Journal of Engineering and Applied Science Vol. 09, No. 02, pp. 58–67, December 2025

Journal of Engineering and Applied Science

Contents are available at www.jeas.ruet.ac.bd

Exploring the Dynamics of Groundwater Level using Innovative Trend Analysis (ITA) Technique over Three Districts of North-West Region of Bangladesh

Md. Shakil Ar Salan[1,*], Md. Hasibul Hasan[2], Md. Mahabubur Rahman[3]

[1]*Department of Urban & Regional Planning, Rajshahi University of Engineering & Technology (RUET), Bangladesh.*
[2]*Rajdhani Unnayan Kartripakkha (RAJUK), Bangladesh*
[3]*Department of Architecture, Dhaka University of Engineering & Technology (DUET), Bangladesh.*

ARTICLE INFORMATION

Received date: 12 May 2025
Revised date: 14 July 2025
Accepted date: 17 July 2025

Keywords

Groundwater
Innovative Trend Analysis (ITA)
Seasonal Variation

ABSTRACT

In northwest Bangladesh, groundwater depletion presents serious obstacles to agricultural sustainability and water security. In order to evaluate groundwater level dynamics (2013–2022) in three drought-prone districts—Rajshahi, Chapainawabganj, and Naogaon—this study used the Innovative Trend Analysis (ITA) technique. Significant spatial heterogeneity is revealed by the results: Chapainawabganj exhibits a statistically significant declining trend in groundwater levels over the study period. In contrast, Naogaon exhibits a strong increasing trend, with most data points falling within the Increasing Triangle, indicating a significant recovery or improvement in groundwater levels. For Rajshahi, the trend appears relatively stable with slight fluctuations, as reflected in the minimal positive slope (0.009) and weak positive cross-correlation (0.15). In 56.67% of monitoring wells, ITA found hidden trends, especially during pre-monsoon periods that connected depletion to decreased rainfall (6.4% decline since 1985) and intensive irrigation using deep tubewell for Boro rice. Implementing localized policies, improving aquifer recharge, and implementing water-efficient irrigation are among the recommendations. In water-stressed areas, this study emphasizes the importance of striking a balance between agricultural demands and aquifer sustainability in groundwater management.

1. Introduction

Rising demand for irrigation, household, and industrial uses is driving hitherto unheard-of pressure on Bangladesh's groundwater supplies. Recent studies show concerning patterns in groundwater depletion over different parts of the nation; some of the most severe effects are found in the northwest districts. Using the Innovative Trend Analysis (ITA) approach, this study explores groundwater level dynamics in three important northwest Bangladesh districts, so offering vital information for sustainable water resource management. One of the most important natural resources available globally, groundwater is the main source of freshwater for almost one-third of all people. Groundwater meets

* Corresponding authors: Department of Urban & Regional Planning, Rajshahi University of Engineering & Technology (RUET), Bangladesh
E-mail addresses: sarsalan@urp.ruet.ac.bd (Md. Shakil Ar Salan)

more than 90% of Bangladesh's drinking water needs as well as those for agricultural irrigation. With irrigation accounting for almost 90% of the estimated 32 cubic kilometers of groundwater the nation withdraws annually [1]. Based on recent studies, Bangladesh ranks sixth worldwide for nations with highest estimated annual groundwater extraction [1]. Particularly in areas suffering fast groundwater depletion, this great consumption of groundwater resources raises serious questions about long-term sustainability.

Comprising districts like Rajshahi, Chapainawabganj, and Naogaon, the northwest of Bangladesh shows a water-stressed area beset with major groundwater problems. This area includes the Barind Tract, which is prone to drought and distinguished by unique hydrogeological features and growing sensitivity to groundwater depletion [1], [2]. Particularly from too high groundwater extraction, experts have found "critical" rates of aquifer depletion in several upazilas (sub-districts), including Godagari, Tanore, and Mohanpur [4]. Recent studies show that parts of the Rajshahi district's groundwater levels are declining yearly, suggesting aquifers under notable stress [3]. Groundwater levels in especially impacted areas including Kolma, Mundumala, Deopara, and Kakonhat have approached near-aquifer limits, posing a concerning scenario for water resource sustainability [3]. More worrisome still, research has shown that some areas, including Tentulia union, lack any accessible aquifers even at depths of 445 meters below the surface [3].

The Barind Tract region of the Rajshahi division in Bangladesh is characterized by unique hydrogeological features that significantly influence water availability. The region is characterized by a series of faults and geomorphic lineaments that form intrabasinal horsts and grabens. These structures influence the regional flow of groundwater, directing it towards major rivers and low-lying areas, which follow the surface gradient of the region [4]. Groundwater flow is primarily driven by a topographically induced hydraulic gradient, enhanced by pumping for irrigation [5]. The region exhibits varying recharge potential, with only a small portion having very good recharge potential [6]. The specific yield of the aquifer in the Barind area varies significantly, with values ranging from 8% to 32%. This variation affects the groundwater availability, with the southern portion of the region having better specific yield values than the central portion. The Barind Tract is a drought-prone area with limited surface water resources, making it heavily reliant on groundwater for irrigation and other uses. Over-extraction of groundwater has led to a decline in groundwater levels, exacerbating water scarcity issues [6]. Groundwater depletion in the northwest region results from several linked causes. Groundwater extractions are mostly driven by agricultural irrigation, especially for water-intensive Boro rice farming [7]. Studies show that in the northwest Boro rice output calls for roughly 1,600 liters of water per kilogram [7]. Rajshahi district alone is expected to have used an estimated 494,710,509 cubic meters of irrigation water just for Boro rice output in 2022[5]. Further aggravating water scarcity issues is this agricultural water demand in line with declining annual rainfall patterns and rising general temperatures. Together, demographic pressures, land use changes, altered cropping patterns, and deforestation have changed the environmental scene and so affect groundwater availability and recharge [7].

