Article

Assessment of Groundwater Level Trends Using Mann–Kendall Test, Sen's Slope Estimator, and GIS Mapping in the Bandikhan District, Surkhandarya, Uzbekistan

Gafurov Zafar [1], Samiev Luqmon [2,5], Eshboyev Navruz *[1,5], Nosirov Nozimbek [3], Doniyorova Kholniso [4]

1 International Water Management Institute, Tashkent, 100070, Uzbekistan
2 Research Institute of Environmental and Nature Protection Technologies, Tashkent, 100000, Uzbekistan
3 National Committee on Ecology and Climate Change of the Republic of Uzbekistan, Tashkent, 100000, Uzbekistan
4 Research Institute of Environment and Nature Conservation Technologies, Central Asian University of Environmental and Climate Change Studies, Tashkent, 100000, Uzbekistan
5 Tashkent Institute of Irrigation and Agricultural Mechanization Engineers National Research University, Tashkent, 100000, Uzbekistan

Z.Gafurov@cgiar.org (G.Z.), luqmonsamiev@mail.ru, samievluqmon@gmail.com (S.L.), N.Eshboev@cgiar.org (E.N.), n.nosirov513@gmail.com (N.N.), xolisxon19930426@gmail.com (D.Kh.)

* Correspondence: N.Eshboev@cgiar.org; Tel.: +998 99 9561326 (E.N.)

Abstract: Water security is a critical concern in the Bandikhan district of Surkhandarya, Uzbekistan, where agriculture predominantly relies on groundwater resources. This study assesses the spatial and temporal trends of groundwater levels during both vegetation (April–September) and non-vegetation (October–March) periods from 2018 to 2023. Data from 63 observation wells were analyzed using the Mann–Kendall trend test, Sen's slope estimator, and linear regression methods. Geographic Information System (GIS) tools were employed to map the spatial distribution of groundwater level changes. The results indicated that the average depth to groundwater during the vegetation period ranged from 1.06 m to 5.84 m, with a mean fluctuation of 2.45 m. During the non-vegetation period, depths ranged from 1.04 m to 5.68 m, with a mean fluctuation of 1.04 m. Significant trends were observed in the groundwater levels. Sen's slope estimates varied from –0.26 to +0.34 m/year, indicating both rising and declining groundwater levels across the district. The average rate of decline was found to be 0.22 m/year, with a standard deviation of 0.07 m/year. These findings highlight the overexploitation of groundwater resources in certain areas due to intensive agricultural practices, leading to declining water tables. Conversely, some areas exhibited rising groundwater levels, possibly due to irrigation return flows or inadequate drainage systems. The study underscores the need for sustainable groundwater management, including the implementation of advanced irrigation techniques and the promotion of crops requiring less water. The results provide valuable insights for planners and decision-makers to develop effective land use and water resource management strategies, ensuring the long-term sustainability of groundwater resources in the Bandikhan district.

Keyword: Groundwater level dynamics; Mann–Kendall test; Sen's slope estimator; Linear regression; GIS; Irrigated lands; Water resource management; Statistical methods; Spatial analysis

Quoting: Gafurov Zafar, Samiev Luqmon, Eshboyev Navruz, Nosirov Nozimbek, Doniyorova Kholniso. Assessment of Groundwater Level Trends Using Mann–Kendall Test, Sen's Slope Estimator, and GIS Mapping in the Bandikhan District, Surkhandarya, Uzbekistan. **2026**, 4, 1, 1. https://doi.org/10.35938/jhee-2026-1-00001

Received: 10.04.2026
Corrected: 18.05.2026
Accepted: 25.05.2026
Published: 30.06.2026

Introduction

Groundwater is an indispensable resource for agricultural activities, particularly in arid and semi-arid regions where surface water sources are scarce or unreliable [1]. In Uzbekistan's Bandikhan district within the Surkhandarya region, agriculture is predominantly sustained through groundwater irrigation, underscoring the critical importance of effective groundwater management for maintaining local agricultural productivity and ensuring socio-economic stability [2]. However, escalating water demands driven by population growth and agricultural expansion have intensified groundwater extraction, leading to significant declines in groundwater levels and associated environmental and economic challenges [3]. Monitoring and analyzing groundwater level trends are fundamental for developing sustainable water resource management strategies [4]. Accurate trend analysis provides insights into the temporal and spatial dynamics of groundwater resources, enabling the identification of areas susceptible to overexploitation and informing policy decisions aimed at ensuring long-term water security [5]. Among the various statistical methodologies available, the non-parametric Mann-Kendall trend test and Sen's slope estimator are widely recognized for their robustness in handling non-normal data distributions and mitigating the influence of outliers in hydrological time series analysis [6]. Additionally, linear regression analysis complements these methods by providing straightforward estimates of the rate of change in groundwater levels over time [7]. The integration of these statistical techniques with Geographic Information Systems (GIS) significantly enhances the spatial analysis and visualization of groundwater level changes, facilitating more informed decision-making and targeted resource management [8]. GIS-based mapping enables the identification of spatial patterns and hotspots of groundwater depletion or recharge, which is essential for implementing localized management practices and mitigating the adverse effects of groundwater overextraction [9].

Extensive research globally has applied these methodologies to assess groundwater trends in diverse regions. For instance, Islam, Rahman, and Rashid (2021) conducted a trend analysis of groundwater levels in an irrigated area of Bangladesh using the Mann-Kendall test and Sen's slope estimator, coupled with GIS mapping, which revealed significant declining trends attributed to intensive irrigation practices. Similarly, Bozkurt and Balaban (2019) examined groundwater level trends in Turkey's Konya Closed Basin, identifying substantial decreases driven by agricultural demands and insufficient natural recharge. In western Odisha, India, Ahmed and Panda (2020) utilized non-parametric tests and GIS to analyze groundwater trends, uncovering declining levels due to overextraction for irrigation purposes.

Further studies highlight the widespread application of these techniques across various geographical contexts. Goyal et al. (2018) applied the Mann-Kendall test in north-western Rajasthan, India, revealing significant downward trends linked to agricultural activities and inadequate recharge. Pandey and Singh (2019) employed statistical and artificial neural network techniques to forecast groundwater levels in Jharkhand State, emphasizing the necessity of sustainable management practices to counteract declining trends. In Gujarat, India, Ghosh and Sharma (2019) analyzed groundwater level trends and variability, finding significant declines resulting from excessive withdrawal for agricultural use.

In the Chinese context, Wu et al. (2020) performed a spatiotemporal analysis of groundwater level trends in the Hebei Plain using non-parametric statistical tests and GIS, discovering that intensive agricultural water use led to significant groundwater declines. Similarly, Zhang, Wang, and Chen (2021) conducted a GIS-based groundwater level trend analysis in the North China Plain, identifying critical areas of groundwater depletion that require immediate management interventions. Moghaddam, Mirhosseini, and Soltani (2018) analyzed groundwater level trends in Iran's Urmia Lake Basin using non-parametric methods and GIS, finding significant declines associated with both agricultural and domestic water use.

In Africa, Omonona et al. (2020) investigated groundwater level dynamics in Lagos, Nigeria, utilizing statistical and GIS techniques, and observed declining trends driven by urbanization and overextraction. Ali et al. (2021) evaluated groundwater level changes in the Nile Delta Aquifer, Egypt, using statistical methods and GIS, identifying significant declines linked to agricultural practices and population growth. In Brazil's semiarid region, Silva et al. (2020) applied the Mann-Kendall test and Sen's slope estimator to analyze groundwater level trends, finding decreasing trends due to prolonged droughts and overuse. Reddy et al. (2020) assessed groundwater level trends and spatial variability in a semi-arid region of South India using GIS, highlighting the impact of irrigation and climatic factors on groundwater depletion.

