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ORIGINAL ARTICLE

Evaluation of spatio-temporal dynamics of water table in NW Bangladesh: an integrated approach of GIS and Statistics

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Abstract The aims of this study are to determine and evaluate the spatial and temporal changes in the groundwater table for the period of 1991–2009 and probable causes of changes of water table depth in northwest (NW) Bangladesh. Trends analyses have been done by linear regression, Mann–Kendall Trend Test and Sen's slope estimator; and spatial analysis by Geographical Information Systems (GIS). The results show decreasing trends in dry and monsoon seasons and annual average groundwater level except a few discrepancies in NW Bangladesh, though the magnitudes of changes very spatially and methodically. Very strong declining trends with high magnitude of changes in all three series that are significant at 99 % confidence level found in the central part of the area where the rate of changes vary from 0.82 to 0.2 m/year in dry season, from 0.67 to 0.2 m/year during monsoon season and 0.6 to 0.1 m/year in annual average time series. Declining trends with low rate of changes are found in the rest of the areas except some pocket areas. The drop of groundwater level is also very high in the central part. Falling trends and drop of groundwater level indicate unsustainable withdrawal of groundwater over the study area. Findings of study indicate rigorous abstraction of groundwater for irrigation, decreasing trend in rainfall and surface geology of the area are attributed to rapid declining trend in groundwater level. Situations will be irreversible if necessary steps are not taken beforehand.

Keywords Groundwater table dynamics · Mann–Kendall trend test · Sen's slope estimator · Linear regression · GIS · North West Bangladesh

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Introduction

Groundwater depletion has been recognized as a global problem and the estimated global groundwater depletion during 1900–2008 is about 4500 km^3 with the maximum rates occurring from 2000 to 2008 (Konikow 2011). Groundwater use for irrigation has intensified around the world. Groundwater-based irrigation is directed to cultivate high-yielding rice during the dry season in South Asia where India and Bangladesh represent the world's second and fourth biggest rice-producing nations, respectively (Scott and Sharma 2009; IRRI 2010). According to Fourth Assessment Report (FAR) in Bangladesh urbanization and industrialization, population growth and inefficient water use cases increase water shortages and its adverse impacts on demand, supply and water quality which increase under changing climate (IPCC 2007). Recent studies in

Bangladesh reported declining trends in groundwater level which indicate unsustainable groundwater abstraction for both irrigation and urban water supplies. Sarkar and Ali (2009) studied water table (WT) dynamics of Dhaka city and its long-term trend analysis by nonparametric Mann–Kendall (MK) Test and Sen's slope estimator. This study reveals that groundwater level in Dhaka city decreases rapidly. Ali et al. (2012) studied sustainability of groundwater resources in the North-Eastern Region of Bangladesh. This study has also been carried out by nonparametric MK Test and Sen's slope estimator using yearly maximum groundwater level of 35 groundwater observation wells during the period 1985–2004. The study indicates that the depth to WT of almost all the wells is declining. In most cases, the depth to WT will approximately double by 2060, if the present trend continues. Jahan et al. (2010) analyzed the long term trend of groundwater level by parametric linear regression method in Barind area; NW Bangladesh. This study also reveals that groundwater level in Barind area decreases. Barind Integrated Area Development Project (BIADP) under the Barind Multipurpose Development Authority (BMDA), to achieve sustainable agricultural growth and to maintain ecological balance, was launched during late 80s of the last century in the NW Bangladesh. Groundwater has been the source of irrigation in the agro-based Barind area, with exploitation by Deep Tube wells (DTWs) and Shallow Tube wells (STWs) (Jahan et al. 2010). BMDA takes initiatives to ensure annual withdrawal of groundwater less than the annual recharge to keep the groundwater level in position. Groundwater exploration in the area is going on the basis of one-third rainfall (Asaduzzaman and Rushton 2006) recharge hypothesis of BMDA that is beyond the sustainable yield (Islam and Kanumgoe 2005). The groundwater-based irrigation system in the area has reached a critical stage as the phreatic water level has dropped below shallow wells in many places (BADC 2005). About 75 % of the land in study area is used for agricultural practice among which 31, 56, 13 % and land are used for single cropping, double cropping and triple cropping, respectively (Shahid and Hazarika 2010). Rice is the dominant crop in the area and about 78, 67 and 47 % of cultivated areas are used for HYV *Aman*, HYV *Boro* and HYV *Aus* cultivation. Moreover, wheat and potato are cultivated in 27 and 39 % of the cultivable area. Rabi (winter) and summer vegetables are also cultivated in less than 5 % area. About 63 % of the land in the area is under irrigation (BMDA 2006) and almost 75 % of the irrigation water comes from groundwater (Jahan et al. 2010).

A number of studies have been carried out on hydrogeology (Ahmed and Burgess 1995; Islam and Kanumgoe 2005), groundwater occurrence potential (Azad and Bashar 2000) and flow of groundwater (Jahan and Ahmed 1997) of the study area. Until recently, no comprehensive studies have been carried out on trend analysis of groundwater level by both parametric and nonparametric methods in NW Bangladesh. The objectives of the study are (1) to detect trends in the annual and seasonal time series of groundwater level for the period of 1991–2009 by both parametric and non-parametric methods (2) to find spatial pattern of trends and WT dynamics by GIS and (3) to explore possible causes of changes in groundwater level over the study area. It is expected that the findings of the study will bring about more insights for understanding spatiotemporal groundwater dynamics in the area and help local water resource managers to take decisions for sustainable use of this resource.

Materials and methods

Study area

The study area, former Greater Rajshahi district that includes newly formed Chapai Nawabganj, Naogaon and Rajshahi districts which include 25 Upazilas (sub-district) in the NW Bangladesh (Fig. 1), covers an area of 7587 km^2. Geographically, the area extends from 24°08′N to 25°13′N latitude and from 88°01′ to 89°10′E longitude. This area enjoys a subtropical monsoon climate characterized by three seasons: winter (Nov–Feb) which is characterized by cool and dry with almost no rainfall; pre-monsoon (Mar–May) characterized by hot and dry; and monsoon (Jun–Oct) characterized by heavy rainfall. The annual average rainfall for the period 1980–2006 is 1600 mm which is less than the national average of 2550 mm in the study area (Jahan et al. 2010).

The study area, NW Bangladesh, is characterized by two distinct landforms (1) the Barind Tract which is dissected and undulating and (2) the floodplains. The area lies in the catchment of the River Ganges (Padma) with drainage system predominantly of the Atrai, Mahananda, Purnabhaba rivers and other minor seasonal streams. Without the Padma, all others are seasonal in nature. Physiographic map of the study area is shown in Fig. 2. According to the soils classification of Soil Resource Development Institute (SRDI 1997) of Bangladesh, the high Barind area that covers the central part of the study area is characterized by mainly level terrace soils and closely dissected terrace soils which are also called Dystric (some Eutric) Cambisols (FAO/UNESCO 1969 supplement, cited in Jahan 1997, 1997), mainly with map leveled fields, whereas, the southwestern corner of the area along the Padma river is characterized by calcareous alluvium that is called Calcaric Fluviosols according to FAO/UNESCO classification (1969). The rest of the southern and southwestern parts of

