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Rainfall and Groundwater Relationship Assessment in the North River Basin, Afghanistan

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Abstract. *Rainfall and groundwater variability are critical for sustainable water-resource management in arid and semi-arid regions like Afghanistan. This study investigates the relationship between precipitations and groundwater levels in the North River Basin, using long-term rainfall data (1979–2022) from 13 meteorological stations and groundwater observations from 216 wells across five sub-river basins during 2022–2023. Descriptive statistics and the Precipitation Concentration Index (PCI) were applied to assess temporal rainfall patterns, seasonal variability, and rainfall concentration. Groundwater trends were analyzed by comparing monthly and annual fluctuations in water-table levels. Results indicate a decline in precipitation from 1979–1999, followed by gradual recovery after 2000, with rising rainfall concentration in recent decades, particularly in the dry season. Groundwater data reveal significant fluctuations across the sub-river basins, with some areas experiencing drawdown, likely due to over-extraction or insufficient recharge. Correlation analysis highlights the influence of rainfall variability on groundwater levels, demonstrating the importance of understanding seasonal recharge dynamics. These findings provide insights into the coupling between rainfall and groundwater, offering valuable information for water-resource planning, drought mitigation, and sustainable management of aquifers in the North River Basin.*

Keywords: *North river basin, rainfall–groundwater interaction, precipitation concentration index, groundwater recharge, water resources management*

1. Introduction

Precipitation is a fundamental component of the hydrological cycle and serves as the primary source of water input for terrestrial systems (Danesh, 2013). It occurs in various forms—including rain, snow, sleet, and hail—and directly influences surface water availability, groundwater recharge, agricultural productivity, and ecosystem health (Nouri & Chahouki Zare, 2018). In arid and semi-arid regions such as Afghanistan, even minor fluctuations in precipitation can significantly impact hydrological and environmental conditions (Liu et al., 2019).

The North River Basin, located in northern Afghanistan, is a critical hydrological system supporting agriculture, domestic water supply, and local livelihoods. Over recent decades, the basin has experienced notable variations in both annual and seasonal rainfall, affecting streamflow, drought frequency, and groundwater levels (National Statistics and Information Authority, 2015). Understanding these changes is essential for effective water-resource planning and climate-risk management.

Previous studies in Afghanistan have largely focused on either precipitation trends or groundwater assessments, with limited integration of both datasets to evaluate recharge

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dynamics. Liu et al. (2019) examined precipitation and drought extremes; Olawoyin and Acheampong (2017) evaluated areal rainfall estimation methods; and Sattari et al. (2016) addressed techniques for handling missing precipitation data. Despite these efforts, few studies have comprehensively linked long-term rainfall variability with groundwater responses to understand seasonal recharge, water-table fluctuations, and the influence of climatic variability on aquifers.

Given these conditions, this study aims to investigate the relationship between rainfall and groundwater levels in the North River Basin. By combining long-term precipitation data with recent groundwater measurements, the study seeks to identify patterns in rainfall concentration, seasonal variability, and their influence on aquifer dynamics. These findings are intended to support sustainable water-resource management and inform drought-mitigation strategies in northern Afghanistan.

2. Materials and Methods

2.1 Study Area

The North River Basin, situated in northern Afghanistan, is a closed hydrological system encompassing approximately 78,546 km². It includes the provinces of Balkh, Samangan, Sare Pul, Jawzjan, and Faryab, and is divided into five sub-river basins (SRBs): Balkhab, Kuhlm, Lower Sare Pul, Shirin Tagab, and Upper Sare Pul. The basin features varied topography, including flatlands, plains, and hills of varying gradients, with central areas predominantly flat or semi-flat. Quaternary sediments dominate the lowlands, while deluvial-proluvial deposits and mudstone formations characterize the higher regions, controlling infiltration, runoff, and aquifer recharge (Ministry of Energy and Water, 1403). The basin supports a population of approximately 3.927 million, with surface-water availability per capita estimated at 560 m³/year, indicating high water stress conditions (National Statistics and Information Authority, 1394). Figure 1 illustrates the geographic distribution of five sub-river basins (SRBs) and 13 meteorological stations across the basin.

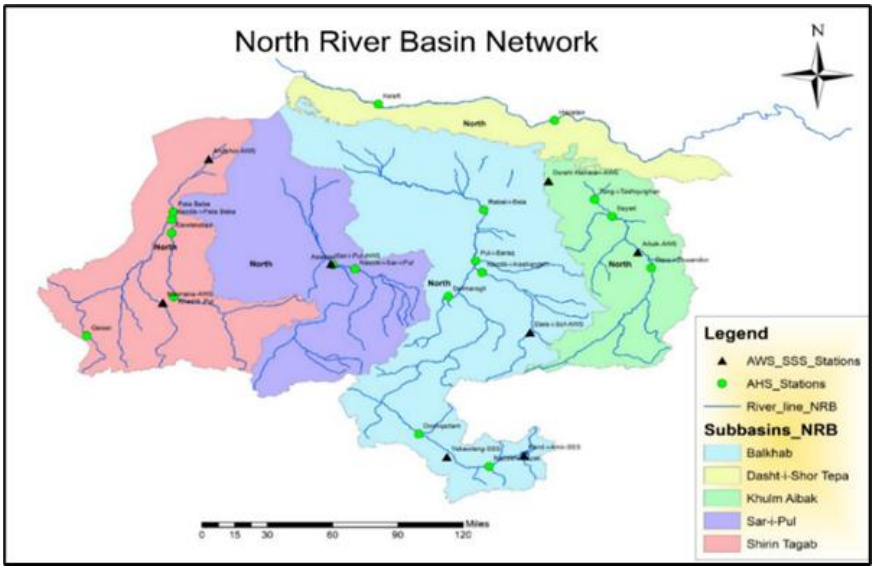


Figure 1. Location of Meteorological Stations in the North River Basin (Ministry of Energy and Water, 1403)

