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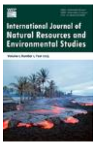

Spatiotemporal Evolution and Attribution of Groundwater in Wuzhi Region

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ABSTRACT

Based on groundwater observation data from the Wuzhi area during 2000–2023, this study integrated the Mann–Kendall trend test, geostatistical analysis, and principal component analysis to investigate the spatiotemporal evolution and driving mechanisms of the groundwater flow field. The results show that during the study period, the groundwater depth generally increased, with a slightly larger rise in the dry season than in the wet season. The groundwater level exhibited a spatial pattern of being higher in the northwest and lower in the southeast, and declined continuously over time. Human activities were the main cause of anomalous changes in the groundwater flow field, with agricultural irrigation and groundwater extraction playing dominant roles. Spatially, groundwater depth decreased from the alluvial zone of the Yellow River and Qin River in the west to the Yellow River alluvial plain in the southeast. The reduction in groundwater storage was primarily due to increased extraction driven by rising irrigation water use, whose impact far exceeded that of natural factors. Sustainable management of agricultural water resources is essential for ensuring groundwater security in this region.

KEYWORDS

Groundwater Level, Groundwater Extraction, Anthropogenic Factors, Natural Factors, Spatiotemporal.

1. INTRODUCTION

The Qin River, located in the middle and lower reaches of the Yellow River, contributes an average annual flow of 4.2% of the total runoff at Huayuankou Station. It serves as a groundwater recharge corridor for the HuangHuaiHai Plain and is a lifeline for drinking water security across 23 counties and cities in Shanxi and Henan provinces [1]. The shallow groundwater in the plain area of the Qin River Basin is not only a primary source of water for agriculture, industry, and urban domestic use but also a critical element in maintaining the stability of the regional ecosystem [2]. Within the lower reaches of the Qin River, in Jiyuan City and Jiaozuo City of Henan Province, major infrastructure projects such as the SouthtoNorth Water Diversion Middle Route Project and the WesttoEast Gas Pipeline intersect extensively. The presence of these significant projects imposes stricter demands on the stability of water resource supply, water quality standards, and ecological environment quality in the Qin River Basin [3].

With the increase in human production activities, the groundwater environment is subjected to growing disturbances. In particular, shallow groundwater, which is situated close to the surface and frequently exchanges with surface water, is especially vulnerable to such disturbances [4]. In recent years, the inflow to the lower reaches of the Qin River has been persistently low, leading to frequent flow interruptions, riverbed drying, and exposure of the river channel [5]. The continuous decline in runoff within the Qin River Basin will constrain the sustainable economic development of Jiaozuo City while significantly reducing the water supply to the main stream of the Yellow River, thereby diminishing the overall water resource capacity of the Yellow River Basin [6]. Issues such as the discharge of industrial wastewater and sewage, agricultural irrigation, overexploitation of water resources, and construction of engineering facilities in the plain area of the lower basin severely affect regional ecology and human livelihoods [7]. Shallow groundwater in the plain area of the lower river reaches, due to its proximity to the surface layer, interacts more closely with surface runoff and atmospheric precipitation, making it susceptible to the combined influences of terrain characteristics, meteorological factors, and human interference. At the same time, it generates corresponding environmental feedback effects [8]. This type of groundwater system plays a crucial role in ensuring local ecological balance, maintaining water supply, and optimizing water resource allocation [9].

The Qin River flows through Wuzhi County, spanning a length of 33.5 km within the county. Studying the spatiotemporal variations of groundwater in Wuzhi County is of significant importance for the development and management of water resources in the Qin River.

2. OVERVIEW OF THE STUDY AREA

Wuzhi County is under the jurisdiction of Jiaozuo City, Henan Province, located in the northwestern part of the province on the north bank of the Yellow River. Its geographic coordinates range from 34°56′ to 35°10′ north latitude and 113°10′ to 113°39′ east longitude. Situated at the center of the radiating zones of Zhengzhou, Jiaozuo, Xinxiang, Luoyang, and Jincheng cities, it lies within the core area of the Central Plains Economic Zone, highlighting its significant regional advantages. Administrative Division: The county covers a total area of 805 square kilometers and comprises 4 subdistricts, 6 towns, and 5 townships.