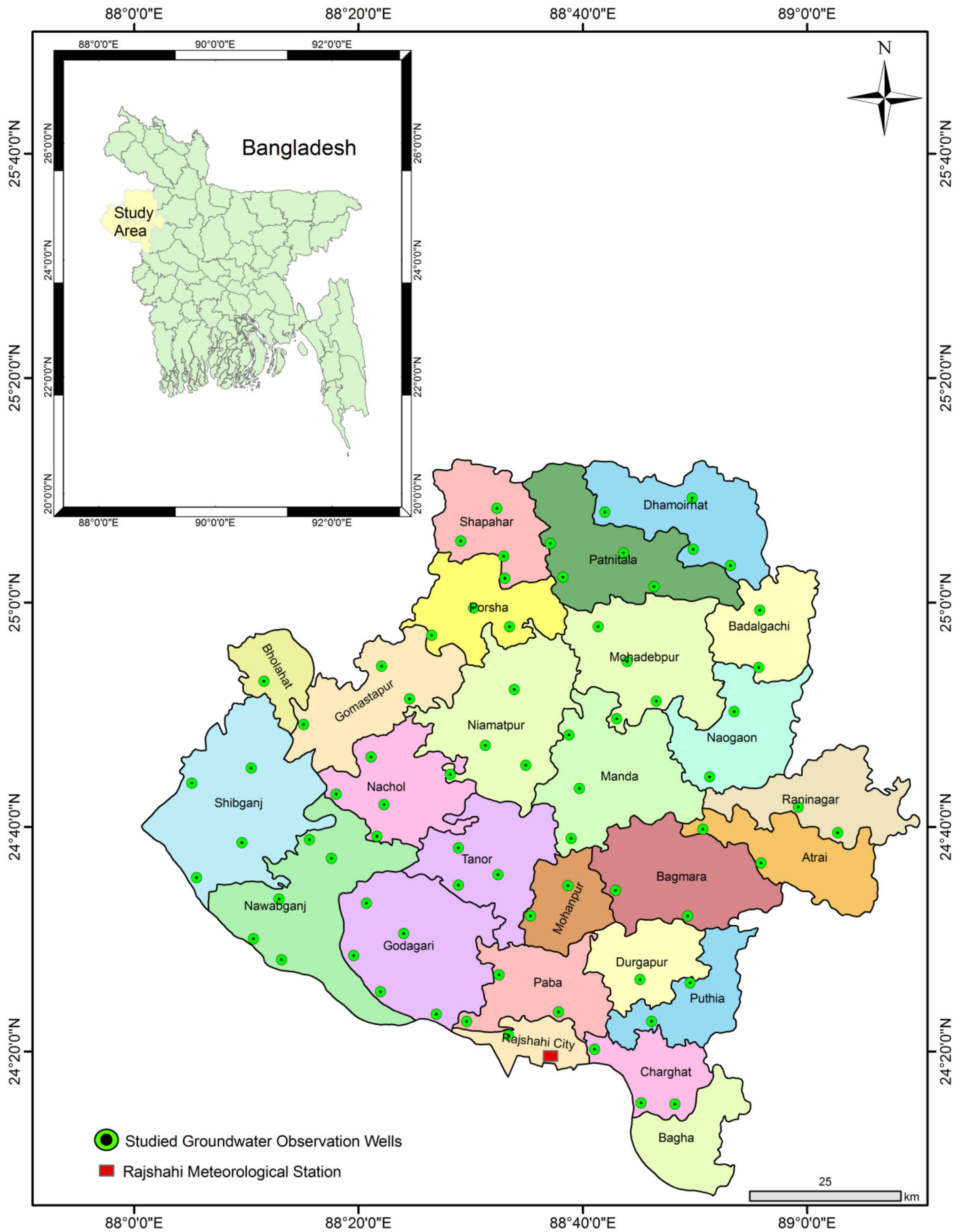

Fig. 1 Study area with locations of groundwater observation wells and meteorological station

the area covering parts of Bholahat, Gomastapur, Chapai Nawabganj Sadar, Rajshahi City, Paba, Puthia, Charghat and Bagha Upazilas are characterized by calcareous dark grey floodplain soils which are called mainly Calcaric Gleysols with some vertisols (FAO/UNESCO 1969) and calcareous brown flood plain soils also called as Calcaric Cambisols with some Calcaric Gleysols (FAO/UNESCO 1969) which are mixed highland, shallowly flooded and deeply flooded phases. Mainly calcareous dark gray floodplain soils are found in Mohanpur and Bagmara

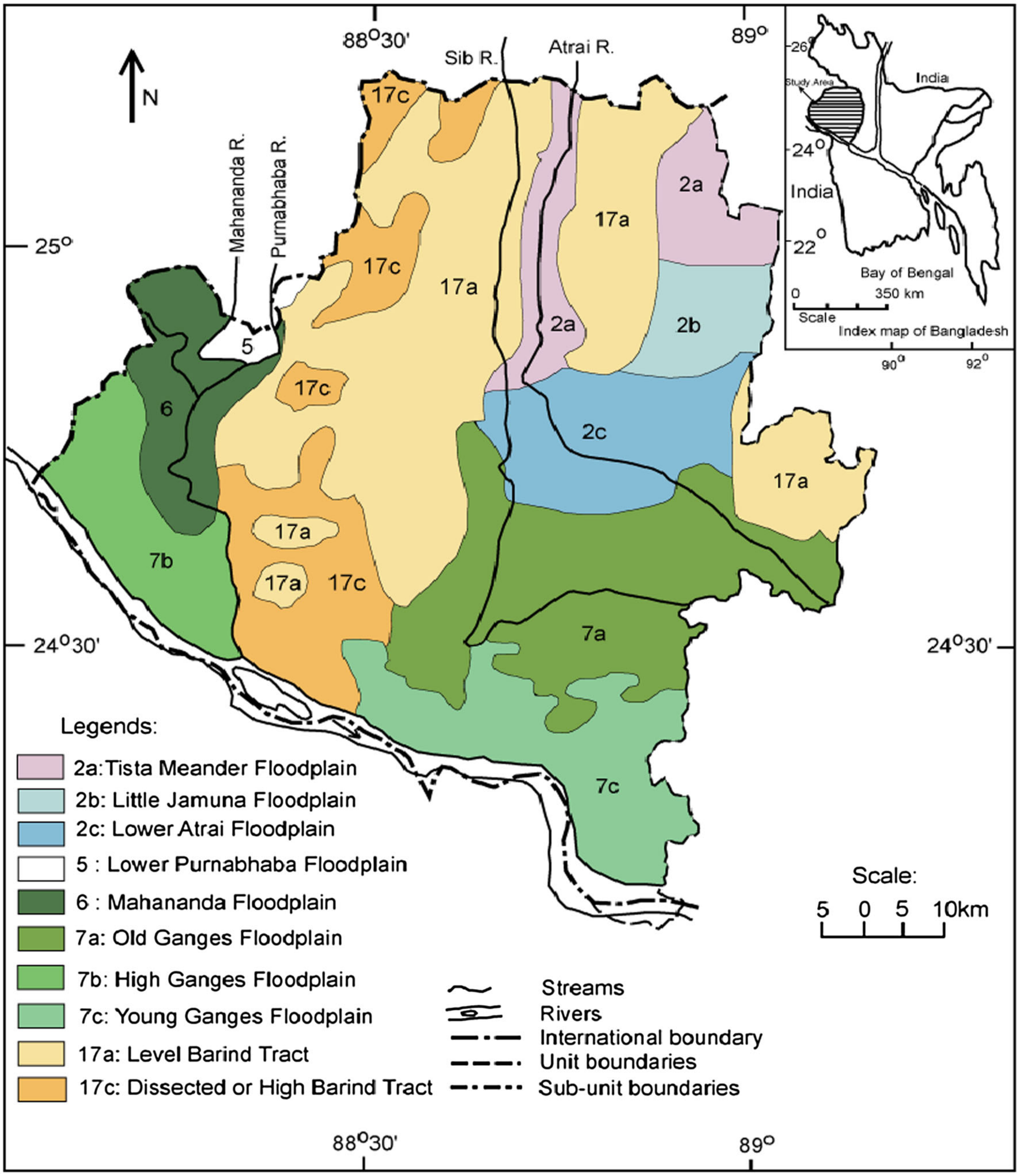

Fig. 2 Physiographic map of the study area (Alam 1998; Brammer 1996)

Upazilas and gray flood plain soils which are mainly shallowly flooded silty soil are present along little Jamuna River and shallowly flooded loams and some sands along Atrai river in the northeastern part of the area. The accretion to groundwater by rainwater and floodwater during monsoon results in the rise of groundwater level. After monsoon, part of the water recharged into groundwater body gets discharged into the rivers, streams and low-lying areas (Jahan et al. 2010). Geologically, the area compose of the stream and inter-stream Recent and Pleistocene sediments. Neogene sediments directly overlie the Gondwana sediments. The Barind Tract flanked by actively subsiding regions has formed into horst block at the close of the Pleistocene (Morgan and McIntire 1959). Faulting is still active with vertical movement at rate of 0.4–1.1 mm/year (Hoque 1982). Aquifer system of NW Bangladesh is characterized by single to multiple layered (two, four) Plio-Pleistocene age (thickness 5.0–42.5 m) and in Barind area where semi-impervious clay-silt aquitard of Recent-Pleistocene period (thickness 3.0–47.5 m) is found (Jahan et al.

