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Assessing the impacts of different crop rotations on groundwater level using MODFLOW in a dry, Barind area of Bangladesh

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ABSTRACT

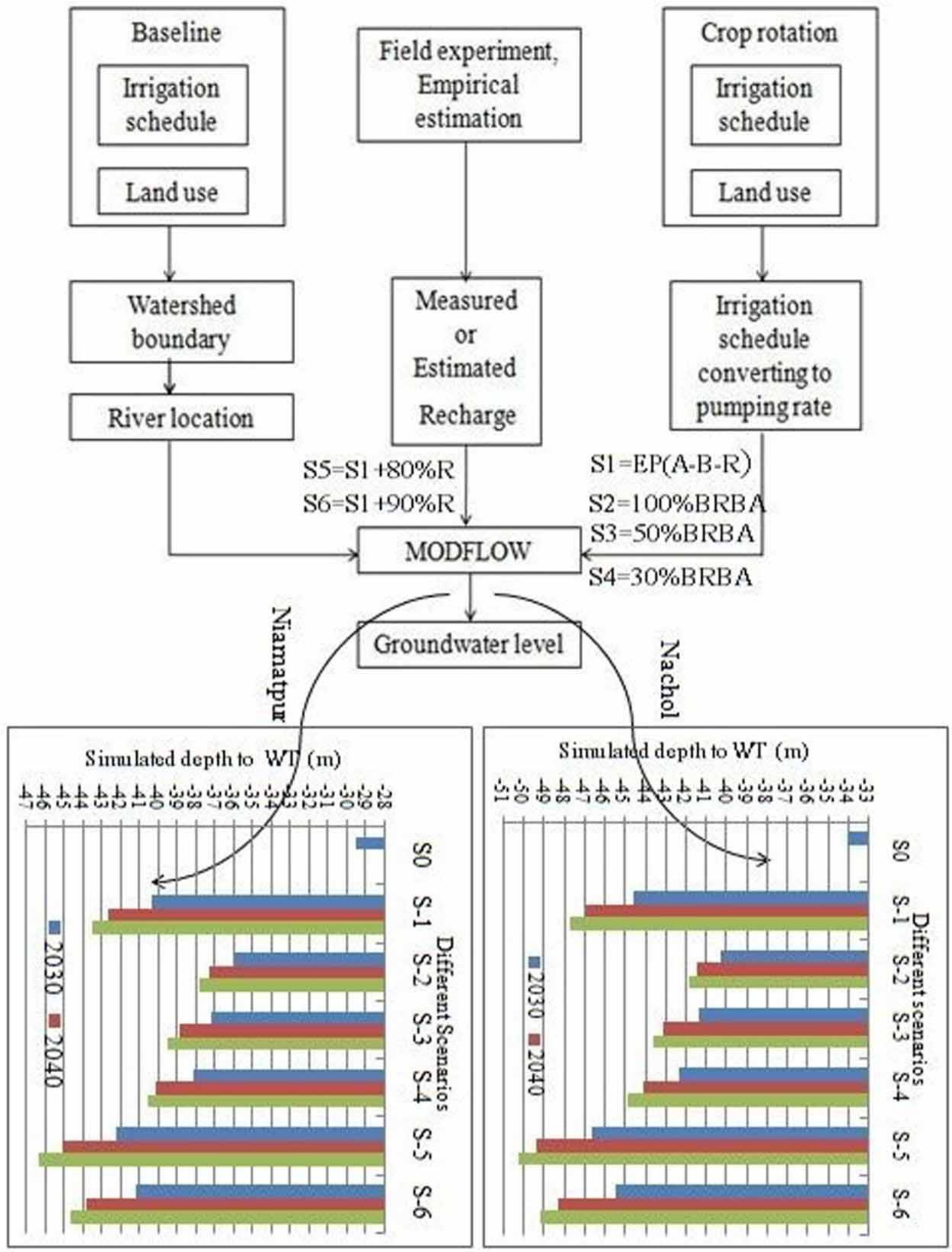
The lowering of the groundwater table caused by increased groundwater use in the dry, Barind region has prompted sustainability concerns. In this study, water-table (WT) scenarios were simulated by the MODFLOW model under different crop rotations in Barind, a dry region of Bangladesh, to examine the effects of crop rotations on groundwater level. The studied crop rotations and recharge conditions were: with existing cropping pattern; 100, 30 and 50% of present Boro rice is replaced by Aus rice; existing cropping pattern, but with reduced recharge to 90 and 80% of present recharge. A calibrated MODFLOW model was used to develop WT scenarios. According to the modeling results, the declination of WT will be lessened and the situation with regard to WT will therefore be improved with the gradual substitution of Boro by Aus and Rabi (30, 50 and 100%). The simulated WT scenario will be useful for policymakers to set policies about cropping patterns or groundwater withdrawal amounts targeting the area's long-term sustainability of groundwater.

Key words: Barind area, Groundwater sustainability, MODFLOW, Recharge, Withdrawal rate

HIGHLIGHTS

- Sustainable agricultural production in the Barind area is under threat due to unsustainable groundwater use.
- A calibrated MODFLOW model was used to predict the water-table (WT) under different cropping patterns.
- With the gradual substitution of Boro rice by Aus rice (e.g. 30%, 50%, and 100%), the situation for WT will be improved.
- The simulated WT scenario will therefore be useful for the policymakers.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Groundwater continuously supports irrigation both temporally and spatially, as opposed to other water resources like precipitation and surface water. But steadily increasing groundwater consumption for irrigation has led to groundwater depletion in many areas of the world (Konikow & Kendy, 2005; Foster *et al.*, 2015; Konikow, 2015; Ruybal *et al.*, 2019; Zaman *et al.*, 2019; RWCH, 2020), which spurs discussion of the sustainability of groundwater supplies in agricultural regions with a focus on agricultural management plans (Wada *et al.*, 2010). Depletion and pollution of groundwater are global sustainability concerns because of a lack of surface water and dependence on it (Sakizadeh *et al.*, 2019; Lall *et al.*, 2020). Additionally, the management of groundwater supplies may become more challenging in some areas as a result of climate change's reduced precipitation and elevated air temperature which causes an increased need for irrigation water (Ali *et al.*, 2007; Gondim *et al.*, 2012; Kirby *et al.*, 2016).

