J Bangladesh Agril Univ 20(1): 79–87, 2022 https://doi.org/10.5455/JBAU.140654

ISSN 1810-3030 (Print) 2408-8684 (Online)

Journal of Bangladesh Agricultural University

Journal home page: http://baures.bau.edu.bd/jbau

Research Article

Groundwater Withdrawal Trend and Management Considerations in an Intensive Groundwater Irrigation Region in Bangladesh

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ARTICLE INFO

Article history
Received: 05 Jan 2022
Accepted: 25 Jan 2022
Published: 31 Mar 2022

Keywords
Irrigated agriculture,
Water use,
Groundwater extraction,
Sustainability

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ABSTRACT

Mounting demand of groundwater in the North-West (NW) hydrological region of Bangladesh requires evaluation of the withdrawal pattern of groundwater to plan for its sustainable usage. This study estimated the quantity of groundwater withdrawn and its trend over the period from 1985 to 2016 by analyzing the annual fluctuation of groundwater levels at 350 monitoring wells and MAKESENS model, respectively. The correlation of the withdrawn groundwater with irrigated acreage was also investigated. Out of 16 districts in the NW region, 4 (Kurigram, Lalmonirhat, Nilphamari and Thakurgaon) show significantly ($p \le 0.05$) and 6 (Rajshahi, Natore, Dinajpur, Gaibandha, Panchagarh and Rangpur) insignificantly increasing trend, while 2 show (Bogura and Joypurhat) significantly and 4 (Naogaon, Chapai Nawabganj, Pabna and Sirajganj) insignificantly decreasing trend of groundwater withdrawal over the years. At the two divisional levels (each comprising 8 districts), groundwater withdrawal followed insignificant decreasing trend with a total decrease of 637.2 Mm^3 (from 7339.04 Mm^3 to 6701.84 Mm^3; 8.68%) in Rajshahi but significantly increasing trend with a total increase of 794.6 Mm^3 (from 4191.87 Mm^3 to 4986.43 Mm^3; 18.95%) in Rangpur division during the period of investigation. For the whole NW region, it followed insignificant increasing trend with a total increase of 148.2 Mm^3 (from 11536.06 Mm^3 to 11684.23 Mm^3; 1.28%). There was no consistent correlation between the quantity of withdrawn groundwater and irrigation acreage. The currently practiced groundwater development and usage policy of the NW region needs updating with special emphasis on the areas with significantly increasing trend of groundwater withdrawal.

Introduction

Globally groundwater provides over 97% of accessible freshwater (Jakeman et al*.,* 2016) and agriculture sector accounts for approximately 70% of the water being used worldwide (Khokhar, 2017). Groundwater provides 45–70% of irrigation water (Wada et al., 2014; Lall et al., 2020) and the amount of abstraction and usage of groundwater are continuously increasing worldwide (Van et al*.,* 2010; Lall et al., 2020). Groundwater levels are often heavily influenced by the groundwater abstraction rate (Mojid et al., 2019) and over-exploitation of groundwater for irrigation is held as one of the main causes of groundwater level depletion (Rodell et al., 2009; Scanlon et al., 2012; Wada et al., 2014; Mojid et al., 2019). The excessive abstraction has already caused groundwater-level declines to worrying magnitudes in many countries (Chawla et al*.,* 2010; Qureshi et al*.,* 2010; Yin et al*.,* 2011; Brückner et al., 2021; Roy and Zahid, 2021). The decline in groundwater level threatens sustainable development of the aquifers (Akther et al*.,* 2009; Mojid et al., 2021). In addition, climate change is presumed to exert significant impact on the future availability of groundwater resources (Goderniaux et al*.,* 2011; Taylor et al*.,* 2013; Abdulla et al., 2018; Jannis et al., 2021).

