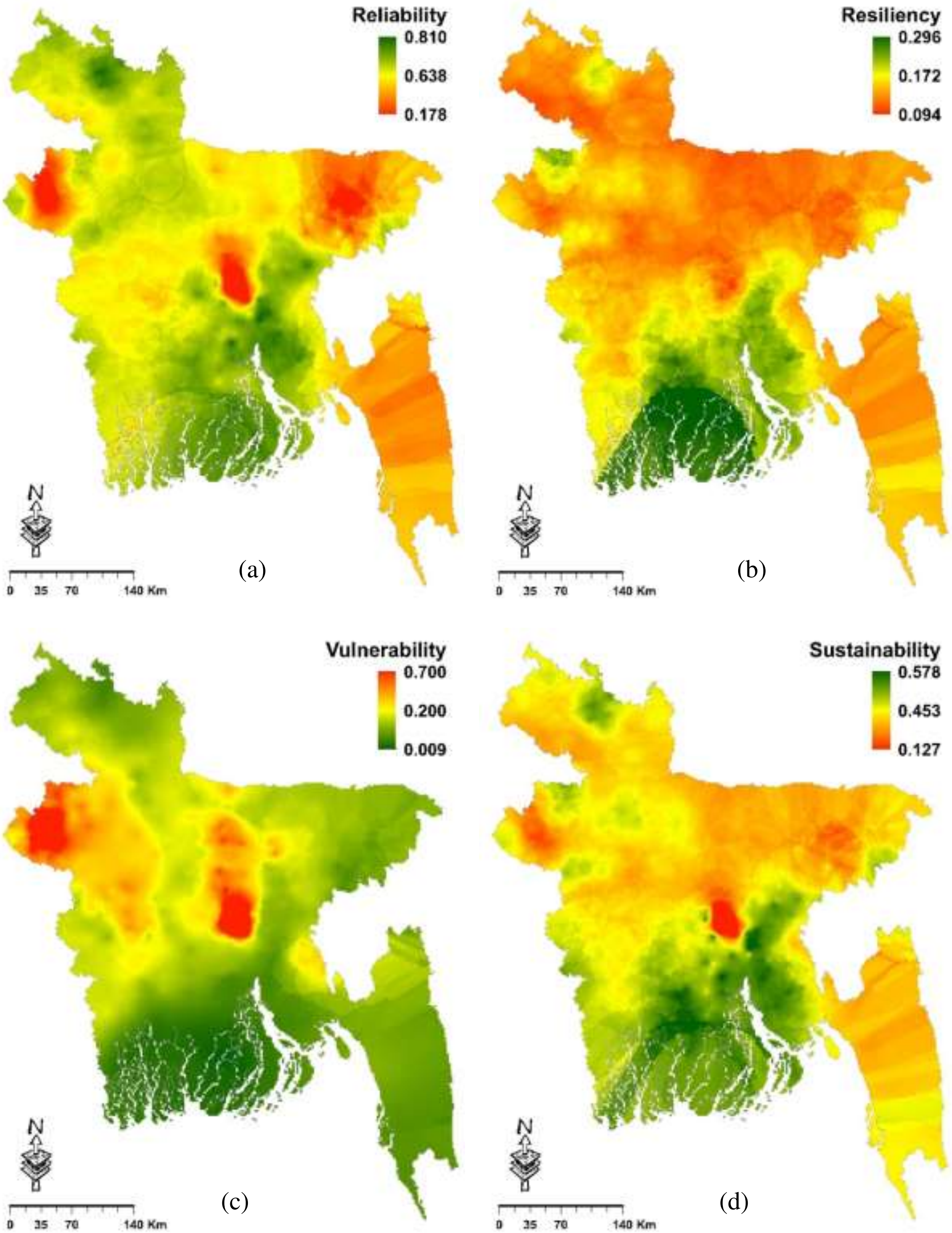


Figure 8 The spatial distribution of GWT (a) reliability; (b) resiliency; (c) vulnerability; and (d) sustainability estimated using the BWDB GWT data during 1995–2019.