2.2 Data Sources

Monthly and annual precipitation records from 13 meteorological stations within the North River Basin were obtained from the Ministry of Energy and Water (Ministry of Energy and Water, 2023). Stations include Asiabad, Nazdik-i-Sarpul, Qaisar, Tangi Tashqurghan, Dara-i-Zhwandon, Dawlatabad, Doshqadam, Hairatan, Kekeft, Khesht Pul, Nazdik-i-Keshandeh, Nazdik-i-Nayak, Pul-i-Baraq, Rabat-i-Bala. And because reliable hydrological analysis requires consistent and complete records (Sattari et al., 2016; Lebel et al., 1987), datasets were reviewed for continuity, missing values, and potential discrepancies. Only stations with sufficient and reliable long-term data were included in the analysis.

Groundwater data were collected from 216 monitoring wells distributed across the five SRBs. Monthly water-level observations for 2022–2023 were provided by the Directorate of Groundwater Resources (Ministry of Energy and Water, 1403). Groundwater trends were analyzed by computing geometric averages for each sub-basin and comparing annual fluctuations between 2022 and 2023. These data allowed the assessment of recharge and discharge dynamics, seasonal variability, and spatial differences across the basin (Ministry of Energy and Water, 1403).

2.3 Analytical Methods

Temporal precipitation variability was evaluated using descriptive statistical measures, including means, standard deviations, and coefficients of variation, following established hydrological assessment methods (Liu et al., 2019; Gandomkar & Husseini, 1387). Long-term, seasonal, and multi-decadal precipitation trends were examined through graphical analysis of the 1979–2022 records.

The Precipitation Concentration Index (PCI) was computed following Oliver and Fairchild in 1981 (Oliver & Fairchild, 1981) to assess rainfall distribution and intensity. PCI values were calculated for the full study period (1979–2022) and for two sub-periods: 1979–1999 and 2000–2022. Seasonal and supra-seasonal PCI values were determined to evaluate changes in rainfall concentration and implications for groundwater recharge.

Groundwater levels were analyzed for each SRB, calculating monthly averages, maximum and minimum water levels, and annual fluctuations. Because groundwater-level measurements exhibited skewed distributions and multiplicative variability across wells, the geometric mean was used to provide a more representative central tendency and to reduce the influence of extreme values compared with the arithmetic mean. Comparisons between 2022 and 2023 highlighted areas of drawdown, potential over-extraction, and recharge limitations. Correlation analyses between precipitation, PCI, and groundwater fluctuations were performed to quantify the rainfall–groundwater relationship (Nouri & Chahouki Zare, 1397).

2.4 Software Tools

Microsoft Excel was used for statistical calculations, graphing, and trend analysis, while Microsoft Word was used for documentation. These tools enabled the analysis of temporal precipitation patterns and the identification of long-term trends across the North River Basin (Sattari et al., 2016; Bigiarini et al., 2017).

3. Result and Discussion

3.1 Long-Term Annual Precipitation Trends

Dividing the dataset into two sub-periods highlights contrasting patterns. From 1979 to 1999, as demonstrated by Figure 3, precipitation declined sharply from 370–330 mm in the early 1980s to 270–230 mm in the late 1990s, representing nearly a 30% reduction. The negative slope of the trend line (y = –2.9931x + 6213.5) confirms an annual decrease of approximately 3 mm, reflecting prolonged drying and increased drought severity.

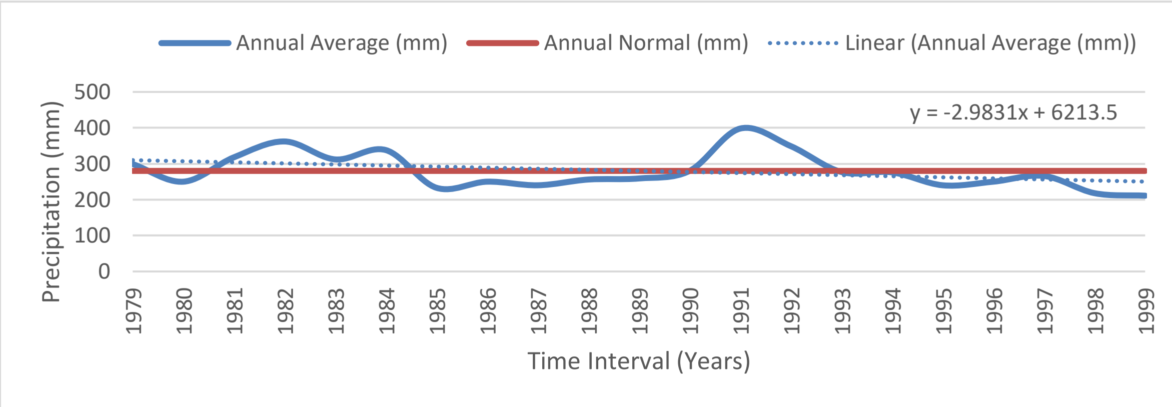


Figure 2. Long-Term Annual Average Precipitation Graph of 13 Hydrometeorological Stations in the North River Basin (1976-1999)

