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Article

Impacts of irrigated agricultural land expansion on groundwater security in Mithapukur Upazila, Bangladesh

Md. Moniruzzaman Monir[1]* and Shapla Akhter[1]

[1]*Department of Geography and Environmental Science, Begum Rokeya University, Rangpur, Bangladesh*

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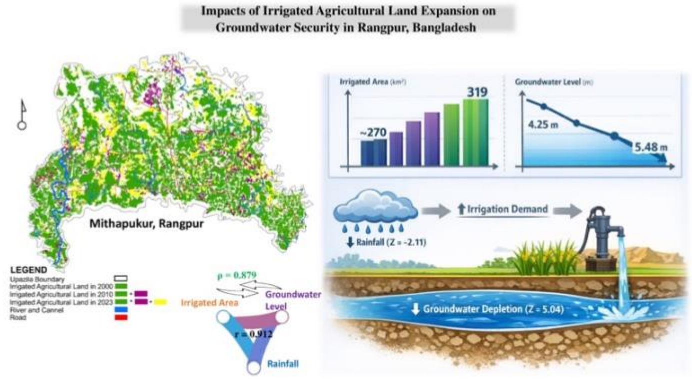

Highlights

- *Irrigated area in Mithapukur Upazila increased from 270 km² (2000) to 319 km² (2023).*
- *Groundwater levels declined, with average depth increasing from 4.25 m (2000) to 5.48 m (2023).*
- *A slight decline in rainfall (Z = -2.11) intensified irrigation demand, leading to declining groundwater levels (Z = 5.04).*
- *Strong correlation between irrigation expansion and groundwater level decline (ρ = 0.879).*

Abstract

The rapid expansion of groundwater-based irrigation has transformed agricultural productivity in Bangladesh, yet it has also intensified pressure on subsurface water resources. This study examined the impacts of irrigated agrarian land expansion on groundwater security in Mithapukur Upazila, Rangpur District, Bangladesh, an agriculturally intensive region characterized by dry-season Boro rice cultivation and limited surface-water availability. High-resolution land use maps derived from Orthorectified and Sentinel-2 imagery of 2000, 2010, and 2023 were combined with long-term groundwater level data from the Bangladesh Water Development Board (BWDB) to analyze spatiotemporal irrigation patterns and aquifer responses. Spearman's rank correlation coefficient (ρ) was used to examine the relationship between irrigated area and groundwater level, while Root Mean Square Error (RMSE) was used to evaluate model prediction accuracy. Results indicate that the irrigated area increased from 269.57 km^2 in 2000 to 318.97 km^2 in 2023, while groundwater levels declined from 4.25 m to 5.48 m below the surface. Statistical analysis revealed a strong positive correlation (ρ = 0.879) between irrigation expansion and groundwater depletion, primarily driven by increased groundwater withdrawals, with limited surface water availability intensifying reliance on groundwater resources. These findings highlighted the urgent need for integrated water management strategies, including regulated pumping, adoption of water-efficient irrigation practices, and coordinated use of seasonal

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**Corresponding author: monirbrur83@gmail.com (MMM)*

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surface water for irrigation, combined with groundwater abstraction during dry periods, to safeguard both agricultural productivity and aquifer sustainability.

1 Introduction

The rapid expansion of groundwater-based irrigation has underpinned remarkable increases in crop production across many parts of South Asia, including Bangladesh (Causapé et al., 2004; Afrin et al., 2019). Over the past two decades, the intensification and spatial expansion of irrigated agriculture, particularly through the widespread installation of shallow and deep tube wells for dry-season (Boro) cultivation, have transformed cropping patterns and livelihoods, but also substantially increased pressure on subsurface water resources (Alauddin and Sharma, 2013; Mojid and Mainuddin, 2021). Groundwater irrigation now constitutes the dominant irrigation source across much of Bangladesh's agrarian regions, with empirical studies demonstrating an overwhelming dependence on groundwater abstraction to sustain dry-season agriculture, particularly in intensively cultivated areas where groundwater supplies nearly all irrigation demand (Mojid et al., 2019; Mojid et al., 2021; Shamsudduha et al., 2022; Monir et al., 2023c; Rokonuzzaman et al., 2023; Amin et al., 2025).