Bangladesh, the nation with the densest population in the world (1,200 person/km^2), according to the World Population Review (2021), is working to increase food production to support its growing population. Currently, the agricultural sector directly contributes 13% to the country's GDP (BBS, 2020a). More crops must be produced per unit of land due to the shrinking amount of arable land as a result of other activities (such as urbanization, housing and industrial development). The primary means of reaching the objective is through improved crop cultivation in conjunction with high inputs (such as irrigation and fertilizer).

The high-yielding Boro rice is grown in Bangladesh during the dry Rabi season (January–April). About 79.2% of the land is irrigated with groundwater (BBS, 2020b) due to the lack of surface water. Water is becoming more and more in demand across a variety of industries and facets of improving one's standard of living. Furthermore, it is expected that climate change would cause water resources to stress to worsen in the future (IPCC, 2014).

The lack of surface water and low rainfall during the dry season (Boro rice season) prompted most parts of Bangladesh to use its groundwater resources. The Barind Track area, which makes up a significant portion of the Rajshahi Division in the country's northwest and receives an average of 1,400 mm of rainfall annually, is in worse condition than other regions in terms of its water resources (Ali *et al.*, 2021). The largest danger to the social and economic sustainability of the region is the substantial fall in groundwater levels and several geological issues brought on by increased water use over the past few decades. Therefore, it is vital in this area to identify the remedial measures for groundwater decline and to create a workable plan for long-term groundwater use. Water usage in the agriculture sector cannot be reduced by conventional cropping methods with a rice-rice pattern. Thus, demand management is one of the alternatives for attaining the sustainability of groundwater (Ali, 2011, 2018; Sarkar *et al.*, 2013; Afruzi *et al.*, 2021).

The equilibrium between the surface and groundwater alters under different groundwater recharge and withdrawal situations, causing the groundwater level to respond in diverse ways (Yang *et al.*, 2002, 2015; Barlow & Clark, 2011). In this regard, simulation models can be quite helpful (Singh, 2014). Various techniques are employed to anticipate groundwater levels, such as physically based models (Reeves & Zellner, 2010; Ni *et al.*, 2020), non-physically based approaches (Roy *et al.*, 2021), statistical models (Sakizadeh *et al.*, 2019), artificial neural networks (Mohanty *et al.*, 2010) and fuzzy logic (Nadiri *et al.*, 2019). Among these, physically based models take into account all conceivable facets of the underlying physical system.

Yang *et al.* (2002) examined groundwater levels in Gaocheng, China, from 1974 to 1998 and found that a fall in groundwater recharge was a factor in the area's groundwater loss. In Nebraska, the United States, Klocke *et al.* (1999) measured drainage volume from fields with continuous corn and corn–soybean rotation and discovered no discernible differences between the two crop rotation strategies. Similar simulations of groundwater recharge were conducted by Dakhlalla *et al.* (2016) under various rotation scenarios. They discovered that differing degrees of groundwater recharge were impacted by the various crop rotation schemes. While corn and soybean rotations produced a similar level of groundwater recharge with continuous corn and soybean, rotations containing rice often had higher groundwater recharge amounts than other types.

In order to create various scenarios aimed at tackling groundwater, Nayak *et al.* (2015) employed the 'Water Evaluation and Planning (WEAP)' model. According to their calculations, a 25% switch to direct seeded rice will almost completely restore the system to sustainable groundwater use. Barlow & Clark (2011) assessed several groundwater conservation programs with groundwater pumping reduced by 5 and 25% for the Mississippi River Valley alluvial aquifer. According to their findings, cutting back on agricultural use increased groundwater storage from 2 to 31.7% while assuming the same recharge rate. Several researchers (Barlow & Clark, 2011; Scanlon *et al*., 2012; Ni *et al*., 2020) studied the impacts of changing groundwater consumption on groundwater resources using Modular Three-Dimensional Finite-Difference Groundwater Flow Model (MODFLOW) (Harbaugh *et al*., 2000).

A simulator for environmental planning studies was produced by Reeves & Zellner (2010) using MODFLOW and an agent-based land-use model. Their research demonstrated potential system responses to various zoning policy scenarios in terms of the spatial patterns of development and subsequent influence on groundwater. The hydraulic performance of two wells in Pakistan's lower Indus basin was assessed by Ali *et al.* (2004) using MODFLOW and MT3D, and operating tactics were suggested. Through the combined use of the SWAT and MODFLOW models, Ni *et al.* (2020) evaluated the effects of agricultural conservation practices on groundwater levels. In the analysis of crop rotation scenarios, they observed that, in comparison to continuous soybean and corn–soybean rotation scenarios, the groundwater level increased more in the continuous corn scenario.

Considering the aforementioned, simulating the groundwater table using MODFLOW is a useful method to evaluate the potential effects of various agricultural rotations on the groundwater. The objective of this study was to evaluate the impact of crop rotations (and therefore, varied withdrawal rates) on groundwater in order to determine the most practicable practical approach to managing groundwater resources and prevent excessive abstraction.

2. MATERIALS AND METHODS

2.1. Study area

2.1.1. Site location

North-western area of Bangladesh is largely engaged by Pleistocene deposits (Morgan & McIntire, 1959). The section is located between 24°22′ to 24°51′ North and 89°18′ to 89°22′ East. The present study is, however, based on part of a configuration of two districts (Chapainawabgonj and Naogaon). The studied locations are Nachol Upazila of Chapainawabgonj district and Niamatpur Upazila of Naogaon district. The location map of the studied area is shown in Figure 1.