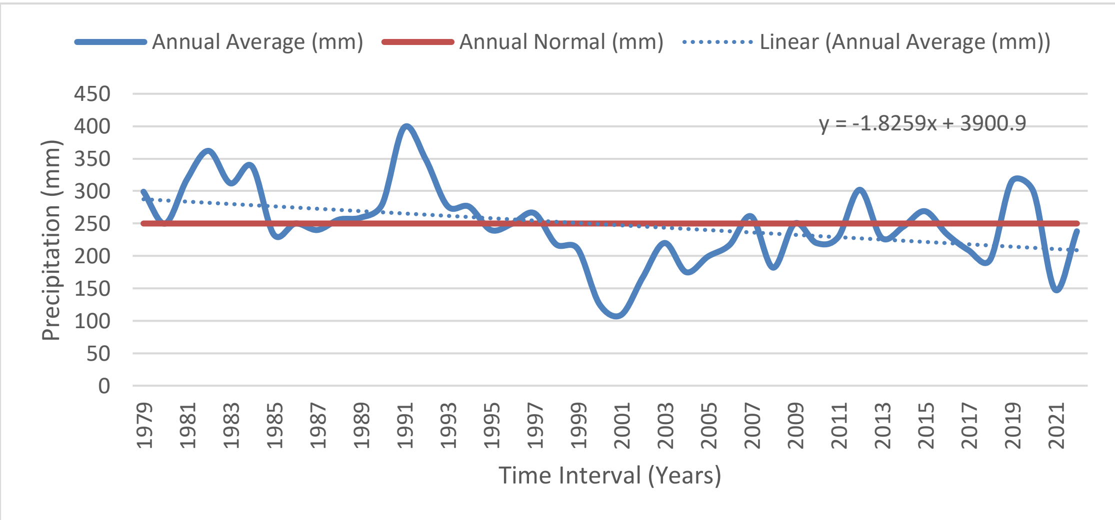


Figure 3. Long-Term Annual Average Precipitation Graph of 13 Hydrometeorological Stations in the North River Basin (1979–2022)

The long-term precipitation records (1979–2022) reveal substantial climatic variability in the North River Basin. Annual precipitation ranged up to approximately 450 mm, with the highest values occurring in the early 1980s and mid-1990s, and the lowest in the late 2010s and early 2020s. A linear trend line for the full period indicates a general decrease in annual average precipitation as depicted in Figure 3.

In contrast, the 2000–2022 period shows gradual recovery as presented in Figure 4, with precipitation increasing from 100–200 mm in the early 2000s to 200–300 mm in the early 2010s, and reaching 320 mm in the late 2010s. The positive trend equation (y = 4.0583x - 7942.3) indicates a steady annual increase, suggesting partial climatic recovery.

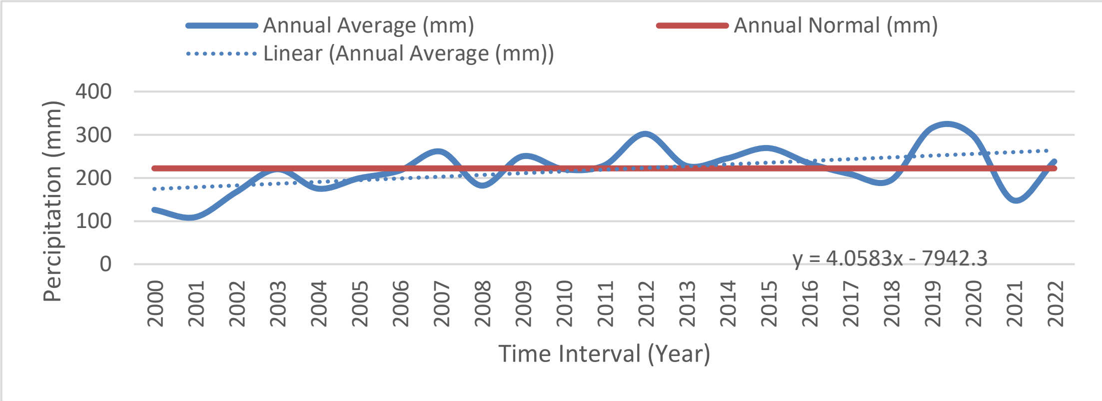


Figure 4. Long-Term Annual Average Precipitation Graph of 13 Hydrometeorological Stations in the North River Basin (2000-2022)

3.2 Seasonal Precipitation Trends

Analysis of wet and dry season precipitation reveals significant shifts over time as demonstrated by Figure 5. During 1979–1999, both seasons showed declining trends, with Z-normal values of –1.84 for the wet season and –0.69 for the dry season, indicating below-normal precipitation. In the 2000–2022 period, trends reversed: the wet season showed a strong positive deviation (+2.46), and the dry season also increased (+1.51). Long-term data (1979–2022) indicate a net decrease in wet season precipitation (–2.75) but a slight increase in the dry season (+0.28), reflecting a shift of rainfall from winter toward spring and summer and a heightened risk of floods during warmer months.