Bangladesh has extensively adopted groundwater-based irrigation to cultivate high-yielding rice during the dry season due to scarcity of surface water (Scott and Sharma, 2009; IRRI, 2010). Also, groundwater is the essential source to meet industrial and household demand (Michael and Voss*,* 2009). It supplies 79% of the water demand for irrigation, livestock, household, and industrial usages (BBS, 2017). Considering the irrigated area of the country, the use of groundwater in its North-West (NW) region is the most intense; over 97% of the total area (85% of net cultivable area) was irrigated by groundwater during 2012–2013 (Mainuddin

Cite This Article
Hossain, M.A. and Mojid, M.A. 2022. Groundwater Withdrawal Trend and Management Considerations in an Intensive Groundwater Irrigation Region in Bangladesh. *Journal of Bangladesh Agricultural University*, 20(1): 79–87. https://doi.org/10.5455/JBAU.140654

et al., 2013). In this region, about 95% of irrigation water comes from groundwater. The proportion of groundwater supplied in the NW region varies from almost 100% in the North-West area to about 40% in the South-West area of the region (Kirby et al., 2013). Large-scale withdrawals of water at the upstream of the trans-boundary rivers in the dry season and recurrent occurrence of droughts have reduced the supply of surface water. Consequently, the NW region is largely dependent on groundwater for irrigation and also other usages.

Understanding the behavior of the groundwater reserve and its long-term trends are crucial for making appropriate management decision in any groundwater basin. In spite of great importance of groundwater, only limited studies were done on temporal trend analysis of groundwater level in Bangladesh, including the NW region (Rahman et al*.,* 2016; Mojid et al*.,* 2019). So, it has become imperative for the water scientists and planners concerned with the region to quantify the available water resources for their judicial usages (Sreekanth et al*.,* 2009).

Direct measurement of groundwater draft at sample locations can be done by installing water meters (Chatterjee and Ray, 2014). However, indirect methods are often used for estimating groundwater withdrawal due to the difficulties in metering it at large number of pumping sites (Massuel et al., 2009). The estimation of groundwater withdrawal is generally troublesome due to the uncertainties in the basic data. Water table fluctuation approach considered to be an adequate technique has been applied often for estimating the groundwater withdrawal due to its straightforwardness, ease of use and relatively low cost (Mojid and Talukder, 1997; Maréchal et al., 2006; Tsanis and Apostolaki, 2009; Yang et al., 2018; Labrecque et al., 2020).

It is crucial to know the withdrawal rate of groundwater to safeguard sustainability of its usage in agricultural basins by adequate management (Martínez-Santos and Martínez-Alfaro, 2010). One of the critical elements for this is the trend analysis of groundwater withdrawal data; it provides possible scenarios of the resources. This study intended to analyze fluctuations of groundwater levels over the period from 1985 to 2016 to quantify the volume of groundwater yearly withdrawn from the aquifers as well as to determine their trend in the NW region of Bangladesh. Trend analysis of the time-series of groundwater withdrawal data can reveal the withdrawal pattern over time period; it can reveal both the direction and magnitude of changes in the groundwater reservoirs. The common methods for trend analysis include regression-based methods, triangular episodic presentation and qualitative scaling (Cheung, 1992), dynamic time-warping (Rabiner and Juang, 1993), wavelets (Pandey et al., 2017), qualitative temporal shape analysis (Konstantinov and Yoshida, 1992), and Mann-Kendall-Sen's (MAKESENS) analysis (Salmi, 2002). Plain technique and relative ease of use have made MAKESENS model a popular tool for trend analysis. One of the important advantages of this model is its applicability for both monotonous and non-monotonic trends. The goal of this study was to determine the long-term (1985–2016) trend of yearly groundwater withdrawal of the NW region of Bangladesh by estimating the volume of groundwater removed from the aquifers and determining the trend of groundwater removal from the aquifers.

Methodology

Study area

The NW hydrological region (Figure 1) of Bangladesh covering the Rajshahi and Rangpur divisions is the study area. The Rajshahi division, consisting of 8 districts and 70 upazilas (sub-districts), has an area of 18,153 km^2, and the Rangpur division, consisting of 8 districts and 58 upazilas, has an area of 16,185 km^2 (BBS, 2018). The sub-surface lithology of the region varies widely. The upper-most layer of the Rajshahi region comprises clay to silty clay of 2.5 to 35 m thick, but in Pabna the upper-most layer of clay to silty clay varies from 1 to 20 m (DPHE, 2010). The aquifers in these areas are generally unconfined (Mojid et al*.,* 2019). The top layer of soil in the northern half of the NW region (Rangpur area) consists of coarse and medium sand and gravel. More details of the subsurface lithology of the NW region have been reported in Mojid et al. (2021).

