

ORIGINAL RESEARCH ARTICLE

Assessing long-term groundwater level trends in Karakalpakstan using non-parametric statistical methods

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Abstract: Climate change has significantly impacted global hydrometeorological variables, placing increasing stress on groundwater resources. This study investigates long-term groundwater level trends in the Republic of Karakalpakstan, Uzbekistan, using a combination of non-parametric statistical models. The Mann–Kendall test, Spearman’s rank correlation, and innovative polygon trend analysis (IPTA) were applied to assess spatiotemporal variations. To address the limitations of parametric methods, this study utilizes robust, assumption-free trend detection techniques. The results reveal statistically significant increasing trends in groundwater levels across most provinces, particularly in Muynak ($Z=3.884, p<0.001$) and Republic-wide ($Z=3.603, p<0.001$). In contrast, provinces such as Turtkul, Ellikkala, and Nukus exhibit no significant trends. The IPTA method highlights seasonal fluctuations, with notable decreases in specific months despite the overall upward trend. These findings emphasize the need for localized groundwater management strategies that consider both seasonal dynamics and long-term changes. By integrating multiple statistical techniques, this study provides a comprehensive evaluation of groundwater variability and offers valuable insights for policymakers and water resource managers in arid regions facing climate-induced water challenges.

Keywords: Groundwater trend analysis; Mann–Kendall test; Innovative polygon trend analysis; Climate change impact; Water resource management

1. Introduction

Hydrometeorological variables – such as precipitation, temperature, streamflow, and evaporation – play a critical role in sustaining human activities, including water

resource management, agriculture, hydroelectric power generation, and groundwater replenishment. However, their inherent stochasticity and complexity necessitate advanced analytical approaches to assess trends and variability accurately. Climate change – driven by

global warming, urbanization, and land degradation – is amplifying shifts in these variables, exacerbating risks such as floods, droughts, and disruptions to hydrological cycles. According to the Intergovernmental Panel on Climate Change, anthropogenic activities have accelerated these changes, with projections indicating a global temperature rise of 1.0 – 5.7°C, a sea-level increase of 0.5 – 1.0 m, and an increased frequency of extreme weather events by 2100. Trend analysis, particularly through non-parametric methods, has become indispensable for evaluating temporal patterns in hydroclimatic data. These methods bypass restrictive assumptions (e.g., normality and independence) and are widely applied to detect trends in variables such as rainfall, evapotranspiration, and wind speed. Such analyses help reveal how climate change alters hydrological systems, impacting water availability, quality, and ecosystem resilience. For instance, precipitation anomalies – linked to both droughts and floods – are increasingly destabilizing economies and ecosystems worldwide.¹⁻⁷

Trend analysis is a fundamental approach for detecting and forecasting future patterns in data using objective, systematic, and quantitative methodologies. It is particularly effective for examining the impacts of climate change on hydrometeorological variables, which are inherently complex and stochastic, often exhibiting significant variability and random fluctuations around an underlying trend. In this context, trend analysis serves as a valuable tool for gaining insights into the behavior of hydroclimatic variables. However, the stochastic nature and intrinsic properties of these variables necessitate specialized analytical techniques. Traditional statistical methods commonly used for trend detection are often constrained by assumptions such as normality, independence, and sufficient record length.⁷⁻⁹ These assumptions are frequently violated in hydroclimatic datasets. To overcome these limitations, non-parametric statistical tests – characterized by minimal distributional assumptions – have become increasingly prevalent in recent years. These methods are better suited to accommodate the inherent variability and irregularities of hydrometeorological datasets.¹⁰⁻¹⁵

Trend analysis models are broadly categorized into two primary classes: Parametric and non-parametric. Parametric models, such as regression models and time series models, rely on specific assumptions regarding the underlying data distribution and relationships. In contrast, non-parametric models, including the Mann–Kendall (MK) test, Sen’s slope estimator, Spearman’s rank (SR) correlation test, and innovative

trend analysis, do not require strict distributional assumptions. Both model classes have been extensively employed by researchers to conduct trend analyses in various fields.¹⁶⁻²⁵ A brief list of trend analysis models is presented in [Table 1](#).

This study introduces a comprehensive comparative analysis of long-term trends in monthly groundwater levels across 16 provinces in the Republic of Karakalpakstan, Uzbekistan, spanning the period from 1990 to 2023. By integrating innovative statistical techniques, including the innovative polygon trend analysis (IPTA), the MK test, and Sen’s slope estimator, this research uniquely captures the temporal and spatial dynamics of groundwater variations. The novelty of this study lies in the combined use of these advanced methodologies, providing deeper insights into regional hydrometeorological patterns and their implications for sustainable water resource management in a climatically sensitive region.

It is important to note that the present study does not incorporate precipitation time series analysis, as long-term records show no significant temporal variations

Table 1. Summary of literature review on trend analysis models

References	Model name	Trend subject
Gaddikeri <i>et al.</i> ²⁶	MK	Meteorological variables
Çelebioğlu and Tayanç ²⁷	RM, MK	Precipitation
Qadem and Tayfur ²⁸	MK, ITA	Temperature
Alashan ²⁹	MK	Precipitation
San ³⁰	ITA	Groundwater level
Kessabi <i>et al.</i> ³¹	MK, ITA, SSE	Rainfall
Likinaw <i>et al.</i> ³²	MK, ITA	Extreme precipitation
Agbo <i>et al.</i> ³³	MK, ITA	Climatic parameters
Sanogo <i>et al.</i> ³⁴	MK	Temperature and rainfall
Gul and Ren ³⁵	ITA	Precipitation
Nguyen <i>et al.</i> ³⁶	MK, ITA	Sea level
Seenu and Jayakumar ³⁷	MK, ITA	Extreme rainfall
Güçlü ³⁸	MK, ITA	Rainfall
Caloiero <i>et al.</i> ³⁹	ITA	Seasonal and annual rainfall

Abbreviations: ITA: Innovative trend analysis; MK: Mann–Kendall test; SSE: Sen’s slope estimator.

in rainfall across the region, which is characterized by infrequent precipitation events. In addition, snowfall statistics were not included in the analysis, representing a limitation that could be addressed in future research.