2007). According to Jahan (1997), the aquifer characteristics of the area reveal (1) lower values of transmissivity (<500 m^2/day) in the central part which is suitable for domestic water supply, (2) medium (500–1000 m^2/day) and (3) higher (>1000 m^2/day) transmissivity values in the rest part that is suitable for irrigation and domestic needs.

Data

The WT data are collected from Bangladesh Water Development Board (BWDB) which is the department responsible for water related records. Depths to WT are recorded fortnightly by 'water level indicator'. There are more than 140 groundwater observation wells in the study area, but almost 50 % (some are new wells with few years of record, some have data with more than 50 % missing record) of wells have not available information. Only 73 wells have long-term good records. Analyses are restricted to the period 1991–2009 in order to find out the consistent dominant observations of the majority of monitoring wells. To explore the possibility that trends may be seasonally varying, three different annual series are analyzed well wise: the mean, maximum and minimum of each year's observations. Trends in annual maximum (observed at the end of dry season) time series correspond roughly to changes during the dry period and trends in annual minimum (observed at the end of monsoon season) time series to changes in the wet season groundwater level. Locations of the studied wells are shown in Fig. 1. Rainfall data of Rajshahi station, the only meteorological station in the study area, and of Bogra station, the nearest but not located in the study area, have been analyzed. Rainfall data of these stations were collected from Bangladesh Meteorological Department (BMD). Time series data of irrigated areas by STWs, DTWs and Power Pumps (PPs) and rice production have been collected from Statistical Yearbooks of Bangladesh published by Bangladesh Bureau of Statistics (BBS 1991–2011).

Trend analysis

Several techniques have been performed for trend analysis in hydro-meteorological records by parametric (linear regression) and non-parametric (Mann–Kendall Test, Sen's slope estimator) methods. Classical approaches such as Mann–Kendall Trend Test (Mann 1945; Kendall 1975) and Sen's slope estimator (Sen 1968) have been widely used for testing trends in hydrological time series (Hirsch et al. 1982; Aziz and Burn 2006; Lee et al. 2006; Thas et al. 2007; Choi and Lee 2009; Sarkar and Ali 2009; Tabari et al. 2011; Ali et al. 2012). In the present study, both parametric and non-parametric methods are used to detect trends in groundwater level time series. Each method has its own advantages and disadvantages. The main advantage of parametric methods is their simplicity, but their correct use requires data to be normally distributed. However, nonparametric methods have the advantage of not assuming any distribution form for any sets of data, have the power similar to its parametric competitors (Zhang et al. 2008) and it can handle outliers appropriately (Partal and Kahya 2006).

Mann–Kendall test

For time series with fewer than 10 data points, the S test is used; for time series with 10 or more data points, the Z test is used.

MK Test is based on the test statistic S, which is given as:

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

$$\operatorname{sign}(x_j - x_k) = \begin{cases} +1 & \text{if } (x_j - x_k) > 0 \\ 0 & \text{if } (x_j - x_k) = 0 \\ -1 & \text{if } (x_j - x_k) < 0 \end{cases} \tag{2}$$

The value of S indicates the direction of trend. A positive value of S indicates increasing trend and vice versa. MK has documented that when data size is ≥ 10, the test statistics S is approximately normally distributed and variance as follows:

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

where, m is the number of tied groups and t_i is the size of the ith tie group. The test statistic $\mathbf{Z}$ is computed as:

$$Z = \begin{cases} \frac{S-1}{\sqrt{\operatorname{Var}(S)}}, & \text{for } S > 0 \\ 0, & \text{for } S = 0 \\ \frac{S+1}{\sqrt{\operatorname{Var}(S)}}, & \text{for } S < 0 \end{cases} \tag{4}$$

The null hypothesis, H_o; that there is no trend in the records is either accepted or rejected depending on whether the computed Z statistic is less or more than the critical value of $\mathbf{Z}$ statistic. In the study, significant levels $\alpha = 0.01$, 0.05 and 0.1 corresponding to 99, 95 and 90 % confidence levels, respectively, have been applied.

Sen's slope estimator

In this research, Sen's slope nonparametric approach is used to estimate the true slope of an existing trend (as change per unit time) where it is assumed to be liner. The estimation of slope of N pairs of data involves the following procedures.

$$Q_i = \frac{x_i - x_k}{j - k} \quad (5)$$

where $j > k$ and x_i and x_k are data values at times j and k, respectively.

The Sen's slope estimator is given by the median slope as:

$$Q_{\text{med}} = Q_{[(N+1)/2]} \quad (6)$$

where N is odd, or

$$Q_{\text{med}} = \frac{1}{2}\left(Q_{(N/2)} + Q_{[(N+2)/2]}\right) \quad (7)$$

where N is even.

Finally, Q_{med} is estimated by the nonparametric method based on the normal distribution and tested with a $100(1-\alpha)$ % two-sided confidence interval. In the present study, confidence intervals are obtained at different confidence levels. The computing procedures are as follows:

$$C_\alpha = Z_{1-\alpha/2}\sqrt{\text{VAR}(S)} \quad (8)$$

where, VAR(S) is computed by Eq. (3) and $Z_{1-\alpha/2}$ is obtained from the standard normal distribution. Further, $M_1 = (N - C_\alpha)/2$ and $M_2 = (N + C_\alpha)/2$ are calculated. The lower limit ($Q_{\min}$) and upper limit ($Q_{\max}$) of the confidence interval are the M_1th largest and $(M_2 + 1)$th largest of the N ordered slope estimates Q_i. If M_1 is not a whole number the lower limit is interpolated. Correspondingly, if M_2 is not a whole number, the upper limit is interpolated (Salmi et al. 2002). "*R*" statistical language by *R* Development Core Team has been used for statistical analysis and "Kendall" and "ZYP" packages have been used.

Linear regression method

Linear regression is commonly used as a parametric method for identifying linear trend in time series data. It is used to obtain the slope of hydro-meteorological variables on time (Tabari and Talaee 2011). Positive values of the slope indicate increasing trend and vice versa. For liner regression analysis software IBM SPSS version 18 has been used.

Geostatistical analysis

In the present study, the inverse distance weighting (IDW) method is used to interpolate groundwater table depth, magnitude of change and values of MK '**Z**' statistic. This method has been used for interpolation of hydrological data by many researchers and finds good results (e.g., Buchanan and Triantafilis 2009; Chen and Liu 2012; Ahmadian and Chavoshian 2012). It is based on the assumption that the weighted average of known values within the neighborhood is used to estimate the value of an unsampled point (Lu and Wong 2008). Details about the IDW methods can be found in Burrough and McDonnell (1998). In this study, Interpolation by IDW method is performed using the Geostatistical Analyst tool integrated into ArcGIS 9.3 software. The interpolation by IDW method follows the following formulas:

$$\widehat{R}_{\text{p}} = \sum\nolimits_{i=1}^{N} W_i R_i. \quad (9)$$

$$W_i = \frac{d_i^{-\alpha}}{\sum_{i=1}^{N} d_i^{-\alpha}} \quad (10)$$

where $\widehat{R}_{\text{p}}$ means the unknown depth of GWT (m); R_i means the depth of GWT (m) data of known groundwater monitoring observation wells; $\boldsymbol{N}$ means the amount of groundwater monitoring observation wells; W_i means the weighting of each groundwater monitoring observation well; d_i means the distance from each groundwater monitoring observation well to the unknown site; α means the power, and is also a control parameter. For other cases (magnitude of change and $\boldsymbol{Z}$ statistic), the same procedures have been followed for interpolation.

Results and discussion

Exploratory statistics and spatiotemporal distribution of groundwater level

Figure 3 represents groundwater level for selected wells in two different land forms of the study area. Figure 3a, b show the monthly maximum and minimum depth to WT of first (1991), median (2000) and last (2009) years of the study period of wells no. RJ-041 and RJ-060, respectively. First one well (RJ-041) is located in high Barind area under Nachole Upazila and another well (RJ-060) is located in a flood plain area under Badalgachi Upazila. The graphs show that the depth to WT reaches its maximum value during April–May that is at the end of dry season and regains its position or minimum value during September–October that is at the end of monsoon. Figure 3c, d show the long-term time series along with linear trend of wells RJ-122 which is located in high Barind area and RJ-015 which is located in flood plain area. To visualize the trends in groundwater level, Fig. 3c (well RJ-122) shows rapidly declining trend in annual maximum (dry season groundwater level), minimum (monsoon/wet season groundwater level) and annual average groundwater level. Figure 3d (well RJ-015) also shows declining trends in all series but the trends are declining slowly.