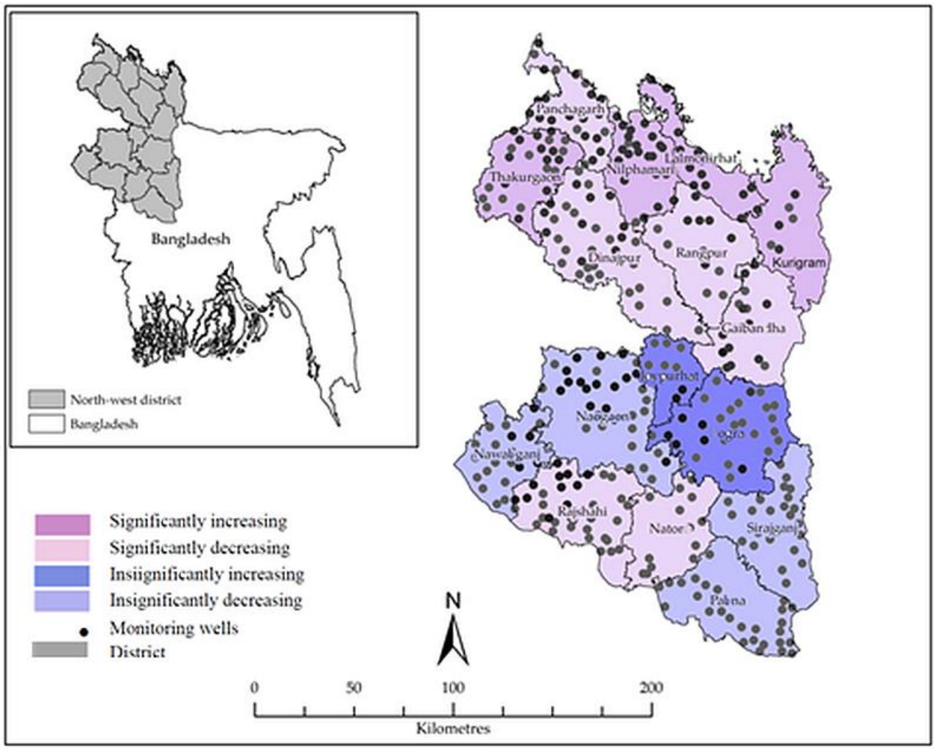

Figure 1. Distribution of groundwater level monitoring wells in sixteen districts of the North-West region of Bangladesh along with groundwater withdrawal trend at the district level over the period from 1985 to 2016

Data collection and preparation

Data of groundwater level and specific yield of the aquifers were used to estimate yearly withdrawal of groundwater in the study area. Specific yield is the volume of water drained by gravity from a unit volume of saturated aquifer material; it is a water yielding property of unconfined aquifers. The specific yield of 109 upazilas was collected from SDIP II Project (Sustaining Groundwater Irrigation for Food Security in the North-West Region of Bangladesh) of CSIRO, Australia. However, data on specific yield was not available for 19 upazilas for which the data was generated using linear interpolation of the data of the conjoined upazilas using Geographical Information System (GIS). Bangladesh Water Development Board (BWDB) measures groundwater levels all over the country on weekly basis. In the NW region, groundwater levels are recorded in 437 geographically distributed monitoring wells. These data for the NW region were collected for the period from 1985 to 2016 from the BWDB. First the reliability of the data was checked. For this, the observed groundwater level data was plotted against time in scatter plots for each monitoring well. The important features of the data, such as trends, seasonality, discontinuities, and outliers, were identified from the scatter plots. The monitoring wells with more than 5 years discontinuous data and irrational or erratic distribution of water tables, and also the wells with identification problems, were discarded. Out of 437 monitoring wells, 350 provided consistent and reliable data for the period of investigation (1985–2016) and hence were selected for this study. The annual maximum and minimum depths of groundwater levels in these monitoring wells were identified and listed separately for each well.

Estimation of groundwater withdrawal

The quantity of groundwater withdrawn annually in an upazila was determined by multiplying the average annual fluctuation of groundwater level with the specific yield of the aquifer and area of the upazila as

$$V_{\text{ext}} = d \times S_{\text{y}} \times A \text{ .... (1)}$$

where V_{ext} is the quantity of groundwater withdrawn (m^3), d is average annual fluctuation of groundwater level (m), S_Y is specific yield of the aquifer, and A is area represented by the groundwater level monitoring well (m^2); in this study, A represents the area of individual upazilas.