Topography: Wuzhi County is part of the alluvial plains of the Yellow River and Qin River, characterized by flat terrain that slopes gently from southwest to northeast. The elevation ranges between 80 and 110 meters. The county’s landforms can be categorized into three types: the Yellow River floodplain, the Qin River alluvial plain, and backriver lowlands.

Climate Features: The region experiences a warm temperate continental monsoon climate with four distinct seasons. Springs are dry and windy, summers are hot and rainy, autumns are clear and cool, and winters are cold with little snow. The average annual temperature is 14.4°C, with an average annual precipitation of 575.1 mm and a frostfree period of approximately 211 days. Abundant sunlight and heat resources support the growth of various crops.

Hydrology: Rivers within the county belong to the Yellow River system. The Yellow River flows along the southern boundary of the county, serving as both its "mother river" and a vital ecological barrier. The Qin River traverses the county from northwest to southeast, eventually merging into the Yellow River within Wuzhi. The abundant water resources provide favorable conditions for agricultural irrigation and industrial production.

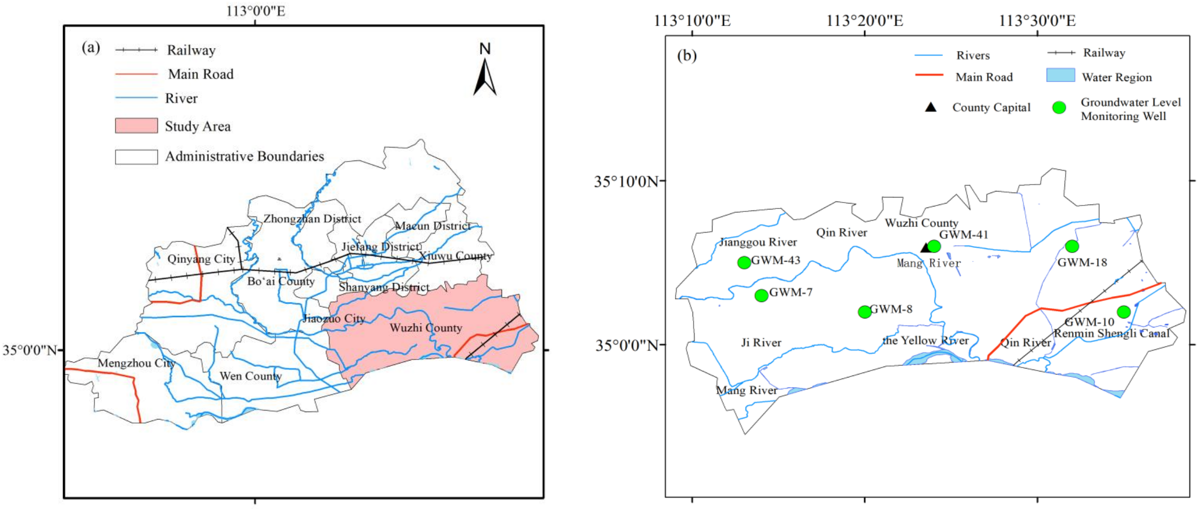


Fig 1. Location of the study area (a) and distribution of groundwater monitoring wells (b).

3. RESEARCH METHODS

3.1. Data Sources

The groundwater level data from 2000 to 2023 used in this study were sourced from the Jiaozuo Water Conservancy Bureau. Inverse distance weighting interpolation was applied in ArcGIS 10.8 to the water level data from six representative groundwater monitoring wells. Data on anthropogenic factors (including water use volume, water supply volume, infiltration recharge from farmland irrigation, total groundwater extraction, total urban and rural water consumption, industrial water use, forestry water use, agricultural, livestock, and fishery water use, livestock drinking water volume, and water supply from diversion projects) were obtained from the Jiaozuo Water Resources Bulletin. Meteorological data (including precipitation, average temperature, maximum temperature, minimum temperature, and evapotranspiration) were derived from the China 1km-resolution meteorological dataset (1901–2023) provided by the National Earth System Science Data Center (https://www.geodata.cn). Land use data came from the 1990–2022 China 30m land cover dataset released by Professors Jie Yang and Xin Huang of Wuhan University. Population density data were sourced from the LandScan population dataset at 1km resolution (https://landscan.ornl.gov). Surface runoff data were obtained from the Yellow River Basin Water Resources Bulletin. All data were preprocessed in ArcGIS 10.8 through clipping and projection transformation and were resampled to a uniform spatial resolution of 30m.