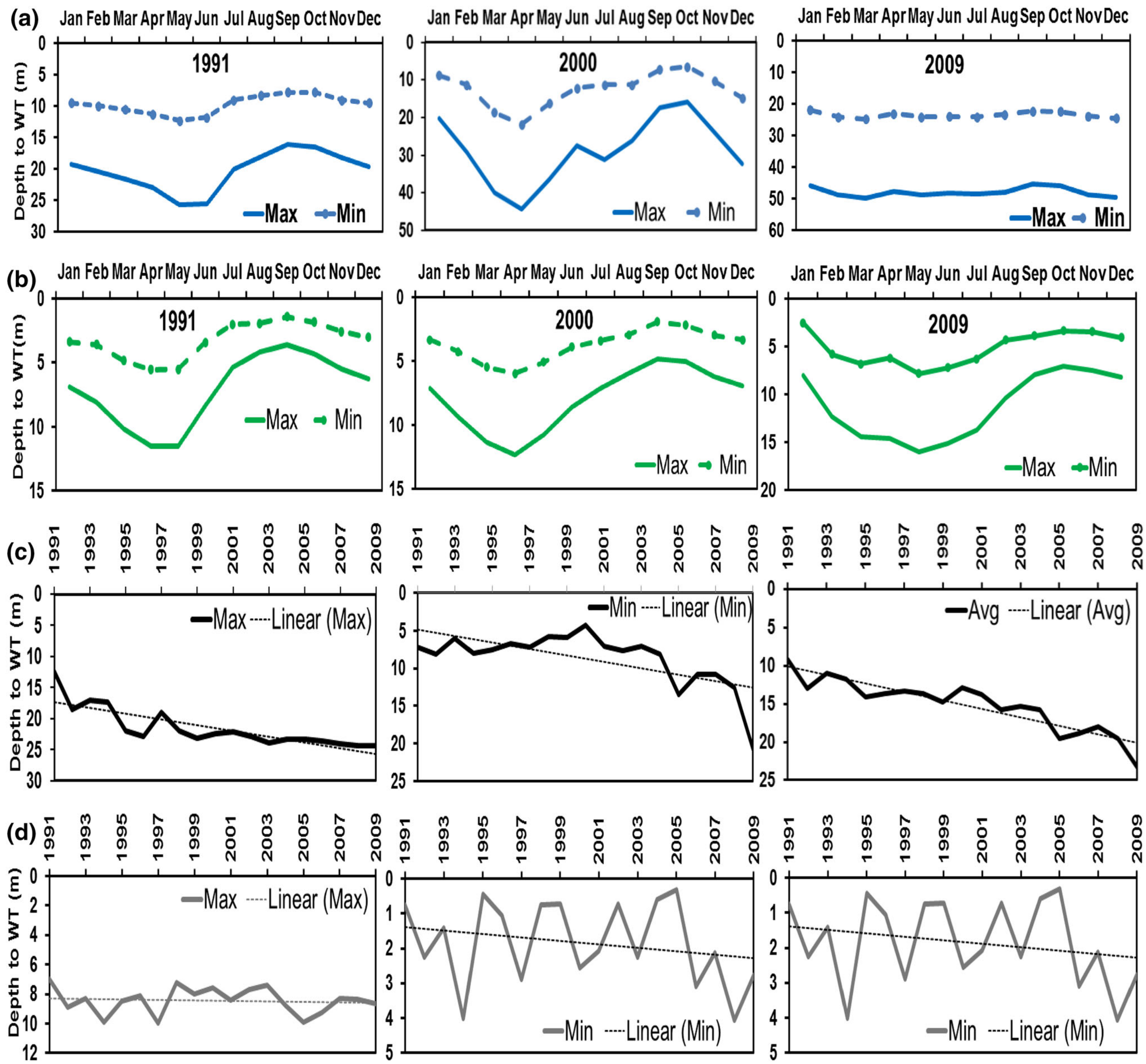

Fig. 3 Groundwater levels in two different landforms in study area **a** monthly minimum and maximum depth to WT (well no. RJ-041) **b** monthly minimum and maximum depth to WT (well no. RJ-060) **c** time series of groundwater levels with linear trend (well no. RJ-122) **d** time series of groundwater level with linear trend (well no. RJ-015)

Figure 4 shows the spatial distribution of water level (depth to water) and fluctuations for shallow aquifers for the years 1991, 2000 and 2009. The water level of the shallow groundwater during dry season in 1991 ranged from 4.29 to 19.05 m (mean = 8.76 m) below ground surface. The relatively lower level of the shallow groundwater mainly occurred in the eastern and northwestern part of the area (flood plains areas). The groundwater level in these areas ranged from 4.29 to 8.0 m that indicate the depths to WT in these areas run and fluctuated in and around the suction limit of pump in 1991 except most of the area of Atrai and Raninagar Upazila. The deepest water level during this season were found in and around Nachole, Sapahar, and Godagari areas (High Barind areas) where the groundwater level ranged from 9 to 19 m that indicate the depths to WT in these areas below the suction limit of pumps from 1991. The water level of the shallow aquifer during wet season/monsoon in 1991 ranged from 0.15 to 13.19 m (mean = 2.68 m) below ground surface (Fig. 4b). The mean water table fluctuation in 1991 was 6.08 m (Fig. 4c). The water level during dry season in 2000 ranged from 3.47 to 22.4 m (mean = 10.15 m) below ground