Understanding temporal dynamics, spotting areas of critical depletion, and creating sensible management plans all depend on accurate trend analysis of groundwater levels. Hydrometeorological time series research has extensively used conventional trend analysis techniques including the Mann-Kendall (MK) test and Spearman's *rho* [8]. However, these conventional approaches have significant limitations when applied to complex groundwater systems. Usually, they call for tight assumptions including independent structure of the time series, normalcy of distribution, and particular data length criteria [8]. Moreover, these techniques mainly identify monotonic trends and usually miss non-monotonic patterns that are regularly found in groundwater systems.

Developed by Şen (2012), the Innovative Trend Analysis (ITA) approach presents a good substitute for groundwater trend analysis that gets beyond many constraints of conventional approaches [8], [9]. Simple identification of trend patterns—including non-monotonic trends that might remain undetectable using conventional techniques—is made possible by this intuitive graphic approach. Additionally, ITA allows for separate trend analysis of low, medium, and high values within a dataset, providing more nuanced insights into groundwater behavior across different intensity levels [10]. Although ITA is increasingly adopted in hydroclimatic studies, its application to groundwater dynamics in Bangladesh—particularly for comparative analysis across districts with acute depletion—remains limited. While foundational work exists in north-western regions, comprehensive spatial-temporal assessments linking depletion patterns to climatic and anthropogenic drivers are still emerging [11].

The primary objectives of this research are to: (1) apply the Innovative Trend Analysis (ITA) technique to analyse groundwater level trends in three selected districts of north-western Bangladesh; (2) identify spatial and temporal variations in groundwater depletion patterns across the study area; (3) investigate relationships between groundwater trends and key factors such as rainfall patterns, and installation of deep tubewell; and (5) develop recommendations for sustainable groundwater management based on identified trend patterns.

This study greatly advances knowledge of groundwater dynamics in one of the most water-stressed areas of Bangladesh. Using the ITA approach, the study offers fresh understanding of intricate trend patterns that might go unnoticed in traditional studies. The results will support evidence-based decision-making about groundwater preservation initiatives, irrigation methods, and water resource distribution. Moreover, the methodological approach shows the advantage of creative trend analysis methods for groundwater monitoring in comparable hydrogeological settings all around. This study provides insightful analysis for sustainable groundwater management in sensitive areas as climate change and growing water demand keep aggravating groundwater problems worldwide.

2. Methodology

The study area for the research is the north-western region of Bangladesh comprising the districts namely Bogura, Joypurhat, Noagaon, Natore, Chapainawabganj, Pabna and Rajshahi, of which Porsha (Noagaon), Gomastapur (Chapainawabganj) and Godagari (Rajshahi) have been selected to conduct this study. All of these Upazilas are ranked as “very severe” drought prone and hard to reach areas in a report prepared by the Ministry of Local Government, Rural Development and Cooperatives [12]. The research is supported by quantitative data (ground water level, rainfall, installation of deep-tubewell). The selected regions cover an area of about 7586 sq. km in the northwest region of Bangladesh [13]. The research region encompasses a significant portion of the Barind Irrigation Project, where rice is the primary cultivated crop and plays a substantial role in the overall agricultural output. The research utilized a quantitative approach to understand the relationship among dynamics of groundwater levels during pre-monsoon, monsoon and post-monsoon period, yearly rainfall distribution and deep tubewell (DTW) development in Bangladesh's North-West Region and propose sustainable groundwater management solutions. Groundwater level data from 58 monitoring wells (installed at 54 unions and 4 paurashavas) across the three districts, sourced from DASCOH Foundation and BMDA records, were analyzed to determine seasonal groundwater level variations (Figure 1). Secondary data from the Bangladesh Bureau of Statistics (BBS) and BMDA for the period of 2013-2022 were also used to assess the impact of of deep tubewell installation and yearly rainfall on temporal groundwater fluctuations across the three Upazilas of the Barind Tract.

After collecting the necessary data, all data have been assembled and processed manually to be used for the analysis. All the collected data have been analyzed using SPSS and Excel software. Descriptive and trend analysis have been followed as analytical strategy for quantitative data. Descriptive analysis has been used to summarize the samples and innovative trend analysis has been used to assess the seasonal variation of groundwater level.

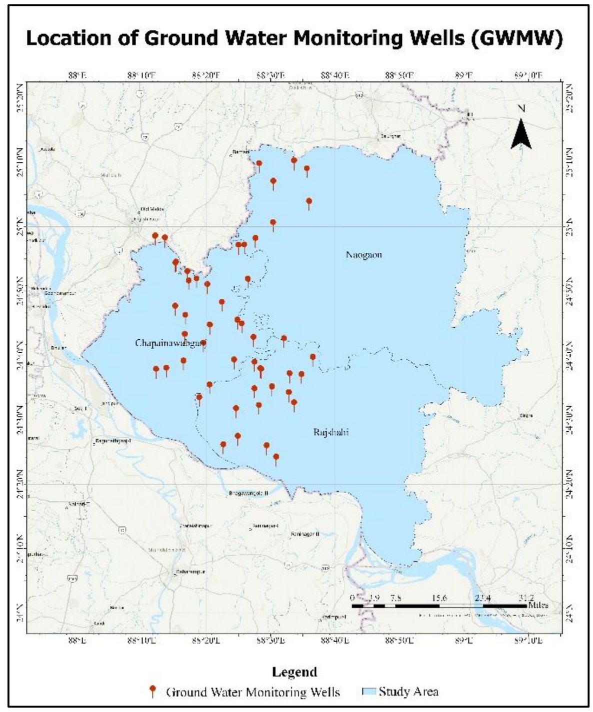


Figure 1: Map of the Study Area (Source: Prepared by Author).