Groundwater is inherently dynamic: recharge, abstraction, climatic variability, and land use change interacts to determine aquifer storage and sustainability (Kumbhakar and Lien, 2010; Rushton et al., 2020; Monir et al., 2023b). In many irrigated regions of Bangladesh, the net effect of intensified pumping has been long-term groundwater depletion despite seasonal return flows from irrigation that can partially replenish shallow aquifers (Mair et al., 2013; Tulip et al., 2022). A study in northwestern Bangladesh found that while about 33% of applied irrigation returns as groundwater recharge during the dry season, overall groundwater levels still show a persistent declining trend over time (Monir et al., 2025). This pattern of persistent groundwater depletion despite return flows has also been observed in other regional investigations, where excessive irrigation pumping overwhelms natural recharge processes (Amin et al., 2025).

Irrigation-driven groundwater stress extends beyond volumetric decline, intersecting with soil salinization, water quality issues (including naturally occurring geogenic contaminants), and climatic variability to amplify socio-ecological risks (Roy and Shah, 2002). Recent assessments using remote sensing and sustainability-mapping techniques in the semi-arid zones of Bangladesh highlighted that parts of the agrarian landscape are becoming increasingly vulnerable to future water security and desertification risks under continued groundwater exploitation (Prodhan et al., 2020; Monir et al., 2024). Despite growing recognition of these issues, important knowledge gaps remain for agriculturally dominated Bangladeshi landscapes (Haque et al., 2012). First, many prior studies focused on regional or national aggregates or on urban groundwater depletion, leaving less resolved the local-to-subregional dynamics where irrigation expansion is most active (Faisal et al., 2005). Previous studies analyzed only the groundwater and irrigated areas trend, but not mapping spatiotemporal changes in irrigated areas using high-resolution satellite imagery (Hossain and Mojid, 2022). Second, the interplay of irrigation returns flows, seasonal recharge, shifting cropping calendars, and farm-level technology adoption (e.g., shift from surface to pressurized systems or deeper tubewells) complicates simple extrapolations of sustainability (Dey et al., 2017). Third, there is limited integration of hydrological observations with recent high-resolution irrigation coverage data and socioeconomic drivers that explain why and where irrigation expands (Dewandel et al., 2008).

It is essential to fill these knowledge gaps to design policy instruments, ranging from regulated abstraction and pricing to conjunctive use strategies that are both effective and socially equitable. This study addressed to those gaps by examining the impacts of recent irrigated agricultural land expansion on groundwater security in an agriculturally dominated area of Bangladesh. Specifically, we combined spatially explicit irrigation-area mapping, long-term groundwater level records, and scenario-based assessments to: (1) quantify the spatial and temporal patterns of irrigation expansion; (2) attribute observed groundwater level trends to irrigation intensification relative to climatic variability and other drivers; and (3) evaluate potential management pathways that could alleviate groundwater stress while maintaining agricultural productivity.

By focusing on a region where irrigation expansion is contemporaneous with measurable groundwater decline (Salam et al., 2023), the analysis aimed to generate actionable insight for policymakers and water managers seeking to balance food security and aquifer sustainability. The results will therefore be of interest not only to hydrogeologists and agronomists but also to decision-makers concerned with sustainable intensification, climate resilience, and water-resource governance in South Asia and other regions undergoing similar irrigation transitions.

2 Data sources and methods

2.1 Selection of the study area

Mithapukur Upazila in Rangpur District is geographically located at approximately 25.54° N latitude and 89.28° E longitude (**Fig. 1**).