2. Materials and methods

2.1. Study area and data description

The Republic of Karakalpakstan is located in the northwest of Uzbekistan (43°10' N and 58°45' E). Administratively, it comprises 16 districts and one central city, Nukus. Covering a total area of 166,600 km², Karakalpakstan accounts for 37.1% of the country's total land area (Figure 1). The study area lies within the Aral Sea basin and shares borders with Kazakhstan to the north and west, the Karakum sand massifs of Turkmenistan to the south – along the modern and ancient Amudarya delta – and the Qizilqum desert to the east. The territory of the Republic of Karakalpakstan is characterized by relatively simple surface topography, with the Ustyurt Plateau occupying the western part and the Turan Plain covering the remainder. Elevations range from 49 m below sea level in the southwest to 466 m above sea level in the northwest. The Republic of Karakalpakstan has a harsh continental climate characterized by arid summers, relatively cold winters, and low annual precipitation, primarily in the form of snow. Average January temperatures range from -4.9°C in the southern region to -7.6°C in the northern region, with absolute minimums reaching -40°C. In July, average temperatures rise to 30°C in the south and

26°C in the north, with recorded maximums as high as 46°C. Annual precipitation averages 110 mm, with the majority occurring during winter and spring. Droughts are frequent, as evaporation rates are 9 – 10 times greater than the average precipitation. The vegetation period spans 194 – 214 days annually.

Karakalpakstan contains more than 21.3% of Uzbekistan's irrigated land and 48.5% of its pasturelands. Due to the arid climate, agriculture in the region is only viable through irrigation.

Groundwater data were obtained from the Karakalpakstan Melioration Expedition, a governmental agency. Monthly groundwater measurements were collected over a 33-year period, from 1990 to 2023. For this study, a total of 16 observation sites were selected for comprehensive groundwater analysis. These include sites from the Southern Melioration system, Amudarya Amelioration system, Left-bank Melioration system, and Right-bank Melioration system. The specific locations are: Turtkul, Ellikkala, Beruniy, Amudarya, Khojeli, Takhiatash, Shumanay, Kanlikul, Kungiro, Muynak, Nukus, Kegeyli, Buzatau, Chimbay, Karauzyak, and Takhtakopir.

2.2. Trend analysis models

2.2.1. MK model

The MK model is a widely recognized non-parametric method for detecting monotonic trends in time series data. Its popularity stems from its robustness against non-normal data distributions and its ability to accommodate missing values, making it an ideal choice

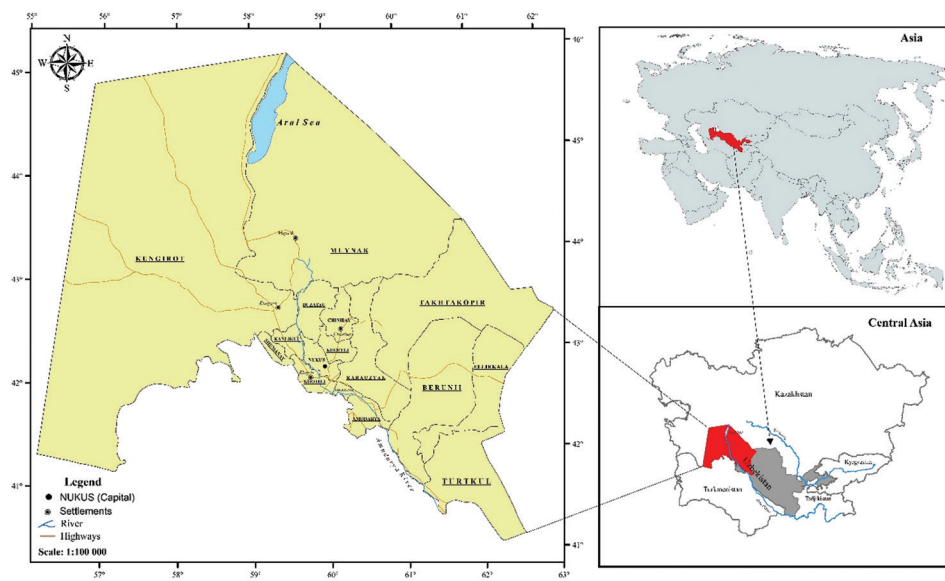


Figure 1. Location of study area in the Republic of Karakalpakstan, Uzbekistan

for environmental and hydrological studies. The test statistic S is calculated using Equation I:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^n \text{sgn}(x_j - x_i) \quad (\text{I})$$

where x_i and x_j are the observed values at time points i and j , and n is the number of data points. Under the null hypothesis of no trend, the expected value of S is zero. The variance of S , denoted as $V(S)$, is given in Equation II:

$$V(S) = \frac{1}{18} \left[n(n-1)(2n+5) - \sum_{t=1}^m t(t-1)(2t+5) \right] \quad (\text{II})$$

where n is the number of data points and m represents the number of tied groups. The standardized test statistic Z is given by Equation III:

$$Z = \begin{cases} \frac{S-1}{\sqrt{V(S)}}; & \text{if } S > 0 \\ 0; & S = 0 \\ \frac{S+1}{\sqrt{V(S)}}; & \text{if } S < 0 \end{cases} \quad (\text{III})$$

A positive Z -value indicates an increasing trend, whereas a negative value signifies a decreasing trend. The significance of the trend is determined by comparing Z to critical values from the standard normal distribution, offering a robust and reliable framework for trend detection across diverse datasets.