Innovative trend analysis was proposed by [14]. The position of a scatter point in relation to a 45-degree line indicates the trend. If all data points are located above the 45-degree line, it indicates a consistently increasing trend. Conversely, if all points are below the 45-degree line, it suggests a consistently falling trend. If the points are not all above or below the line, the trend may not be consistently increasing or decreasing [15], [16]. By examining the plotted points, trends for each magnitude category can be analyzed individually. Comparatively, novel trend analysis offers an advantage over nonparametric trend testing by being able to detect trends beyond just monotonic ones. This is important since hydrological events of varying magnitudes may exhibit different trends. The process for conducting innovative trend analysis is as follows:

1. The magnitude of trend

$$s = \frac{2(y_2 - y_1)}{n}$$

Where, y_1 and y_2 are the mean values of the first-half and second-half sub-series, respectively; n is the total number of data points in the entire time series.

2. Confidence limit (CL) of trend may be calculated using the following relationship

$$CL\ (1-\alpha) = 0 \pm S_{crit}\ \sigma_s$$

3. Slope standard deviation

$$\sigma_s^2 = \frac{8\sigma^2\ (1 - \rho y_2 y_1)}{n^3}$$

4. Cross-Correlation coefficient of averages of two halves given by

$$\rho y_2 y_1 = \frac{E(y_2 y_1) - E(y_2)E(y_1)}{\sigma y_2\ \sigma y_1}$$

5. Critical slope (significance level of 5%) is given by

$$s_{crit} = 1.96 \times \sigma_s$$

In this analysis, the dataset was first divided into two equal halves: the first half and the second half. The average of the first half (Y_1) and the average of the second half (Y_2) were calculated using the arithmetic mean. The standard deviation (σ) was computed by determining the variance of each half, summing them, dividing by two, and then taking the square root to obtain the pooled standard deviation. The cross-correlation (ρxy) between the two halves was measured using Pearson's correlation coefficient to assess the linear relationship between them. The trend slope (s) was calculated by subtracting the average of the first half (Y_1) from the average of the second half (Y_2) and then dividing the result by Y_1 to determine the relative change. To check the statistical significance of the trend, the critical slope (Scr) was computed using the formula: $Scr = (1.96 \times \sigma) / (Y_1 \times \sqrt{n})$, where "n" referred to the number of paired data points in each half, and 1.96 was the critical value for a 5% significance level in a two-tailed test. The comparison between the trend slope (s) and the critical slope (Scr) indicated whether the observed trend was statistically significant or not.

3. Results and Discussions

Seasonal Variation of Groundwater Level

The results of ITA for DGWL at different locations in Chapainawabganj district for pre-monsoon, monsoon and post-monsoon period are presented in Figure 2. The trend line clearly lies to the right of the 1:1 line during pre-monsoon and left to right both for monsoon and post-monsoon periods, indicating a gradual decreasing trend of DGWL. In the pre-monsoon period, both the low and moderate water levels show significantly downward trends while high water levels represent slightly upward trend. Majority of the points plot below the 1:1 line in the post-monsoon period indicating declining trend. In the monsoon period, the low water levels fall in the second half of the DGWL thus show significant increasing trend while both the moderate and high-water levels fall both in the first and second half thus represents significant non-monotonic fluctuation of the water level in this period, suggesting that increases are localized and not dominant.

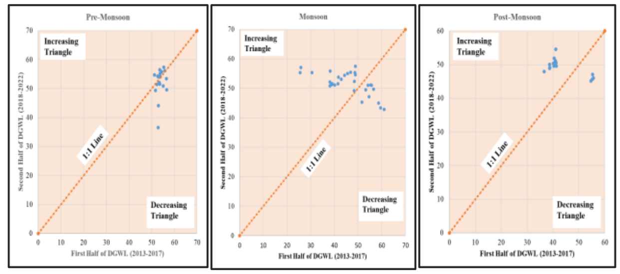


Figure 2: Trend of Ground Water Level (2013-2022) in Chapainawabganj District.

The data points for pre-monsoon, monsoon and post-monsoon period of chapainawabganj district fall on a curve, thus indicating the absence of a monotonic trend. These cases correspond to nonmonotonic trends where within the same time series there are increasing and decreasing trends at different scales even hidden ones.

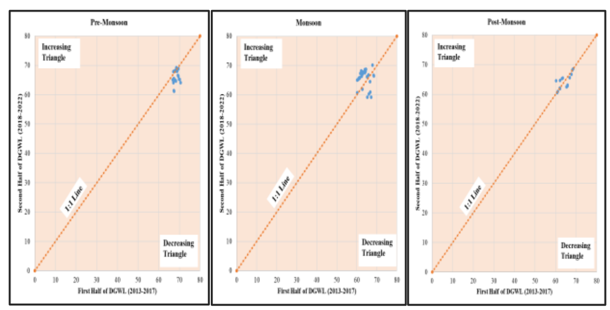


Figure 3: Trend of Ground Water Level (2013-2022) in Rajshahi District.

The results of ITA for DGWL at different locations in Rajshahi district for pre-monsoon, monsoon and post-monsoon period are presented in Figure 3. The trend line clearly lies to the right of the 1:1 line during pre-monsoon, left to right for monsoon and do not represent any significant trend for post-monsoon periods, indicating a gradual decreasing trend of DGWL for pre-monsoon and monsoon period. In the pre-monsoon period, both the low and moderate water levels show significantly downward trends while high water levels do not represent any trend. Majority of the points of low and high-water levels plot on the 1:1 line in the post-monsoon period do not represent any trend, while the moderate water levels plot on both side of the 1:1 line indicating gradual declining trend. In the monsoon period, the low water levels fall in the first half of the DGWL thus show significant decreasing trend while majority of the moderate and high-water levels fall in the second half thus represents significant non-monotonic fluctuation of the water level in this period. The data points for pre-monsoon, monsoon and post-monsoon period of Rajshahi district fall on a curve, thus indicating the absence of a monotonic trend. These cases correspond to nonmonotonic trends where within the same time series there are increasing and decreasing trends at different scales even hidden ones.