Trend analysis

The trends of groundwater withdrawal were examined by using the Mann–Kendall test and the Sen's slope estimator. MAKESENS performs two types of statistical analyses. First, the presence of a monotonic increasing or decreasing trend is tested with the non-parametric Mann-Kendall test and, secondly, the slope of a linear trend is estimated with the non-parametric Sen's method (Gilbert, 1987). The Mann-Kendall test is suitable for cases where the trend may be monotonic and thus no seasonal or other cycle is present in the data.

MAKESENS utilizes Gilbert's (1987) S-statistics and Z-statistics. The S-statistics is used for time series with less than 10 data points, while the Z-statistics is used for time series with 10 or more data points. If $x_1, x_2, x_3 \ldots x_j$ represent n data points where x_j represents the data point at time j then the S-statistics is given by

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} sign(x_j - x_k) \quad \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

where

$sign(x_j - x_k) = 1, \quad \text{if } x_j - x_k > 0$

$sign(x_j - x_k) = 0, \quad \text{if } x_j - x_k = 0$

$sign(x_j - x_k) = -1, \quad \text{if } x_j - x_k < 0$

The normalized Z-statistics is given by

$$Z = \frac{S-1}{[VAR(S)]^{\frac{1}{2}}} \quad \text{if } S > 0$$
$$Z = 0 \quad \text{if } S = 0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$
$$Z = \frac{S+1}{[VAR(S)]^{\frac{1}{2}}} \quad \text{if } S < 0$$

The Sen's non-parametric method estimates the true slope of an existing linear trend as

$$f(t) = Qt + B \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

where Q is the slope and B is a constant.

First, the slopes (Q_i) of all data pairs are calculated by

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

where x_j and x_k are data values at time j and k (j>k), respectively.

If there are n values of x_j in the time series, there will be as many as $N = n(n-1)/2$ estimates of slope Q_i. The Sen's slope estimator is the median of these N values of Q_i. The N values of Q_i are ranked from the smallest to the largest and the Sen's estimator is given by

$$Q = Q_{[(N+1)/2]} \quad \text{if } N \text{ is odd}$$

or

$$Q = \frac{1}{2}\left(Q_{N/2} + Q_{[N+2]/2}\right) \quad \text{if } N \text{ is even} \ldots\ldots (6)$$

To obtain an estimate of B in equation (4), the n values of differences ($x_i - Qt_i$) are calculated. The median of these values gives an estimate of B (Salmi, 2002).

The MAKESENS model provides trends of groundwater withdrawal in terms of Z-statistics, slope, intercept and statistical significance. The Z-statistics is a deterministic index of the trend. The slope of the trend lines reveals if the trend is increasing or decreasing. Also, the slope determines the magnitude of the trend. The intercept and slope together provide the trend line. Based on data type, especially the sensitivity of change, statistical significance of the trend is determined and presented by the model for significant levels $p \le 0.1$, ≤ 0.05 and ≤ 0.01. For this study, $p \le 0.05$ was taken as base for determining statistical significance of the groundwater withdrawal trends.

Correlation analysis between irrigation acreage and withdrawn groundwater

Boro rice, wheat, maize and potato are the most dominant irrigated crops in the NW region (Nasim et al., 2017). The irrigated acreages of these crops were collected from the Bangladesh Bureau of Statistics (BBS, 2017) and Nasim et al. (2017). The correlation between the irrigated acreage of the crops and the quantity of groundwater withdrawal was analyzed for each crop individually and also for all crops together.

Results

Groundwater withdrawal trend at different spatial scales

The annual groundwater withdrawal systematically increased in 67 upazilas, decreased in 58 upazilas and remained unchanged in one upazila over the 32 years (1985–2016) period. The district level results reveal increasing trend of groundwater withdrawal in Rajshahi and Natore districts in Rajshahi division and in all districts in Rangpur division (Figure 1). Groundwater withdrawal showed either only increasing or decreasing trend or both trends in the upazila level in 15 out of 16 districts in the two divisions. It showed all three trend types (increasing, decreasing and constant) only in Bogura district. All upazilas of Joypurhat district showed decreasing trend but all upazilas of Thakurgaon district showed increasing trend of groundwater withdrawal.