2.2.2. Spearman's rho model

The SR rank correlation test is another robust non-parametric method used to identify monotonic trends in time series data by measuring the strength and direction of the association between two variables. Its ability to detect non-linear relationships and its resistance to outliers make it a widely used approach in trend analysis across various scientific disciplines. The SR rank correlation coefficient, ρ , is calculated using Equation IV:

$$\rho = 1 - \frac{6 \sum_{i=1}^n d_i^2}{n(n^2 - 1)} \quad (\text{IV})$$

where $d_i = R(x_i) - R(y_i)$ is the difference between the ranks of the paired values x_i and y_i , and n is the number of data points. The test evaluates whether the calculated ρ significantly deviates from zero, indicating the presence of a trend. For significance testing, the correlation coefficient is transformed into a t -statistic, calculated using Equation V.

$$t = \rho \sqrt{\frac{n-2}{1-\rho^2}} \quad (\text{V})$$

This t -value follows a Student's t -distribution with $n - 2$ degrees of freedom under the null hypothesis of no trend. A positive ρ value suggests an increasing trend, while a negative value indicates a decreasing trend. The SR test is particularly effective for datasets with non-linear patterns, making it a versatile tool for trend detection and analysis in environmental, hydrological, and climate studies.

Before conducting the MK and SR tests, the presence of lag-1 autocorrelation (serial correlation) must be evaluated. Serial correlation in a dependent time series can influence the effectiveness of these tests. For instance, positive serial correlation can increase the likelihood of detecting a significant trend even when none exists.⁴⁰ Therefore, it is essential to assess and address serial correlation prior to trend analysis. If significant serial correlation is present, test statistics must be adjusted, or a pre-whitening technique should be applied to eliminate its impact.

In this research, the trend-free pre-whitening method introduced by Yue *et al.*⁴¹ was utilized. The first-order autocorrelation coefficient (r_1) is calculated as shown in Equation VI:

$$r_1 = \frac{\frac{1}{N-i} \sum_{k=1}^{N-i} (x_i - \bar{x})(x_{i+k} - \bar{x})}{\frac{1}{N} \sum_{k=1}^N (x_k - \bar{x})^2} \quad (\text{VI})$$

If the absolute value of r_1 is less than the critical threshold $\frac{1.96}{\sqrt{N}}$ at the 5% significance level, as applied by Douglas *et al.*⁴² and Tosunoglu,⁴³ the data are deemed to be serially independent. Otherwise, the series is classified as serially dependent.

2.2.3. Polygon trend analysis model

The IPTA technique, introduced by Sen *et al.*,⁷ is versatile and can be utilized for analyzing time series across various temporal scales, including monthly and seasonal intervals.⁴⁴⁻⁴⁸ For a monthly time series x_1, x_2, \dots, x_n , where n represents the number of years, the data should be structured in a matrix format as outlined by Sen *et al.*⁷:

$$\begin{bmatrix} x_{1,1} & \cdots & x_{12,1} \\ \vdots & \ddots & \vdots \\ x_{1,n} & \cdots & x_{12,n} \end{bmatrix}$$

The first half of the dataset, referred to as the upper series, comprises the years $n=1, 2, 3, \dots, \frac{n}{2}$, while the second half, known as the lower series, includes the years $\frac{n}{2}+1, \frac{n}{2}+2, \dots, n$. Implementing the IPTA method on both monthly and seasonal scales involves a multi-step procedure, utilizing a predefined framework with 12 dispersion points to represent each month of the year. The model incorporates the calculation of arithmetic mean and standard deviation (SD) values for the dataset.

By analyzing successive months, the IPTA model identifies trends, allowing for the determination of slopes, lengths, and associated values that characterize these monthly transitions. Subsequently, trend polylines are generated by connecting successive segments of the time series, forming the foundation for further analysis. This graphical representation facilitates both numerical and qualitative interpretations of the examined time series, offering deeper insights into the climatic variations captured in the data.

The calculation procedure for the IPTA model is as follows:

- (i) The dataset of size n is divided into two equal parts for comprehensive analysis.
- (ii) The mean and SD are computed for each month in both subsets.
- (iii) The first series is plotted on the horizontal axis of a scatter chart, whereas the second series is represented on the vertical axis.
- (iv) Points representing consecutive months are connected using straight lines to form a polygon.
- (v) The slope and length of each connecting line are calculated using Equations VII and VIII, respectively.

$$S = \frac{y_2 - y_1}{x_2 - x_1} \quad (\text{VII})$$

$$L = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2} \quad (\text{VIII})$$

The IPTA model template for monthly records offers a framework for both qualitative and quantitative analyses of hydrometeorological systems, yielding several key insights. First, the straight line connecting 2 consecutive months represents changes in monthly values, whereas the closed polygon indicates the natural balance of the system over a year. The length of each line illustrates the magnitude of monthly variations. When the slopes of these lines are relatively consistent in both vertical and horizontal directions, it suggests minimal monthly contributions to the overall variation.