2.1.2. Hydrogeological conditions and topography

The topography of the region is characterized by two distinct landforms: (a) the Barind tract – dissected and undulating and (b) the floodplains. The elevated Barind tract is characterized by less infiltration due to clayey and semi-to impermeable Barind clay with excessive surface runoff. Morpho-stratigraphically, the region is subdivided into three geological units: (1) Barind clay residuum – overlies and developed on Pleistocene alluvium, (2) Holocene Ganges flood-plain alluvium and (3) Active channel deposits of the Ganges and major distributaries (modern alluvium). The lithology types include alluvial sand, alluvial silt, Barind clay residuum, and Marsh clay and peat (Alam *et al*., 1990). Hydrogeologically, the area is covered by a semi-impervious clay-silt aquitard of the recent

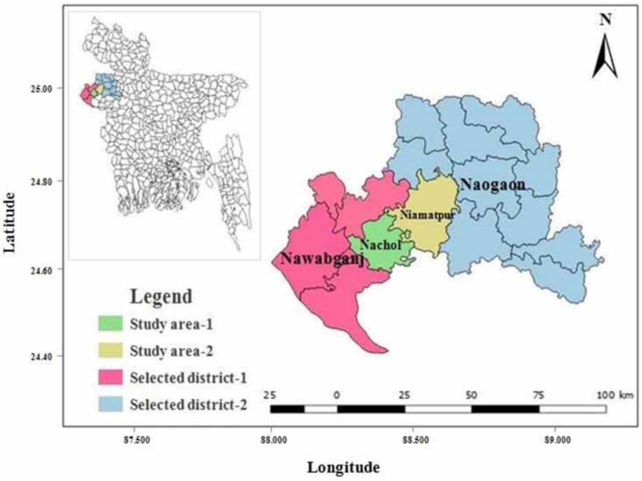


Fig. 1 | Location map of the study area (Nachol and Niamatpur).

Pleistocene period (thickness 3.0–47.5 m), and is characterized by the single to multiple layered (2–4) aquifer system of Plio-Pleistocene age (thickness 5.0–42.5 m) (Jahan *et al.*, 2005).

2.1.3. Rainfall pattern of the area

The monthly pattern of rainfall (mean of 2001–2020) data collected from BMDA Nachol office is presented in Figure 2. The yearly rainfall fluctuates considerably (843–2,241 mm); having mean, standard deviation and coefficient of variation of 1,532 mm, 294 mm and 19%, respectively. Approximately 83% of this rainfall occurs during the months of May–September which is noted as monsoon season.

2.1.4. ET determination

The evapotranspiration (ET) for different crops was estimated as follows:

(a) For dry-land crops (lentils, mustard, wheat)

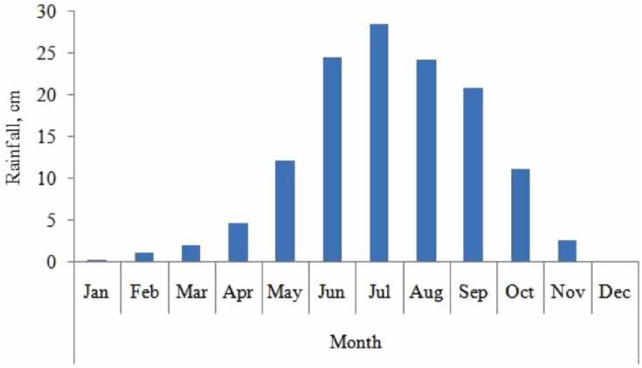


Fig. 2 | Mean monthly rainfall distribution at the study area.

For the dry-land crops (where $(I + R_e) \leq ET)$), the *ET* was calculated from the following water balance equation (Ali, 2010; Ali & Mubarak, 2017):

$$I + R_e = ET \pm \Delta S \text{ or,} \tag{1}$$

$$ET = I + R_e \pm \Delta S \tag{2}$$

where *I* is the irrigation amount (cm); R_e is the effective rainfall (cm); ΔS is the change in soil moisture within the effective root-zone of the crop (cm) and ET is the crop evapotranspiration (cm).

(b) For wet-land crops (Boro, Aus and Aman rice)

For wet-land crops, where the 'rainfall' *or* 'sum of rainfall and irrigation' exceeds or equals the crop evapotranspiration demand, the *ET* was calculated as (Ali, 2010; Ali & Mubarak, 2017):

$$ET_a = ET_0 \times Kc \tag{3}$$

where ET_0 is the reference evapotranspiration (cm); *Kc* is the crop coefficient and *ET* is the crop evapotranspiration (cm).

2.2. Estimation of recharge rate

Recharge rate was estimated using the applied tracer, water balance (WB) and water-table fluctuation (WTF) methods in the study area and reported elsewhere (Ali *et al.*, 2022a). The average yearly recharge at the Nachol location varied from 104.9 to 195.8 mm/year under different methods, having a mean of 136.1 mm/year over the methods. At the Niamatpur location, the recharge rate varied from 125.1 to 210 mm (9.9–15.1% of yearly rainfall) under different methods, having a mean of 157.6 mm/year.

2.3. MODFLOW simulation model

The Modular Finite-Difference Flow Model (MODFOW) is a physical-based three-dimensional groundwater flow model (McDonald & Harbaugh, 1988; Harbaugh, 2005; Harbaugh *et al.*, 2017). It is the United States Geological Survey's (USGS's) modular hydrologic model and is considered as the international standard for simulating and predicting groundwater conditions with the interaction between surface water and groundwater.

MODFLOW was utilized for future groundwater level prediction of the studied unconfined aquifer of Nachol and Niamatpur Upazila. Pumping rates under different cropping patterns and different recharge rates (measured recharge value, and also changing scenario of 80 and 90% of recharge present recharge) were used for this modeling. The schematic of the MODFLOW application is shown in Figure 3.

2.3.1. Model domain

Model domain has been selected based on the coverage of GPS locations of field sites. A rectangle is chosen in such a way that it covers all the field locations (Figures 4 and 5).

The total domain area is divided into 266 rows and 247 columns with 100 m × 100 m cell size. Daily evapotranspiration and recharge rate are calculated from monthly data (Table 1).