4.4 Trends in groundwater sustainability and its indicators

The weekly GWT data was used to estimate RRV indicators and sustainability in GWT for each year to prepare the corresponding time series and trend analysis at each location. The obtained trends in RRV indicators and sustainability are shown in Figure 9. The reliability in the country is noticed to change in the range of -0.259 to 0.101 per year (Figure 9(a)). The spatial distribution of GWT reliability trends revealed a decrease in most of the north half and southeast, while an increase in the south of the country. The highest decrease (0.20 to 0.259 per year) in reliability is observed in the regions where it is already low. The resiliency showed an increasing trend over most of the country, except in the northeast and southeast (Figure 9(b)). However, the decrease is significant in only a few locations. Interestingly, an increase in GWT resiliency is noticed in the regions where GWT is very low.

The vulnerability in GWT is changing between -0.047 to 0.107 per year in Bangladesh (Figure 9(c)). The spatial distribution of GWT vulnerability is different from the other two indicators. It is increasing in the north, central north and central west of the country while decreasing at a few locations sporadically distributed in the south, southeast and west. The trends in sustainability reveal a change in the range of -0.095 to 0.084 per year (Figure 9(d)). Overall, an increase in GWT sustainability is noticed over the country, except in the central north and some sporadically distributed patches in different regions. The largest increase in GWT sustainability is observed in the southeast by 0.084 per year, while the largest decrease is in the central north by -0.095 per year. There is no significant change or a minor increase in GWT sustainability at the locations where GWT is decreasing at a higher rate.