The arrangement of straight lines within the 12-point polygon reveals the annual variation pattern and allows for location-specific qualitative interpretations. Each side of the polygon assumes a linear transition between months. Applying this linearity assumption to shorter periods enhances the accuracy of trend analyses. If the slopes of all connecting lines are similar and the polygon edges align in a consistent direction, the resulting polygon resembles a narrow band close to a global regression line. This indicates uniform, isotropic variation in the hydrometeorological variable. Conversely, wider polygons suggest greater temporal variability.

A polygon with a rising orientation generally suggests balanced hydro-climatic conditions. However, the appearance of multiple polygons or internal loops may occur under certain circumstances, reflecting dynamic and complex variability. Horizontal intersections with the polygon represent the expected range of monthly variations, whereas vertical intersections indicate the magnitude and limits of hydrometeorological quantities. A smaller polygon area reflects consistent monthly precipitation and stable hydrological events, while a reduced overall slope from the horizontal axis indicates higher-intensity hydrometeorological phenomena. Ultimately, the IPTA model serves as a valuable tool in water resource planning, operation, and management, enabling systematic evaluation of both quantitative and qualitative properties of hydrometeorological dynamics.

3. Results and discussion

3.1. Serial correlation analysis

Before applying the MK and SR tests to detect trends in the groundwater time series, it was necessary to assess the presence of serial autocorrelation in the data. To this end, lag-1 autocorrelation coefficients (r_1) were calculated and evaluated for statistical significance under the null hypothesis at the 95% confidence level using a two-tailed test: $r_1 = \pm \frac{1.96}{\sqrt{N}}$.

The autocorrelation coefficients for the monthly groundwater level data across various provinces were computed, with the results summarized in Table 2. The analysis revealed that all calculated serial correlation coefficients remained below their respective critical thresholds. This indicates that the monthly groundwater level time series do not exhibit significant serial dependence. Consequently, the MK and SR trend tests were applied directly to the full datasets without

Table 2. Lag-1 autocorrelation coefficients for monthly groundwater level data across the provinces

Province	January	February	March	April	May	June	July	August	September	October	November	December	Annual
Turtkul ^a	-0.1159	-0.0659	-0.0156	0	-0.0179	-0.0109	-0.0021	0	-0.0672	-0.1841	-0.2289	-0.0858	-0.1616
Ellikkala ^a	-0.0149	-0.0286	-0.012	-0.0085	0	-0.0023	-0.0077	-0.0064	-0.0004	-0.0036	-0.01	-0.0049	0.0142
Beruniy ^a	-0.0409	-0.0004	-0.0565	-0.0015	-0.0264	-0.0138	-0.0231	-0.031	-0.0003	-0.0299	-0.0699	-0.0093	0.0027
Amudary ^a	-0.0097	-0.0021	-0.065	-0.0077	-0.0097	-0.0112	-0.0384	-0.0083	-0.0677	-0.1345	-0.1069	-0.0471	-0.021
Khojeli ^a	-0.0006	-0.0057	-0.0636	-0.0692	-0.0064	-0.0026	-0.0027	-0.0044	-0.027	-0.0516	-0.0394	-0.0004	0.0065
Takhtiatash ^b	0.1328	0.0138	0.0232	0.07	-0.0141	-0.049	-0.047	-0.0464	-0.0009	-0.0506	-0.117	0.0246	-0.108
Shumanay ^a	-0.0018	-0.005	-0.0121	-0.0376	-0.0438	-0.0172	-0.0199	-0.015	-0.0032	-0.0021	-0.0012	-0.0196	0.0081
Kanlikul ^a	-0.0004	-0.0005	-0.0105	-0.0118	-0.0094	-0.0063	-0.0034	-0.0032	-0.0002	0	0	-0.0001	0.0033
Kunjirot ^a	-0.0008	-0.0023	-0.0105	-0.012	-0.0051	-0.006	-0.001	-0.0021	-0.0004	-0.0006	-0.0011	-0.0007	0.01
Muynak ^a	-0.0738	-0.075	-0.0884	-0.0963	-0.0877	-0.0918	-0.0908	-0.0813	-0.0529	-0.051	-0.0458	-0.0568	-0.0629
Nukus ^a	-0.0825	-0.0983	-0.2219	-0.0108	-0.088	-0.0097	-0.0104	-0.001	-0.0928	-0.0559	-0.0345	-0.0082	-0.0029
Kegyli ^a	-0.0032	-0.0055	-0.0197	-0.0291	-0.023	-0.021	-0.0279	-0.0282	-0.0213	-0.0106	-0.0102	-0.0253	-0.013
Buzatau ^c	-0.0011	-0.0001	-0.0005	-0.0009	-0.007	-0.006	-0.0089	-0.009	-0.0129	-0.0003	0.3484	0.0481	-0.0059
Chimbay ^a	-0.0004	-0.0002	-0.0251	-0.0143	-0.0054	-0.0039	-0.0061	-0.0114	-0.0004	-0.002	0	-0.0202	0.0178
Karauzyak ^a	-0.0026	-0.0075	-0.0165	-0.0137	-0.0112	-0.0011	-0.0073	-0.007	0	0	-0.0052	-0.0292	0.0068
Takhtakopir ^a	-0.012	-0.0131	-0.0034	-0.0028	-0.0001	0	0	-0.0025	-0.0063	-0.0076	-0.0086	-0.0089	-0.0004
Total ^a	-0.0004	-0.0036	-0.0325	-0.0233	-0.0196	-0.011	-0.0176	-0.0134	-0.0008	-0.0001	0	-0.0082	0.011

Notes: ^aCritical autocorrelation coefficient is 0.336; ^bCritical autocorrelation coefficient is 0.800; ^cCritical autocorrelation coefficient is 0.475.

requiring pre-whitening or other adjustments, given the absence of serial correlation that might otherwise bias the results.