Additional studies further corroborate the global applicability and importance of these methodologies. Singh et al. (2018) applied the Mann-Kendall test and Sen's slope estimates for groundwater level trend analysis in Jharkhand State, India, demonstrating significant downward trends due to overextraction. Jha et al. (2020) conducted trend analysis of groundwater levels using non-parametric tests and GIS in a canal command area of eastern India, revealing spatial variations in groundwater depletion. Abdalla and Al-Rawabdeh (2021) examined groundwater level trends in the Azraq

Basin, Jordan, using the Mann-Kendall test, Sen's slope estimator, and GIS techniques, identifying significant declines attributable to agricultural and climatic factors.

Moreover, regional studies such as those by Brindha and Elango (2018) on coastal aquifers, Thakuri et al. (2019) on the central Himalayas, and Ma et al. (2020) on China's Loess Plateau further emphasize the critical role of groundwater trend analysis in diverse environmental contexts. These studies collectively highlight the necessity of integrating robust statistical methods with advanced GIS technologies to effectively monitor and manage groundwater resources.

Despite the extensive global focus on groundwater trend analysis, there is a noticeable gap in research specifically targeting Central Asian regions like Uzbekistan, particularly the Bandikhan district. Given the region's reliance on groundwater for irrigation and the challenges posed by its arid climate, it is imperative to conduct comprehensive studies to understand the temporal and spatial dynamics of groundwater levels. Such studies are essential for informing sustainable management practices that can mitigate the adverse effects of overextraction and ensure the long-term viability of groundwater resources.

Materials and Methods

Objectives of the study

This study aims to:

1. Analyze the temporal trends of groundwater levels in the irrigated lands of the Bandikhan district using the Mann-Kendall trend test, Sen's slope estimator, and linear regression analysis.

2. Map the spatial distribution of groundwater level changes utilizing GIS to identify areas of significant decline or recharge.

3. Provide insights and recommendations for sustainable groundwater management in the region based on the findings.

By achieving these objectives, the research will contribute to the understanding of groundwater trends in arid and semi-arid regions and support the development of effective water resource management strategies in the Bandikhan district.

Study Area

Bandikhon is a district located in the central part of Surkhandarya region. Geographically, the Bandikhan district is positioned between 37°30'N and 38°00'N latitudes and 67°10'E and 67°30'E longitudes. The district covers an area of approximately 0.20 thousand square kilometers and is bordered by the neighboring districts Kumkurgan, Kyzyrik, Jarkurgan, Sherabad, Boysun. Bandikhan is situated in the southern part of Uzbekistan, close to the country's border, and is characterized by its agricultural significance within the Surkhandarya region, being one of the small districts of Surkhandarya region (Figure 1). The economy is agrarian.

Topography and hydrography

The terrain of Bandikhan district is largely flat with some gentle undulations, and elevations range from 410 to 503 meters above sea level. The district is part of an irrigated agricultural zone, with surface water bodies such as Bandikhansoy, P-1, P-2, Urlugsoy, Dustlik, Oqqopchigay canals, contributing to groundwater recharge. The area's irrigation infrastructure plays a critical role in supporting local agriculture.

Climate

Bandikhan district experiences a semi-arid climate, with hot summers and mild winters. Temperatures range from 2.5-31 °C, with the warmest months typically from June to August (Figure 2). This climatic variability impacts the availability and recharge of groundwater resources.

The average annual precipitation varies from 160 to 200 mm (Figure 3), which mainly occurs during the spring and winter months.

Agriculture

Bandikhan district is predominantly agricultural, with key crops including cotton, wheat, or viticulture. The total irrigated area is approximately 17267 hectars, with irrigated cropland making up 72 % of the district's land fund. Traditional and modern irrigation techniques, such as drip irrigation, flood irrigation, are used to sustain crop production.

Land use/land cover

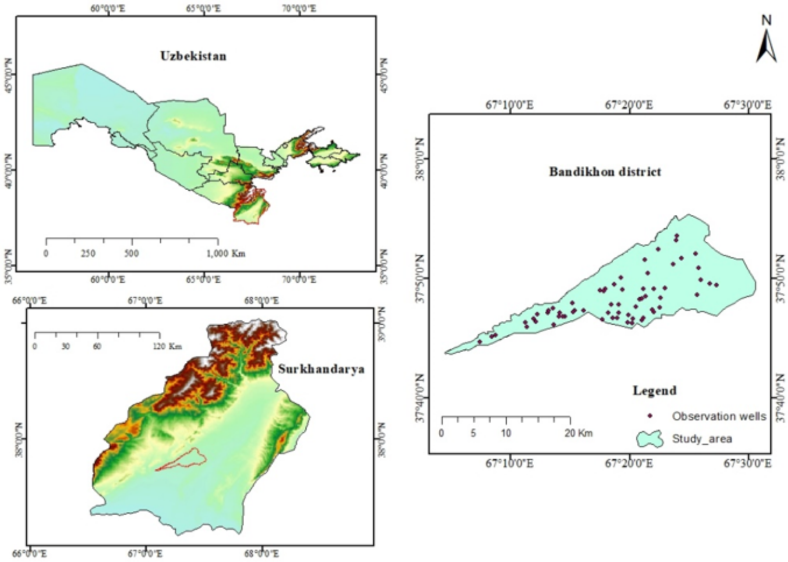


Figure 1. Map of the study area

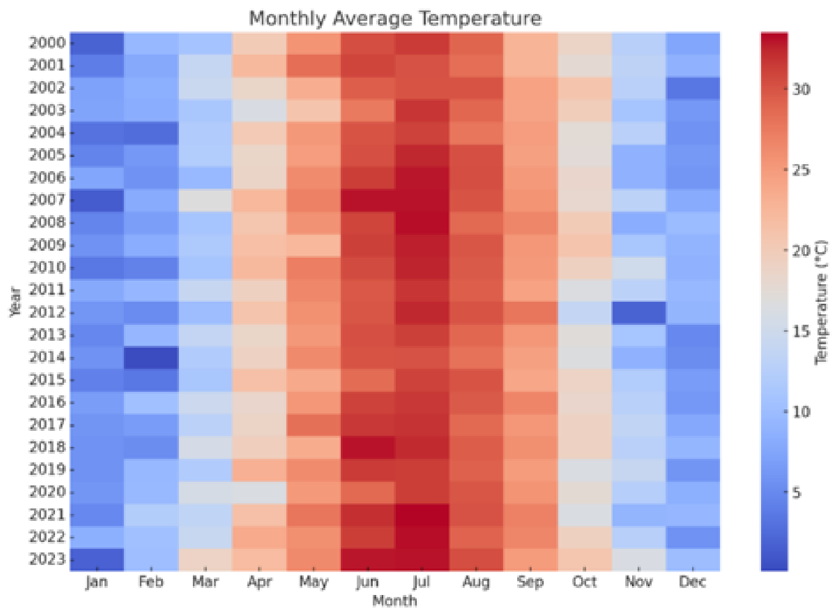


Figure 2. Average temperature of research area in long-term

The Bandikhan district, located in the Surkhandarya region of Uzbekistan, exhibits a diverse range of land use and land cover types, as shown in the map (Figure **??**). Below is a detailed description of the major land use categories observed in the district:

Land use and land cover (LULC) classification plays a key role in understanding groundwater dynamics in the Bandikhan district. Different land types influence groundwater recharge, extraction, and sustainability in various ways:

• Cropland (72.22 %) impacts groundwater significantly, as irrigation demands are high, potentially lowering groundwater levels. However, efficient irrigation can support recharge.

• Grassland (11.52 %) and shrubland (3.99 %) areas typically allow more natural groundwater recharge, as they experience less human intervention.

• Built-up areas (6.11 %) with impervious surfaces reduce water infiltration, limiting groundwater recharge and increasing runoff.

• Tree cover (0.23 %) and vegetative areas help retain water, promoting infiltration and recharge, while bare/sparse vegetation (5.68 %) is more prone to erosion and limits recharge.