2.4. Scenario statement

From the survey of the study area, it is revealed that the major cropping patterns practiced by the farmers are: (1) Aman-Boro-Fallow and (2) Aman – Rabi/Kharif – Fallow. A very negligible amount of 'Aus rice' is cultivated instead of Boro rice. Existing Boro rice cultivars are long duration (160–165 days). In Rabi and Kharif seasons,

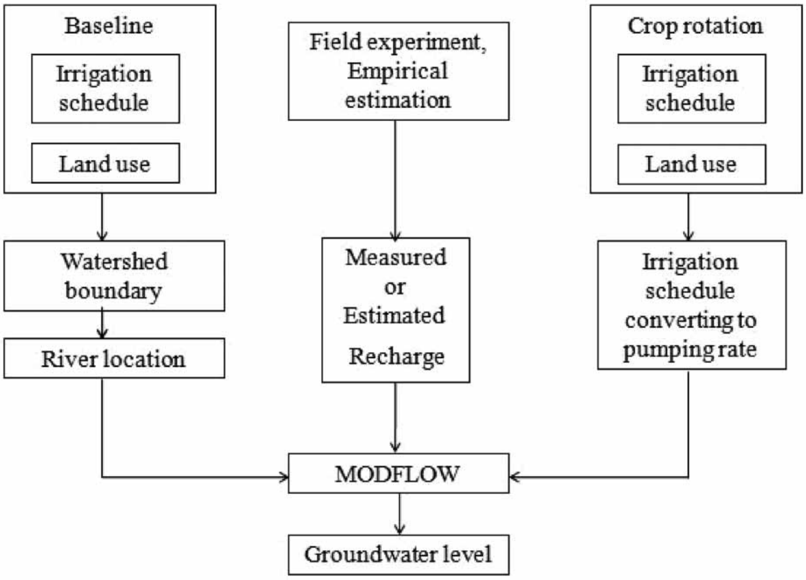


Fig. 3 | Schematic of simulation modeling using MODFLOW.

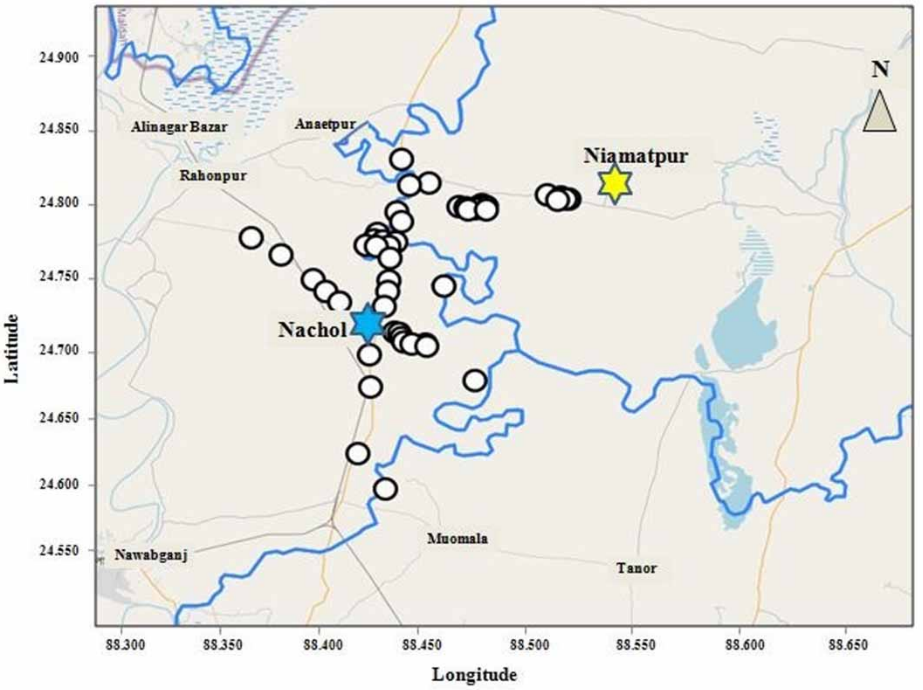


Fig. 4 | Field site locations.

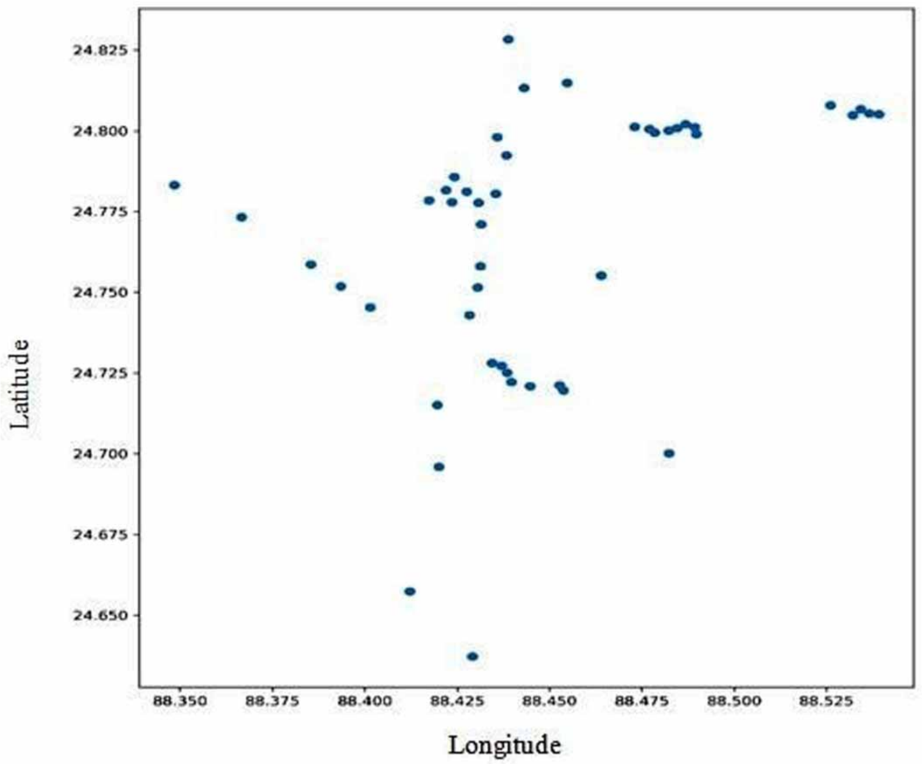


Fig. 5 | Model domain rectangle.