Mithapukur Upazila was selected because it is one of the most agriculturally intensive regions in northern Bangladesh, where irrigation demand has been rising rapidly (Afrin et al., 2019). This area is situated on fertile alluvial floodplain soils of the Barind region, with some local variations such as reddish-brown "Khiyari" soils. Groundwater is the main source for irrigation through shallow tubewells, while seasonal ponds and canals provide limited surface water (Bangladesh Agricultural Development Corporation, 2023a). Hydrologically, the area experiences significant seasonal variation, with water tables rising during the monsoon and falling in the dry season (Monir et al., 2023c). Agriculture dominates the landscape, with cropping patterns largely following the availability of water: Boro rice is grown in the dry season under irrigation, Aman rice during the monsoon, and potato, maize, wheat, mustard, and other vegetables are cultivated in rotation (Bangladesh Agricultural Development Corporation, 2023b).

2.2 Data type and sources

The irrigated agricultural area map was generated by analyzing Orthorectified (0.31 m) images from WorldView-3 Satellite (European Space Agency, n.d.) and Sentinel-2 (10 m) images (E.U. Copernicus Programme. 2025) for 2000, 2010, and 2023 during the peak irrigation month of February. The plot-level land parcels were verified, and crop patterns were assessed before delineating the spatial extent of irrigated areas. The land parcels refer to individual farmer-owned or farmer-managed agricultural plots, whose boundaries were verified through field surveys. Crop pattern assessment was conducted using high-resolution satellite imagery, where visually interpreted and digitized plot-level land parcels were analyzed to identify dominant cropping sequences. Temporal variations in spectral characteristics and field-level land cover signatures were examined to distinguish different crop types and seasonal cropping combinations.

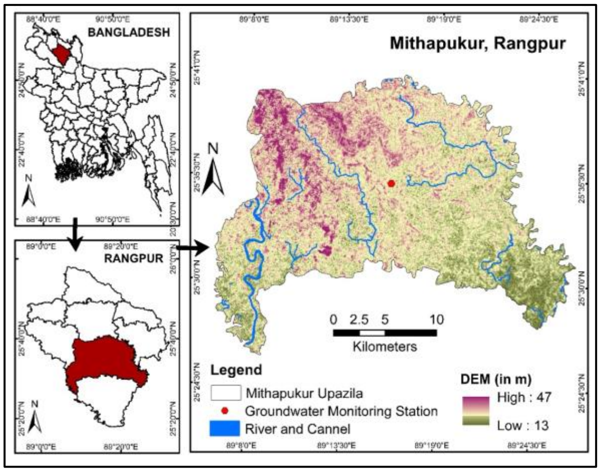

Figure 1. *Map showing the geographical location of the Mithapukur Upazila, Bangladesh.*

Groundwater level data were obtained from one BWDB (Bangladesh Water Development Board,) observation well (Mithapukur GT8558010), where measurements were recorded weekly and subsequently converted into annual mean values for the period 2000–2023. Linear irrigated area records for the same period (2000–2023) were sourced from the Bangladesh Agricultural Development Corporation (BADC) and were collected in square kilometers (km^2) for this study. Irrigated and non-irrigated croplands were differentiated based on the presence of an artificial water supply during the cropping season. Croplands that were cultivated at any time of the year using irrigation (e.g., groundwater or surface-water sources) were classified as irrigated, whereas croplands cultivated without irrigation and dependent solely on rainfall were classified as non-irrigated. This distinction was made using seasonal satellite imagery, cropping-season continuity, and ancillary irrigation information to accurately locate irrigated agricultural areas. To assess partial correlation, the rainfall data were collected from the Bangladesh Meteorological Department (BMD). The daily rainfall data were aggregated to obtain annual totals, and the partial correlations with groundwater levels and irrigated agricultural area were examined.

2.3 Statistical analysis

This study employed the Spearman rank correlation coefficient (ρ) to assess the relationship between irrigated area and groundwater level, while the Root Mean Square Error (RMSE) was used to quantify the average discrepancy between observed and predicted values, thereby evaluating the accuracy of the predictive models. Trend analyses for rainfall and groundwater level data were performed using the modified Mann–Kendall (MK) test to assess their variability.