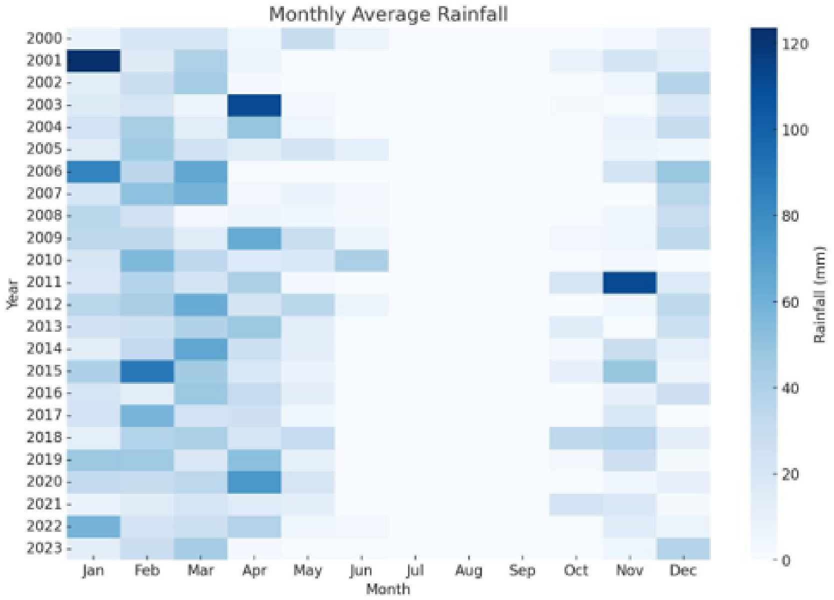


Figure 3. Total precipitation of research area in long-term

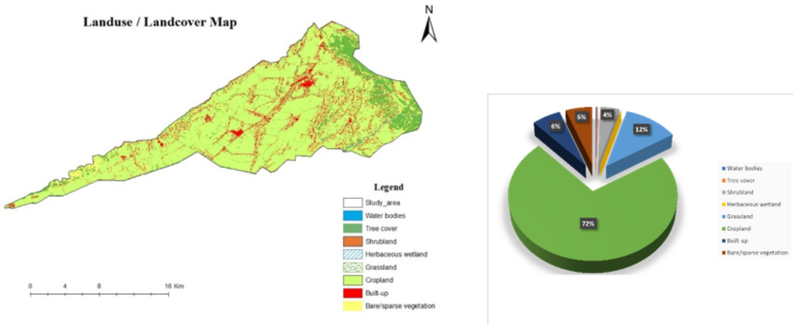


Figure 4. Land Use / Land Cover map of Bandikhan district and the distribution of various land cover types

• Water bodies (0.24 %) contribute to groundwater recharge, while herbaceous wetlands (0.01 %) help retain water and gradually release it into aquifers.

Soil texture. The soil types within the Bandikhan district are distributed across different regions, each playing a significant role in agricultural productivity, water retention, and groundwater recharge (Figure **??**). The following soil classifications have been identified:

This table offers a clear summary of the soil types, their characteristics, and their influence on both agriculture and groundwater recharge in Bandikhan district.

2.2 Data Collection

Groundwater level data. The groundwater level data for the years 2018–2023 were obtained from the Surkhandarya Land Reclamation Expedition (SLRE), which operates under the Amu-Surkhan irrigation systems basin administration of the Ministry of Water Management of the Republic of Uzbekistan. SLRE regularly monitors groundwater levels in agricultural lands, recording data once every ten days using water level loggers. Although SLRE conducts monthly evaluations of groundwater levels, the data are not statistically processed or analyzed by the expedition itself. This study utilized primary data from more than 63 observation wells within the study area to analyze groundwater level changes during both vegetation and non-vegetation periods over the six-year period.

The locations of the studied wells are shown in Figure 1. Meteorological parameters such as precipitation and average air temperature in the studied area were analyzed using data from the Sherabad Meteorological Station. Precipitation and air temperature data of this station were collected from the Hydrometeorological Service Agency of Uzbekistan.

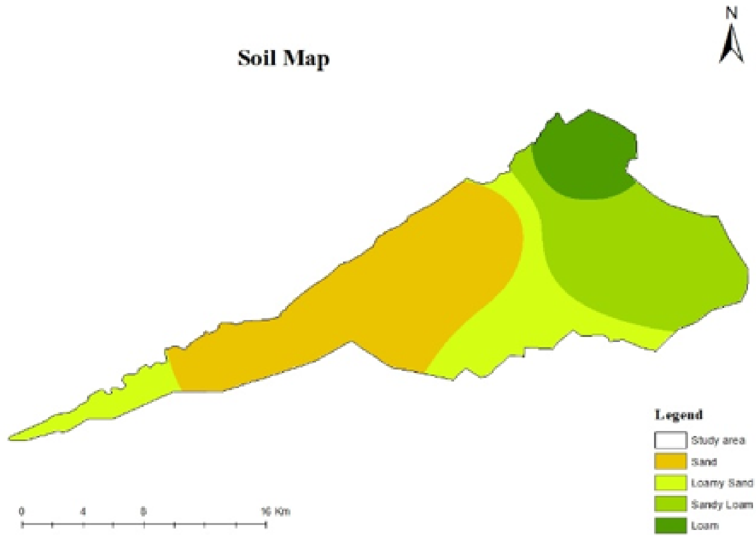


Figure 5. Soil map of Bandikhan district

2.3 Methods of Analysis

This study utilized the Mann-Kendall trend test, Sen's slope estimator, and linear regression to assess trends and quantify changes in groundwater levels. These methods were applied to estimate both the trend direction and the magnitude of change. Geostatistical analysis using Inverse Distance Weighting (IDW) interpolation was employed to analyze the spatial distribution of groundwater levels. A land use/land cover (LULC) map, generated from satellite data, was integrated with the groundwater level map to explore spatial trends in the study area.

2.3.1 Mann-Kendall test

The Mann-Kendall trend test for assessing the trend present in the data. Initially, this test was used by Mann (Beniston 2003) and Kendall [10] and subsequently derived the test statistics [11]. This hypothesis test is nonparametric, rank-based method for evaluating the presence of trends in time series data. The data are ranked according to time and then each data point is successively treated as a reference data point and is compared to all data points that follow in time. Compared with parametric statistical tests, nonparametric test is thought to be move suitable for nonnormally distributed data [12]. The Mann-Kendall test statistics is given by:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} (x_j - x_i) \tag{1}$$

where x_j and x_i are the sequential data values, n is the length of the data series, and $\text{sgn}(x_j - x_i)$ is the sign function, which is defined as:

$$\text{sgn}(\theta) = \begin{cases} +1, & \text{if } \theta > 0, \\ 0, & \text{if } \theta = 0, \\ -1, & \text{if } \theta < 0. \end{cases} \tag{2}$$

The Mann-Kendall test has two parameters that are of importance to the trend detection. These parameters are the significance level that indicated the trend's strength and the slope magnitude estimate which indicates the direction as well as the magnitude of the trend. For independent, identically distributed random variables with no tied data values, we have E(S) = O;

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

When some data values are tied, the correction to Var(S) is

Table 1. Soil Classification in Bandikhan District

Soil type	Location in District	Characteristics	Agricultural Suitability	Impact on Groundwater Recharge
Sand	Predominantly in the western region	Low water retention, low fertility, high permeability	Less suitable for intensive agriculture without management	High infiltration, supports groundwater recharge
Loamy Sand	Central areas	Moderate water retention, better fertility than sand	Moderately suitable for agriculture	Allows moderate water infiltration, contributing to recharge
Sandy Loam	Spread across various parts of the district	Balanced water retention and fertility, better than sandy soils	Highly suitable for agriculture	Supports moderate groundwater recharge
Loam	Northern and eastern regions	High fertility, excellent water retention	Highly suitable for a wide range of crops	Balanced infiltration, good for groundwater recharge

$$\mathrm{Var}(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{g} t_i(t_i-1)(2t_i+5)}{18} \tag{4}$$

Where ti denotes the number of ties of extent i. For n larger than 10, the test statistic.

$$Z_S = \begin{cases} \frac{S-1}{[(S)]^{0.5}}, & \text{if } S > 0, \\ 0, & \text{if } S = 0, \\ \frac{S+1}{[(S)]^{0.5}}, & \text{if } S < 0. \end{cases} \tag{5}$$

Zs follows the standard normal distribution

Sen's slope estimator

The magnitude of trend slopes can be also calculated using the Mann-Kendall test as follows:

$$\beta = \mathrm{Median}\left(\frac{x_j - x_i}{j - i}\right) \tag{6}$$

where β is the Theil–Sen slope estimator, and x_i and x_j are the data values at times i and j, respectively.

$$Q_i = \begin{cases} \beta_{\frac{N+1}{2}}, & \text{when } N \text{ is odd}, \\ \frac{1}{2}\left(\beta_{\frac{N}{2}} + \beta_{\frac{N+2}{2}}\right), & \text{when } N \text{ is even}. \end{cases} \tag{7}$$

A positive value of Q_i indicates an upward trend, whereas a negative value represents a downward trend.