Among the 67 upazilas with increasing trend of groundwater withdrawal, 30 upazilas showed significantly ($p \le 0.05$) increasing trend. Of the 58 upazilas with decreasing trend of groundwater withdrawal, 26 upazilas showed significant trend. The overall trend at the district level revealed four different scenarios (Figure 1): (i) significantly increasing trend for 4 districts (Kurigram, Lalmonirhat, Nilphamari and Thakurgaon), (ii) significantly decreasing trend for 2 districts (Bogura and Joypurhat), (iii) insignificantly increasing trend for 6 districts (Rajshahi, Natore, Dinajpur, Gaibandha, Panchagarh and Rangpur), and (iv) insignificantly decreasing trend for 4 districts (Naogaon, Chapai Nawabganj, Pabna and Sirajganj).

At the two divisional levels (each comprising 8 districts), groundwater withdrawal followed insignificant decreasing trend (from 7339.04 Mm^3 to 6701.84 Mm^3; 8.68%) in Rajshahi but significantly increasing trend (from 4191.87 Mm^3 to 4986.43 Mm^3; 18.95%) in Rangpur division (Figure 2). The overall withdrawal of groundwater in the entire NW region revealed an insignificant increasing trend (Figure 3). The withdrawn groundwater was 11536.06 Mm^3 in 1985 and increased to 11684.23 Mm^3 in 2016. The estimated groundwater withdrawal was closely comparable to that of Kirby et al. (2014) who estimated the quantity of groundwater usage for irrigation from the regional water balances as 11000 Mm^3 in the NW.

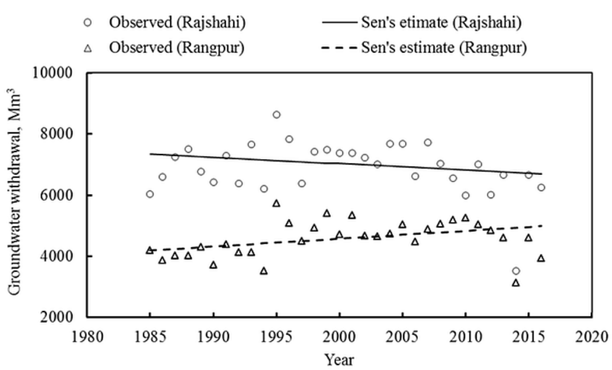

Figure 2. Trend of groundwater withdrawal in Rajshahi and Rangpur divisions in the North-West region of Bangladesh over the period from 1985 to 2016

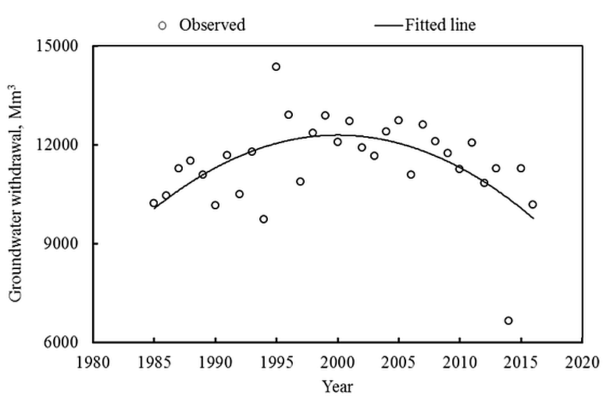

Figure 3. Overall trend of groundwater withdrawal in the North-West region of Bangladesh over the period from 1985 to 2016

Withdrawn groundwater versus irrigated area relation

Figure 4 illustrates the variation of the irrigated areas of Boro rice, wheat and other cereals, maize, and potatoes, and the withdrawn volume of groundwater over the period of investigation (1985–2016) in the whole NW region. The irrigated area of wheat and other cereals fluctuated over the years; it significantly decreased after the year 2000. But the total irrigated acreage of the main crops increased over the years approximately linearly from 665675 ha to 2446428 ha. However, the volume of groundwater withdrawn did not show any systematic variation with the increasing irrigated area of the crops.