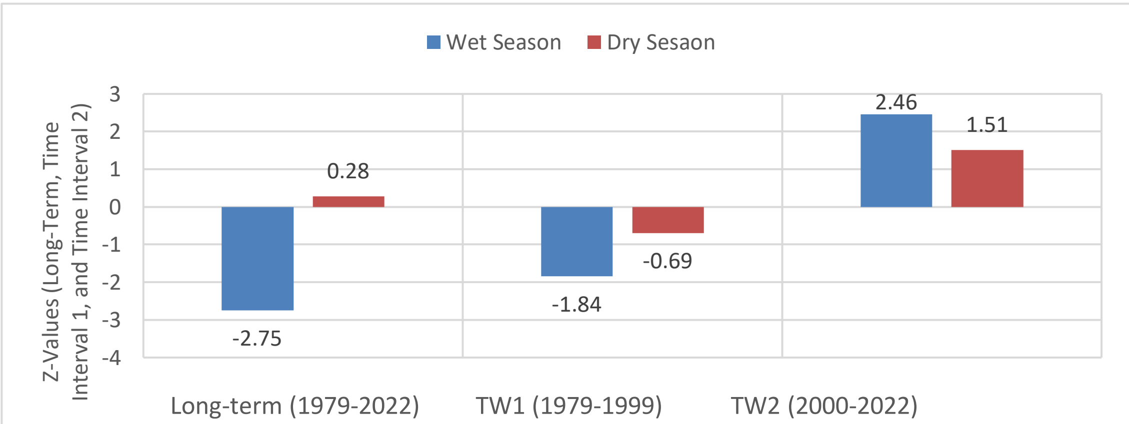


Figure 5. Seasonal (Wet and Dry) Variations in Precipitation Trends in the Northern River Basin between 1979 to 2022

3.3 Precipitation Concentration Index (PCI)

The Precipitation Concentration Index (PCI) was used to evaluate changes in rainfall intensity and temporal distribution in the North River Basin across different time intervals as illustrated in Figure 6. The long-term annual PCI (1979–2022) averages 16.3, indicating moderate rainfall concentration. During the first-time window (TW1: 1979–1999), the PCI slightly decreased to 15.9, reflecting more evenly distributed rainfall, whereas in the second time window (TW2: 2000–2022), it rose to 16.6, suggesting that precipitation events have become more concentrated, occurring in fewer but more intense episodes. This increase highlights a trend toward irregular and potentially more hazardous rainfall, which may exacerbate flash floods and complicate water management.

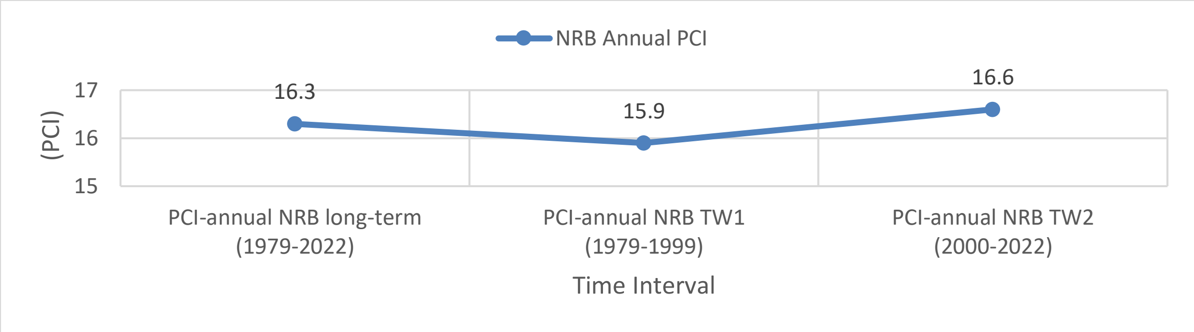


Figure 6. Annual Precipitation Concentration Index (PCI) for the North River Basin across three-time intervals

Seasonal PCI analysis further emphasizes these patterns as shown in Figure 7. Autumn shows the most pronounced increase, with PCI values rising from 13.0 in TW1 to 16.8 in TW2, indicating increasingly clustered rainfall events. Summer PCI also increased from 10.8 to 12.6, while winter and spring remained relatively stable. These shifts suggest a redistribution of precipitation toward warmer months, consistent with observed trends of rainfall moving from winter to spring and summer.