Table 1 | Monthly total evapotranspiration (mm), evapotranspiration rate (m/d), monthly total recharge (mm) and recharge rate (m/d).

Month	ET, (mm)	ET rate, (m/)d	Recharge, (mm)	Recharge rate, (m/d)
Jan	85	2.82×10^{-3}	0.0	0
Feb	114	3.81×10^{-3}	0.0	0
Mar	219	7.29×10^{-3}	0.0	0
Apr	242	8.08×10^{-3}	0.0	0
May	161	5.38×10^{-3}	22.5	7.50×10^{-4}
Jun	79	2.63×10^{-3}	25.0	8.34×10^{-4}
Jul	43	1.43×10^{-3}	33.4	1.11×10^{-3}
Aug	61	2.04×10^{-3}	30.3	1.01×10^{-3}
Sep	92	3.06×10^{-3}	33.0	1.10×10^{-3}
Oct	84	2.80×10^{-3}	4.9	1.63×10^{-4}
Nov	84	2.81×10^{-3}	0.0	0
Dec	91	3.02×10^{-3}	0.0	0

wheat, lentil or mustard are cultivated. The existing pattern 'Aman-Boro-Fallow' is water consuming and on average about 110–115 cm water is needed per year. In Boro rice cultivation, about 80–85 cm of irrigation water is needed, whereas in Aus rice cultivation, about 40–50 cm is required (a lower amount due to rainfall contribution during the Aus season). Ali (2018) showed that in the Barind area, 'Aus rice' instead of 'Boro rice' can save a substantial amount of irrigation water. That's why an 'Aus based' cropping pattern along with non-rice 'Rabi crops' was included in this simulation study. The description of scenario conditions is given in Table 2. The different 'Scenario Conditions' (S1–S5) were calculated considering the groundwater withdrawal rate/amount of respective cropping patterns.

2.5. Model parameters and model calibration

Pumping tests were performed to determine aquifer hydraulic properties such as hydraulic conductivity (K), transmissibility (T) and specific yield (S_y), and reported elsewhere (Ali *et al.*, 2022b). The Model parameters for Nachol and Niamatpur (determined by bore-log and pumping test) are given in Table 3.

2.5.1. Model calibration

Model calibration was conducted by adjusting the vertical hydraulic conductivity. The vertical hydraulic conductivity has been selected one-tenth times the horizontal hydraulic conductivity based on the literature value (IWM, 2012).

The calibration curve (WT throughout the year) is given in Figure 6(a), and the fitted equation is shown in Figure 6(b) for the Nachol area. Likewise, the calibration and fitted curve for Niamatpur are shown in Figure 7(a) and 7(b), respectively.

The simulations were performed for the years 2030, 2040 and 2050.

Table 2 | Description of different scenario conditions.

Sl.	Description of conditions
Scenario-1 (S1)*	With existing cropping pattern (and hence, the existing withdrawal rate of groundwater). Aman-Boro-Fallow
Scenario-2 (S2)	100% of present Boro rice is replaced by Aus rice and Rabi crop
Scenario-3 (S3)	50% of present Boro rice is replaced by Aus rice
Scenario-4 (S4)	30% of present Boro rice is replaced by Aus rice
Scenario-5 (S5)	With existing cropping pattern (S1), but recharge = 90% of present recharge
Scenario-6 (S6)	With existing cropping pattern (S1), but recharge = 80% of present recharge

*For Nachol area: In the existing cropping system, during winter (Boro season), 58% of the land is occupied by Boro rice.
For Niamatpur area: In the existing cropping system, during winter (Boro season), 76.1% of the land is occupied by Boro rice.

Table 3 | Model parameters for Nachol and Niamatpur.

Model parameters	Nachol	Niamatpur
Aquifer depth	58 m	58 m
Hydraulic conductivity	32.7 $m^3/m^2/d$	28.9 $m^3/m^2/d$
Initial water table	34 m	29.56 m