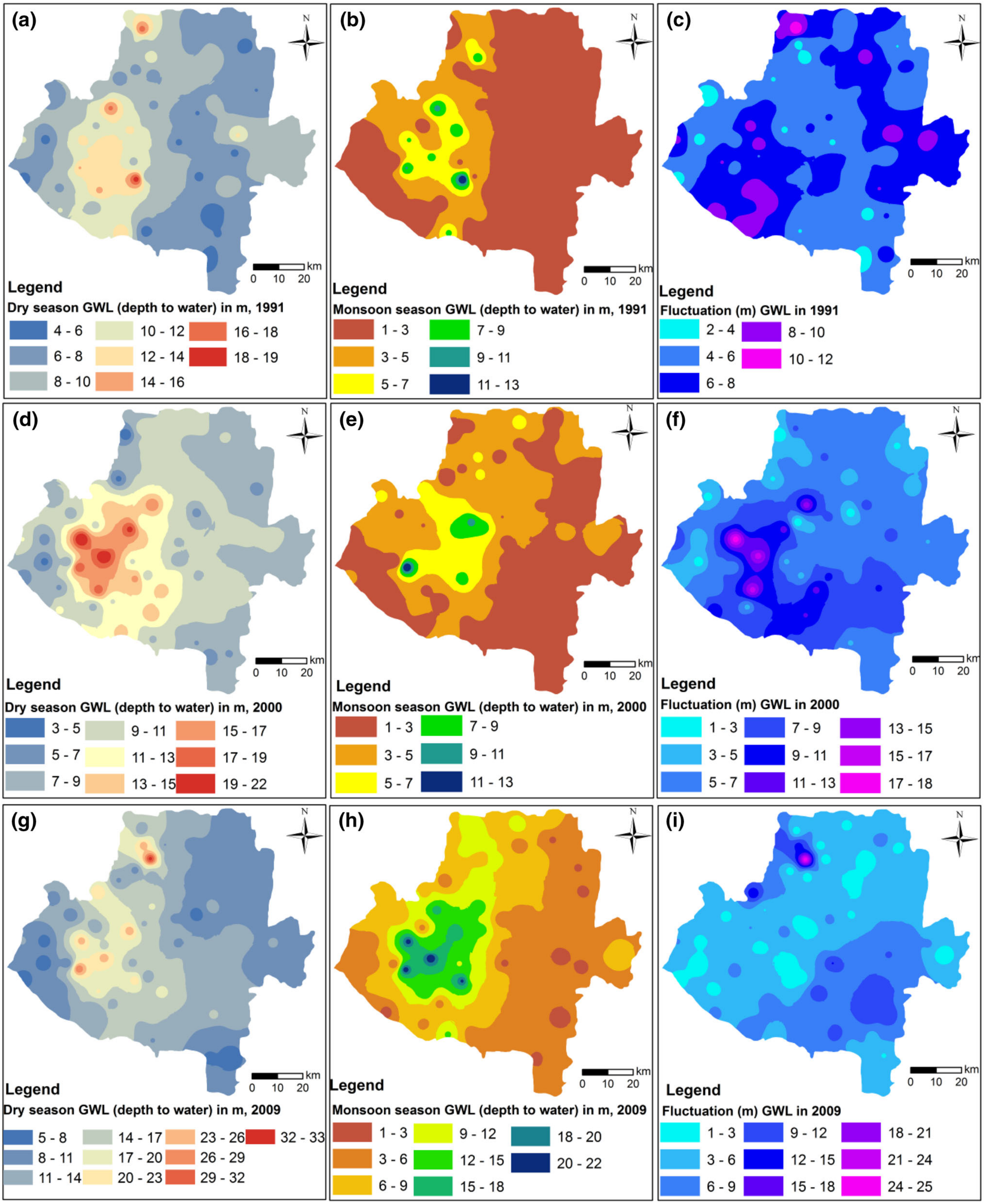

Fig. 4 Spatial distribution of groundwater level and fluctuation of **a** groundwater level at the end of dry season in 1991, **b** groundwater level at the end of Monsoon season in 1991, **c** fluctuation in 1991, **d** groundwater level at the end of dry season in 2000, **e** groundwater level at the end of Monsoon season in 2000, **f** fluctuation in 2000, **g** groundwater level at the end of dry season in 2009, **h** groundwater level at the end of Monsoon season in 2009 and **i** fluctuation in 2009

surface. The water level at Niamatpur, Nachole, Gomastapur, Chapai Nawabganj Sadar and Tanore that are located in southwestern central part of the area ranged from 11.0 to 22.4 m and in these areas depth to WT during this season increases (groundwater level decreases) than that of 1991 and areal extents of higher level of groundwater (depth to water) increases (Fig. 4d). The water level of during wet season in 2000 ranged from 0.6 to 13.17 m (mean = 3.39 m) below the ground surface (Fig. 4b). The mean water table fluctuation in 2000 was 6.76 m (Fig. 4f). The water level in 2009 range from 5.91 to 33.08 m with mean 12.95 m during dry season and from 1.2 to 21.86 m with mean 5.54 m during monsoon. The mean water table fluctuation in 2009 is 5.5 m (Fig. 4i). There are some places in the northeast that cover Badalgachi, northern portion of Naogaon Sadar and southeastern portion of Dhamoirhat, southeastern like Charghat and south western like some part of Shibganj and Nawabganj Sadar Upazilas where groundwater level runs within suction limit during dry season. WT data indicate that in some areas, the groundwater level permits the use of shallow tube wells, which are a cheaper pumping unit than deep tube wells.

Trends in groundwater table

Trends in dry season groundwater table

Long-term (1991–2009) trends in dry season groundwater level time series of shallow aquifers across the study area are shown in Fig. 5. Panels (a–b) show the spatial distribution of magnitude of changes (m/year) assessed by linear regression method and Sen's slope estimator, respectively, and panel (c) shows the distribution of MK '*Z*' statistic that indicates levels of significance of the direction of trends. Panel (d) is discussed below. All of the maps show generally declining trends over the study area except some pocket areas, although the magnitudes of these trends vary spatially and methodically. The rates of change vary from 0.9 to −0.1 m/year (mean = 0.19 m/year) by linear regression method and 0.82 to −1.14 m/year (mean = 0.18 m/year) by Sen's slope estimator, respectively, during the period 1991–2009 over the study area. The slope difference between the parametric and non-parametric methods is small. The difference is only the assumptions related to the degree of normality of the distribution (Huth and Pokorna 2004). Very strong declining trends that are significant at 99 % confidence level where MK '***Z***' statistic ranges from 2.58 to 5.454 (Fig. 5c) are found in the central part of the area that covers the Barind region. The rates of changes vary from 0.82 to 0.2 m/year in this area. These negative changing rates are higher in the high Barind area (0.82–0.4 m/year) that covers Nachole, Sapahar and northern part of Nawabganj Sadar Upazila rather than Level Barind area (0.3–0.2 m/year). Declining trends that are significant at 95 and 90 % confidence level are also found in some places of northeastern and southwestern part of the area (Flood plain areas) and the magnitude of changes are relatively low (0.1 m/year). There are few areas where groundwater level shows slowly increasing or stable trends (0 to −0.14 m/year) during this season.

The differences between the dry season water table between the years 1991 and 2009 are calculated at each site as the representative of the total change (Uyan and Cay 2013) in the 19 years. Simple Voronoi map (Fig. 5d) using the Geostatistical Analyst tool in ArcGIS software of the study area are prepared from these data and five classes driven that are considered as very high, high, moderate, low and very low changes in groundwater level. Figure 5d indicates that in five places which are located in Sapahar, Nachole, Gomastapur and Nawabganj Sadar Upazilas drop (depletion) of groundwater level is very high and ranges from 22.03 to 12.03 m. The drop of groundwater level is high (12.09–5.65 m) in some places most of them located in the southeast and some areas in and around Nawabganj Sadar. Moderate drop (5.65–1.58 m) of groundwater level is dominant over the study area. It occurs mainly in the central part of the area and irregularly scattered in north and south east. Low changes (1.58 to −1.01 m) in groundwater level are found in southwestern part along the Padma river that covers Shibganj Upazila and southeastern part (Atrai flood plain) that includes Atrai and Raninagar upazilas where groundwater level is in stable conditions. Depth to WT in five observation wells decreases or in stable conditions (−1.01 to −5.08 m) during the period 1991–2009 and three out of five are located along the mighty river Padma.

Trends in monsoon season groundwater table

Spatial distribution of long-term (1991–2009) trends in monsoon season groundwater level time series of shallow aquifers are shown in Fig. 6. All of the maps show generally declining trends like dry season over the study area except some pocket areas, although the magnitudes of these trends vary spatially and methodically. The rate of changes vary from 0.55 to −0.06 m/year (mean = 0.17 m/year) by linear regression method and 0.67 to −0.02 m/year (mean = 0.17 m/year) by Sen's slope estimator, respectively during the period 1991–2009 over the study area.

Very strong declining trends that are significant at 99 % confidence level where MK '*Z*' statistic ranges from 2.58 to 5.53 (Fig. 6c) are found in the central part of the area like dry season except some pocket areas that covers the high Barind region. The rate of changes varies from 0.67 to 0.2 m/year in this area. These negative changing rates are very high (0.67–0.4 m/year) in some pocket areas in high