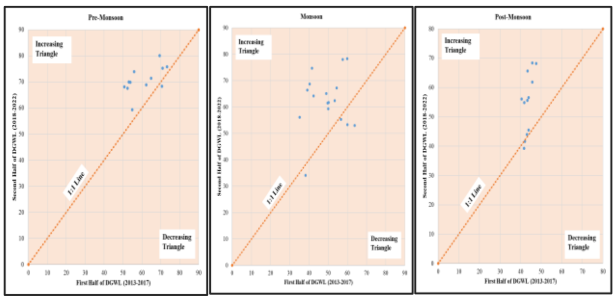


Figure 4: Trend of Ground Water Level (2013-2022) in Naogaon District.

The results of ITA for DGWL at different locations in Naogaon district for pre-monsoon, monsoon and post-monsoon period are presented in Figure 4. The trend line clearly lies to the left of the 1:1 line during pre-monsoon, monsoon and post-monsoon periods, indicating a gradual increasing trend of DGWL for pre-monsoon monsoon and post-monsoon period. In the pre-monsoon period, the low, moderate and high-water levels show significantly upward trends. Majority of the points of low levels plot on the 1:1 line in the post-monsoon period do not represent any trend, while the moderate and high-water levels plot on left side of the 1:1 line indicating gradual increasing trend. In the monsoon period, the low water levels fall in the first half of the DGWL thus show significant decreasing trend while the moderate water levels fall both in the first and second half thus represents significant non-monotonic fluctuation of the water level in this period. The high-water levels plot in the second half of the 1: 1 line indicating increasing trend. The data points for pre-monsoon, monsoon and post-monsoon period of Naogaon district fall on a curve, thus indicating the absence of a monotonic trend. These cases correspond to nonmonotonic trends where within the same time series there are increasing and decreasing trends at different scales even hidden ones.

The integrated analysis of Depth of Ground Water Level (DGWL) trends across Chapainawabganj, Rajshahi, and Naogaon districts reveals nuanced variations in groundwater dynamics during different periods (Figure 5, Table 1). For Chapainawabganj, a notable concentration of data points in the Decreasing Triangle suggests a statistically significant declining trend in groundwater levels over the study period. Although the district historically maintained relatively higher groundwater levels, as evidenced by high values even in the decreasing zone, recent years (2013–2023) show a consistent decline compared to the first half (2001–2012).

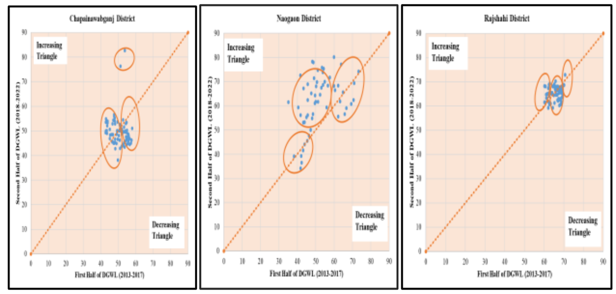


Figure 5: District Wise Trend of Ground Water Level (2013-2022).

This trend likely results from increased groundwater abstraction for dry-season irrigation, particularly for water-intensive crops like Boro rice, coupled with limited surface water availability and inadequate recharge capacity, which is characteristic of this semi-arid Barind tract.

Table 1: Statistical Results of Innovative Trend Test

Study Region	Average of First Half (Y1)	Average of Second Half (Y2)	Standard Deviation (σ)	Cross-Correlation (ρ_{xy})	Trend Slope (s)	Critical Slope (S_{cr})
Chapainawabganj	51	49.44	5.13	-0.14	-0.019	0.016
Rajshahi	66	65.36	2.76	0.15	0.009	0.008
Naogaon	52	61.94	10.2	0.45	0.2	0.05

Significant trend at 5% significance level If $|S| > |S_{cr}|$, i.e., the magnitude of the slope is greater than the magnitude of S_{cr}, then the trend is regarded as significant [14].

In contrast, Naogaon District exhibits a strong increasing trend, with most data points falling within the Increasing Triangle. The statistical analysis supports this with a relatively high positive slope (0.2) exceeding the critical slope (0.05), indicating a significant recovery or improvement in groundwater levels during the second half of the study period. This improvement may be attributed to enhanced water management practices, such as the adoption of rainwater harvesting, managed aquifer recharge, or a possible reduction in groundwater-dependent agricultural activities in certain pockets. Additionally, localized hydrogeological advantages and variations in water governance structures might have contributed to this positive trend.

For Rajshahi District, the trend appears relatively stable with slight fluctuations, as reflected in the minimal positive slope (0.009) and weak positive cross-correlation (0.15), both of which are below the critical threshold (0.008) for statistical significance. The scatter plot shows most points clustered around the 1:1 line, with a slight lean towards the Decreasing Triangle, suggesting a marginal declining tendency. This stability could result from a balance between extraction and recharge, possibly supported by comparatively better water governance, lower dependence on deep groundwater, or more diversified cropping patterns relative to Chapainawabganj.

Table 2: Current State of Ground Water Level (GWL).

Status of Ground Water Level (GWL)	Number of Ground Water Monitoring Well (GWMW)	Percent age (%)
Stable	15	25.00
Increasing	11	18.33
Decreasing	34	56.67
Total	60	100.00

Source: BMDA

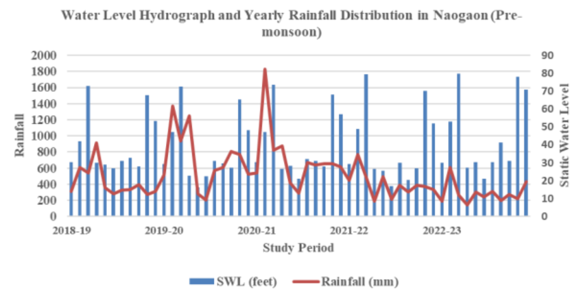
Based on information gathered from a network of 60 ground water monitoring wells (GWMW), the table 2 describes the current state of ground water level (GWL). The data suggests that a significant fraction of the wells under observation—56.67% of all wells—are exhibiting a declining trend in GWL. Regarding groundwater sustainability and management in the examined area, this finding raises serious issues. A declining GWL may be a sign of excessive extraction, insufficient recharge, or geological conditions affecting the availability of groundwater. The comparatively smaller proportions of wells exhibiting rising (18.33%) and steady (25.00%) GWL trends highlight the critical need to address groundwater depletion concerns. The information highlighted the necessity of all-encompassing approaches such expanded monitoring programs, conservation initiatives, and sustainable groundwater management techniques to guarantee the long-term.