3.2. Trend analysis results

3.2.1. MK test

The MK test results presented in Table 3 and Table S1 provide a comprehensive analysis of monthly and annual groundwater level trends across various provinces and the Republic of Karakalpakstan, Uzbekistan. These results reveal significant spatial and temporal variations, highlighting both consistent patterns and local anomalies.

In Turtkul Province (Table 3), the MK test reveals predominantly stable groundwater levels with no significant annual trend. However, statistically significant decreasing trends are observed in January ($Z=-2.270$, $p=0.023$) and February ($Z=-1.973$, $p=0.048$), reflecting a reduction in groundwater levels during the winter months. Conversely, a significant increasing trend in August ($Z=2.261$, $p=0.024$) suggests a localized summer increase in groundwater levels. In Ellikkala Province, the annual trend is not statistically significant. However, the monthly analysis indicates strong increasing trends from April ($Z=4.065$, $p<0.001$) through September, with the most pronounced change occurring in April. This seasonal pattern suggests a consistent rise in groundwater levels during the warmer months, likely influenced by regional hydrological or climatic conditions.

The results for Beruniy Province (Table S1) highlight a significant annual increase ($Z=2.906$, $p=0.004$), with monthly increases from April to November, with the strongest monthly trend in May ($Z=4.033$, $p<0.001$), indicating favorable seasonal recharge. Similarly, Amudarya Province (Table S1) displays a significant positive annual trend ($Z=2.906$, $p=0.004$), with monthly increases from April to November, mirroring the seasonal pattern observed in Beruniy and suggesting similar hydrological influences. In Khojeli Province, no significant annual trend is observed. However, significant monthly increases are observed in April, May, and August, reflecting seasonal groundwater variability. Takhiatash Province shows no significant trends annually or in most months, except for a notable increase in November ($Z=-2.205$, $p=0.027$), which suggests a late-autumn increase in groundwater levels. For Shumanay Province, both the annual trend ($Z=3.158$, $p=0.002$) and monthly trends are significantly positive, with consistent increases observed across nearly all months except November,

indicating a general rise in groundwater levels throughout the year. Kanlikul Province also exhibits a significant annual increase ($Z=2.595$, $p=0.009$), with monthly increases from April to November, peaking in May ($Z=3.651$, $p<0.001$), again indicating seasonal recharge. In Kungirov Province, a significant annual increase ($Z=2.846$, $p=0.004$) is observed, supported by increasing trends from April to October, with the strongest trend in May ($Z=3.499$, $p<0.001$), further underscoring seasonal patterns. Muynak Province exhibits one of the strongest trends, with a highly significant annual increase ($Z=3.884$, $p<0.001$) and consistent monthly rises throughout the year. In Nukus Province, the annual trend is not significant; however, May shows a significant increase ($Z=2.047$, $p=0.041$), whereas other months do not. Kegeyli Province shows a significant annual increase ($Z=2.668$, $p=0.008$), with monthly trends indicating widespread increases from May to September, consistent with seasonal recharge. In Buzatau Province, both annual ($Z=2.879$, $p=0.004$) and monthly trends are positive, with May showing the strongest increases ($Z=3.106$, $p=0.002$). Chimbay Province exhibits significant positive trends annually ($Z=3.172$, $p=0.002$) and monthly, especially in April ($Z=3.619$, $p<0.001$), indicating year-round groundwater level rises. Karauzyak Province also demonstrates significant positive annual ($Z=3.172$, $p=0.002$) and monthly trends, with particularly strong increases from March to October, peaking in May ($Z=3.324$, $p<0.001$). In Takhtakopir Province, a significant annual trend ($Z=2.254$, $p=0.024$) is observed, with significant monthly increases in May and September, suggesting localized seasonal variations. Finally, for the Republic of Karakalpakstan, which aggregates data from all provinces, a significant positive annual trend ($Z=3.603$, $p<0.001$) is evident. Monthly trends highlight widespread increases, with the strongest trends from April to August aligning with the seasonal patterns observed at the provincial level. Generally, the MK test results across the province-level seasonal patterns.

In summary, the MK test results indicate varied groundwater trends across provinces. While some show no annual trend, most exhibit clear seasonal increases during the warmer months. These findings underscore the importance of implementing localized and seasonally adaptive groundwater management strategies in response to these temporal and spatial patterns.