2.3.1 Spearman's rank correlation

The degree of statistical reliance was determined using Spearman's rank (Eq. 1), a non-parametric measure (Hamer et al., 2020).

$$\rho = 1 - \frac{6\sum d_i^2}{n(n^2-1)} \tag{1}$$

Here, the variation between each observation's two rankings is d_i and n is the total number of observations. The range of values of Spearman's rank correlation is negative 1 to positive 1 (Gauthier, 2001). A value of positive 1 indicates a perfect rank relationship. During this study, the significance level of 99% was used.

2.3.2 Modified Maan-Kendal trend test

The MK test treats y_i and y_j as two subsets of a time series of *n* data points, where *i* and *j* refer to years and *j* > *i*. The MK statistics specified in Eqs. 2, 3, and 4 are as follows:

$$S = \sum_{j=1}^{n-1} \sum_{j=i+1}^{n} sgn(y_j - y_i) \tag{2}$$

y_j is the yearly value for *j* year, and y_i is the yearly value for i^{th} year.

$$Var(S) = \frac{(n(n-1)(2n+5) - \sum_t t(t-1)(2t+5))}{18} \tag{3}$$

$$Z = \begin{Bmatrix} \frac{S-1}{\sqrt{Var(S)}}, & if \quad S > 0 \\ 0, & if \quad S = 0 \\ \frac{S+1}{\sqrt{Var(S)}}, & if \quad S < 0 \end{Bmatrix} \tag{4}$$

The upward (increasing) trend is therefore shown by positive values of "Z", whereas the downward (decreasing) trend is shown by negative values of "Z" (Anand et al., 2020). The significance threshold for the current study was α = 0.05, which had a 95% confidence level.

2.3.3 Root Mean Square Error

The RMSE is a frequently used metric for assessing the accuracy of predictive models. According to Chai and Draxler (2014), RMSE is the square root of the average of squared deviations between the model's predicted values and the actual field measurements (Eq. 5).

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(O_i - P_i)^2} \tag{5}$$

Here, O_i is the observed value and P_i is the modeled value. N is the number of observations. Better model performance is shown by lower RMSE values; 0 denotes perfect accuracy.

3 Results

3.1 Spatiotemporal variation in irrigated agricultural land

The spatiotemporal changes in irrigated agricultural land across Mithapukur Upazila, Bangladesh, highlighted the distribution patterns for the years 2000, 2010, and 2023 (**Fig. 2**). It allows us to directly observe changes in the extent and location of irrigated land over time, highlighting areas of expansion and shifts in irrigation patterns. Irrigated croplands in 2000 (green) were predominantly clustered around major canal networks and road corridors, indicating early reliance on accessible water sources and transport routes. By 2010 (purple), irrigation had become more spatially dispersed, extending into previously less-utilized interior zones. The 2023 irrigated area (yellow) revealed a substantial intensification and outward expansion, particularly across the central and eastern parts of the study area, reflecting increased groundwater extraction and agricultural intensification.

Table 1 summarizes the annual changes in estimated irrigated area, rainfall amounts, and corresponding groundwater levels in Mithapukur Upazila from 2000 to 2023. The results showed a consistent and substantial expansion of irrigated agricultural land from approximately 269.57 km^2 in 2000 to nearly 318.97 km^2 in 2023, reflecting