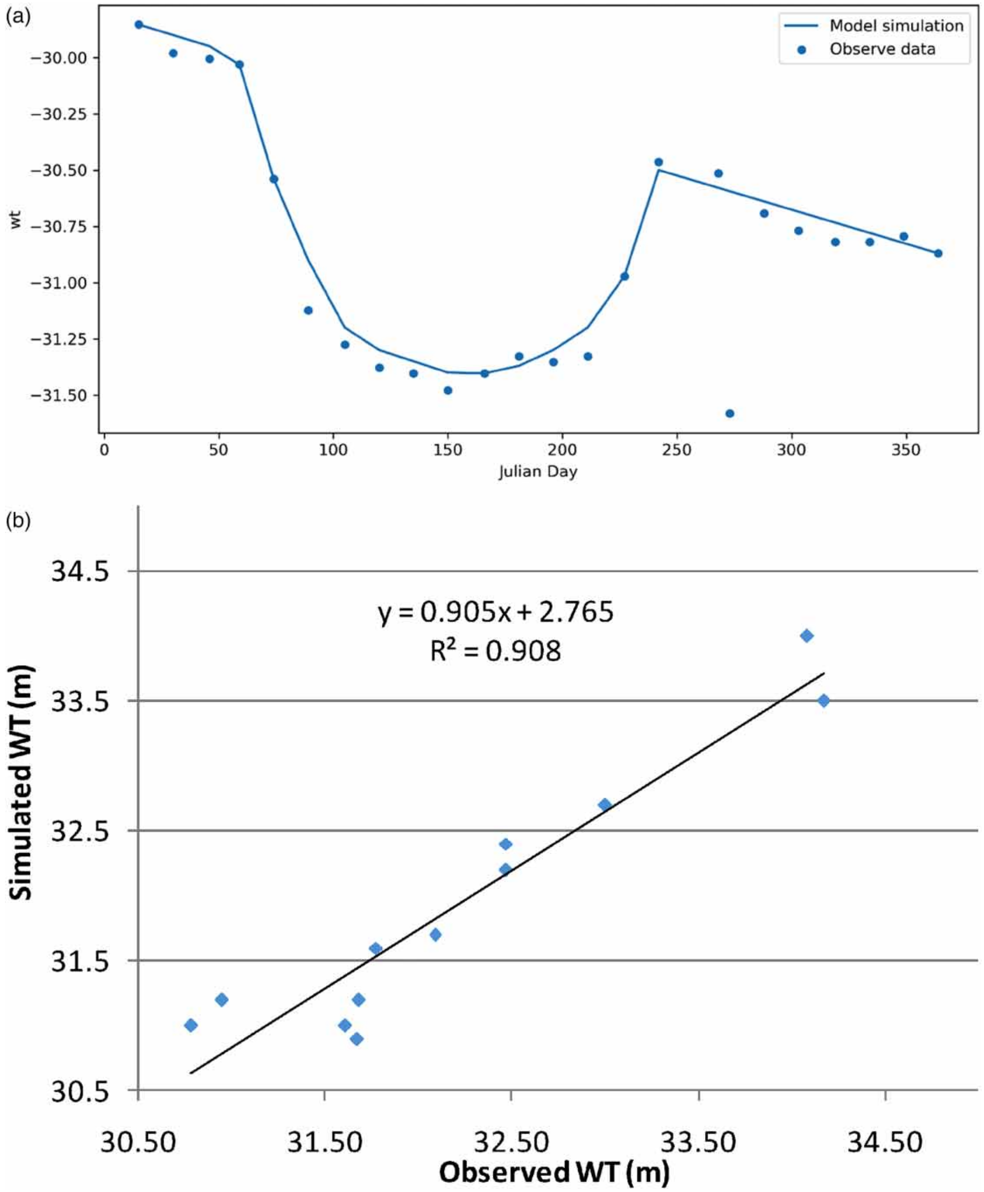


Fig. 6 | (a) Calibration curve (Nachol). (b) Calibration curve with fitted equation (Nachol).

3. RESULTS AND DISCUSSION

3.1. Simulation of WT position under different cropping patterns/withdrawal rate for Nachol (Location-1)

The water-table (WT) scenarios for various ‘cropping patterns’ (and consequently for various ‘groundwater extraction scenarios’) are shown in Figure 8. Here, S0 represents the WT in 2018.

Under the present withdrawal condition (scenario S1), the simulated depth to WT at Nachol for the years 2030, 2040 and 2050 will be 44.5, 46.9 and 47.7 m, respectively (Figure 8).

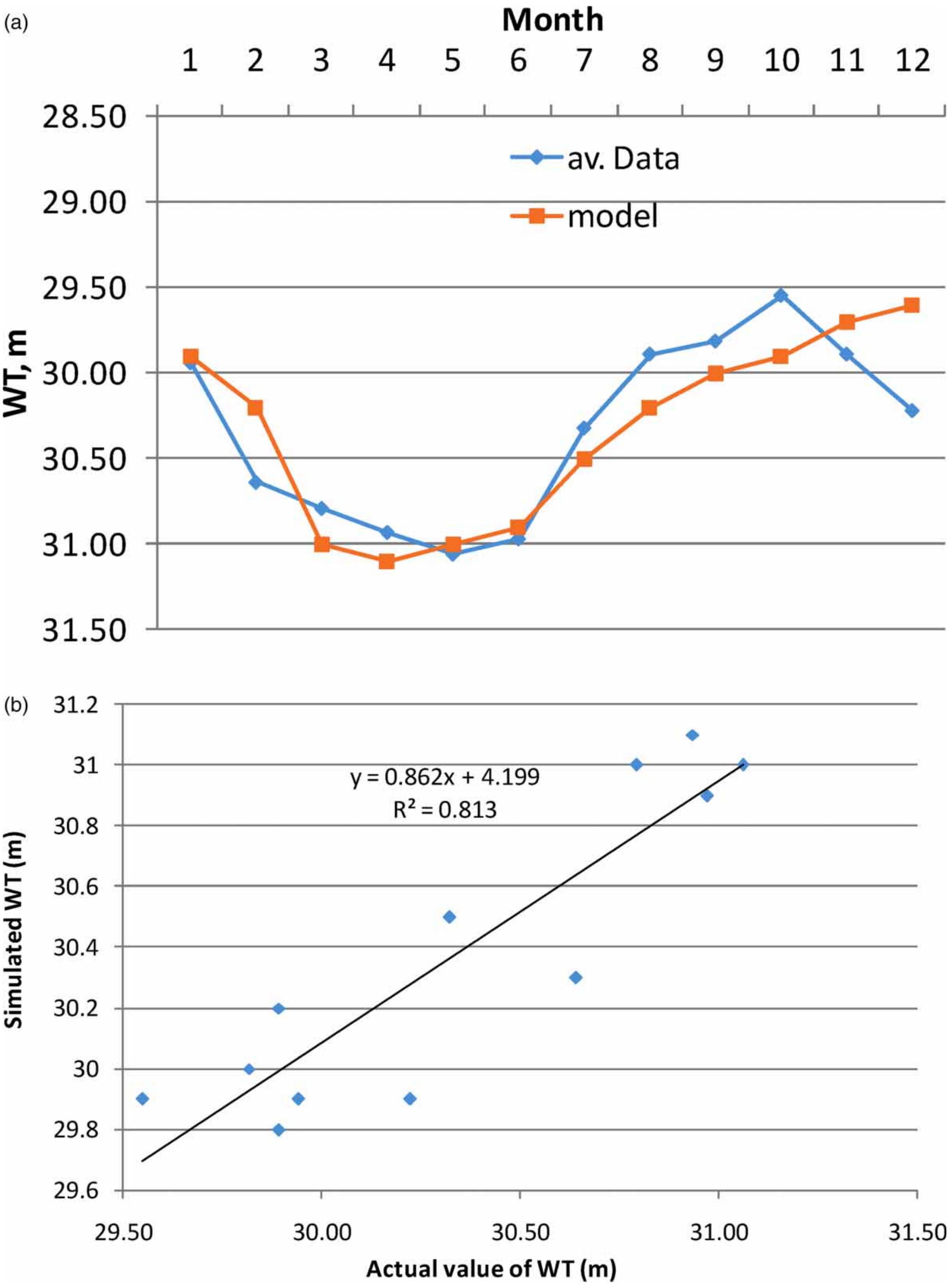


Fig. 7 | (a) Calibration curve (Niamatpur). (b) Calibration curve with fitted equation (Niamatpur).