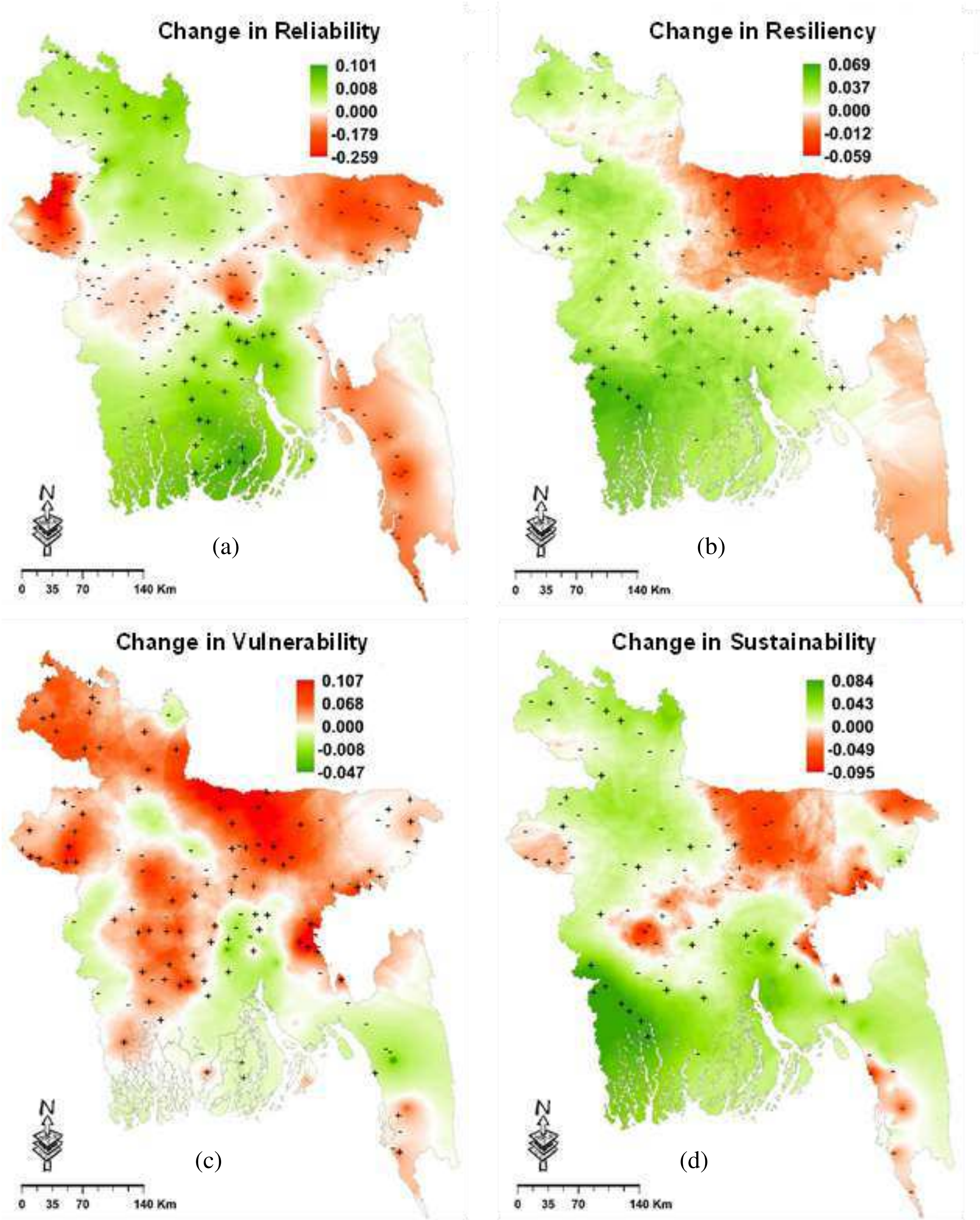
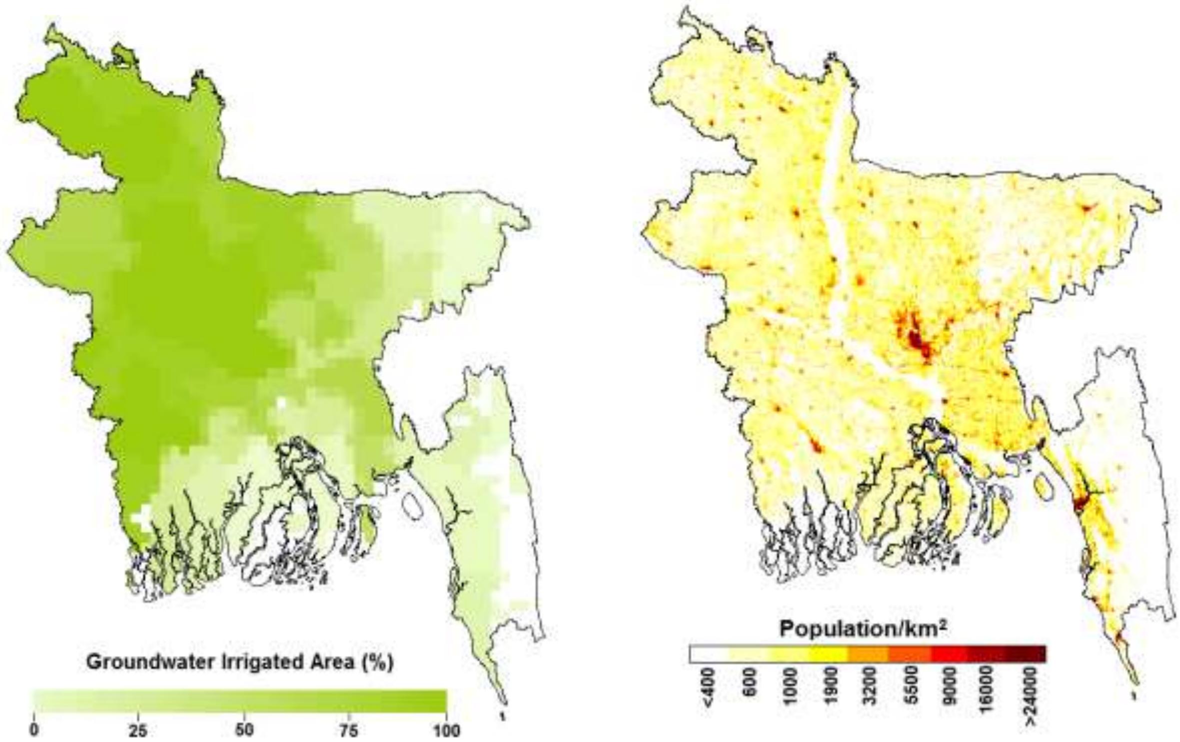


Figure 9 The change in (a) reliability; (b) resiliency; (c) vulnerability; and (d) sustainability based on Sen's slope values derived from BWDB GWT data during 1995–2019. The color ramp represents the change per year, whereas the sign '-' or '+' represent the significant decrease or increase in GWT derived using the M-K test.