3.2.2. IPTA test

Insights derived from Tables 4 and S2, along with Figures 2 and S1, reveal detailed hydrometeorological

Table 3. Mann–Kendall test for groundwater levels in Turtkul and Elikkala provinces

Province	Statistical parameter	January	February	March	April	May	June	July	August	September	October	November	December	Annual
Turtkul	<i>n</i>	34	34	34	34	34	34	34	34	34	34	33	33	34
Province	Alpha	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
	MK state	-154	-134	-108	2	-16	43	43	153	49	-69	-97	-110	-104
Elikkala	S.E.	67.407	67.407	67.406	67.364	67.027	67.339	67.339	67.233	67.341	67.387	64.444	64.467	67.453
	Z-test	-2.270	-1.973	-1.587	0.015	-0.224	0.624	0.624	2.261	0.713	-1.009	-1.490	-1.691	-1.527
Province	<i>p</i> -value	0.023	0.048	0.112	0.988	0.823	0.533	0.533	0.024	0.476	0.313	0.136	0.091	0.1268
	Trend	Yes	Yes	No	No	No	No	No	Yes	No	No	No	No	No
Elikkala	<i>n</i>	34	34	34	34	34	34	34	34	34	34	33	33	34
	Alpha	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Province	MK state	-80	-53	4	275	243	223	239	270	247	141	53	22	105
	S.E.	67.407	67.434	67.445	67.403	67.403	67.403	67.387	67.407	67.387	67.281	64.444	64.514	67.422
Province	Z-test	-1.172	-0.771	0.044	4.065	3.590	3.294	3.532	3.991	3.651	2.081	0.807	0.326	1.543
	<i>p</i> -value	0.241	0.441	0.965	0.000	0.000	0.001	0.000	0.000	0.000	0.037	0.420	0.745	0.123
Province	Trend	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No

Notes: *n*: Sample size; α : Significance level; MK state: Mann–Kendall test statistic; S.E.: Standard error; Z-test: Standardized test statistic; *p*-value: Probability value for significance; Trend: “Yes” indicates statistically significant trend at $\alpha=0.05$.

Table 4. Monthly innovative polygon trend analysis statistical metrics (arithmetic mean and standard deviation) for Turtkul Province

Index	Section	Months											
		January	February	March	April	May	June	July	August	September	October	November	December
Mean	1 st half	236.6	234.1	205.5	174.4	182.4	181.5	172.5	166.7	178.5	199.6	214.0	228.5
	2 nd half	216.1	213.8	189.0	170.7	177.9	180.5	174.9	172.6	178.1	189.6	200.8	214.4
SD	1 st half	26.1	25.1	24.1	14.9	16.4	16.4	16.4	17.4	20.5	23.9	27.5	25.2
	2 nd half	31.7	32.4	22.4	10.9	8.6	10.4	12.3	14.8	17.8	21.2	20.5	24.1
Index	Metric	January–February	February–March	March–April	April–May	May–June	June–July	July–August	August–September	September–October	October–November	November–December	December–January
Mean	Trend length	28.9	26.2	17.0	5.8	4.6	2.6	6.3	5.9	10.0	16.5	19.3	24.9
	Trend slope	0.9	0.9	0.6	0.9	-3.2	0.6	0.4	0.5	0.5	0.8	0.9	0.2
SD	Trend length	9.2	7.5	4.3	8.8	9.8	7.2	4.8	3.7	3.8	7.4	7.0	5.7
	Trend slope	-0.6	10.4	1.2	-1.5	-98.0	127.1	2.4	1.0	1.0	-0.2	-1.6	8.4

Note: SD: Standard deviation.

patterns for each province in the Republic of Karakalpakstan, Uzbekistan, enriched by specific numerical and graphical representations.

In Turtkul Province (Table S2 and Figure S1), groundwater levels exhibit clear seasonal patterns, with mean values decreasing from 236.6 mm in January to a minimum of 166.7 mm in August, followed by a recovery to 214.4 mm in December. The SD peaks in February (32.4 mm), indicating considerable variability during the winter months. The narrow IPTA polygon reflects consistent monthly trends, suggesting relatively stable hydrometeorological conditions. Minimal variability during summer months reflects reduced groundwater recharge. Ellikkala province demonstrates a steady rise in groundwater levels over the year, with mean values increasing from 246 mm in January to 247.6 mm in December. Seasonal variability is evident, with the SD peaking at 57 mm in February and March, indicating significant temporal fluctuations. The IPTA polygon is broader from July to October, reflecting hydrologically active periods influenced by regional climatic factors. In Beruniy Province, groundwater levels increase significantly throughout the year, with the mean rising from 192.5 mm in January to 207.5 mm in December. The wettest months, particularly May and July, indicate strong seasonal recharge. The highest SD occurs in January (42.4 mm). The elongated IPTA polygon with steep slopes highlights pronounced seasonal dynamics. Amudarya Province shows a steady annual increase in groundwater levels from 174.1 mm in January to 191.5 mm in December. The SD peaks in January (41.9 mm) and decreases during spring, suggesting reduced variability during drier months. The IPTA polygon alternates between narrow and broad sections, indicating general stability interspersed with episodes of significant temporal variability. In Khojeli Province, groundwater levels rise from 185.4 mm in January to 228.4 mm in November. Variability is highest in January (SD=48.1 mm), decreasing through summer. The symmetrical IPTA polygon suggests predictable seasonal variations and stable hydrometeorological patterns. Takhiatash Province begins the year with lower groundwater levels (154 mm in January), rising to 224.3 mm in November. The SD peaks in December (22.0 mm), indicating greater end-of-year variability. The narrow IPTA polygon reflects uniform temporal changes and a stable annual pattern with limited fluctuations. Shumanay Province records high groundwater levels year-round, increasing from 220.1 mm in January to 257.2 mm in November. Seasonal variability decreases significantly in the latter half of the year, with the