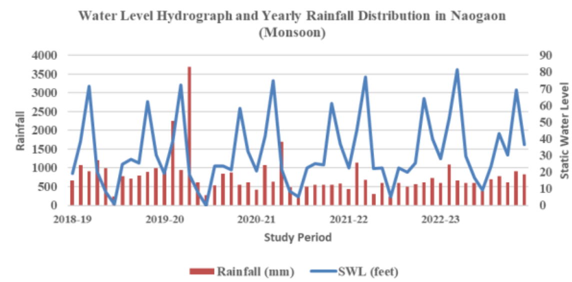
Seasonal Dynamics of the Rainfall-Groundwater Nexus

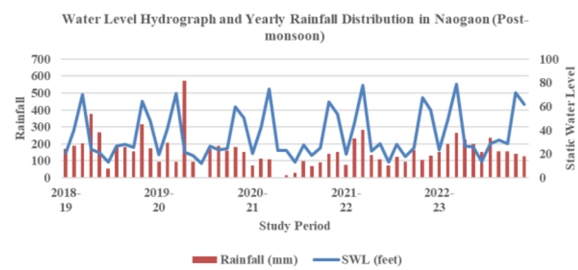
Across all three districts, the pre-monsoon hydrology shows similar trends marked by declining groundwater levels as extraction increases with little re-charging. Usually reflecting the combined effect of dry-season extraction, this period sees SWL measurements at their maximum depths.

Studies find that most of the groundwater abstractions take place in the dry months starting from January and continues up to May also June in some dry seasons [17]. Natural recharge is low during this time, and irrigation's extraction rules the water balance equation. According to studies in the north-west, groundwater irrigation is likely to continue until the limits of land or sustainable groundwater withdrawals are reached [18].

In areas that grow intensive Boro rice, which calls for large irrigation, the pre-monsoon groundwater drop is especially acute. For Boro rice farming in Rajshahi district, for instance, around 68,600 hectares were used, needing an estimated 494,710,509 cubic meters of irrigation water [18].





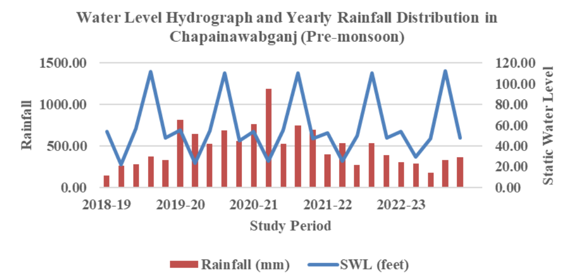


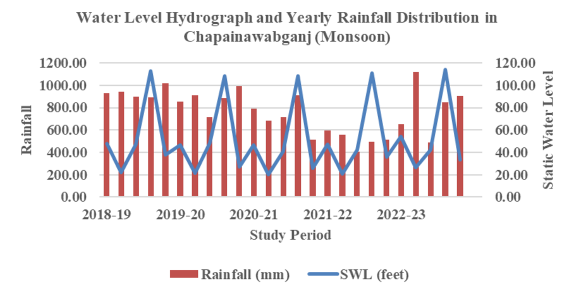
Dramatic increases in rainfall during the monsoon period across all districts set off processes of groundwater recharge. Though sometimes with obvious time lags, the hydrographs unequivocally show rising groundwater levels (decreasing SWL measurements) corresponding with increasing precipitation.

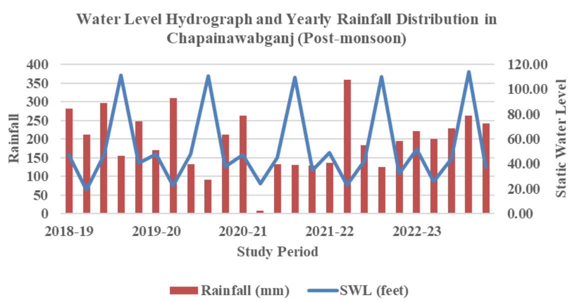
Studies of literature confirm that groundwater recharge occurs mostly during the wet or monsoon season (June to September [19]. With studies noting that the recharge characteristics in the northwest region are highly varied spatially, mainly due to variations in surficial geology and rainfall patterns [3], the efficacy of this recharge varies spatially depending on geological conditions.

Recent studies point to a changing trend in recharge sources: ~50% increase in recharge from stationary surface water bodies instead of direct rainfall infiltration [10]. This change affects our knowledge of the intricate rainfall-groundwater interaction going beyond basic precipitation measurements.

The shift toward recharge from surface water bodies has significant implications for groundwater quality and management. Surface water is more vulnerable to contamination from agricultural runoff, domestic wastewater, and industrial effluents, which can lead to degraded groundwater quality. This calls for integrated water resource management approaches that consider both quantity and quality, including pollution control near recharge zones and enhanced monitoring system [20]. Policies should also promote managed aquifer recharge using treated water to ensure safe and sustainable groundwater use.