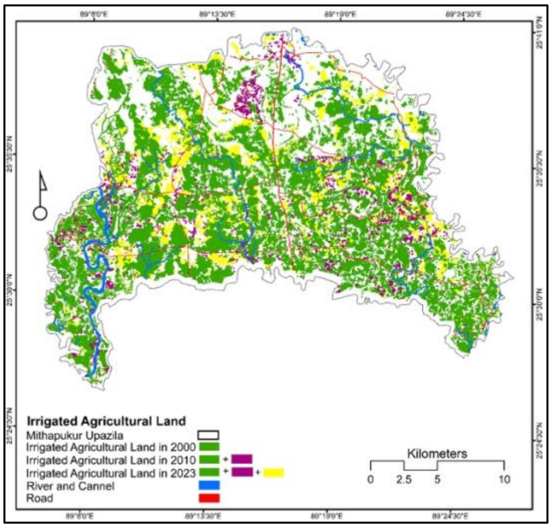

Figure 2. *Spatiotemporal distribution of irrigated agricultural land for the years 2000, 2010, and 2023 in Mithapukur Upazila, Bangladesh.*

Table 1. *Irrigated agricultural area, annual groundwater level (GWL), and annual rainfall in Mithapukur, Rangpur.*

Year	Irrigated agricultural area (km^2)	Annual GWL (in m) from surface	Annual Rainfall (in mm)	Year	Irrigated agricultural area (km^2)	Annual GWL (in m) from surface	Annual Rainfall (in mm)
2000	269.57	4.25	3,965.34	2012	282.09	4.7	3,686.9
2001	270.16	4.35	5,100.49	2013	285.40	4.8	3,394.49
2002	270.75	4.45	3,252.17	2014	288.70	4.95	3,226.42
2003	271.34	4.6	3,879.95	2015	292.00	5.05	3,239.61
2004	271.93	4.4	5,532.75	2016	295.31	5.15	2,547.82
2005	272.52	4.15	4,122.64	2017	298.61	5.3	4,219.19
2006	273.12	4.0	4,308.38	2018	301.91	5.34	3,818.48
2007	273.71	4.15	4,668.03	2019	305.22	5.23	3,436.87
2008	274.30	4.25	2,922.91	2020	308.52	5.65	2,649.67
2009	274.89	4.4	3,537.22	2021	311.82	5.4	3,805.97
2010	275.49	4.5	3,306.94	2022	315.13	5.2	3,464.59
2011	278.79	4.6	4,027.25	2023	318.97	5.48	3,367.87

a steady intensification of irrigation-driven cultivation over the study period. In contrast, groundwater levels exhibited a gradual increasing trend, with water depths increasing from 4.25 m below the surface in 2000 to 5.48 m in 2023, indicating progressive groundwater depletion. The simultaneous expansion of irrigated areas and increasing groundwater levels underscores a growing dependency on groundwater-based irrigation and highlights emerging risks to long-term groundwater sustainability in the region.

The results showed a positive trend in groundwater levels (Z = 5.04), reflecting a gradual increase over time, and a negative trend in rainfall (Z = -2.11), indicating a slight decrease in annual rainfall. The decrease in rainfall likely drives an increase in irrigation demand, contributing to greater reliance on groundwater and further deepening of water levels.

3.2 Correlation between irrigated area and groundwater level

Figure 3 illustrates the multi-dimensional relationship between irrigated agricultural area and rainfall with groundwater level in Mithapukur Upazila from 2000 to 2023. The two variables showed a strong and synchronized upward trajectory. Irrigated area has steadily expanded, while groundwater levels have progressively increased. Statistical analysis revealed a very high positive correlation ($\rho = 0.879$), indicating that the expansion of irrigated land is closely associated with increased groundwater withdrawal.

To account for the influence of climatic variability, particularly annual rainfall, on groundwater dynamics, a partial correlation analysis was performed between irrigated agricultural area and annual groundwater level, controlling for annual rainfall. The results indicate a strong positive partial correlation ($r = 0.912$), suggesting that the observed relationship between groundwater level and irrigation expansion is largely independent of rainfall variability. This implies that the expansion of irrigated agricultural land has a robust effect on groundwater dynamics in the study area, beyond natural recharge driven by monsoonal rainfall.