Linear regression method

Linear regression analysis was used to detect and evaluate trends in groundwater levels. This method is widely recognized for its simplicity and effectiveness in trend analysis [13]. The slope derived from the regression represents the average rate of change over time, with positive values indicating an increase in groundwater levels and negative values indicating a decrease. The overall change during the observation period can be calculated by multiplying the slope by the duration of the study period [14].

Geostatistical analysis

In this study, the Inverse Distance Weighting (IDW) method was utilized to interpolate groundwater table depths, magnitudes of change, and Mann-Kendall (MK) Z-statistic values. This method has been widely applied in recent hydrological research and has demonstrated reliable results in spatial interpolation of groundwater data. IDW operates on the principle that the value at an unsampled point is estimated as a weighted average of known values from surrounding points, with weights inversely related to the distances between points [15]. The IDW interpolation was performed using the Geostatistical Analyst tool integrated into ArcGIS 10.8.2 software. The method follows these formulas:

$$Z(x_p) = \frac{\sum_{i=1}^{N} W_i Z(x_i)}{\sum_{i=1}^{N} W_i} \tag{8}$$

$$W_i = \frac{1}{d_i^a} \tag{9}$$

Where: • Z(xp) is the estimated value at the unsampled point xp. • Z(xi) is the known value at the sampled point xi. • N is the total number of sampled points used in the estimation. • Wi is the weight assigned to each sampled point xi. • di is the distance between the unsampled point xp and the sampled point xi.

• a is the power parameter controlling the influence of distance (commonly set to 2).

The weighting factor Wi decreases as the distance di increases, meaning that closer points have a more significant influence on the estimated value than those farther away. This approach was consistently applied for interpolating groundwater table depth, magnitude of change, and MK Z-statistic values across the study area. Recent studies have effectively utilized IDW in groundwater mapping and analysis, highlighting its continued relevance in hydrological research [16]. These studies demonstrate the method's applicability in various hydrogeological contexts and support its use in the current research.

Results and Discussion

Geostatistical analaysis

Changes in the level of groundwater during the vegetation period

In the regions of the Amu Darya basin, agricultural practices are organized on the basis of irrigation. In this research, changes in the level of groundwater were analyzed in the vegetation (April-September) and non-vegetation (October-March) periods for the period 2018-2023. The depth to groundwater level maps were generated for the vegetation period for the study period (2018–2023). Using these 6 years of data from multiple wells, average depth to groundwater level and water level fluctuation were prepared. The average depth to water level map for the vegetation period was created by taking the mean of all years (Figure **??**).

The analysis indicates a noticeable trend of increasing groundwater depths over the six-year period. The maximum groundwater levels have increased from 5.23 m in 2018 to 5.84 m in 2023, suggesting a deepening of the water table in certain areas. Meanwhile, the minimum groundwater levels have remained relatively stable, fluctuating slightly between 1.06 m and 1.32 m (Figure **??**). This stability in minimum levels suggests that some areas still maintain shallow groundwater levels, which are crucial for ecological balance and surface water interactions.

The mean groundwater levels reflect minor fluctuations but an overall steady condition, with the average level being 2.45m.

Well location-wise vegetation period max, min, average groundwater level and water level fluctuations are shown in Figure 8. Maximum and minimum water level fluctuation in vegetation period was 5.84 and 1.06 m, respectively. The mean and standard deviation of water level fluctuation was 2.45 and 0.67 m.

Changes in the level of groundwater during the no vegetation period

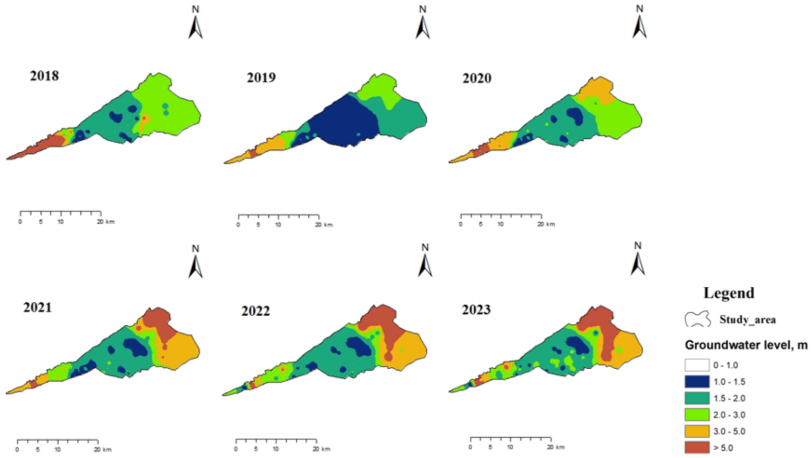


Figure 6. Groundwater level during the vegetation period (2018-2023)

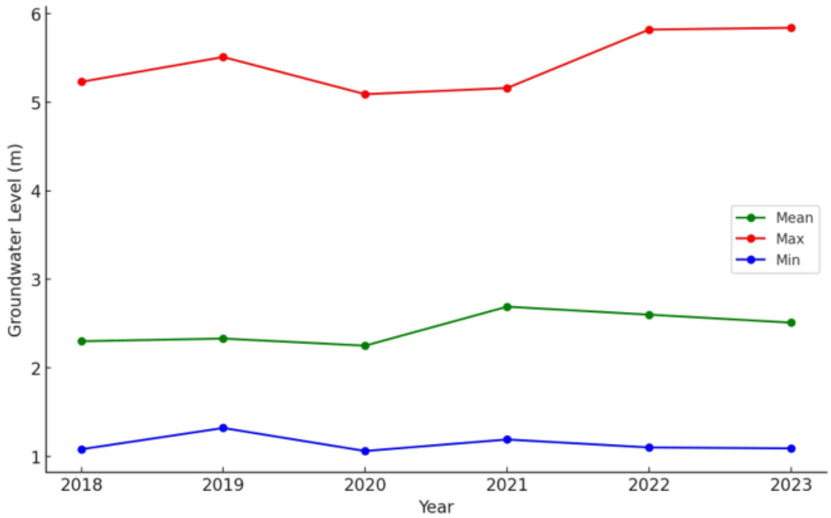


Figure 7. Vegetation period (2018-2023) groundwater level in Bandikhan district

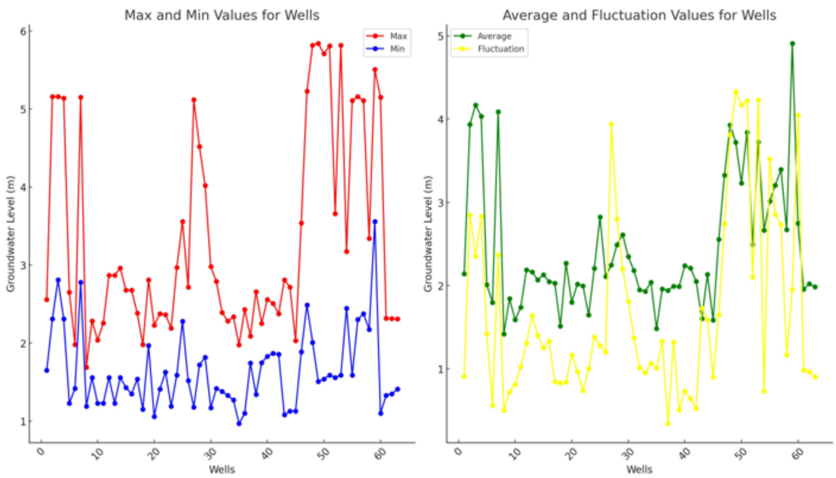


Figure 8. Well wise vegetation (2018-2023) max, min, average groundwater level and fluctuation

A similar analysis of groundwater behavior was conducted for the non-vegetation period, following the approach used for the vegetation period.