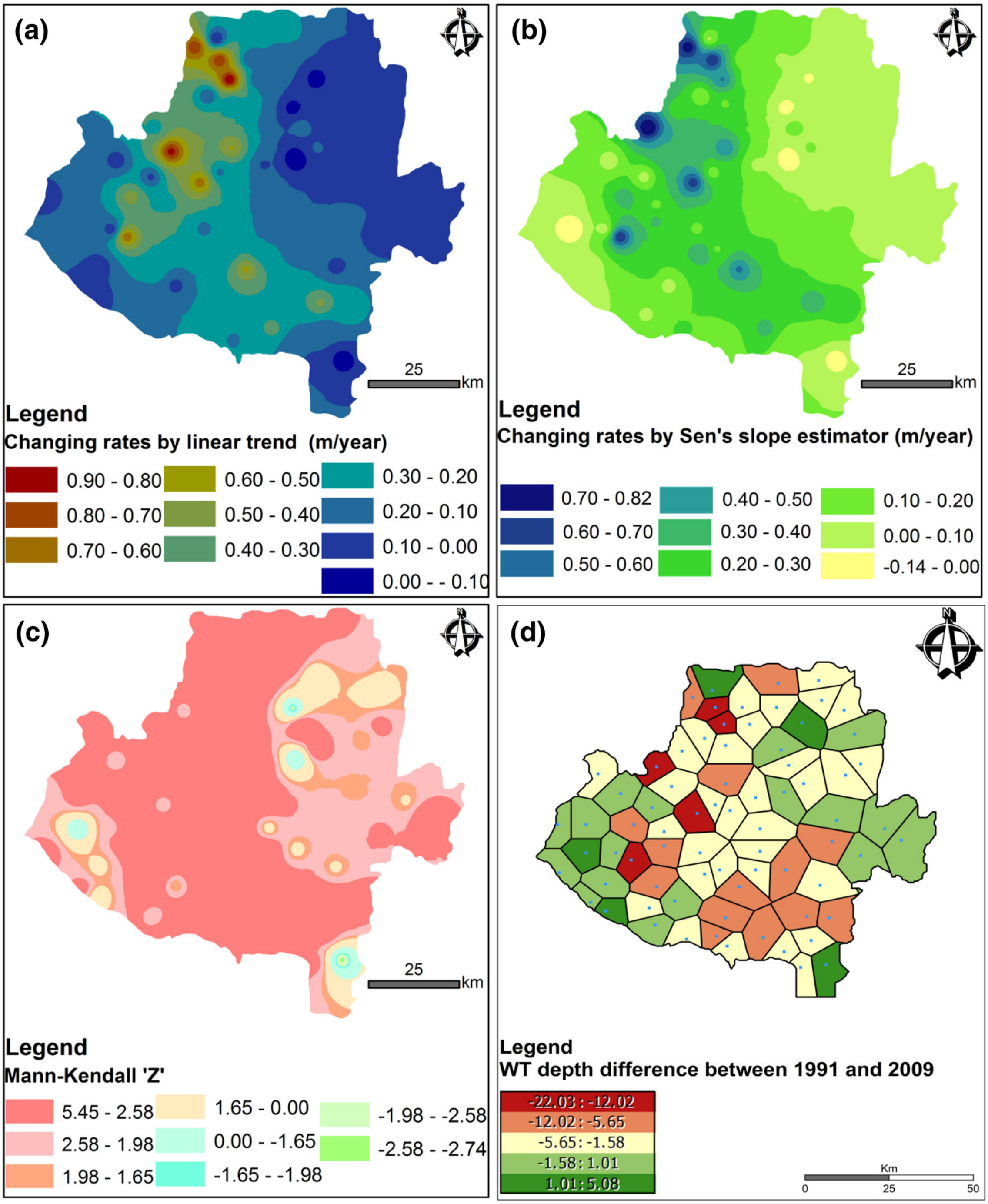

Fig. 5 Spatial distribution of dry season groundwater trends in study area, **a** changing rates by linear trend, **b** changing rates by Sen's slope estimator, **c** Mann–Kendall Z statistic, **d** difference between 1991 and 2009

Barind Tract. Declining trends in groundwater level or increasing trends in WT depth that are significant at 95 and 90 % confidence levels are found around high Barind Tract that covers level Barind Tract, Little Jamuna, Lower Atrai, Lower Purnahaba flood plain and some part of high Ganges and the magnitude of changes vary from 0.2 to 0.1 m/year. Insignificant decreasing trends at these confidence intervals where MK '*Z*' statistic range from 1.645 to 0 are found in the eastern part of the study area without in Atrai and Raninagar Upazilas. In this areas, groundwater level decreases at a rate of 0.1 m/year during the monsoon season. There are some pocket areas where depth to WT below ground surface shows slowly stable trends or decreasing (0 to −0.02 m/year) during this season.

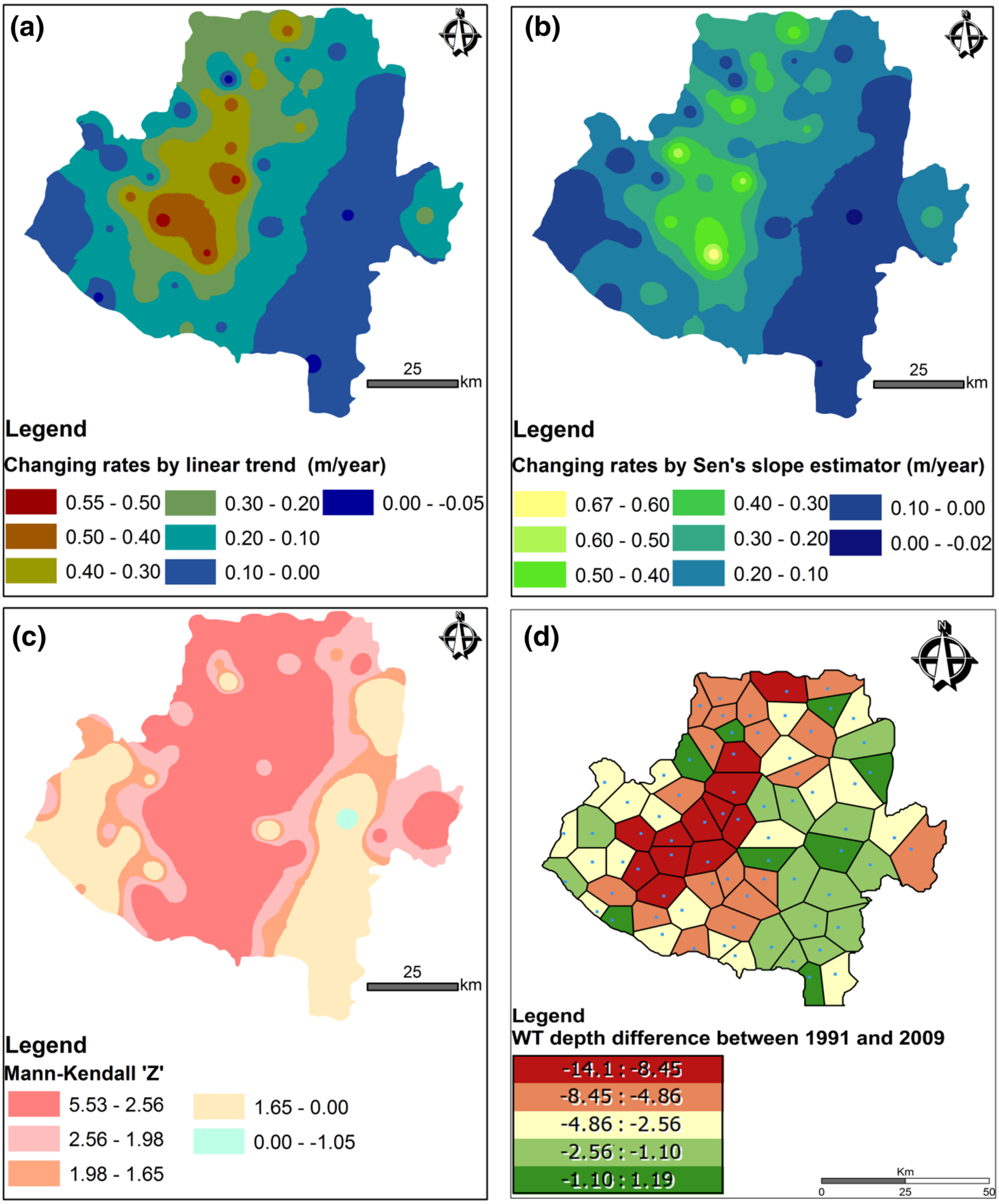

Fig. 6 Spatial distribution of monsoon season groundwater level trends in study area, **a** changing rates by linear trend, **b** changing rates by Sen's slope estimator, **c** Mann–Kendall Z statistic, **d** difference between 1991 and 2009

Simple Voronoi map using the differences between the monsoon season water table between the years 1991 and 2009 is shown in Fig. 6d. The map shows that the areas of very high drop (14.1–8.46 m) of groundwater level are located in high Barind Tract and Level Barind Tract that is covered Nawabganj Sadar area. The drop of groundwater level is high (8.46–4.86 m) in some places which covers Tanore, Godagari, some parts of Paba and Nawabganj Sadar Upazilas in the north and Sapahar, Porsha, Potnitola in the south and part of Atrai and Raninagar in the south-east. Moderate drop (4.86–2.57 m) of groundwater level occurs mainly in southwest and irregularly scattered in northeast and south of the study area. The map (Fig. 6d) show that the areas of low drop of groundwater level is located at the southeast that covers Durgapur, Puthia, Bagha and Charghat Upazilas. Groundwater level in some places is in stable conditions or very low change (1.1 to −1.9 m) occurred irregularly scattered over the study area.