5. Discussion

The GWT showed coherence to the climate of different Köppen-Geiger climate zones. Rainfall is much higher in Zone 2 than the other two climate zones, and therefore, GWT is higher in Zone 2 than the other two zones. GWT goes up during post-monsoon months due to recharge from high monsoon rainfall. It goes down to the lowest level during the premonsoon months due to insufficient recharge for a longer period due to inadequate rainfall during winter months and high PET in premonsoon months (Figure. 7). This demonstrates the sensitivity to groundwater availability to climate throughout the country. The results also indicate the possible implication of climate on GWT in the country. Rising PET due to increasing temperature while inhomogeneous changes in rainfall have been projected for the country (Alamgir et al., 2019; Pour et al., 2019). These changes would have significant impacts on GWT.

It is required to understand the main anthropogenic drivers of GWT to understand the cause of the spatial variability of GWT and their trends. Nearly 90% of total groundwater in Bangladesh is used for irrigation, and the rest 10% for drinking and domestic purposes (Hanasaki et al., 2018). The groundwater irrigation and population density maps of Bangladesh are shown in Figure 10. The 10-km resolution global data of the irrigated area (version 5) (Siebert et al., 2013) and LandScan population data of 2019 are used to generate the maps. Figure 10(a) shows intensive groundwater irrigated regions in the north, northwest, central west and central north of the country. High groundwater abstraction in the regions caused a decline of GWT; therefore, the mean GWT is less in those areas. The lowest GWT is observed over a strip in the northwest and a small patch in the central region. Figure 10(b) shows a high population concentration in the central region (Dhaka), where GWT is the lowest. The drinking and domestic water supply in the city mainly come from groundwater. Therefore, a higher abstraction of groundwater of domestic supply caused the mean GWT to be low in the region. The northwest strip with the lowest GWT coincides with High Barind Tract, a distinct uplifted (40–50 m above sea level) zone. The uplifting of land caused aquifer depth in the region to be very high.

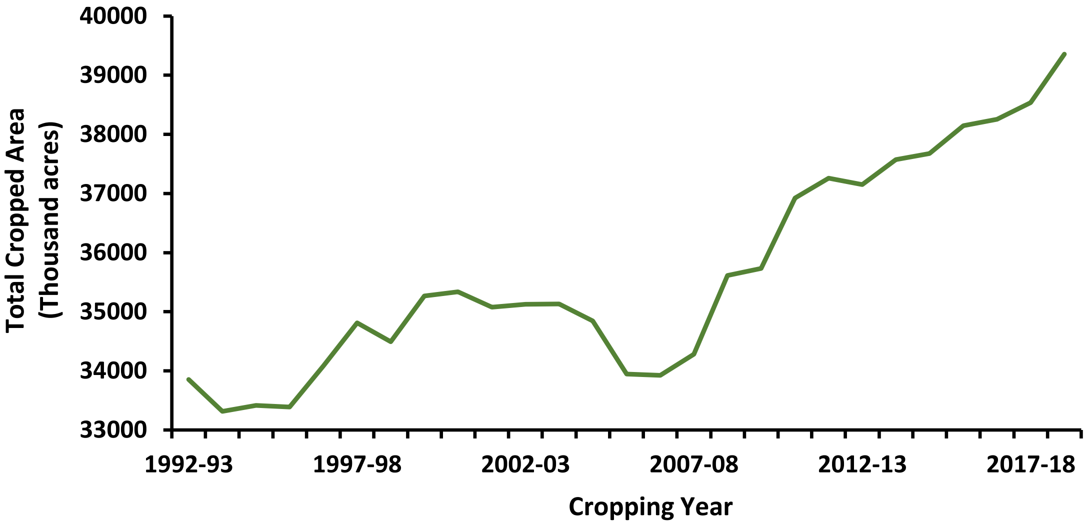


(a) (b)

Figure 20 (a) percentage of area equipped for groundwater irrigation; (b) population density in 2019.