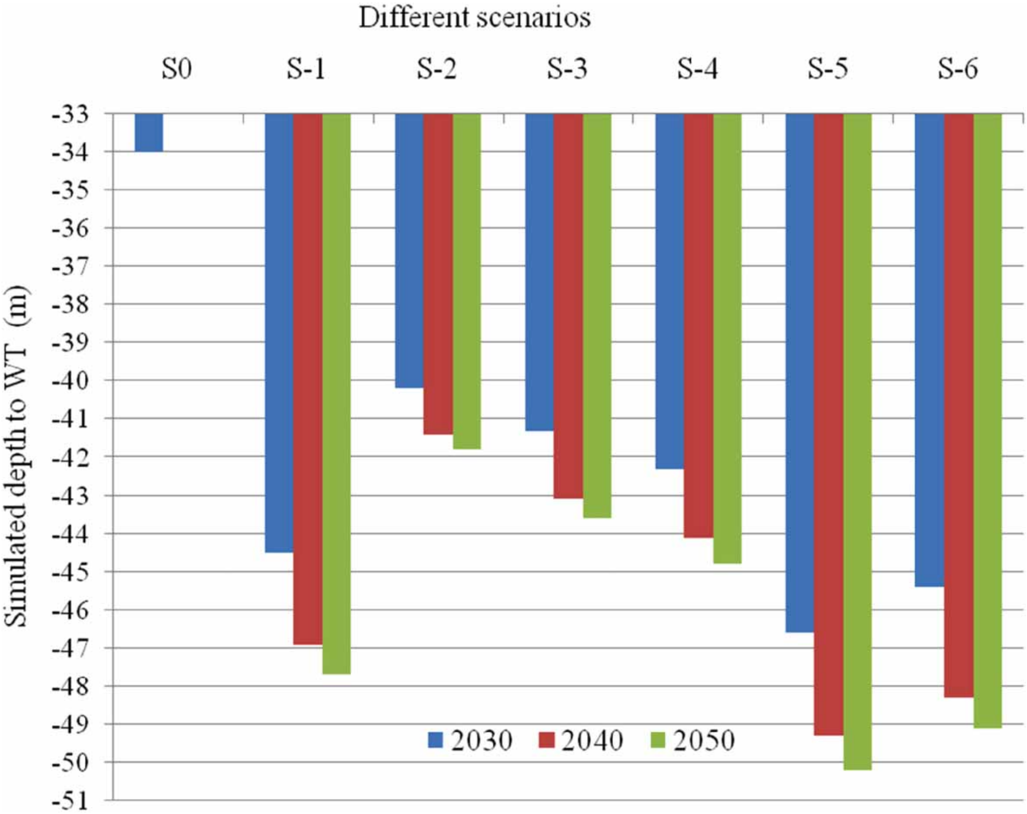


Fig. 8 | Simulated scenario of WT by MODFLOW model under different withdrawal patterns for Nachol.

If the present Boro rice (100%) is replaced by Aus (scenario S2), the WT for the years 2030, 2040 and 2050 will be 40.2, 41.4 and 41.8 m, respectively; which indicates that the WT condition will be nearly stable, that is, no significant declination of WT.

The anticipated WT declination ranges from 42.3 to 44.8 m and 41.3 to 43.6 m, respectively, for the years 2030–2050 for the 50 and 30% replacement of Boro by Aus (S3 and S4). These suggest that the situation for WT will improve when Boro is gradually replaced by Aus.

The WT responded accordingly if the recharge rate was decreased from its current level (S1) to 80% (S5) and 90% (S6). In comparison to the control (S1 scenario), the position of WT declined.

3.2. Simulation scenario for Niamatpur area (Location-2)

Figure 9 shows the WT scenarios for various ‘cropping patterns’ (and consequently, for various ‘groundwater extraction scenarios’). Here, S0 denotes the WT position for the year 2018.

The simulated depth to the WT at Niamatpur for the years 2030, 2040 and 2050 will be 40.3, 42.7 and 43.5 m, respectively, under the current withdrawal condition (S1).

The WT for 2030, 2040 and 2050 will be 35.9, 37.3 and 37.8 m, respectively, if the current Boro rice (100%) is replaced with Aus (S2); this shows a slower decline in WT. Compare with the rate of change/replacement of Boro rice, the rate of change of WT is lower. This is due to the fact that the change in groundwater level is caused by