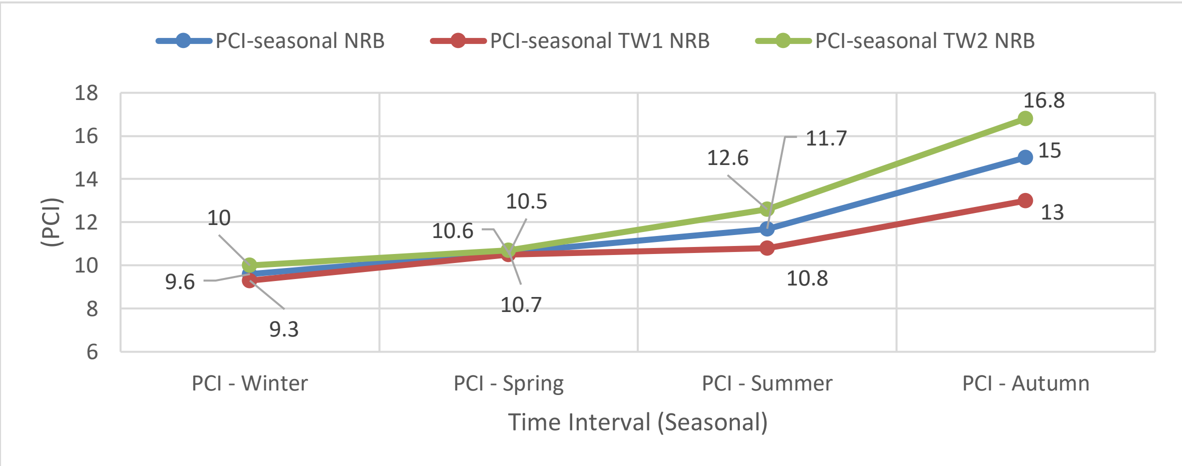


Figure 7. Seasonal PCI values for the North River Basin across three-time intervals

Supra-seasonal PCI values reveal more dramatic changes as demonstrated by Figure 8. Wet season PCI declined slightly from 10.7 to 10.2 in TW2, while dry season PCI surged from 16.0 to 24.0, indicating that dry season rainfall is now highly concentrated in short, intense bursts rather than being evenly distributed. Such patterns underscore growing climatic imbalance and increased flood risk during the dry season, emphasizing the need for adaptive strategies in flood control and water resource planning.

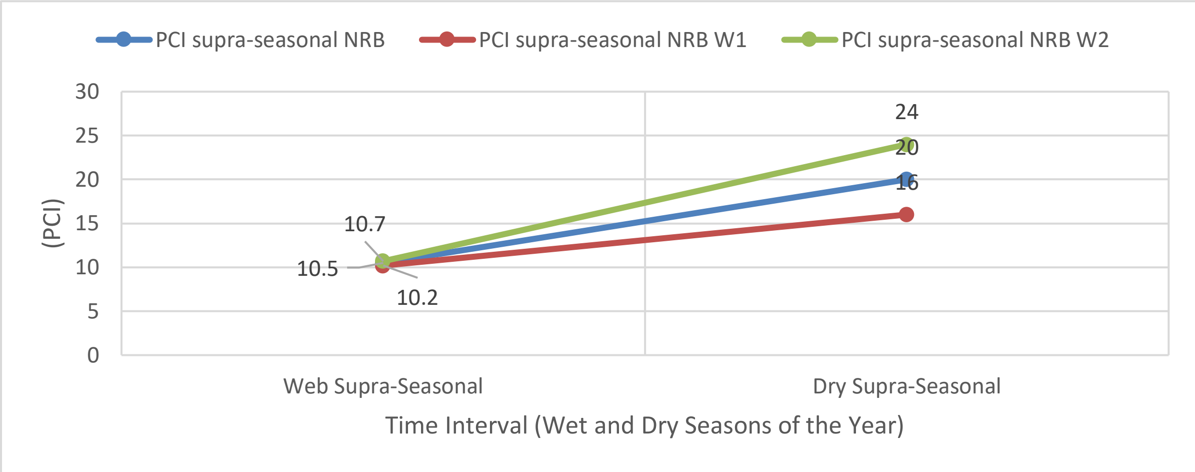


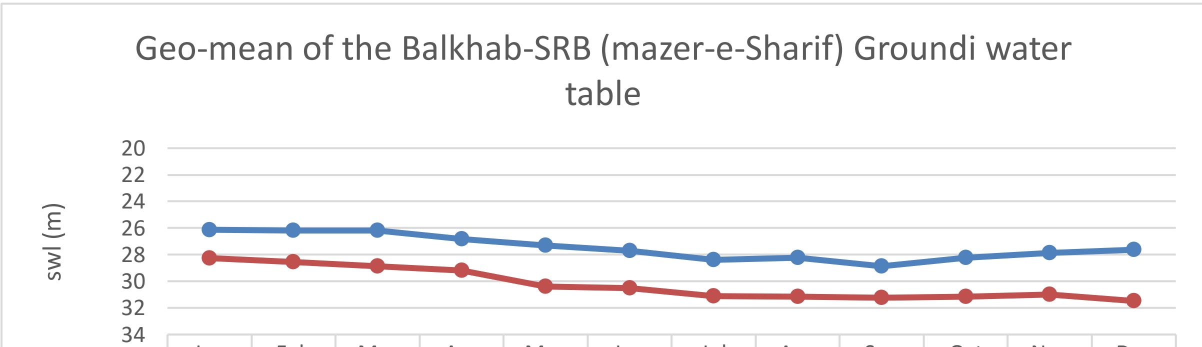
Figure 8. PCI values for wet and dry supra-seasonal intervals across three time periods

Overall, the PCI trends demonstrate a clear intensification of rainfall in the North River Basin, with precipitation becoming more erratic, concentrated, and seasonally skewed. These findings provide critical insight into evolving rainfall dynamics, with important implications for hydrological planning, agriculture, and disaster risk management.