The average depth to the groundwater level during the non-vegetative period ranges from 1.04 to 5.68 meters across the study area. The overall average groundwater level during this period was found

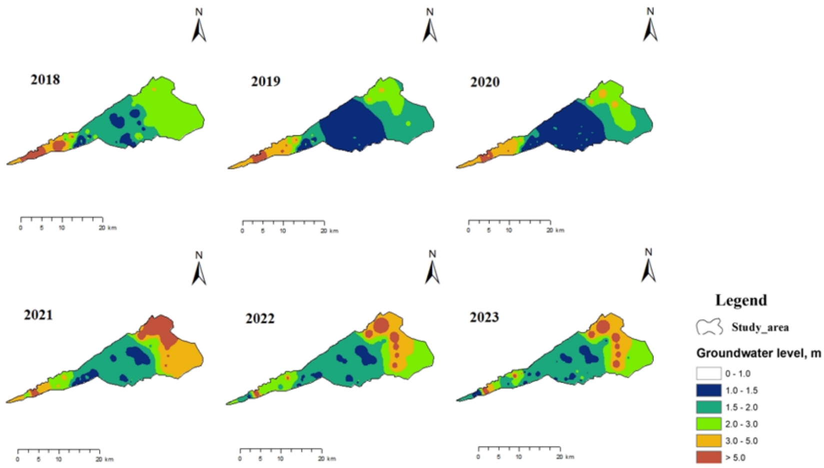


Figure 9. Groundwater level during the no vegetation period (2018-2023)

to be 2.27 ± 1.0 meters. The spatial distribution of groundwater levels during the non-vegetative period is visualized in Figure 10.

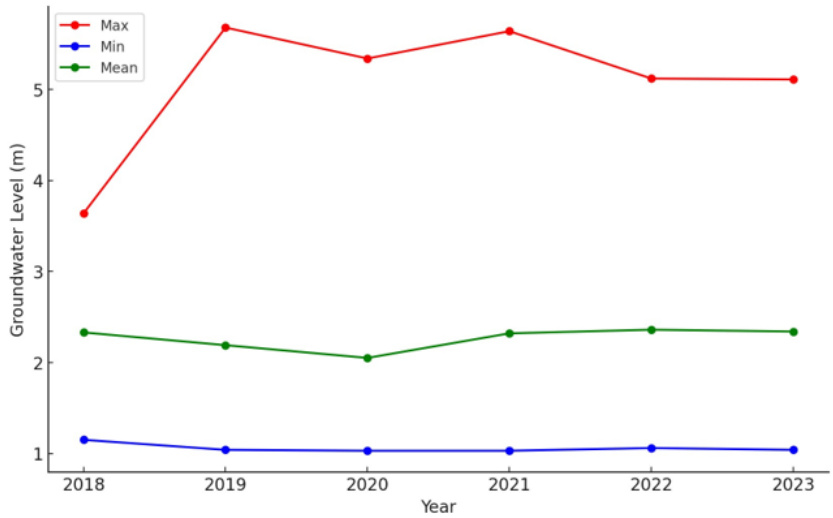


Figure 10. Non-vegetation period (2018-2023) groundwater level in Bandikhan district

The maximum groundwater level observed varies from 3.64 meters (2018) to 5.68 meters (2019), while the minimum level ranges from 1.03 meters (2020-2021) to 1.15 meters (2018). The average groundwater level fluctuates between 2.05 meters (2020) and 2.36 meters (2022). Figure 11 presents the well location's maximum, minimum, average groundwater levels along with the fluctuation patterns.

The maximum and minimum water level fluctuation during the non-vegetative period was 2.50 m and 0.34 m, respectively. The mean and standard deviation of the water level fluctuation were found to be 1.04 m and 0.63 m, respectively.

Trends in the groundwater level

To identify spatial and temporal trends in groundwater levels within the study area, we employed statistical methods including the Mann-Kendall test, Sen's slope estimator, and linear regression analysis. Each observation well captures the dynamics of the local groundwater, so analyzing their trend values provides insights into how water levels have changed over time in those specific areas. Geographic Information System (GIS) technologies were utilized to visualize these changes, using the Inverse Distance Weighted (IDW) interpolation method to create detailed maps of the affected regions.

Vegetation period

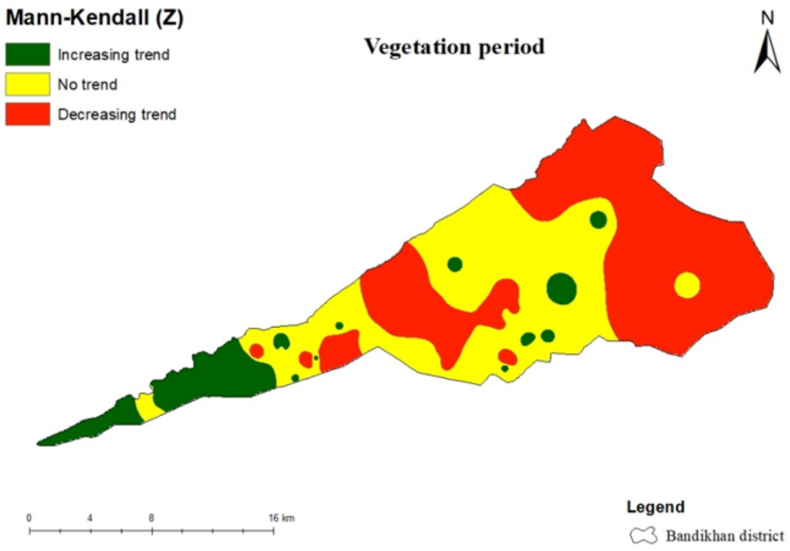


Figure 11. Well location's maximum, minimum, average groundwater levels along with the fluctuation

An analysis of data from 63 monitoring wells in the study area revealed significant trends in groundwater levels. Results of analysis of MK test for each monitoring well along with Z statistics are shown in Figure 12. Using the Mann-Kendall test and Sen's slope estimator, a statistically significant downward trend at the 95 % confidence level was observed in 7 wells, indicating a decline in groundwater levels at these locations. Conversely, an increase in groundwater levels was observed in 6 wells, suggesting that certain areas are experiencing a rise in water levels.

Notably, 6 wells exhibited a decline rate exceeding 0.6 meters per year but did not show statistically significant trends. These findings highlight that while some areas within the study region are undergoing significant decreases in groundwater levels, this trend is not uniform across all monitoring sites.