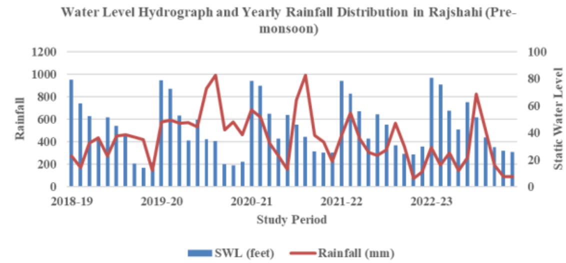


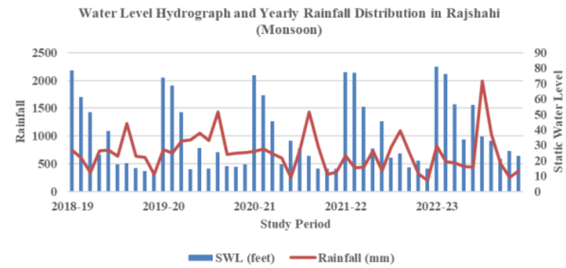


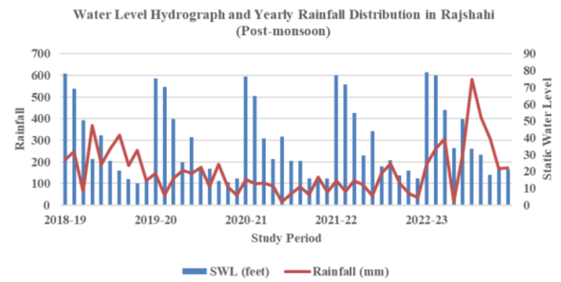
Post-monsoon trends show slow groundwater depletion starting as rainfall decreases. As extraction starts once more to surpass recharge, the hydrographs show rising SWL depths across all three districts.

Studies show that during October, November and December when the intensity of rainfall decreases, groundwater level starts deplete rapidly [17]. Since it marks the start of the phase of the annual cycle dominated by extraction, this transitional period is crucial for planning of water resources.

Over Naogaon, Chapainawabganj, and Rajshahi districts, the rainfall-groundwater nexus shows clear seasonal trends with alarming long-term trends. The hydrographs show that although monsoon rain is essential for replenishment, in many places current extraction rates exceed sustainable limits, resulting in ongoing groundwater depletion.







Geographic differences in geological conditions, extraction rates, and climate patterns generate challenges unique to each district needing specialized management strategies. The great reliance on groundwater for both household and agricultural purposes call for quick and thorough water management plans to guarantee long-term viability.

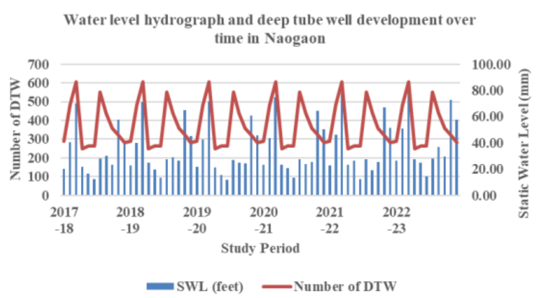
Changing recharge systems further complicates the rainfall-groundwater interaction; studies indicate higher recharge from stationary surface water bodies instead of direct rainfall intrusion. This complexity emphasizes the need of combined water resource management strategies considering surface and groundwater dynamics.

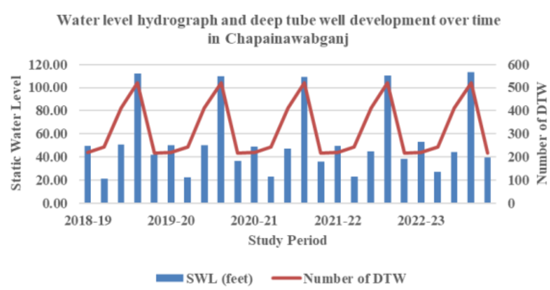
Maintaining water security and agricultural output in this vital part of Bangladesh will depend on addressing the district-specific rainfall-groundwater nexus as climate variability rises and agricultural needs grow.

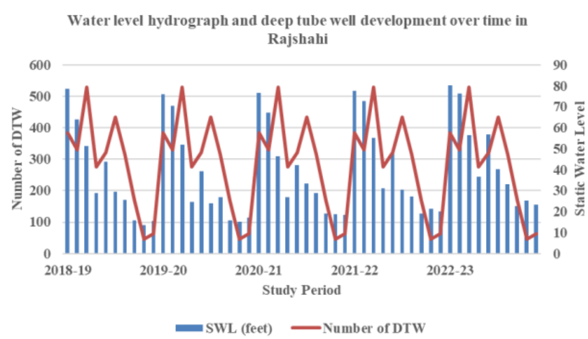
District Wise Ground Water Level and Installation of DTW Nexus

The graphs depict the correlation between the static water level (SWL in feet) and the establishment of deep tube wells (DTWs) in Naogaon, Chapainawabganj and Rajshahi from 2018 to 2023. The quantity of deep tube wells (DTWs) consistently rises during the duration of the study, suggesting an increasing dependence on

DTWs for extracting water. The periodic decreases in static water level (SWL) are associated with the times of increased water withdrawal, most likely caused by agricultural practices, particularly during dry seasons or before the monsoon season. As the quantity of Deep Tube Wells (DTWs) rises, the variations in Static Water Level (SWL) become more noticeable, indicating that the increasing extraction is exerting further strain on the groundwater supplies.







This pattern underscores the potential hazard of excessive extraction resulting in the depletion of groundwater, underlining the necessity of implementing sustainable water management methods to maintain a balance between water demand and the rate at which the aquifer is replenished.

Hydrogeological research shows that although over-abstraction risks long-term sustainability, the Barind (eastern) side—where DTWs are concentrated—is arsenic-free and more productive [21]. Furthermore, mentioned in the literature are possible reduction in shallow aquifer accessibility and stifling of crop diversification resulting from higher DTW use [3]. With almost 70% of annual extraction from uncontrolled private DTWs [7], the area depends much on groundwater for irrigation. According to the literature, the spread of DTWs-while increasing agricultural output-has resulted in declining groundwater levels, endangering irrigation and drinking water [22].