Discussion

Implication of groundwater withdrawal trend on planning of groundwater use

The quantity of groundwater withdrawal estimated from groundwater level fluctuation over the years from 1985 to 2016 revealed the past scenarios of groundwater withdrawal in the NW region of Bangladesh. The groundwater pumping wells (e.g., deep tubewells and shallow tubewells) are not geographically uniformly distributed over the entire NW region. The intensity of the wells is greater in areas having good aquifers and more water demand than in areas with poor aquifers and also in areas with less water demand or a combination of both. So, the quantity of groundwater withdrawal varied among different areas over the region. In most cases, groundwater withdrawal per year at the upazila level increased systematically following linear trend. These upazilas are of intensive Boro rice cultivation area (Shamsudduha et al., 2009) and hence it is spontaneous that groundwater withdrawal increased due to its increased usage in irrigation. Additionally, increased industrialization is another major cause for increased withdrawal of groundwater. The decreasing trend of groundwater withdrawal implies its reduced usages and/or increased annual recharge to the aquifers; both could reduce the annual fluctuation of groundwater levels. However, the increase in annual recharge to the aquifers was a less possibility since Hasanuzzaman et al. (2017) and Mojid et al. (2019) demonstrated that the quantity of annual rainfall was declining in the NW region over the study period, and Mojid et al. (2021) clearly demonstrated significant decrease in the annual recharge in most areas of the NW region over the past three decades. The unchanged trend of groundwater withdrawal (obtained only in Shibganj upazila of Bogura district) indicated consistent groundwater usage practice over time.

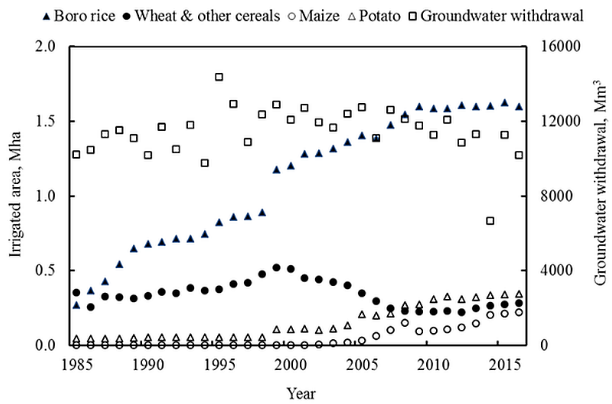

Figure 4. Variation of the major irrigated crop areas and groundwater withdrawal for the North-West region of Bangladesh over the period from 1985 to 2016

When the quantity of withdrawn groundwater totalled over the division level, it showed insignificant decreasing trend (from 7339 Mm^3 to 6702 Mm^3) in Rajshahi division but significantly increasing trend (4192 to 4986 Mm^3) in Rangpur division. Similarly, the total quantity of the withdrawn groundwater in the entire NW region showed insignificantly increasing trend. These observations clearly demonstrate that the trend of groundwater withdrawal over a large region does not reflect the actual local situations of groundwater dynamics. So, any planning of groundwater usage based on the past trend over a large region will be misleading.

Groundwater withdrawal versus irrigation acreage

The irrigated area of Boro rice continuously increased from the year 1985 to 2009 after which it remained almost unchanged (Figure 4). In the same period, the quantity of groundwater withdrawal increased by 148 Mm^3 (from 11536 Mm^3 to 11684 Mm^3; 1.28% obtained from trend line) without following any definite pattern with the irrigated Boro rice acreage (Figure 4). The irrigated area of potatoes and maize also increased from the year 1992 and 2002, respectively. Irrigation acreage of wheat and other cereals increased from 267799 ha to 284162 ha during 2008 to 2016. In spite of increasing irrigation acreage, the total quantity of groundwater withdrawal decreased over this time period (Figure 5). These observations indicate that the quantity of groundwater withdrawal did not depend only on irrigation acreage although it was the main controlling factor. The domestic and industrial usages also influenced the quantity of groundwater withdrawal. This is strongly supported from the fact that the total groundwater withdrawal in Bangladesh in 2008 was 36 km^3 of which 31.5 km^3 was used for irrigation, 3.6 km^3 for domestic use and 0.8 km^3 for industrial use (FAO, 2010).