3.2. Research Methods

3.2.1. Spatiotemporal Dynamics of Groundwater Depth

Understanding the spatiotemporal dynamics of groundwater under the influence of climate change and human activities is crucial for achieving sustainable groundwater management. The nonparametric MannKendall method[10], widely applied for trend detection in hydrometeorological data, and linear regression analysis[11] were employed. These methods were used to detect trends in the monthly, seasonal, and annual dynamics of groundwater depth, with statistical significance assessed at significance levels of $P < 0.05$ and $P < 0.01$. Box plots were utilized to analyze the variability in monthly groundwater depth changes.

Spatial variations in groundwater depth provide a more intuitive reflection of the evolutionary characteristics of groundwater systems[12]. Using groundwater depth data from six time periods (2000, 2005, 2010, 2015, 2020, and 2023), spatial distribution maps of groundwater depth for the study area were generated by applying the Inverse Distance Weighting interpolation method within the geostatistical module of ArcGIS software. These maps were reclassified into different depth ranges (<1 m; 0–6 m; 6–8 m; 8–10 m; 10–12 m; 12–14 m; 14–16 m; 16–18 m; 18–20 m). Histograms for each classified category were generated, the areal extents of different depth ranges were calculated, and their intersecting changes were analyzed.

3.2.2. Analysis of Factors Influencing Groundwater Evolution

The spatiotemporal dynamics of groundwater evolution are primarily influenced by a combination of natural factors and human activities. Natural factors typically include air temperature, precipitation, evaporation, and surface runoff, while anthropogenic factors mainly consist of groundwater extraction, agricultural irrigation water use, total groundwater extraction, total urban and rural water consumption, industrial water use, water use for forestry, animal husbandry, fisheries, and livestock, and water supply from water diversion projects.

Given that groundwater dynamics are affected by multiple factors, principal component analysis (PCA) was conducted using the PCA module in the SPSS statistical software to assess the degree of influence of each factor on groundwater depth. Principal component analysis transforms multiple variables into a smaller number of principal components, each of which is a linear combination of the original variables. This approach enables the principal components to reflect the original variables while overcoming the limitations of singlefactor analysis and highlighting the key influencing factors[13].

Using SPSS, the original data of multiple influencing factors were processed to calculate the contribution rates of each principal component. Principal components with a cumulative contribution rate exceeding 85% were selected to establish a comprehensive PCA model. Based on this model, comprehensive scores were calculated to evaluate the main influencing factors of groundwater dynamics [14].

4. SPATIOTEMPORAL EVOLUTION PATTERNS OF THE GROUNDWATER SYSTEM

4.1. Regional Variation Characteristics of Groundwater Depth over the Past Two Decades.

The dynamics of phreatic groundwater reflect the recharge–discharge conditions and the exploitation intensity of the aquifer system. This study analyzed the dynamic changes in groundwater depth from 2000 to 2023 based on longterm observation wells in the Wuzhi County area. The results indicate an increasing trend in groundwater depth in the surrounding regions of Wuzhi over the years.

Observation Well GWM 7, located in the eastern transitional zone of the piedmont alluvial–proluvial fan plain in western Wuzhi County, showed an increase in groundwater depth from 14.29 m in 2000 to 15.37 m in 2023. The water table declined by 1.08 m, with an average annual decline rate of 0.05 m/a.

Observation Well GWM 8, situated in the Yellow River floodplain and alluvial plain in southern Wuzhi County, exhibited an increase in groundwater depth from 8.80 m in 2000 to 14.92 m in 2023. The water table declined by 6.12 m, with an average annual decline rate of 0.27 m/a.

Observation Well GWM 10, located in the alluvial plain of the old Yellow River course in southeastern Wuzhi County, recorded an increase in groundwater depth from 1.18 m in 2000 to 5.38 m in 2023. The water table declined by 4.20 m, with an average annual decline rate of 0.23 m/a.