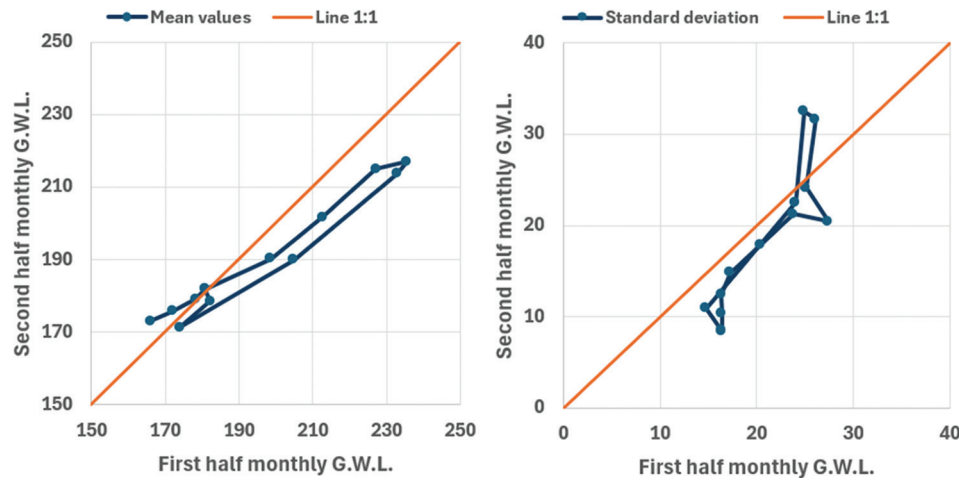


Figure 2. Innovative polygon trend analysis graph: Groundwater level (G.W.L.) records for Turtkul Province

lowest SD in July (40.0 mm). The IPTA polygon, with steep slopes, reflects strong month-to-month variability during recharge periods. Kanlikul province exhibits a rising trend, with mean groundwater levels increasing from 220.1 mm in January to 257.2 mm in November. The IPTA polygons vary in slope and length, indicating significant temporal changes during wetter periods. Variability decreases significantly during the second half of the year. Kungiroi Province experiences an annual increase in groundwater levels, from 134 mm in January to 215 mm in December. The SD peaks in January (67.4 mm), highlighting substantial winter variability. Moderate broad IPTA polygons reflect balanced seasonal change with pronounced recharge phases. Muynak Province exhibits the highest seasonal variability, with groundwater levels rising sharply from 244.8 mm in January to 271.5 mm in December. Variability is highest in January (SD=78.6 mm), signifying substantial temporal heterogeneity. Broad IPTA polygons represent strong inter-month differences, particularly during peak wet periods. Nukus Province shows relatively stable groundwater levels, with a notable increase in May (139 mm). The highest SD is recorded in January (67.4 mm). The narrow IPTA polygons reflect consistent hydrometeorological conditions with minimal monthly variability. Kegeyli Province saw groundwater levels rise from 152 mm in January to 186 mm in November. January again shows the highest variability (SD=67.4 mm). Steep IPTA polygon slopes indicate substantial seasonal variability, likely driven by pronounced recharge during wetter months. Buzatau Province displays a gradual increase in groundwater levels from 53.0 mm in January to 77 mm in December. SD remains relatively stable. The

IPTA polygons alternate between narrow and broad, reflecting intermittent heterogeneity and steady seasonal recharge. Chimbay Province shows a consistent increase in groundwater levels from spring to autumn, with values rising from 134 mm in January to 215 mm in December. The moderately broad IPTA polygons suggest well-balanced seasonal changes and a continuous upward trend. Karauzyak Province demonstrates a sharp increase in groundwater levels, from 136 mm in January to 215 mm in December. The peak SD in January (67.4 mm) signals significant variability during colder months. The broad IPTA polygons highlight intense seasonal variability during peak recharge periods. Takhtakopir Province maintains stable groundwater levels throughout the year, increasing from 97 mm in January to 153 mm in December. Low SD values across all months and narrow IPTA polygons reflect uniform temporal patterns with limited month-to-month differences. Finally, the aggregated data for the Republic of Karakalpakstan reflect significant increases in groundwater levels during wetter months, with a regional peak of 291 mm in July. The broader IPTA polygons capture the diverse climatic and hydrological influences across the provinces. These patterns underscore the importance of comprehensive water resource management strategies to address seasonal variability and ensure sustainable groundwater use.

3.2.3. SR correlation test

The SR trend analysis across different provinces of the Republic of Karakalpakstan, Uzbekistan, highlights significant spatial and temporal variations in groundwater level trends.

In Turtkul province (Table 5), most months exhibit no statistically significant trends, with the exception

Table 5. Outcomes of Spearman's rank correlation trend analysis for Turtkul province

Month	r_s	Trend	t -static	t -distribution	Significance
January	-0.33	Decreasing	-1.98	2.04	Not significant
February	-0.305	Decreasing	-1.81	2.04	Not significant
March	-0.253	Decreasing	-1.48	2.04	Not significant
April	0.013	Increasing	0.08	2.04	Not significant
May	-0.04	Decreasing	-0.23	2.04	Not significant
June	0.086	Increasing	0.49	2.04	Not significant
July	0.313	Increasing	1.87	2.04	Not significant
August	0.385	Increasing	2.36	2.04	Significant
September	0.117	Increasing	0.67	2.04	Not significant
October	-0.132	Decreasing	-0.75	2.04	Not significant
November	-0.163	Decreasing	-0.94	2.04	Not significant
December	-0.22	Decreasing	-1.28	2.04	Not significant

Note: r_s : Spearman's rank correlation coefficient.

of August, which shows a significant increasing trend. This suggests a seasonal increase in groundwater levels, potentially driven by recharge from precipitation or irrigation activities.