Declining trends in shallow groundwater level during the wet season over the study area are found by both methods and spatially varying depth of groundwater drop has also occurred during the 19-year period. These observations reveal that shallow aquifers in the study area are not fully recharged each year during monsoon season. As a result, shallow groundwater storage is dropped. These findings reject the widely held assumption that shallow aquifers attain the apparently full condition every monsoon in Bangladesh (UNDP 1982; WARPO 2000; BGS/DPHE 2001; Harvey et al. 2006), but consistent with the findings of Shamsudduha et al. 2009.

Trends in average groundwater table

A similar pattern like monsoon trends is found in annual average groundwater level and indicate that magnitudes of changes range from 0.6 to −0.013 m/year (mean = 0.18 m/year) (Fig. 7a) by linear regression and 0.6 to −0.11 m/year (mean = 0.18 m/year) (Fig. 7b) by Sen's slope estimator, respectively. Spatially varying depth of groundwater level drop is occurred over the study area (Fig. 7d). Declining trends significant at 99 % confidence levels (Fig. 7c) are also found in the central part of the study area. There are also declining trends at 95 and 90 % confidence levels located in the northeast and southwest except Shibganj area. Very high (14.15–9.15 m) and high (9.15–6.24 m) drop of groundwater are found in high Barind area (Fig. 6d). Moderate (6.24–4.54 m) drop of groundwater occurs at Level Barind and Ganges flood plain areas. The drop of groundwater level is low (4.54–1.62 m) in east and some places in south and southwest along the Padma river in the study area. Low changes (1.62 to −3.37 m) in groundwater level are found in southwestern Shibganj Upazila and southeastern Bagha Upazila along the bank of Padma river and few areas irregularly scattered in flood plain areas where groundwater level is in stable conditions or rising/declining slowly (Fig. 7d).

Causes of groundwater table depletion

Agriculture in Bangladesh was almost dependent on surface water and monsoon rainfall prior to the 1970s (UNDP 1982). In the 1970s, to produce high-yielding (Boro) rice, irrigated agriculture was introduced using groundwater by power-operated pumps (PPs) in some parts of Bangladesh (MPO 1987). Boro rice grows during the dry season when rainfall is low and episodic and requires 0.4–1.5 m of irrigation that is almost groundwater-fed (Ravenscroft et al. 2009). Initially, a few irrigation wells (Shamsudduha et al. 2011) were installed in northwestern parts where groundwater-fed irrigation is the highest in Bangladesh (BADC 2008). In 2006, Boro rice was produced in 78 % of irrigated areas in Bangladesh (BBS 2008).

Figure 8a shows the trends in irrigated areas by PPs, STWs and DTWs during the period 1993–2010 in the study area. Areas irrigated by STWs and DTWs increase rapidly during this period and areas irrigated by PPs also show steadily increasing trends. The areas irrigated by PPs, DTWs and STWs are almost 81, 180 and 368 thousand acres in 1993 and increased to approximately 121, 679 and 978 thousand acres, respectively, in 2010. Almost 50, 266, 278 % of irrigated areas by PPS, DTWs and STWs, respectively, are increased during this period. Rice production in the study area also shows steadily increasing trend (Fig. 8b) between 1990 and 2010. Although records of groundwater usages for irrigation are not available, the study provides an approximation of increasing trends of groundwater abstraction for irrigation by different tube wells in the study area. These observations of the study indicate that intensive abstraction of groundwater for irrigation exhibits declining trends in long-term groundwater level and drop of groundwater level over the study area.

The time series with linear trend of annual, summer (Mar–May) and rainy (Jun–Oct) seasons rainfall of Rajshahi and Bogra meteorological stations are presented in Fig. 9. The calculated Z statistic for annual, summer and rainy seasons rainfall are −1.07, 0.91 and −1.07 for Rajshahi station; and −0.75, −0.23 and −0.68 for Bogra station, respectively. These Z statistic values indicate that the trends are negative except summer rainfall series of Rajshahi but not statistically significant at 90, 95 and 99 % confidence levels. The linear trend analysis also reflects same results (Fig. 9). The slopes estimated by Sen's slope estimator indicate that annual and rainy season rainfall decrease at a rate of −15.90 and −14.50 mm/year at Rajshahi; and −15.60 and −14.90 mm/year at Bogra stations, respectively, for the period 1991–2010. During this period, summer rainfall of Bogra station decreases at a rate of −1.70 mm/year while rainfall of Rajshahi station increases at a rate of +2.00 mm/year. Shahid and Khairulmaini (2009) also found decreasing trends in annual and rainy season rainfall but increasing trend in summer rainfall at Rajshahi station for the period of 1969–2003. The study found increasing trend in annual and summer rainfall but decreasing trend in rainy season rainfall for Bogra station, but all the trends are statistically insignificant. Kamruzzaman et al. (2015) also studied annual and seasonal rainfall trends of both stations by MK test and found negative trends for all-time series for the period of 1971–2011. The increase or decrease of the precipitation can greatly affect

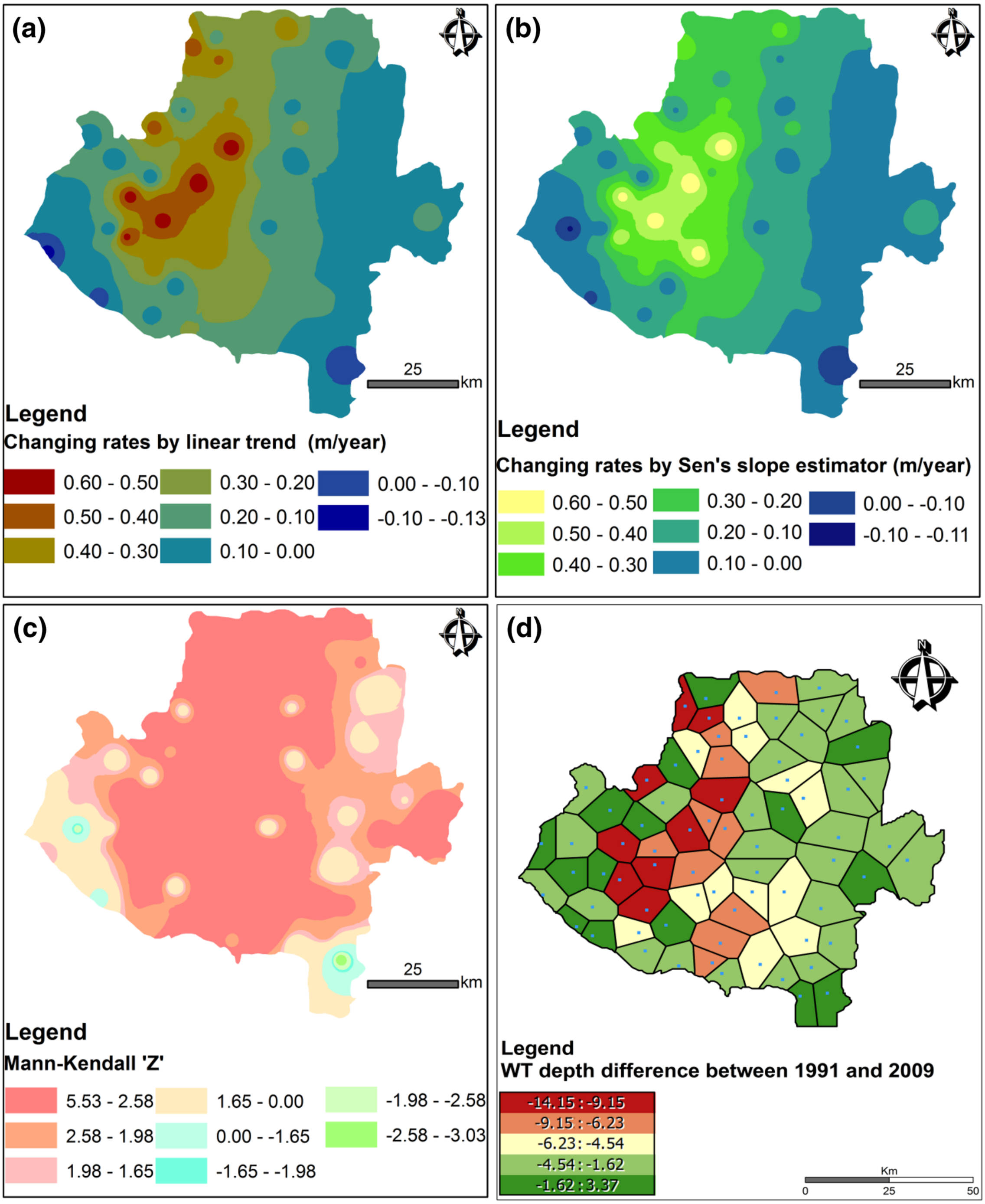

Fig. 7 Spatial distribution of annual average groundwater level trends in study area, **a** changing rates by linear trend, **b** changing rates by Sen's slope estimator, **c** Mann–Kendall Z statistic, **d** difference between 1991 and 2009

the groundwater level as it is the primary source for the groundwater recharge (Park et al. 2011). This decreasing trend of rainfall which is consistent with widespread and prevailing decreasing trend in groundwater level over the study area cannot be ignored as responsible factor.