3.4 Groundwater Level Trends (2022–2023)

3.4.1 Balkhab SRB (Mazar-e-Sharif):

The monitoring network established in the centers of Balkh recorded a maximum groundwater level of 86 meters and a minimum of 9.3 meters in 2022. From January to December 2023, a notable decline was observed, with levels reaching a maximum of 100 meters and a minimum of 10.6 meters. This downward shift in both maximum and minimum levels suggests increased groundwater extraction or reduced recharge, indicating negative changes in regional water management and hydrological conditions, as shown in Figure 9.

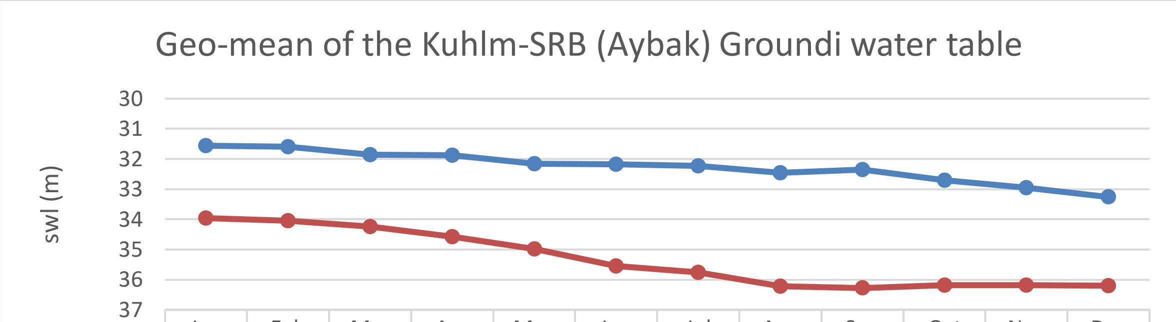


	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2022	26.13	26.17	26.2	26.81	27.29	27.73	28.38	28.22	28.87	28.23	27.87	27.62
2023	28.26	28.55	28.89	29.2	30.41	30.5	31.13	31.16	31.22	31.15	30.99	31.48

Figure 9. Annual Groundwater Level Trends in the Balkhab SRB (Mazar-e-Sharif) (2022-2023)

3.4.2 Kuhlm_SRB (Aybak)

In the centers of Aybak, groundwater monitoring results indicated a maximum water level of 72.91 meters and a minimum of 5.1 meters during 2022. Between January and December 2023, the maximum increased slightly to 75 meters, while the minimum declined to 7.2 meters. These trends reflect a gradual decrease in groundwater availability, possibly due to insufficient recharge or changes in local water use, as illustrated in Figure 10.

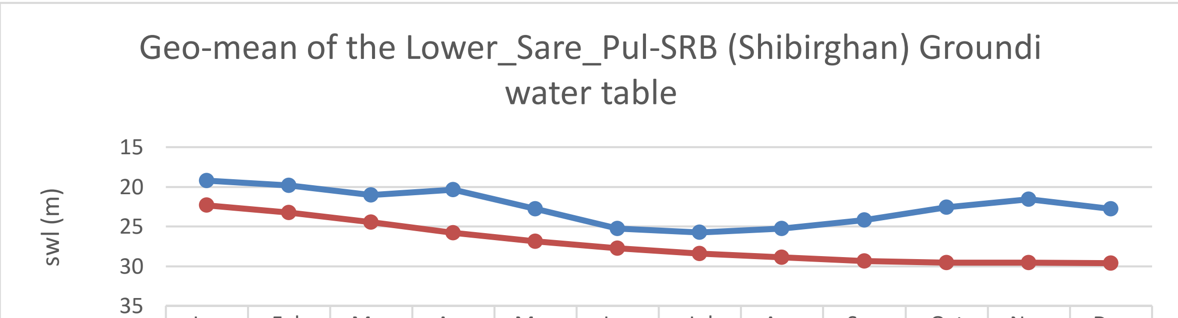


	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2022	31.56	31.6	31.85	31.87	32.15	32.18	32.23	32.45	32.35	32.7	32.95	33.26
2023	33.96	34.05	34.24	34.57	34.99	35.54	35.76	36.21	36.28	36.18	36.19	36.2

Figure 10. Annual Groundwater Level Trends in the Kuhlm_SRB (Aybak) (2022-2023)

3.4.3 Lower Sare Pul SRB (Shibirghan)

Within the Jawzjan monitoring area, groundwater levels in 2022 ranged from a maximum of 27.5 meters to a minimum of 16.8 meters. By 2023, the maximum level declined significantly to 36.5 meters, with the minimum slightly decreasing to 17.7 meters. This substantial drop in maximum levels indicates intensified groundwater withdrawal across the basin, as shown in Figure 11.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2022	19.22	19.83	21.02	20.33	22.75	25.26	25.75	25.23	24.2	22.61	21.58	22.81
2023	22.34	23.27	24.44	25.81	26.9	27.77	28.43	28.89	29.35	29.54	29.58	29.62

Figure 11. Annual Groundwater Level Trends in the Lower_Sare Pul_SRB (Shibirghan) (2022- 2023)

3.4.4 Shirin Tagab SRB (Maimana)

Monitoring across Faryab province showed a 2022 maximum groundwater level of 90.9 meters and a minimum of 15 meters. During 2023, the maximum increased to 93.2 meters, while the minimum dropped slightly to 16 meters. These changes suggest fluctuating recharge–discharge dynamics, where increased extraction may be occurring despite occasional recharge events. Trends are presented in Figure 12.