Deep tubewell development and groundwater level trends in Naogaon, Chapainawabganj, and Rajshahi show a clear, literature-validated nexus based on district-wise analysis: the spread of DTWs has resulted in ongoing, in some areas severe groundwater depletion. Seasonal irrigation needs and inadequate recharge accentuate this link, so endangering the sustainability of both domestic water supply and agriculture. The results highlight how urgently integrated water resource management—including surface water development, lowering of groundwater abstraction, and policy changes guaranteeing long-term water security in northwest Bangladesh—is needed [7], [10], [21], [22].

4. Conclusions and Implications

Critical new understanding of regional aquifer sustainability comes from a thorough study of groundwater dynamics in northwest Bangladesh. Key results show notable spatial variability; Naogaon showed a 0.2 m increase that remained statistically significant, while Chapainawabganj district showed groundwater level declines of 0.019 m and Rajshahi showed relatively stable GWL with slight fluctuations of 0.009 m over the 2013–2022 period [23]. The Innovative Trend Analysis (ITA) approach revealed intricate seasonal patterns where 56.67% of tracked wells showed declining water tables compared to 18.33% with increasing levels [23], so effectively capturing non-monotonic trends undetectable by conventional means. These findings complement more general regional studies showing 20-foot groundwater declines in Barind Tract areas since 1988 and aquifer depletion rates in important zones approaching 250 mm/year [2]. While climate drivers show declining rainfall (6.4% reduction since 1985) and rising temperatures (0.8°C rise), the identified trends strongly correlate with anthropogenic factors - irrigation demands for Boro rice farming account for 494 million m^1 annual groundwater extraction in Rajshahi alone, so aggravating recharge deficits [2], [24]. With the low-permeability clay layers (1.5–4.5 m thick) of the Barind Tract restricting vertical recharge despite monsoon precipitation [1], hydrogeological heterogeneity emerges as a major control. Particularly useful was the ability of the ITA to differentiate low/moderate/high value trends in pre-monsoon periods when irrigation demand peaks and recharge is low [23]. This helped to identify critical depletion phases.

By capturing both monotonic and hidden trends across Rajshahi, Chapainawabganj, and Naogaon, the research reveals seasonal and spatial variations often overlooked by conventional methods. These insights are vital for shaping groundwater policies, promoting efficient irrigation, and supporting localized solutions like managed aquifer recharge and crop diversification. Moreover, the approach presents a scalable framework for groundwater monitoring in other drought-prone or data-limited areas, contributing to sustainable water resource management under increasing climate and human pressures.

To address the challenges revealed by this study, several targeted recommendations are proposed for sustainable groundwater management in the region. Scale acceptance of alternate wetting-drying (AWD) technology, proven to reduce irrigation water use by 30% while maintaining rice yields [24] Establish crop diversification initiatives in important depletion areas (such as Godagari, Tanore) favoring drought-resistant varieties like wheat and maize. Create surface water storage systems along rejuvenated river channels (such as Padma, Mahananda) to offset 42% of groundwater demand during dry seasons [2] Using monsoon floodwaters, build managed aquifer recharge (MAR) systems based on successful models in India's Telangana State (15% recharge enhancement). Hossain et al. (2024) add volumetric groundwater pricing to overused blocks (such as Chapainawabganj Sadar) combined with smart metering technologies [6]. Implement wetland preservation programs to protect 18% of natural sources of recharging threatened by development [23], [24]. Extend real-time groundwater monitoring systems from present 60 wells to more than 200+ IoT-enabled stations. Apply machine learning models for predictive resource management, combining ITA outputs with climate projections. Promote inclusive stakeholder participation in groundwater management planning so that farmers, local authorities, and underprivileged areas are actively engaged. Initiatives for capacity-building should provide local managers with the tools and knowledge required for efficient use of resources [23], [25].

The implications of these findings are significant for both policy and practice in groundwater management. Sustained depletion risks irreversible aquifer compaction (subsidence rates >5mm/year observed in analogy basins) and ecological degradation of 12 protected wetlands in the research area [23], [25]The observed non-monotonic trends imply that climate change could cause more hydrological variability, so aggravating groundwater stress during droughts caused by El Niño [1] Current extraction trends compromise the rice output capacity of northwest Bangladesh 38% of which is Model projections show, without intervention, 22–40% yield declines for Boro rice in critical zones resulting from water quality degradation and increasing pumping costs [2], [24] Socio-economically, 2.1 million smallholder households are vulnerable depending on groundwater. The noted 1.4 m drop in Chapainawabganj directly relates to 17% higher irrigation energy costs, so compromising farm profitability [24]. This work validates ITA's superiority over conventional methods in complex aquifer systems, especially its capacity to identify latent trends in medium groundwater values (ρ_{xy} = -0.14 to 0.45) that conventional methods overlook [23]. Under anthropogenic pressure, the technique provides a repeatable framework for examining non-stationary hydrological systems. These results highlight how urgently integrated water governance solutions balancing aquifer sustainability with agricultural output are needed. The shown spatial heterogeneity in groundwater responses (56.67% declining vs 18.33% increasing wells) calls for localized management strategies instead of consistent policy approaches [23]. Future studies should give coupling ITA top priority in order to estimate depletion thresholds and maximize intervention timing by means of machine learning approaches.

References

[1] G. M. M. A. P.-A. J. ; I. Md. T. M. M. Hodgson, “Groundwater trends in the northwest region of Bangladesh ,” 2021.

[2] S. I. M. M. I. M. T. M. M. A. J. P.-A. Janardhanan, “Groundwater balance in northwest Bangladesh – modelling and scenario analyses ,” 2021.

[3] The Daily Star, “Groundwater decreasing at alarming levels in Rajshahi,” Nov. 15, 2022. Accessed: May 12, 2025. [Online]. Available: https://www.thedailystar.net/news/news/groundwater-decreasing-alarming-levels-rajshahi-3169881

[4] R. M. Ferozur, C. S. Jahan, R. Arefin, and Q. H. Mazumder, “Groundwater potentiality study in drought prone barind tract, NW Bangladesh using remote sensing and GIS,” *Groundw Sustain Dev*, vol. 8, pp. 205–215, Apr. 2019, doi: 10.1016/J.GSD.2018.11.006.