In Ellikkala Province (Table S3), no significant trends are observed in the early months. However, a clear increasing trend emerges from April to August, indicating a shift in groundwater availability during the warmer months. Beruniy Province exhibits statistically significant positive trends from March through September, suggesting a steady increase in groundwater levels, which may be attributed to enhanced recharge or reduced extraction. Similarly, Amudarya Province demonstrates significant upward trends from April to November, emphasizing the influence of seasonal variations on groundwater storage. In Khojeli Province, notable increasing trends are recorded from April to September, reinforcing the role of seasonal recharge. Conversely, Takhiatash Province presents a mixed pattern, with some months – such as March and April – showing decreasing trends. These declines may reflect excessive extraction or climatic influences that limit recharge. Shumanay Province shows statistically significant increasing trends in nearly all months except November, indicating a consistent year-round rise in groundwater levels. In Kanlikul Province, significant increasing trends are observed in the summer months, while the early spring months show no clear trend, possibly suggesting a delayed or gradual recharge onset. Kungirov Province demonstrates steady increases in groundwater levels, particularly between March and October, whereas Nukus Province reveals notable

increases during summer and autumn, likely reflecting a dependency on seasonal hydrological inputs. Kegeyli Province exhibits increasing trends from February to December, emphasizing a prolonged period of groundwater accumulation, potentially due to improved water conservation strategies. In Buzatau Province, strong increasing trends are observed throughout the year, particularly in the summer months, which may result from surface water recharge or changes in groundwater management practices. Chimbay Province also exhibits a steady rise in groundwater levels, aligning with trends observed in adjacent regions. Both Karauzyak and Takhtakopir Provinces exhibit consistent and statistically significant increasing trends across most months, further highlighting the overall positive trajectory of groundwater levels. At the national level, the Republic of Karakalpakstan demonstrates a dominant pattern of increasing groundwater levels throughout the year, with the most significant trends observed in the summer months. This widespread upward trend likely reflects a combination of improved water management practices, favorable climatic conditions promoting groundwater storage, and possibly decreased abstraction rates.

In summary, the SR trend analysis confirms a general increase in groundwater levels across the region, although localized and seasonal variations exist. These findings highlight the importance of monitoring groundwater resources continuously to ensure sustainable water management and mitigate potential risks associated with groundwater depletion in certain provinces where decreasing trends were noted.

3.3. Sustainability implications of the findings

Agriculture remains one of the primary livelihoods in Uzbekistan; however, it is increasingly threatened by the impact of climate change.⁴⁹⁻⁵¹ Therefore, the country must develop and implement effective adaptation strategies to ensure food security and enhance its economic resilience. The observed trend – both increasing and decreasing – in groundwater levels presents a complex challenge for agriculture, as water availability directly influences crop productivity and irrigation planning. These variations complicate the formulation of sustainable adaptation measures in response to a changing climate. The findings of the present study provide valuable insights that can support the development of region-specific adaptation strategies for future climatic challenges.

The rising groundwater levels observed in several provinces suggest a potential improvement in water availability. However, seasonal fluctuations and localized areas of groundwater stability or decline highlight the need for targeted interventions and adaptive water governance. These groundwater trends directly impact agricultural productivity. Therefore, continuous monitoring of groundwater levels, combined with data-informed irrigation strategies, can play a crucial role in enhancing crop resilience and ensuring food security.

Previous studies have already demonstrated that climate change has significantly impacted water availability in Uzbekistan.^{52,53} Understanding the spatial and temporal patterns of groundwater trends is, therefore, essential for long-term resource planning. The application of non-parametric trend analysis methods – namely the MK test, SR test, and IPTA – demonstrates how scientific approaches can inform climate adaptation efforts and ensure that groundwater resource management evolves in line with environmental change.

4. Conclusion

Groundwater resources are vital for sustaining arid and semi-arid regions, yet they are subject to variability driven by complex climatic and environmental factors. This study employed a robust multi-method trend analysis framework – integrating the MK test, SR test, and IPTA – to evaluate long-term groundwater trends across the Republic of Karakalpakstan, Uzbekistan.

Results from the MK test reveal that nine out of 14 provinces exhibit significant increasing trends in groundwater levels, with Muynak Province showing the strongest upward trend ($Z=3.884$, $p<0.001$). At

the national level, the analysis confirms an overall groundwater increase ($Z=3.603$, $p<0.001$). Several provinces, such as Beruniy ($Z=2.906$, $p=0.004$), Amudarya ($Z=2.906$, $p=0.004$), and Chimbay ($Z=3.172$, $p=0.002$), show consistent groundwater rise, especially during the warmer months. In contrast, provinces such as Turtkul, Ellikkala, and Nukus exhibit no statistically significant trends, indicating localized groundwater stability.

The IPTA method provides deeper insights into seasonal dynamics, identifying months with significant increases (e.g., April – May) and decreases (e.g., May – June). These seasonal variations suggest that, despite the overall positive trend, groundwater recharge dynamics fluctuate depending on climatic conditions and water usage patterns.

These findings carry important policy implications. Provinces experiencing rising groundwater levels may benefit from improved water retention and hydrological balance, while those showing neutral trends warrant further investigation into potential contributing factors, such as groundwater extraction, irrigation intensity, or climate anomalies. The study underscores the importance of adaptive and region-specific groundwater management strategies to ensure sustainable use of water resources in response to both seasonal and long-term climatic variability. Future research should focus on evaluating the influence of anthropogenic activities – such as land use change and over-extraction – and integrate hydrological modeling to improve water resource planning and resilience in climate-sensitive regions.

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Availability of data

Data are available from the corresponding author upon reasonable request.

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