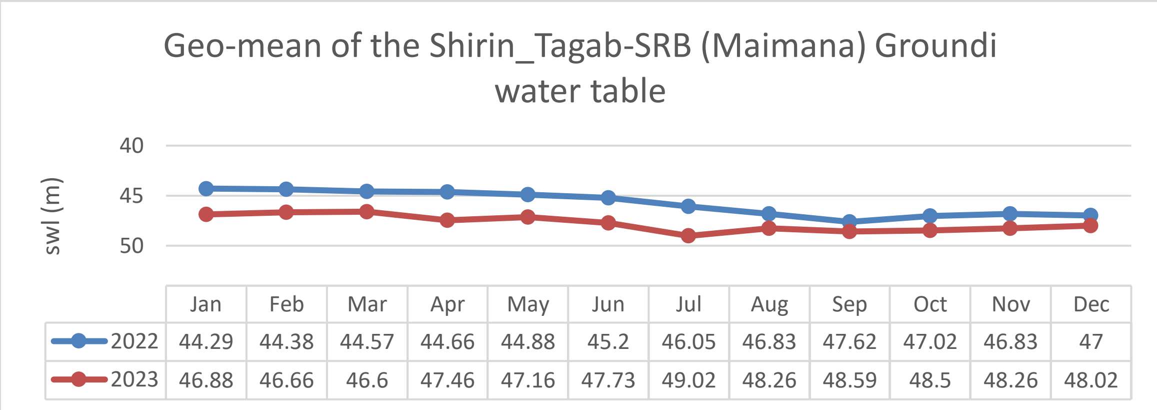


Figure 12. Annual Groundwater Level Trends in the Shirin Tagab_SRB (Maimana) (2022-2023)

3.4.5 Upper_Sare_Pul_SRB (Sare Pul):

In the Sare Pul monitoring centers, groundwater levels ranged from a maximum of 60.65 meters to a minimum of 5.45 meters in 2022. Over the course of 2023, both levels declined further, with the maximum reaching 69 meters and the minimum increasing to 9.2 meters. This overall reduction implies decreased groundwater storage, likely due to elevated discharge rates or expanded water use, as shown in Figure 13.

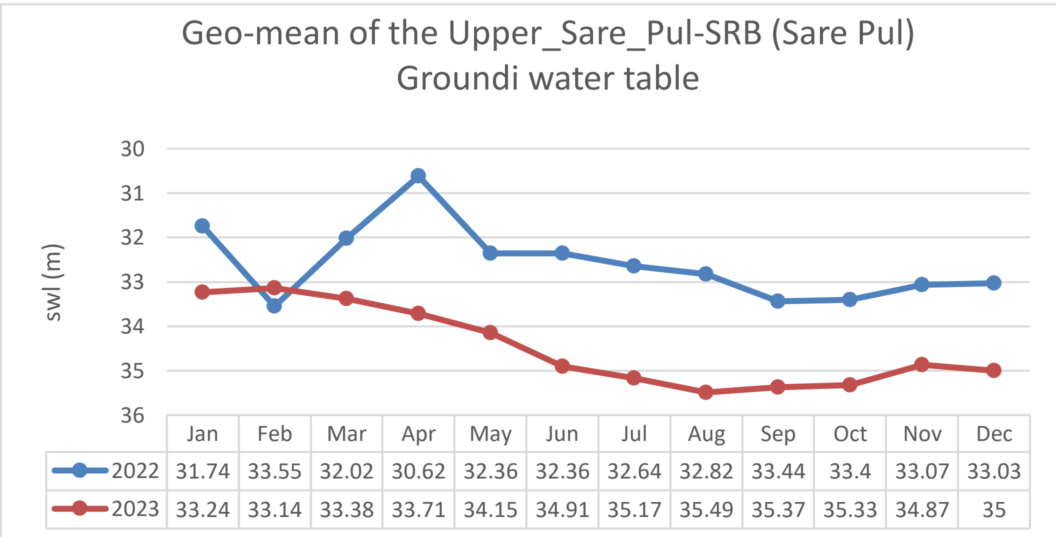


Figure 13. Annual Groundwater Level Trends in the Upper_Sare_Pul_SRB (Sare Pul) (2022-2023)

Groundwater levels across the five sub-river basins (SRBs) show variable responses, summarized in Table 1.