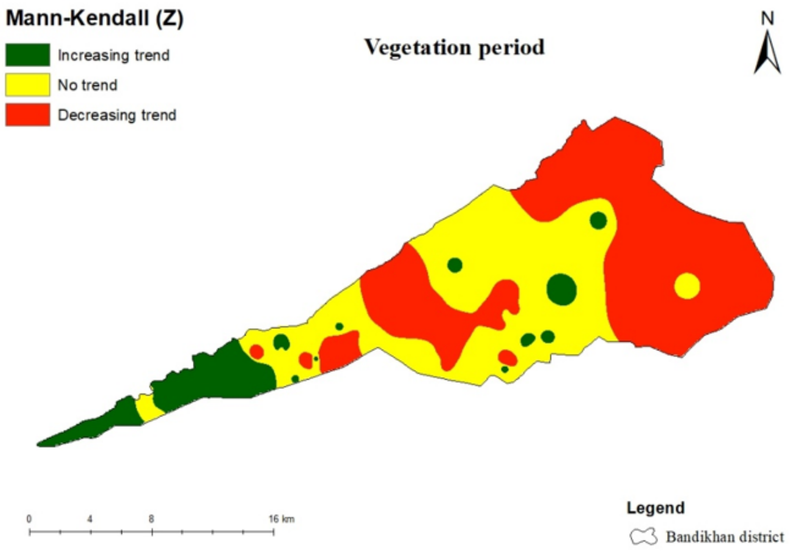
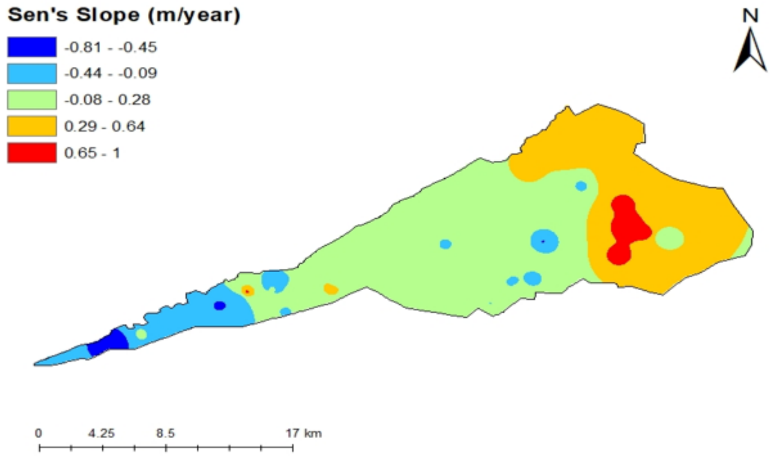


Figure 12. Mann-Kendall Z statistics with trend for vegetation period (2018-2023)

The groundwater level trend line slopes for the study area, derived using Sen's slope estimator and the linear regression method, are presented in Table 2. Slopes calculated using Sen's estimator ranged from -0.46 to -0.81 m/year, suggesting an increase of 2.3 to 4.05 meters over the quinquennial. The Sen's slope and linear regression slope computed for the vegetation period are shown in Figure

13. The average rate of increase, along with the standard deviation, based on Sen's slope was found to be 0.61 m/year and 0.17 m/year, respectively. According to the linear regression method, the minimum and maximum rates of increase were -0.46 and 0.78 m/year, respectively.



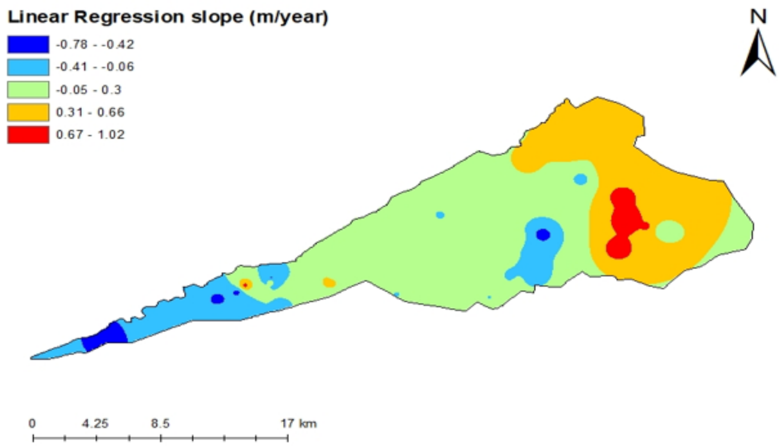


Figure 13. Sen's slope and linear regression slope for vegetation period (2018-2023)

The corresponding mean and standard deviation were 0.60 m/year and 0.11 m/year. These results indicate a significant rise in groundwater levels throughout the study period, which could have a positive impact on water-dependent activities, particularly agricultural water management in the area.

Table 2. Mann-Kendall Z statistics, Sen's slope and linear regression for vegetation and non-vegetation periods (2018-2023)

No	Well ID	Latitude	Longitude	Vegetation period			Non-vegetation period		
				Mann-Kendall statistic, Z	Sen's slope (m/year)	Linear regression slope (m/year)	Mann-Kendall statistic, Z	Sen's slope (m/year)	Linear regression slope (m/year)
1	W246	37,853	67,394	0,19	0,01	-0,01	-0,20	0,00	-0,08
2	W66	37,893	67,399	0,00	-0,02	-0,04	2,25	0,46	0,41
3	W47	37,886	67,398	1,50	0,52	0,53	2,25	0,56	0,59
4	W182	37,861	67,406	1,50	0,56	0,60	-1,50	-0,05	-0,05
5	W328	37,859	67,354	-1,13	-0,18	-0,17	0,00	0,01	-0,01
6	W102	37,874	67,373	0,19	0,01	0,03	2,63	0,56	0,58
7	W217	37,841	67,358	1,50	0,53	0,51	0,00	0,00	-0,01

8	W420	37,835	67,321	0,00	0,01	-0,01	0,00	-0,02	0,01
9	W392	37,825	67,311	-0,94	-0,09	-0,08	2,25	0,05	0,05
10	W277	37,818	67,323	0,00	-0,02	-0,04	2,25	0,05	0,05
11	W318	37,797	67,308	0,00	-0,16	-0,04	0,19	0,00	0,03
12	W11	37,776	67,295	1,50	0,16	0,15	-0,75	-0,06	-0,06
13	W9	37,785	67,303	-0,38	-0,08	-0,07	0,00	-0,01	0,00
14	W117	37,796	67,318	0,00	0,00	0,02	2,25	0,02	0,02
15	W21	37,778	67,309	1,50	0,17	0,16	0,00	-0,06	-0,03
16	W28	37,778	67,316	0,38	0,06	0,08	0,75	0,03	0,10
17	W36	37,782	67,332	0,75	0,08	0,08	0,00	0,00	-0,13
18	W97	37,786	67,318	0,00	0,01	0,00	0,38	0,06	0,02
19	W97	37,786	67,318	0,00	0,01	0,00	0,38	0,06	0,02
20	W54	37,777	67,338	1,50	0,17	0,15	2,25	0,07	0,07
21	W55	37,771	67,336	0,38	0,08	0,04	0,38	0,02	-0,03
22	W71	37,772	67,331	0,00	0,02	0,05	0,38	0,06	-0,06
23	W208	37,774	67,351	0,00	0,01	0,01	-1,50	-0,05	-0,12
24	W176	37,787	67,367	-1,13	-0,10	-0,09	0,00	-0,03	-0,06
25	W142	37,778	67,352	0,38	0,06	0,04	1,50	0,07	0,05
26	W293	37,790	67,364	2,25	0,23	0,24	-1,88	-0,07	-0,08
27	W79	37,820	67,382	-1,50	-0,22	-0,18	-2,10	-0,08	-0,24
28	W228	37,793	67,376	-2,25	-0,46	-0,64	0,57	0,05	0,01
29	W331	37,806	67,376	-0,75	-0,21	-0,34	0,00	0,00	0,01
30	W212	37,794	67,342	0,00	0,02	-0,15	-0,38	-0,10	-0,04
31	W234	37,804	67,347	0,38	0,27	0,22	-0,57	-0,07	-0,08
32	W232	37,805	67,350	1,88	0,23	0,21	-0,38	-0,08	-0,08
33	W243	37,809	67,356	0,00	0,04	0,06	0,00	0,03	-0,02
34	W244	37,819	67,353	0,75	0,05	0,09	2,10	0,02	0,02
35	W29	37,786	67,254	1,13	0,18	0,17	-1,13	-0,24	-0,34
36	W5	37,789	67,269	1,69	0,64	0,64	-1,13	-0,17	-0,17
37	W339	37,789	67,256	2,25	0,07	0,06	2,25	0,08	0,07
38	W61	37,768	67,227	-0,56	-0,12	-0,13	-0,96	-0,04	-0,11
39	W42	37,780	67,243	2,25	0,10	0,10	2,25	0,09	0,09
40	W335	37,799	67,253	-0,75	-0,08	-0,05	-2,25	-0,05	-0,06
41	W42/1	37,780	67,239	-1,13	-0,04	-0,02	-1,50	-0,13	-0,15
42	W49	37,780	67,234	2,25	0,10	0,10	2,25	0,08	0,08
43	W274	37,819	67,367	0,38	0,04	0,02	-1,13	-0,04	-0,17
44	W59	37,792	67,225	-0,38	-0,11	-0,10	-2,25	-0,04	-0,07
45	W305	37,786	67,236	0,00	0,00	0,00	-0,75	-0,14	-0,20
46	W262	37,786	67,219	-0,38	-0,01	0,04	-0,75	-0,02	-0,05
47	W261	37,788	67,219	-1,13	-0,46	-0,46	-0,38	-0,13	-0,02
48	W612	37,848	67,430	1,88	0,80	0,87	2,25	0,60	0,66
49	W542	37,831	67,433	2,25	1,00	1,02	1,34	0,78	0,74
50	W267	37,826	67,445	1,88	0,78	0,70	1,88	0,36	0,38
51	W75	37,810	67,428	1,50	0,83	0,91	1,88	0,64	0,76
52	W501	37,824	67,455	0,00	0,01	0,09	-0,38	-0,04	-0,11
53	W235	37,783	67,203	2,25	0,69	0,75	2,25	0,58	0,61
54	W100	37,773	67,202	-2,25	-0,09	-0,13	-2,25	-0,15	-0,16
55	W109	37,772	67,187	-2,25	-0,62	-0,58	-2,25	-0,16	-0,20
56	W222	37,777	67,198	-2,25	-0,43	-0,52	-2,25	-0,18	-0,22
57	W127	37,754	67,145	-0,75	-0,30	-0,32	-0,75	-0,19	-0,21
58	W122	37,766	67,190	-2,25	-0,16	-0,19	-2,25	-0,23	-0,23
59	W174	37,752	67,140	0,38	0,01	-0,06	-0,38	-0,02	0,25
60	W86	37.819	67.299	1.88	0.23	0.21	0.38	0.02	-0.07
61	W77	37.815	67.296	2.25	0.19	0.19	-1.50	-0.19	-0.15
62	W72	37.817	67.296	2.25	0.19	0.19	-1.50	-0.19	-0.15