The spatial distribution of GWT trends reveals significantly declining GWT trends throughout the country. This is largely due to intense and imbalanced groundwater abstraction compared to the recharge for irrigation and domestic purposes. The trends in groundwater irrigated cropland in Bangladesh is shown in Figure 11(a). The groundwater irrigated cropland of Bangladesh has increased at the rate of 208.08 thousand acres/cropping year) over the last three decades. Increased abstraction of groundwater to irrigate the expanding land caused a declination of GWT in the northwest and central region of Bangladesh. However, the GWT trend showed the highest declination of GWT in Dhaka city. This is due to the increased abstraction of groundwater to meet the growing population's demand. Figure 12(b) shows the population density of Dhaka city has increased rapidly with time. This caused a continuous increase in groundwater abstraction in the vicinity, which caused a sharp declination of GWT. The obtained results agree with the previous studies conducted for different periods (Hanasaki et al., 2018; Mojid et al., 2019; Shamsudduha et al., 2011).

(a)



(b)

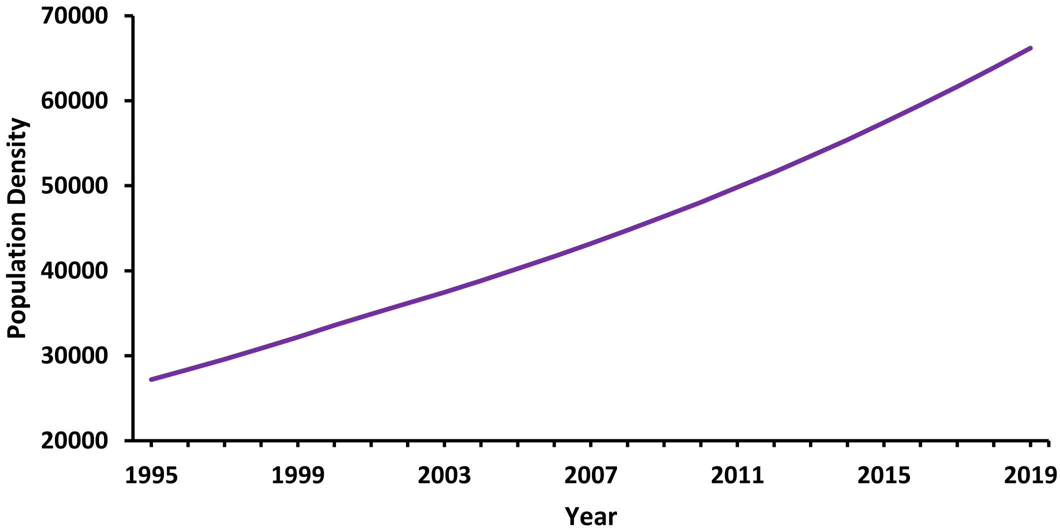


Figure 31 Change in (a) the total cropped area (thousand acres) from 1992-93 to 2018-19; (b) population density (people/km^2) of Dhaka city during 1995-2019 (BBS, 2021)

The present study also showed an increase in year variability of GWT almost all over the country. This means the yearly lowest GWT is becoming lower, and the highest GWT is becoming higher with time. The higher abstraction of groundwater caused a large declination of GWT during the dry season. However, groundwater recharge during monsoon helps the GWT return high in the post-monsoon months. Recent studies showed increased rainfall in some parts, particularly the western part of Bangladesh (Shahid, 2010). A higher concentration of rainfall has also been reported in the monsoon months (Mohsenipour et al., 2020). This may cause a higher recharge of groundwater in the monsoon and thus, make the GWT more variable. However, a declining trend in GWT indicates a higher decline in yearly lowest GWT during premonsoon than an increase in yearly highest GWT in post-monsoon.

Trends in GWT reliability showed a decrease in the regions where GWT is decreasing. It is justifiable as the declining trend caused GWT a longer period below the threshold. The resiliency is noticed to increase in most Bangladesh, including in the region where GWT is decreasing. This is due to the increased variability of GWT, which caused the GWT to return to the satisfactory level more frequently. The vulnerability increased in most regions in the country's northern half, particularly intensively irrigated regions. This is due to the large declination of GWT in premonsoon months caused by the large groundwater abstraction for irrigation. The GWT sustainability is noticed to decrease mostly in the central northern region, while it is increasing and in most of the northwest regions where GWT is decreasing. This may be due to increased groundwater recharge in the region driven by increased rainfall. Shahid (2010) showed a significant increase in annual and premonsoon rainfall in the west part of the country. This is also visible from the resiliency trend of the country. The increased resiliency caused increased GWT sustainability in the northwest water stress region. In contrast, no change in rainfall but a continuous increase in groundwater abstraction has caused a declining trend in GWT sustainability in the central north. Here, it should be noted that the GWT sustainability trend is estimated considering weekly GWT data in a year. Therefore, the increased GWT in the post-monsoon months contributed to an increase in GWT sustainability. In the future, data only for the irrigation period (January to April) can be considered to assess groundwater sustainability.