Table 1. Groundwater levels across the five sub-river basins (SRBs)

Sub-River Basin	Max Water Level 2022 (m)	Min Water Level 2022 (m)	Max Water Level 2023 (m)	Min Water Level 2023 (m)	Observed Trend
Balkhab (Mazar-e-Sharif)	86.0	9.3	100.0	10.6	Overall decline
Kuhlm (Aybak)	72.91	5.1	75.0	7.2	Gradual decline
Lower Sare Pul (Shibirghan)	27.5	16.8	36.5	17.7	Maximum drawdown
Shirin Tagab (Maimana)	90.9	15.0	93.2	16.0	Slight increase in max, min decline
Upper Sare Pul (Sare Pul)	60.65	5.45	69.0	9.2	Overall decline

The groundwater trends across the five sub-river basins reveal clear signs of stress on regional aquifer systems. In the Balkhab SRB, both maximum and minimum groundwater levels declined, indicating increased extraction or reduced recharge. Similarly, the Kuhlm SRB shows a gradual decrease in water levels, reflecting continued pressure on the aquifer. The Lower Sare Pul SRB experienced a substantial drop in maximum levels, suggesting intensified groundwater withdrawal. In contrast, the Shirin Tagab SRB exhibited a slight increase in maximum level accompanied by a decline in minimum level, pointing to variable recharge–discharge dynamics. Meanwhile, the Upper Sare Pul SRB showed reductions in both maximum and minimum levels, indicating an overall decrease in groundwater storage across the region.

3.5 Rainfall-Groundwater Relationship

Comparing precipitation trends with groundwater fluctuations shows that areas with declining rainfall generally exhibited greater drawdown, while regions with stable or increased rainfall showed minor improvements in groundwater levels. This indicates a direct link between rainfall variability, seasonal concentration, and aquifer recharge in the North River Basin.

The results of this study highlight strong linkages between long-term rainfall variability, seasonal precipitation distribution, and groundwater dynamics across the North River Basin. The pronounced decline in rainfall during the period 1979–1999, followed by partial recovery after 2000, is consistent with regional climate fluctuations documented in other semi-arid basins (Liu et al., 2019; Shah et al., 2019). Reduced precipitation during the earlier decades likely limited natural recharge, while more favorable rainfall conditions after 2000 only partly compensated for historical deficits, a pattern also observed in similar drought-prone regions (UNESCO, 2019).

Groundwater monitoring results from the five sub-river basins reveal widespread declines between 2022 and 2023. While direct data on extraction rates, land use, and population growth were not included in this study, increased groundwater withdrawal is likely a contributing factor, as suggested by regional studies in semi-arid areas (UNESCO, 2019; Sattari et al., 2016).

The Precipitation Concentration Index (PCI) analysis reinforces this interpretation. Increasing PCI values, especially during the dry season, indicate more irregular and intense rainfall events. Studies have shown that high PCI values are associated with reduced infiltration and higher surface runoff, which diminish groundwater recharge efficiency (Olawoyin & Acheampong, 2017). The shift toward more concentrated rainfall events in the North River Basin therefore contributes to the observed disconnect between rising rainfall trends and limited groundwater recovery.

Groundwater monitoring results from the five sub-river basins further reveal widespread declines between 2022 and 2023. These findings parallel other research showing that groundwater depletion in semi-arid regions often results from combined effects of climate variability and increased extraction for agriculture, domestic use, and small-scale industry (UNESCO, 2019; Sattari et al., 2016). In Balkhab, Kuhlm, Lower Sare Pul, and Upper Sare Pul, persistent declines indicate heavy dependence on groundwater resources and limited natural recharge. The mixed pattern observed in Shirin Tagab, where maximum levels slightly increased while minimum levels dropped, suggests episodic recharge events followed by sustained discharge—an indicator of stress in aquifer systems dealing with inconsistent inflow.

However, an important limitation must be acknowledged: groundwater data were available only for a two-year period (2022–2023), which restricts the ability to draw robust or long-term conclusions when comparing groundwater behavior to multi-decadal precipitation trends (1979–2022). This short temporal window limits the study's capacity to capture delayed recharge responses, multi-year groundwater cycles, or long-term depletion trajectories.

Overall, the comparison between rainfall and groundwater levels demonstrates that improved rainfall alone is insufficient to stabilize groundwater resources in the basin. Increasing rainfall concentration, expanding water demand, and reduced recharge capacity collectively intensify aquifer depletion—echoing conclusions from regional hydroclimatic studies (Liu et al., 2019; UNESCO, 2019). To mitigate these impacts, sustainable groundwater management strategies should include recharge-focused interventions such as managed aquifer recharge (MAR), rainwater harvesting, and land-use management practices. Implementing these measures, alongside improved monitoring, can help prevent long-term water scarcity and support resilient water-resource management across the North River Basin.

Conclusion

This study assessed long-term precipitation variability and groundwater level fluctuations across selected sub-river basins of northern Afghanistan using historical rainfall records (1979–2022) and seasonal water-table measurements. The findings reveal a noticeable decline in annual precipitation during recent decades, accompanied by increasing variability in seasonal distribution. Such shifts indicate heightened climatic stress and a growing tendency toward drier conditions in the region. Correspondingly, groundwater levels showed consistent declines in most sub-basins, confirming reduced recharge and increased extraction pressure. Only limited areas exhibited slight seasonal improvements, which were insufficient to counterbalance the overall downward trend.

The combined analysis highlights a clear imbalance between groundwater abstraction and natural replenishment, aggravated by diminishing rainfall inputs. This poses significant risks for agricultural productivity, domestic water supply, and long-term aquifer sustainability. Strengthening water-resource management, reducing reliance on groundwater during dry seasons, and enhancing recharge practices are critical for safeguarding future water security. Continued monitoring, improved data collection, and integrated hydrological assessments are strongly recommended to support sustainable water-resource planning in Afghanistan.

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