Observation Well GWM 18, in the Yellow River alluvial plain in eastern Wuzhi County, experienced an increase in groundwater depth from 2.88 m in 2000 to 11.63 m in 2023. The water table declined by 8.75 m, with an average annual decline rate of 0.38 m/a.

Observation Well GWM 41, located in the transitional zone from the piedmont sloping plain to the alluvial plain in northern Wuzhi County, showed an increase in groundwater depth from 18.42 m in 2000 to 19.81 m in 2023. The water table declined by 1.40 m, with an average annual decline rate of 0.06 m/a.

Observation Well GWM 43, situated at the front edge of the Taihang Mountains piedmont alluvial–proluvial fan in northwestern Wuzhi County, recorded an increase in groundwater depth from 12.86 m in 2000 to 18.59 m in 2023. The water table declined by 5.73 m, with an average annual decline rate of 0.25 m/a.

Results of the MK trend analysis[15] (Table 1) indicate that: For Well GWM 7, monthly, seasonal, and annual groundwater depths all exhibited a significant increasing trend ($p < 0.05$).For Well GWM 8, monthly, seasonal, and annual groundwater depths all showed a significant decreasing trend. For Well GWM 10, monthly, seasonal, and annual groundwater depths all displayed an increasing trend.

Figure 3 presents the monthly time-series variations from 2000 to 2023 for the six observation wells, along with the maximum, minimum, median, and quartile values of monthly groundwater depths. The box plots reveal that groundwater depths are generally highest in June and July. Well GWM 7 showed the greatest variability in June and the least in November. Well GWM 8 exhibited the greatest variability in June and the least in January. Well GWM 10 demonstrated the greatest variability in November and the least in April.Well GWM 18 displayed the greatest variability in July and the least in June. Well GWM 41 showed the greatest variability in November and the least in January. Well GWM 43 exhibited the greatest variability in July and the least in January.

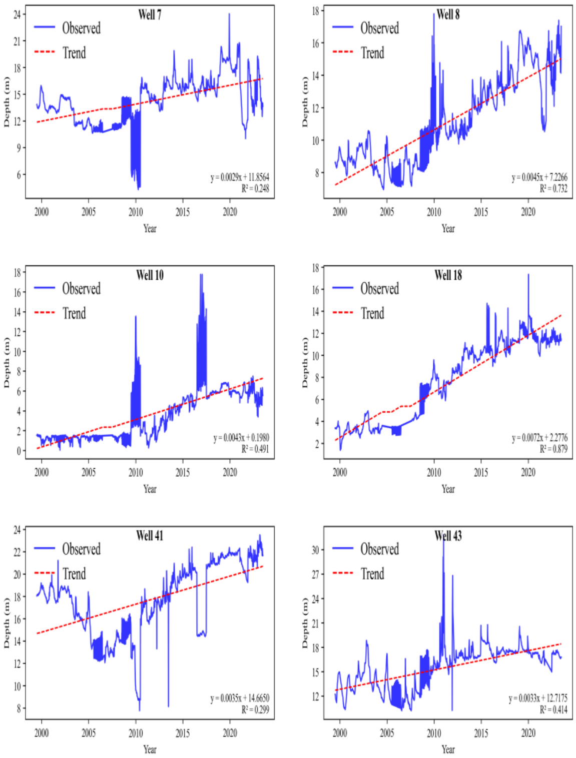
Table 1 Significance of annual, seasonal and monthly trends in groundwater depth for observation wells (GWM 7, GWM 8,GWM 10)during 2000–2023