The MK test statistics are also presented in Table 2. Figure 14 displays the spatial distribution of wells and groundwater trends obtained using the Mann-Kendall (MK) test during the non-vegetation period, along with the corresponding Z statistics. To analyze water level trends during the non-vegetation period, Figure 15 shows the calculated Sen's slope and linear regression slope. Significant groundwater level trends—both declining and rising—were observed at a 95 % significance level for most stations across the study area.

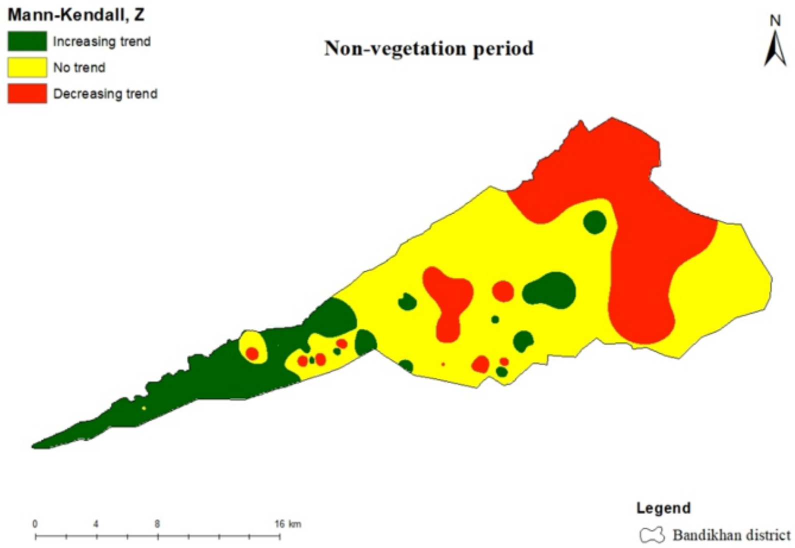


Figure 14. Mann-Kendall Z statistics with trend for non-vegetation period (2018-2023)

The trend analysis using the MK test and Sen's slope estimator indicates a sharp change in groundwater levels, with some areas exhibiting negative trends while most show positive trends. Most of these negative and positive trends are statistically significant at the 95 % confidence level. The results revealed that about 13 monitoring wells demonstrated significant negative trends, while 8 wells exhibited positive trends.

Based on the results, it is evident that during the non-vegetation period, the rate of groundwater level change using the Sen's slope method varies from -0.26 to +0.78 m/yea r. Here, negative (-) values indicate a rise in groundwater levels, while positive (+) values signify a decline. The mean and standard deviation for the rising rate calculated by Sen's slope are -0.22 m/year and 0.03 m/year, respectively. For the declining rate, the mean and standard deviation are +0.22 m/year and 0.07 m/year, respectively.

The linear regression method showed minimum and maximum rates of change ranging from -0.28 to +0.76 m/year. The mean and standard deviation for the rising rate calculated by linear regression are -0.24 m/year and 0.06 m/year, respectively, while for the declining rate, they are +0.23 m/year and 0.08 m/year, respectively. In the Bandixon district of the Surkhandarya region, groundwater level changes exhibit regional variations, with rises observed in some areas and declines in others. This situation underscores the necessity of adopting individualized approaches and considering local conditions in water resource management. To ensure the sustainability of water resources, it is crucial to implement comprehensive measures, utilize advanced technologies, and raise awareness among the local population. These strategies will not only help preserve water resources but also contribute to the ecological and economic stability of the region.

Conclusions

This study has provided a comprehensive analysis of groundwater trends in the Bandikhan district using advanced statistical and geospatial methods. The findings reveal that groundwater levels exhibit both rising and declining trends across the district, depending on the location and seasonal period. During the vegetation period, significant declines were observed, likely due to

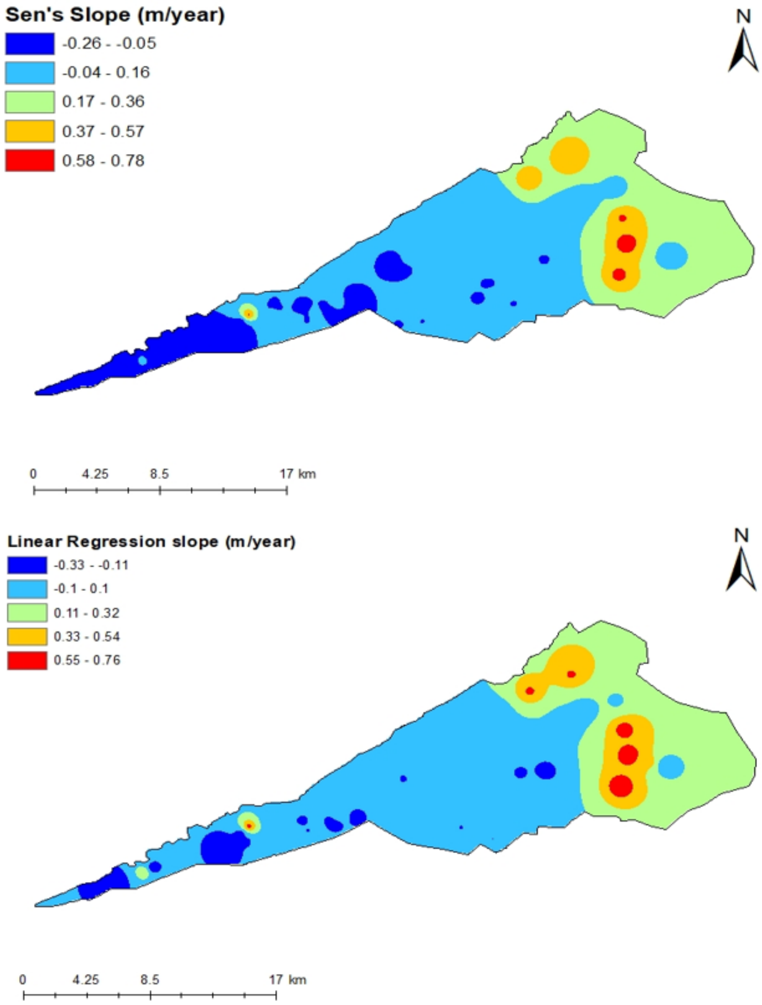


Figure 15. Sen's slope and linear regression slope for non-vegetation period (2018-2023)