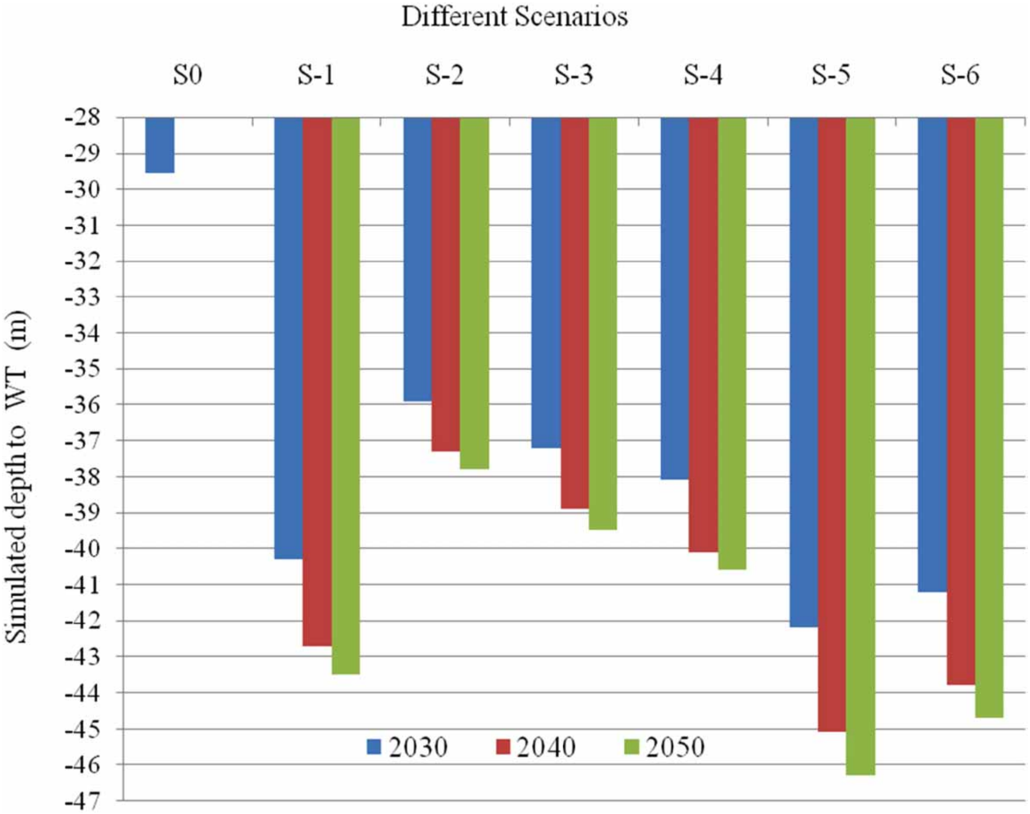


Fig. 9 | Simulated scenario of WT by MODFLOW model under different withdrawal patterns for Niamatpur.

more than just irrigation withdrawal. Other factors include residential uses, the quantity and timing of rainfall (which impacts the amount of recharge), and GW internal flow, etc.

The estimated WT decline for the years 2030–2050 will be from 38.1 to 40.6 m and 37.2 to 39.8 m, respectively, assuming 50 and 30% substitution of Boro by Aus rice (S3 and S4). This suggests that the position for WT will improve compared with the current circumstance with the gradual replacement of Boro by Aus (S1).

When the recharge rate dropped from its current level to 80% (S5) and 90% (S6), the WT also responded accordingly. In comparison to the S1 scenario, the control, the WT position decreased.

Zaman *et al.* (2017) studied the WT dynamics of the Bogra district (*a part of the Barind area*) of Bangladesh and projected WT for 2040 and 2060, using MAKESENSE software. They reported that considering the present declining trend, the WT depth will approximately double by the year 2060 from those of the year 2013 (i.e. in 47 years period). Ali *et al.* (2012) analyzed the WT declination trend of the Rajshahi district (*main Barind area*) and presented the future scenario simulated by MAKESENSE software. They noted that over 25 years period (2005–2030), the WT will nearly double in some areas; and for the rest, it will nearly double over 45 years (2005–2050). Asraf & Ali (2015) also reported almost similar predictions for Charghat, Godagari and Tanore Upazila of Rajshahi district.

In our present study, Nachol and Niamatpur, the driest zone of the Barind tract, the WT exhibited nearly 1.5 times of declination over 22 years (2018–2050) under the current practice of cropping pattern (S1).

Connecting the surface agricultural practices (cropping patterns/rotations) to the groundwater was the main theme, and novelty of this study. Nachol and Niamatpur Upazila are the two most groundwater-depleting areas of the dry, Barind area of Bangladesh. The groundwater withdrawal rate in this region needs to be optimized in view of the natural recharge and aquifer properties/'supply capacity' of the aquifer. Three different crop planning scenarios along with existing practices were evaluated in this study. In addition, the study evaluated the impact of groundwater recharge variation on groundwater level. The MODFLOW model performance was good ($R^2 > 0.80$). Thus, within the modeling period, the model could represent the groundwater level response to the change of crops/'cropping patterns'.

Objectives 1 and 2 of the United Nations' Sustainable Development Goals (UN, 2020) focus on producing enough food, whereas goals 6 and 11 are concerned with sustainability and clean water, respectively (i.e. avoidance of pollution and sustainability of water resources).

In order to implement the proper policy about cropping patterns or groundwater withdrawal amount that targets the long-term sustainability of groundwater, the policymaker will find the findings of this study and the simulated WT scenario beneficial.

The results of this study will aid in the planning of management choices to counter the trend of the groundwater table decline as well as the effects of climate change and drought. Revision of the current Boro-based cropping pattern may be a useful option for demand management. The government's investment in expanding upon and putting into practice the current findings may be superior to a supply-side solution given that it will cost several times as much (in addition to environmental cost).

4. CONCLUSION

4.1. Conclusions for Nachol

- The simulated depth to WT at Nachol for the years 2030, 2040 and 2050 will be 44.5, 46.9 and 47.7 m, respectively, under the current withdrawal condition (S1).
- According to the modeling results, the declination of WT will be lessened and the situation with regard to WT will therefore be improved with the gradual substitution of Boro by Aus (30, 50 and 100%).
- The depth to WT will also grow if the recharge rate is decreased from its current level (e.g. to 80 or 90%).

4.2. Conclusions for Niamatpur location

- At Niamatpur, the simulated depth to the WT for the years 2030, 2040 and 2050 will be 40.3, 42.7 and 43.5 m, respectively.
- The simulation findings show that the declination of WT will be lessened and, as a result, the situation with regard to WT will be better with the progressive replacement of Boro by Aus (30, 50 and 100%).
- If the recharge rate is decreased from its current level (e.g. to 80 or 90%), the depth to WT will likewise be raised.

The simulation scenario will be helpful to the watershed managers or policy planners for watershed planning and understanding how various crop rotations (and hence, different withdrawal rates) impact groundwater.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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