In Bangladesh, groundwater levels are affected by irrigation during the dry season in most parts of the country except in the coastal region, where groundwater use is less for dry-season rice cultivation. In the northwest region, where groundwater abstraction for irrigation is the highest, dry season water levels dropped over time. However, in many areas where the deposited clay thickness is thin or eroded over time, dry-season water levels kept dropping, while the wet-season levels remained relatively stable or slightly decreasing. This is due to increased groundwater storage resulting from sustained groundwater pumping for irrigation. This is also seen in other parts of the country where surface geology and rainfall favour increased groundwater recharge over time (Shamsudduha et al., 2011). In those areas, the sustainability index may not properly reflect the increased groundwater storage over time due to induced recharge from pumping rather than decreasing over time. In those areas, perpetual groundwater decline in the dry season does not mean the depletion of groundwater storage. Besides, groundwater quality, such as arsenic and salinity in the south, is a major concern in the country (Shamsudduha et al., 2021). Groundwater sustainability analysis in this study considered only storage but also quality. In the future, the points mentioned above should be considered to assess the changes in groundwater sustainability of Bangladesh.

6. Conclusion

The study used BWDB GWT data of 844 observation wells to assess spatiotemporal variability and sustainability. The trends of GWT are estimated from BWDB data for the period 1995–2019 using the M-K at a 95% significance level. Besides, the reliability, resiliency, and vulnerability in GWT are estimated and subsequently employed to calculate groundwater sustainability. The trends in RRV indicators and sustainability are also assessed. The main conclusions of this study can be summarized as follows. (1) GWT shows coherence with different climate zones. The temporal variations in GWT reveal distinctive groundwater patterns in three different climatic zones, indicating dependency on GWT climate. (2) Mean GWT is remarkably low in the northwest and central (Dhaka), representing groundwater stress in the region. (3) GWT is declining almost all over the country, with the highest rate in the region where GWT is already low, indicating an increasing groundwater scarcity in those areas. (4) The cause of the GWT decrease in Dhaka is increased abstraction to meet the domestic need, while in the northwest, the increased abstraction for irrigation. (5) The country's groundwater has remarkably low sustainability for most areas, particularly in parts of central and northern regions. (6) GWT sustainability is decreasing in some areas, with the highest rate of decrease in the central north.

This study successfully identified the areas where the groundwater level is critically low and alarmingly declining and the areas with the lowest sustainability and highest decreasing rate. The findings would help policymakers put special emphasis on those areas to ensure balanced and sustainable groundwater management to protect and rejuvenate the groundwater system of the country. This study has some aspects that limit the accuracy of the results to some extent. BWDB GWT data contain some or a few missing data in the majority of the wells. Although they were filled using the cubic spline method, the precision of the RRV approach was compromised to some extent. Furthermore, there are limited wells to observe the deep aquifers (only two wells greater than 250 m depth).

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Conflict of interest

The authors declare no conflict of interest.

Funding

Not Applicable

Authors contribution

All the authors contributed to conceptualizing and designing the study. Abul Kashem Faruki Fahim gathered data, prepared the figures, and wrote the first draft. ASM Maksud Kamal validated the results, revised the article repeatedly to prepare the final version and coordinated the whole research. Shamsuddin Shahid developed the codes for data analyses and helped others prepare results and complete the research article.

Availability of data and materials:

Climate data used in this study are available in the public domain. Requests can be made for groundwater table data online through the official website of Processing and Flood Forecasting Circle, BWDB (http://www.hydrology.bwdb.gov.bd/).

Code Availability

The codes used for data processing can be provided on request to the corresponding author.

Ethics approval

Not Applicable

Consent to participate

Not Applicable

Consent for publication

All the authors consented to publish the paper

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