Time	GMW 7				GMW 8				GMW 10			
	2000-2022				2000-2022				2000-2022			
	(35.04°N，113.22°E)				(34.98°N,113.2°E)				(35.03°N,113.57°E)			
	MK		LM		MK		LM		MK		LM	
Month	Z	β	p	Sen_ Slope	Z	β	p	Sen_ Slope	Z	β	p	Sen_ Slope
1	4.99	11.56	0.00	0.03	10.34	7.06	0.00	0.05	10.35	0.05	0.00	0.05
2	5.92	11.45	0.00	0.04	10.66	6.88	0.00	0.05	10.94	0.12	0.00	0.05
3	6.75	11.45	0.00	0.04	10.16	7.01	0.00	0.05	11.1	0.09	0.00	0.05
4	7.01	11.44	0.00	0.04	10.31	7.57	0.00	0.05	11.67	0.09	0.00	0.05
5	6.97	11.76	0.00	0.04	9.79	7.8	0.00	0.05	11.44	0.03	0.00	0.05
6	8.26	11.34	0.00	0.06	10.49	7.78	0.00	0.06	10.96	-0.03	0.00	0.05
7	8.02	11.55	0.00	0.05	10.7	7.76	0.00	0.06	10.48	-0.13	0.00	0.05
8	6.24	11.67	0.00	0.04	10.27	7.34	0.00	0.06	9.82	-0.05	0.00	0.05
9	5.47	11.61	0.00	0.03	10.46	7.08	0.00	0.06	8.29	-0.13	0.00	0.05
10	5.58	11.68	0.00	0.03	10.58	6.91	0.00	0.06	9.35	-0.05	0.00	0.05
11	5.75	11.55	0.00	0.03	10.24	6.84	0.00	0.06	10.2	-0.04	0.00	0.05
12	5.77	11.31	0.00	0.04	9.88	6.88	0.00	0.06	10.53	-0.04	0.00	0.05
Spring	12.21	11.54	0.00	0.01	17.96	7.43	0.00	0.02	19.79	0.05	0.00	0.02
Summer	12.70	11.51	0.00	0.02	18.27	7.61	0.00	0.02	18.07	-0.09	0.00	0.02
Autum	9.81	11.61	0.00	0.01	18.06	6.93	0.00	0.02	16.11	-0.09	0.00	0.02
Winter	9.89	11.30	0.00	0.01	18.01	6.95	0.00	0.02	18.60	0.13	0.00	0.02
Annual average	22.17	11.52	0.00	0.00	36.57	7.22	0.00	0.00	35.95	-0.03	0.00	0.00

Table 2 Significance of annual, seasonal and monthly trends in groundwater depth for observation wells (GWM 18,GWM 41,GWM 43)during 2000–2023

Time	GMW 18				GMW 41				GMW 43			
	2000-2022				2000-2022				2000-2022			
	(35.10°N,113.54°E)				(35.11°N,113.41°E)				(35.09°N,113.22°E)			
	MK	LM			MK	LM			MK	LM		
Monthly	Z	β	p	Sen_Slope	Z	β	p	Sen_Slope	Z	β	p	Sen_Slope
1	11.96	1.91	0.00	0.09	6.22	14.60	0.00	0.04	10.60	10.96	0.00	0.05
2	12.05	2.04	0.00	0.09	6.51	14.75	0.00	0.04	10.09	11.32	0.00	0.05
3	12.86	2.07	0.00	0.09	6.28	14.81	0.00	0.04	9.25	12.34	0.00	0.04
4	12.87	2.40	0.00	0.08	6.57	15.11	0.00	0.04	7.63	13.36	0.00	0.03
5	12.75	2.40	0.00	0.08	6.49	15.37	0.00	0.03	6.94	13.80	0.00	0.03
6	12.83	2.43	0.00	0.09	5.91	15.49	0.00	0.04	6.94	14.48	0.00	0.03
7	13.18	1.83	0.00	0.10	5.50	15.41	0.00	0.04	6.74	14.00	0.00	0.03
8	13.01	1.48	0.00	0.11	5.35	15.17	0.00	0.03	7.61	12.62	0.00	0.04
9	12.56	1.56	0.00	0.10	5.28	14.83	0.00	0.03	8.49	12.00	0.00	0.05
10	13.34	1.74	0.00	0.10	6.08	14.62	0.00	0.04	8.92	11.69	0.00	0.05
11	13.71	1.79	0.00	0.10	6.01	14.44	0.00	0.05	8.33	11.50	0.00	0.05
12	13.52	2.01	0.00	0.09	6.07	14.27	0.00	0.05	9.15	11.11	0.00	0.05
Spring	22.47	2.26	0.00	0.03	11.36	15.08	0.00	0.01	13.71	13.15	0.00	0.01
Summer	22.36	1.89	0.00	0.03	9.55	15.36	0.00	0.01	12.15	13.71	0.00	0.01
Autum	23.25	1.66	0.00	0.03	9.89	14.62	0.00	0.01	15.07	11.72	0.00	0.02
Winter	20.29	2.62	0.00	0.03	11.89	14.25	0.00	0.02	17.14	11.28	0.00	0.02
Annual average	44.47	1.93	0.00	0.01	21.15	14.89	0.00	0.00	29.34	12.43	0.00	0.00