Surface geology characterizes shallow aquifers in Bangladesh and largely controls the timing and pathways of groundwater recharge to aquifers (MPO 1987; WARPO 2000). The declining shallow groundwater storage in NW Bangladesh relates not only to the intensity of abstraction but also to areas of high thickness of surface clay where rates of rainfall-fed recharge are inhibited by the low hydraulic conductivity of this surface geology (Shamsudduha et al. 2011).

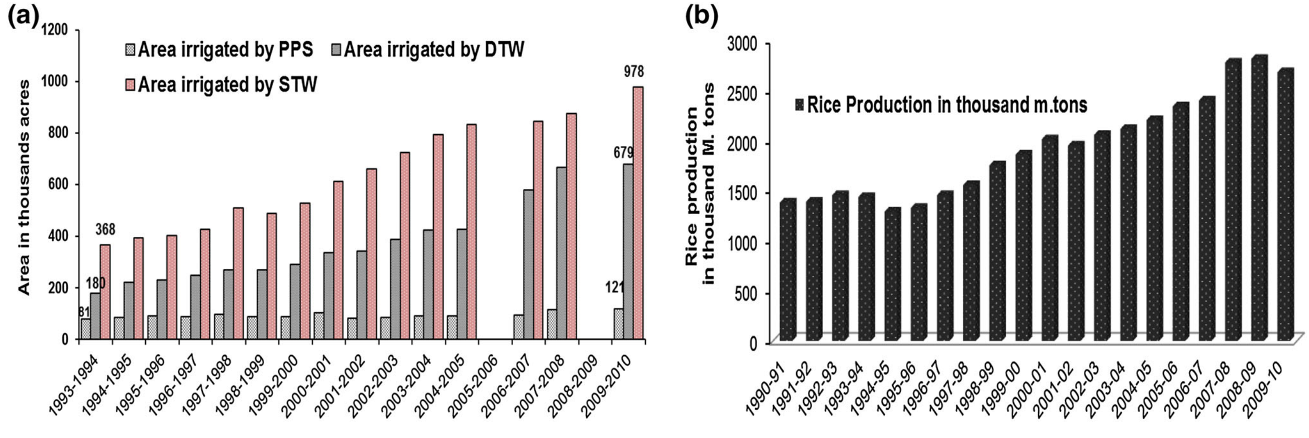

Fig. 8 Trends in **a** irrigated areas and **b** rice production in the study area

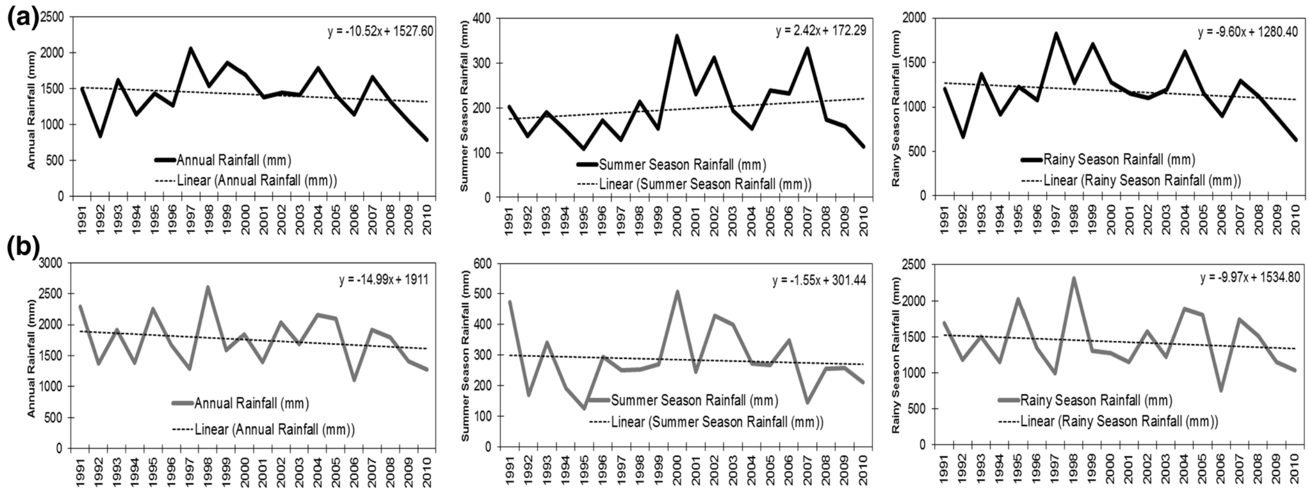

Fig. 9 Time series of annual and seasonal rainfall with linear trend **a** Rajshahi, **b** Bogra meteorological stations

Thus, these observations of the study indicate that rigorous abstraction of groundwater for irrigation, decreasing amount of rainfall that is one of the effects of climate change and surface geology of the area can be attributed to rapid declining in groundwater level in the study area.

Conclusions and recommendations

WT data of 73 groundwater observation wells at 25 different Upazilas in NW Bangladesh for the period 1991–2009 have analyzed to evaluate the spatial and temporal changes in the groundwater level and probable causes for changes.

Trends in groundwater level using linear regression, MK Test and Sen's slope estimator show generally declining trends in all three time series in NW Bangladesh except some pocket areas. The magnitude of changes varies spatially and methodically. The rates of change calculated by liner trend and Sen's slope estimator vary from 0.9 to −0.1 m/year (mean = 0.19 m/year) and 0.82 to −1.14 m/year (mean = 0.18 m/year) during dry season, 0.55 to −0.06 m/year (mean = 0.17 m/year) and 0.67 to −0.02 m/year (mean = 0.17 m/year) during monsoon and 0.6 to −0.013 m/year (mean = 0.18 m/year) and 0.6 to −0.11 m/year (mean = 0.18 m/year) in annual average groundwater level, respectively. The difference between these methods is small and related to the degree of normality of the distribution. Very strong declining trends with high magnitude of change that are significant at 99 % confidence level are found in the central part of the area that covers the Barind region. The rate of changes in this area varies from 0.82 to 0.2 m/year during dry season, from 0.67 to 0.2 m/year during monsoon season and, 0.6 to 0.1 m/year in annual average time series, respectively. Declining trends with low rate of changes that are significant at 95 and 90 % confidence levels are found in the rest of the areas except some pocket areas.

Simple Voronoi maps of differences in groundwater level between 1991 and 2009 show that the areas of very high and high drop of groundwater level are generally located in the central part of the area that covers high Barind Tract. Moderate drop of groundwater level is dominant and irregularly scattered over the study area. Low changes in groundwater levels are found in south along the mighty river Padma and in few areas irregularly scattered over the study area where groundwater level are in stable conditions or slowly raising or slowly decreasing. Reckless abstraction of groundwater for irrigation, decreasing trend of rainfall and surface geology of the area are responsible for rapid declining trends and drop of groundwater level in the area.

Falling trends and drop of groundwater level indicate unsustainable withdrawal of groundwater. This situation will be irreversible if necessary steps are not taken beforehand. The water must be used according to saving rules. Irrigation methods need to develop and update. The water resource managers need to explore solutions to the misusage of groundwater and have to control irrigation using groundwater. Rainwater harvesting in farm ponds and *Khari* (small channel) needs to promote to use for irrigation purpose. With increasing surface water using practice, number of STWs, DTWs and PPs need to close. The water resources management program should be ensured avoiding further installation of STWs, DTWs and PPs for sustainable solution of falling trends in groundwater level in NW Bangladesh.

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