Considerations for future withdrawal of groundwater

The increased irrigation coverage associated with increased groundwater withdrawal from the aquifers over the last three decades has caused decline in groundwater levels. Mojid et al. (2019), by evaluating the long-term (1985–2016) trends of groundwater levels of the same 350 monitoring wells in the NW region as used in this study, reported a significant ($p \leq 0.05$) falling trend of the annual maximum depths of groundwater levels in 65.7% of the monitoring wells, and a significant falling trend of the annual minimum depths of groundwater levels in 69.7% of the monitoring wells. These trends of the annual maximum and minimum depths of groundwater levels revealed continuous increase in groundwater withdrawal and groundwater mining, respectively. The projected scenarios of groundwater level for the year 2020, 2030 and 2050 revealed worse condition (Ali et al., 2012); the depth to groundwater level would be double in some cases by 2030 and almost in all cases by 2050, if the trend of current withdrawal is continued. Therefore, the NW region, specifically the Barind area, is of the greatest concern over falling groundwater levels (Kirby et al., 2013), which in some localities has already caused a lack of access to water for drinking and irrigation.

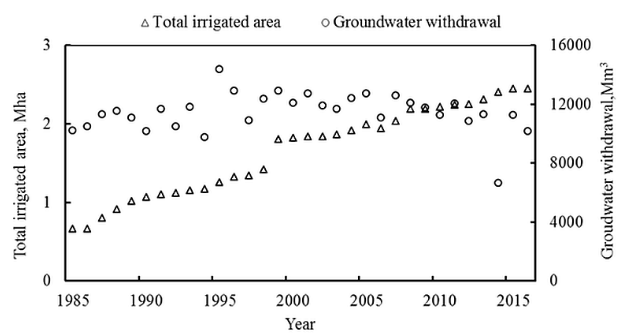

Figure 5. Variation of the total irrigated crop area and groundwater withdrawal in the North-West region of Bangladesh over the period from 1985 to 2016

The upper limit of groundwater withdrawal is generally based on sustainable/safe yield of groundwater, which is commonly defined as the development and use of groundwater resource in a manner that can be maintained for an indefinite time without causing adverse environmental, economic, or social consequences (Heath and Spruill, 2003; Alley and Leake, 2004). To maintain stable groundwater system in a region, the recharge and discharge components must be balanced; groundwater withdrawal must be less than the total recharge. In addition to the falling groundwater levels in the study area, there are evidences that the recharge to groundwater in the Barind area within the NW region is less than the quantity withdrawn for irrigation. As a result, the groundwater resource is under a constant threat of over-exploitation due to anthropogenic pressure (Sophocleous, 2005). Several studies (e.g., Adham et al., 2010; Rahman and Roehrig, 2006; Mojid et al., 2021) demonstrated clear evidence of over-withdrawal of groundwater, thus revealing the threat to groundwater sustainability. To ensure sustainable use of groundwater in the North-West region, withdrawal of groundwater needs to be reduced by 60% of the current abstraction (Mustafa et al., 2019).

Conclusion

The past trend of groundwater withdrawal in the North-West hydrological region of Bangladesh provides information to plan for sustainable usage of the groundwater resource. The trend of groundwater withdrawal varied spatially over the region, thus leading to localized sustainability issues of groundwater usage. The withdrawn groundwater followed insignificantly increasing trend for the entire NW region, but insignificantly decreasing trend in Rajshahi division and significantly increasing trend in Rangpur division. In the district level, the quantity of annual withdrawal followed significant ($p \leq 0.05$) increasing trend in four districts and decreasing trend in two districts out of total sixteen districts. Over-exploitation of the aquifers with inadequate recharge is the primary cause for the observed negative equilibrium of the aquifers. So, the currently practiced groundwater development and usage policy of the region needs to be revised to make groundwater usage sustainable with special attention to the areas facing significantly increasing trend of groundwater withdrawal. This will need determining area-wise sustainable level of groundwater withdrawal, and reducing groundwater extraction where the current extraction level has exceeded the sustainable limit. To maintain growth in food production with limited water resources, crop diversification will also have to be enhanced. In this regard, trend analysis of groundwater withdrawal is of practical importance due to the effects of various changes in the patterns of climate, land use and water demand. In this study, only a single value of specific yield for each upazila was utilized in quantifying groundwater withdrawal due to lack of additional data. More data of specific yield should be determined in the future studies to get more precise information on the nature of groundwater withdrawal in the region.

Authors' contribution

MAM conceptualized the idea, collected historical data and designed numerical analysis. MAH conducted most of the analysis and drafted the manuscript. MAM edited the manuscript to its final form.

Acknowledgments

This research work was funded by the Bangladesh Agricultural University Research System (BAURES) (Project No. 2021/1076/BAU). The authors gratefully acknowledge the funding support of the BAURES.

Competing interests

The authors declare that no competing interests exist.

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