[5] K. M. U. AHMED, M. NISHIGAKI, and A. M. DEWAN, “Constraints and issues on sustainable groundwater exploitation in Bangladesh,” *Journal of Groundwater Hydrology*, vol. 47, no. 2, pp. 163–179, 2005, doi: 10.5917/JAGH1987.47.163.

[6] M. Z. Hossain, S. K. Adhikary, H. Nath, A. Al Kafy, H. A. Altuwaijri, and M. T. Rahman, “Integrated Geospatial and Analytical Hierarchy Process Approach for Assessing Sustainable

Management of Groundwater Recharge Potential in Barind Tract," *Water (Basel)*, vol. 16, no. 20, pp. 2918–2918, Oct. 2024, doi: 10.3390/W16202918.

[7] S. Shahrear, M. Al Amin, M. Waliullah, F. Hasan, and M. Rashidul Hasan, "ASSESSMENT OF GROUNDWATER IN RAJSHAHI DISTRICT 2022," in *7th International Conference on Civil Engineering for Sustainable Development (ICCESD 2024), Bangladesh*, 2024.

[8] Z. Şen, "Innovative Trend Analysis Methodology," *J Hydrol Eng*, vol. 17, no. 9, pp. 1042–1046, Dec. 2011, doi: 10.1061/(ASCE)HE.1943-5584.0000556.

[9] Y. S. Güçlü, "Improved visualization for trend analysis by comparing with classical Mann-Kendall test and ITA," *J Hydrol (Amst)*, vol. 584, p. 124674, May 2020, doi: 10.1016/J.JHYDROL.2020.124674.

[10] Y. Alifujiang, J. Abuduwaili, and A. Abliz, "Precipitation trend identification with a modified innovative trend analysis technique over Lake Issyk-Kul, Kyrgyzstan," *Journal of Water and Climate Change*, vol. 14, no. 6, pp. 1798–1815, Jun. 2023, doi: 10.2166/wcc.2023.413.

[11] M. A. H. M. Kamal and Md. T. U. Rahman, "Application of the Novel Innovative Trend Analysis (Ita) Technique for Analyzing Groundwater Fluctuation Trends in the Drought-Prone Northwestern Region of Bangladesh," 2024, doi: 10.2139/SSRN.5056693.

[12] R. D. and C. Ministry of Local Government, "National Strategy for Water and Sanitation Hard to Reach Areas of Bangladesh 2012," 2012.

[13] M. Harun, A. Rashid, A. B. M. J. Islam, B. J. Shirazy, and S. M. Shahidullah, "Cropping Systems and Land Use Pattern in Rajshahi Region," 2017.

[14] Z. Şen, "Innovative Trend Analysis Methodology," *J Hydrol Eng*, vol. 17, no. 9, pp. 1042–1046, Sep. 2012, doi: 10.1061/(asce)he.1943-5584.0000556.

[15] T. Caloiero, R. Coscarelli, and E. Ferrari, "Application of the Innovative Trend Analysis Method for the Trend Analysis of Rainfall Anomalies in Southern Italy," *Water Resources Management*, vol. 32, no. 15, pp. 4971–4983, Dec. 2018, doi: 10.1007/s11269-018-2117-z.

[16] Y. S. Güçlü, Dabanlı, E. Şişman, and Z. Şen, "Air quality (AQ) identification by innovative trend diagram and AQ index combinations in Istanbul megacity," *Atmos Pollut Res*, vol. 10, no. 1, pp. 88–96, Jan. 2019, doi: 10.1016/j.apr.2018.06.011.

[17] M. Ahmeduzzaman and S. Kar, "A Study on Ground Water Fluctuation at Barind Area, Rajshahi," *International Journal of Engineering Research and Applications (IJERA)*, vol. 2, pp. 1465–1470, 2012, [Online]. Available: www.ijera.com

[18] S. Janardhanan *et al.*, "Groundwater balance in northwest Bangladesh-modelling and scenario analyses A project of the South Asia Sustainable Development Investment Portfolio (SDIP)," 2021. [Online]. Available: http://research.csiro.au/sdip.

[19] M. Esit, "Investigation of innovative trend approaches (ITA with significance test and IPTA) comparing to the classical trend method of monthly and annual hydrometeorological variables: a case study of Ankara region, Turkey," *Journal of Water and Climate Change*, vol. 14, no. 1, pp. 305–329, Jan. 2023, doi: 10.2166/WCC.2022.356.

[20] M. A. Rahman *et al.*, "Mechanism of arsenic enrichment and mobilization in groundwater from southeastern Bangladesh: Water quality and preliminary health risks assessment," *Chemosphere*, vol. 294, p. 133556, May 2022, doi: 10.1016/J.CHEMOSPHERE.2022.133556.

[21] A. Tuinhof and K. Kemper, "Mitigation of Arsenic Contamination in Drinking Water-Supplies of Bangladesh — the Case of Chapai Nawabganj," 2010. [Online]. Available: www.bwspp.org

[22] P. S. Banerjee and S. De Silva, "Pro-Poor Groundwater Development The Case of the Barind Experiment in Bangladesh," 2015.

[23] M. Azad, "Ground water fluctuations in Northwestern Bangladesh (Over last 30 years) Impact on environment," 2022. Accessed: May 12, 2025. [Online].

[24] Dhaka Tribune, "Groundwater table sinks 20-feet in some parts of northwest Bangladesh," 2022. Accessed: May 12, 2025. [Online]. Available: https://www.dhakatribune.com/bangladesh/nation/286397/groundwater-table-sinks-20-feet-in-some-parts-of

[25] M. M. Monir, S. C. Sarker, R. N. Biswas, and M. N. Islam, "Assessment of the environmental impacts of regional groundwater flow path fluctuations in the water-stressed drought prone Northern Region of Bangladesh," *Sci Rep*, vol. 15, no. 1, pp. 1–25, Dec. 2025, doi: 10.1038/S41598-024-77617.