MK is the abbreviation for the Mann–Kendall trend test, and z represents the standardized statistical variable value; LM stands for the Linear Regression Method, B denotes the regression coefficient, and P indicates the significance level of the F-test, where $P < 0.01$.



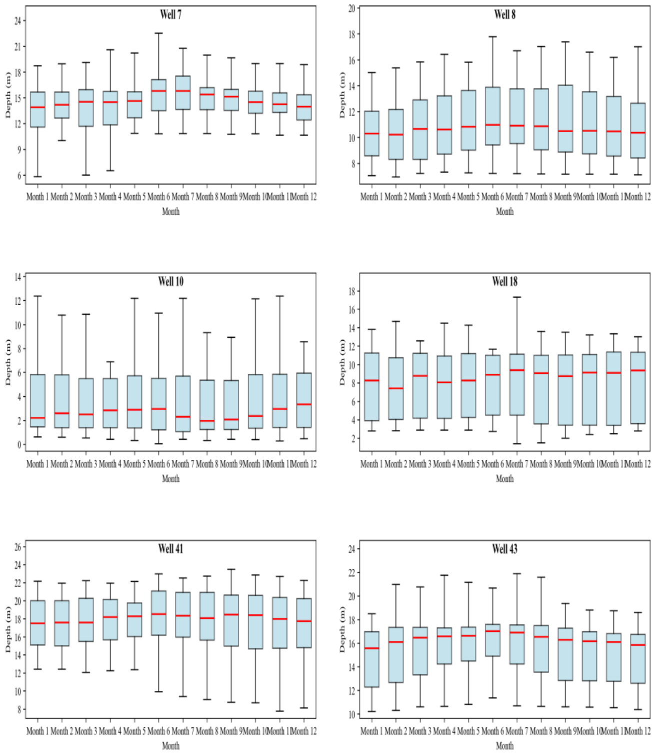


Fig 2. Monthly TimeSeries of Groundwater Depth for Observation Wells in the Wuzhi Area(2000-2023)

Fig 3. BoX Plots of Monthly Groundwater Depth for Observation Wells in the Wuzhi Area (2000-2023)

Table 3 Area under different depth zones(2000~2023)