A key driver behind this relationship is that Mithapukur Upazila lacks major inland surface-water sources, such as perennial rivers or large irrigation canals (**Fig. 1**). Consequently, agricultural production in this region is almost entirely dependent on groundwater extraction, particularly during the dry-season Boro cultivation period. The observed GWL decline, therefore, reflects the adverse pressure on aquifers as irrigation demand expands. This strong coupling between irrigation growth and groundwater depletion highlighted the increasing vulnerability of local groundwater resources and emphasized the need for sustainable water-management interventions in the area.

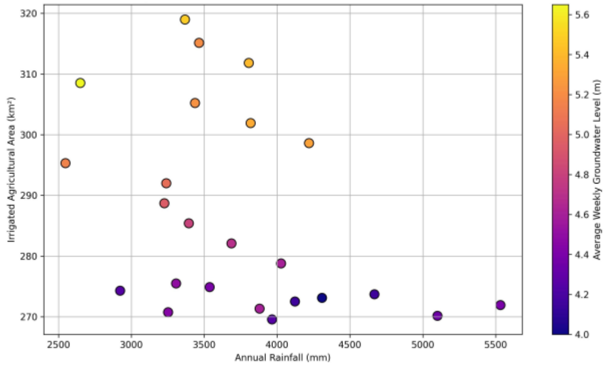

Figure 3. *Relationship between irrigated agricultural area, annual rainfall, and annual groundwater level in Mithapukur Upazila, Bangladesh.*

4 Discussion

The spatiotemporal analysis of irrigated agricultural land in Mithapukur Upazila, Bangladesh, demonstrated a pronounced expansion of irrigation-driven cultivation over the past two decades. Between 2000 and 2023, the irrigated area increased from approximately 269.57 km^2 to 318.97 km^2, reflecting a near-continuous intensification of dry-season agriculture. Much of this newly irrigated area was previously uncultivated land, fallow lands, or rain-fed cropland, which provided natural ecological functions such as groundwater recharge, soil moisture retention, and habitat for local flora and fauna. Conversion to intensive irrigation has likely reduced these recharge opportunities and altered natural hydrological processes, potentially contributing further to the observed decline in groundwater levels (Hossain and Mojid, 2022). This expansion has largely occurred in the interior parts of the Upazila, beyond traditional canal networks, highlighting the increasing reliance on groundwater as the primary irrigation source. Such patterns are consistent with broader regional trends in northwestern Bangladesh, where dry-season Boro rice cultivation (23,08,712 tonnes in Rangpur in 2024) has driven widespread groundwater abstraction (Vallet-Coulomb et al., 2017; Afrin et al., 2019; Monir et al., 2023c; Department of Agricultural Extension (DAE), 2025).

The groundwater level data revealed a clear, long-term declining trend, with the water table dropping from 4.25 m in 2000 to 5.48 m in 2023. The observed strong positive correlation between irrigated area and groundwater depth ($\rho = 0.879$) highlighted the significant role of agricultural expansion in driving aquifer stress. The lack of significant surface-water sources in Mithapukur (e.g., perennial rivers or large irrigation canals) makes the region almost entirely dependent on groundwater, amplifying the impacts of irrigation intensification on subsurface water storage.

To better understand the effect of irrigation, rainfall data were incorporated into a partial correlation analysis, acknowledging that climate also strongly influences both groundwater recharge and irrigation demand. These findings are consistent with previous studies in Bangladesh, which highlighted the vulnerability of aquifers in agriculturally intensive zones to over-extraction and seasonal depletion (Mainuddin et al., 2020; Sarker et al., 2024; Monir et al., 2025), while similar trends have also been reported in other countries such as China and Korea (Mair et al., 2013; Zhao et al., 2021). The progressive deepening of groundwater levels despite partial recharge from irrigation return flows suggests that abstraction exceeds natural replenishment, raising concerns about the long-term sustainability of groundwater resources (Villano et al., 2015). Persistent aquifer depletion may have multiple cascading effects: it can compromise water availability for future irrigation, groundwater quality deterioration, exacerbate energy costs for pumping, increase susceptibility to soil salinization, and interact with climate variability to heighten socio-ecological risks (Prodhan et al., 2020; Monir et al., 2023a; Gutierrez et al., 2025). Monir et al. (2023c) also established a strong relationship between GWL and climate in Rangpur District, supporting the present findings. The spatially explicit expansion into previously uncultivated interior zones further emphasizes that intensification is not merely a local phenomenon but a systemic process with region-wide implications (Wilson et al., 2001).