intensive irrigation practices, while some areas experienced an increase in groundwater levels. In the non-vegetation period, fluctuations were also noted, with both positive and negative trends detected.

The integration of the Mann-Kendall test, Sen's slope estimator, and GIS-based mapping has proven effective in identifying critical areas of groundwater depletion and recharge. These findings underscore the importance of adopting localized groundwater management practices tailored to the specific needs of the district. Moreover, the results suggest that current irrigation practices, particularly during the vegetation period, contribute to the depletion of groundwater resources.

For sustainable water resource management, it is recommended to implement advanced irrigation techniques that reduce water consumption, promote groundwater recharge, and monitor groundwater levels more effectively. This study serves as a valuable resource for water managers in the Bandikhan district and other similar regions to develop strategies that balance agricultural productivity with the preservation of groundwater resources, ensuring long-term sustainability.

Authors' contribution

Conceptualization, G.Z. and D.K.; methodology, G.Z., S.L. and D.K.; software, N.E. and D.K.; validation, G.Z., S.L. and N.N.; formal analysis, D.K. and N.E.; investigation, D.K., N.E. and N.N.; resources, G.Z. and S.L.; data curation, N.E. and D.K.; writing—original draft preparation, D.K.; writing—review and editing, G.Z., S.L., N.E., N.N. and D.K.; visualization, D.K. and N.E.; supervision, G.Z.; project administration, G.Z.; funding acquisition, G.Z. All authors have read and agreed to the published version of the manuscript.

Funding source

This research received no external funding.

Ethics approval

Not applicable.

Consent for publication.

Not applicable.

Data Availability Statement

The data presented in this study are available from the corresponding author upon reasonable request.

Acknowledgments

The authors would like to thank the Surkhandarya Land Reclamation Expedition (SLRE) under the Amu-Surkhan Irrigation Systems Basin Administration and the Hydrometeorological Service Agency of Uzbekistan for providing groundwater and meteorological data used in this study. The authors also express their sincere appreciation to all specialists who contributed to field observations and data collection.

Conflict of interest

The authors declare no conflict of interest.

Abbreviations

GIS	Geographic Information System
MK	Mann–Kendall
IDW	Inverse Distance Weighting
LULC	Land Use/Land Cover
SLRE	Surkhandarya Land Reclamation Expedition
Z	Mann–Kendall standardized test statistic
S	Mann–Kendall test statistic
Var(S)	Variance of the Mann–Kendall statistic
sgn	Sign function
Q	Sen's slope estimator
β	Sen's slope coefficient
DEM	Digital Elevation Model

References

[1] Islam, M. S., Rahman, M. A., & Rashid, M. H. Trend analysis of groundwater levels using Mann–Kendall and Sen's slope estimator in an irrigated area of Bangladesh. *Groundwater for Sustainable Development*, 12, 100529 (2021). https://doi.org/10.1016/j.gsd.2020.100529

[2] Zhang, Y., Wang, X., & Chen, H. GIS-based groundwater level trend analysis using non-parametric tests in the North China Plain. *Journal of Hydrology*, 598, 126192 (2021). https://doi.org/10.1016/j.jhydrol.2021.126192

[3] Ahmed, A., & Panda, S. K. Groundwater level trend analysis using non-parametric tests and GIS in western Odisha, India. *Journal of the Geological Society of India*, 96(1), 35–42 (2020). https://doi.org/10.1007/s12594-020-1408-7

[4] Silva, M. S. L. L., et al. Trend analysis of groundwater levels in the Brazilian semiarid region using Mann–Kendall and Sen's slope estimator. *Hydrological Sciences Journal*, 65(9), 1480–1490 (2020). https://doi.org/10.1080/02626667.2020.1769108

[5] Kumar, S., & Kumar, A. Spatial and temporal variations of groundwater levels in an irrigated region using GIS and statistical methods. *Environmental Earth Sciences*, 78(18), 549 (2019). https://doi.org/10.1007/s12665-019-8561-3

[6] Bozkurt, E. E., & Balaban, H. Ş. Application of Mann–Kendall trend test and Sen's slope estimates for groundwater levels in the Konya Closed Basin, Turkey. *Environmental Monitoring and Assessment*, 191(10), 605 (2019). https://doi.org/10.1007/s10661-019-7733-4

[7] Moghaddam, A. A., Mirhosseini, A., & Soltani, A. Groundwater level trend analysis in Urmia Lake Basin, Iran using non-parametric methods and GIS. *Sustainable Water Resources Management*, 4(2), 371–384 (2018). https://doi.org/10.1007/s40899-017-0138-3

[8] Shamsudduha, M., et al. Recent trends in groundwater levels in a highly seasonal hydrological system: the Ganges–Brahmaputra–Meghna Delta. *Hydrology and Earth System Sciences*, 23(11), 4933–4947 (2019). https://doi.org/10.5194/hess-23-4933-2019

[9] Ali, A. A., et al. Evaluation of groundwater level changes using statistical methods and GIS in the Nile Delta Aquifer, Egypt. *Journal of African Earth Sciences*, 181, 104257 (2021). https://doi.org/10.1016/j.jafrearsci.2021.104257

[10] Wu, H., et al. Spatiotemporal analysis of groundwater level trends using GIS and non-parametric statistical tests in the Hebei Plain, China. *Science of the Total Environment*, 712, 136512 (2020). https://doi.org/10.1016/j.scitotenv.2019.136512

[11] Singh, S. K., et al. Application of Mann–Kendall test and Sen's slope estimates for groundwater level trend analysis in Jharkhand State, India. *International Journal of Pure and Applied Mathematics*, 119(17), 1487–1500 (2018).

[12] Pandey, P. K., & Singh, V. Groundwater level trend analysis and forecasting using statistical and artificial neural network techniques. *Journal of the Geological Society of India*, 94(3), 251–258 (2019). https://doi.org/10.1007/s12594-019-1187-6

[13] Jha, S. K., et al. Trend analysis of groundwater levels using non-parametric tests and GIS in a canal command area of eastern India. *Journal of the Geological Society of India*, 96(2), 163–169 (2020). https://doi.org/10.1007/s12594-020-1412-y

[14] Reddy, K. H., et al. Groundwater level trend and its spatial variability analysis using GIS in a semi-arid region of South India. *Applied Water Science*, 10(6), 149 (2020). https://doi.org/10.1007/s13201-020-01218-7

[15] Mwakalila, J. H. H. Analysis of groundwater level trends and variations using statistical techniques in Dar es Salaam, Tanzania. *Journal of Water Supply: Research and Technology–AQUA*, 70(5), 738–747 (2021). https://doi.org/10.2166/aqua.2021.109

[16] Mondal, N. K., et al. Evaluation of groundwater level trends and variability in the Purulia district of West Bengal, India using statistical analysis and GIS techniques. *Groundwater for Sustainable Development*, 11, 100423 (2020). https://doi.org/10.1016/j.gsd.2020.100423