The analysis of land use changes revealed that much of the newly irrigated area was previously uncultivated or used for rain-fed cropping. Conversion to intensive irrigation has implications for groundwater recharge, as increased imperviousness and continuous water withdrawal reduce natural infiltration. Ecologically, these changes may alter soil moisture regimes, affect local wetlands, and reduce the ecosystem services previously provided by uncultivated lands (Mukherjee et al., 2015). From a management perspective, these results highlight an urgent need for integrated water resource governance strategies in Mithapukur and similar agrarian regions (Mukherjee et al., 2015), recognizing that effective management involves more factors than the two variables (agricultural land use expansion and groundwater level) analyzed here. Potential interventions to address groundwater stress include regulated abstraction limits, promotion of water-efficient irrigation technologies such as alternate wetting and drying (AWD) for rice (Bouman and Tuong, 2001; Lampayan et al., 2015), conjunctive use of surface and groundwater where feasible (FAO, 2010), and adjustments in cropping patterns to reduce dry-season water demand. These measures are particularly relevant in intensively cultivated regions of Bangladesh, where dry-season irrigation exerts sustained pressure on shallow aquifers (Vanitha, 2017). Importantly, policy responses must adopt a balance between agricultural productivity and aquifer sustainability to safeguard local livelihoods while mitigating long-term water security risks.

5 Limitations

A key limitation of this study is the reliance on data from a single groundwater observation well, which restricted the ability to assess spatial variations in aquifer response across the Upazila. Also, we have noted that river stage data could not be included due to data limitations, which represented a constraint in fully assessing all factors influencing groundwater levels. Incorporating multiple monitoring points in future research would allow for a more comprehensive understanding of groundwater dynamics and support targeted management strategies.

6 Conclusion

This study demonstrated that the expansion of irrigated agricultural land in Mithapukur Upazila has been closely linked to progressive groundwater depletion. The integration of climatic data, local hydrogeological context, previous land use information, and analysis of other water users strengthens the statistical and scientific robustness of the study. Between 2000 and 2023, irrigated areas increased substantially, while groundwater levels consistently declined, reflecting the region's heavy reliance on groundwater due to the absence of major surface-water sources. The strong correlation ($\rho = 0.879$) between irrigation growth and declining groundwater highlighted the vulnerability of local aquifers to unsustainable abstraction. The strong statistical coupling between irrigated area and groundwater depth highlighted the need for targeted water-management interventions. Mithapukur Upazila is considered an "intensively cultivated area" due to near-continuous, year-round cropping, high reliance on irrigation, especially for Boro rice, and repeated cultivation of high-water-demand crops, unlike typical rain-fed or seasonally cropped areas. Overall, these findings emphasized the urgent need for sustainable groundwater management through regulated abstraction, adoption of water-efficient irrigation, and integrated planning to safeguard both agricultural productivity and long-term aquifer sustainability in intensively cultivated regions of northern Bangladesh.

7 Data availability statement

The data will be made available upon reasonable request from the corresponding author.

8 Ethical statements

Not applicable for this research.

9 Conflict of interest

The authors declare that there are no financial or personal conflicts of interest that could have influenced the results of this study.

10 Acknowledgement

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11 Author contributions

Md. Moniruzzaman Monir: Writing – original draft, Investigation, Formal analysis, Data curation, Validation, Methodology, and Conceptualization. Shapla Akhter: Formal analysis, and Supervision. All authors approved the final version of the manuscript.

12 Copyright statement

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