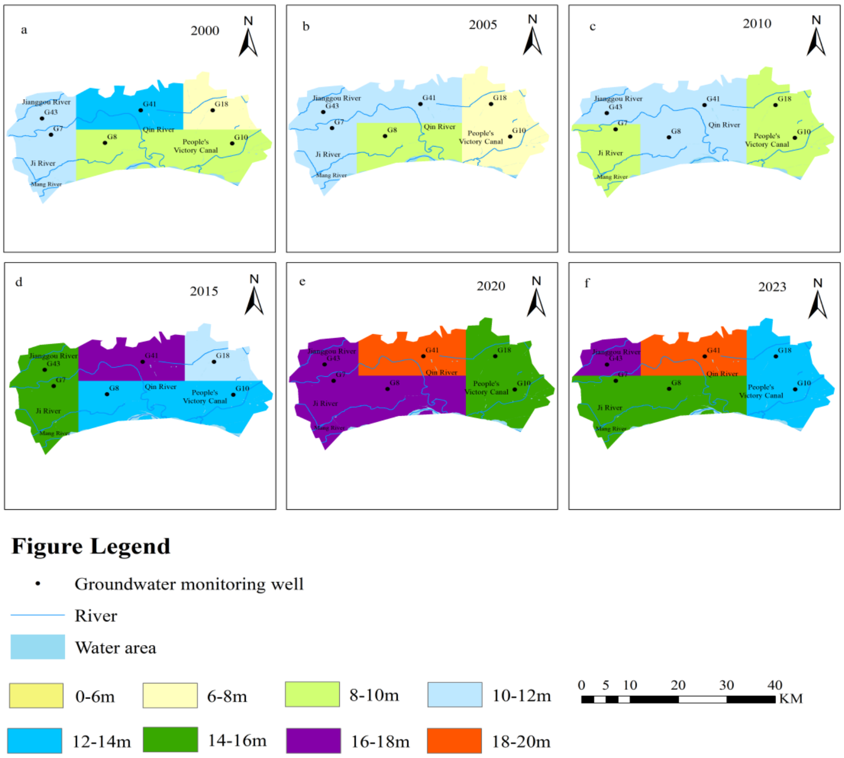
Ground Water Depth (m)	2000		2005		2010		2015		2020		2023	
	Area (km^2)	Percentage (%)	Area (km^2)	Percentage (%)	Area (km^2)	Percentage (%)	Area (km^2)	Percentage (%)	Area (km^2)	Percentage (%)	Area (km^2)	Percentage (%)
<1	0	0	0	0	0	0	0	0	0	0	0	0
13	8.09	0.01	3.92	0.00	13.45	0.02	14.05	0.02	0.11	0.00	0.08	0.00
36	191.03	0.24	161.65	0.20	212.93	0.27	112.84	0.14	32.38	0.04	14.16	0.02
610	202.71	0.25	274.21	0.34	507.27	0.63	377.71	0.47	243.98	0.30	210.13	0.26
1015	337.41	0.42	330.54	0.41	65.30	0.08	269.20	0.34	302.50	0.38	277.96	0.35
1520	61.69	0.08	30.66	0.04	2.02	0.00	27.16	0.03	216.69	0.27	285.94	0.36
>20	0	0	0	0	0	0	0	0	5.26	0.01	12.67	0.02

4.2. Regional Variation Characteristics of Groundwater Depth over the Past Two Decades

The spatial variation of groundwater depth across six time periods (2000, 2005, 2010, 2015, 2020, and 2023) is shown in Figure 4.

The distribution of groundwater depth in 2000 largely reflects the natural pattern of groundwater in the alluvial plain aquifer, controlled by topographic conditions, aquifer storage characteristics, and groundwater recharge conditions. With urbanization and the expansion of builtup areas, groundwater depth has exhibited a yearbyyear increasing trend.2005 vs. 2000:Compared with 2000, the area of the 0–2 m depth range decreased by 51.55%, the 12–14 m range decreased by 36.91%, the 14–16 m range decreased by 42.7%, the 16–18 m range decreased by 64.81%, and the 18–20 m range decreased by 100%. Meanwhile, the area of the 4–6 m range increased by 19.46%, the 6–8 m range increased by 70.12%, the 8–10 m range increased by 18.77%, and the 10–12 m range increased by 24.29%. Overall, groundwater depth in 2005 was greater than that in 2000. 2010 vs. 2005: Compared with 2005, the area of the 0–2 m range increased by 243.11%, the 2–4 m range increased by 156.6%, the 6–8 m range increased by 120.98%, and the 8–10 m range increased by 60.59%. Conversely, the area of the 4–6 m range decreased by 1.07%, the 10–12 m range decreased by 77.77%, the 12–14 m range decreased by 86.7%, the 14–16 m range decreased by 92.7%, and the 16–18 m range decreased by 100%. Overall, groundwater depth in 2010 was lower than that in 2005, indicating a recovery of the water table.2015 vs. 2010: Compared with 2010, the area of the 0–2 m range increased by 4.46%, the 10–12 m range increased by 318.83%, the 12–14 m range increased by 283.58%, and the 14–16 m range increased by 1071.29%. Meanwhile, the area of the 4–6 m range decreased by 50.99%, the 6–8 m range decreased by 41.97%, and the 8–10 m range decreased by 10.21%.2020 vs. 2015: Compared with 2015, the area of the 0–2 m range decreased by 99.22%, the 2–4 m range decreased by 96.95%, the 4–6 m range decreased by 50.34%, the 8–10 m range decreased by 58.94%, and the 10–12 m range decreased by 45.29%. In contrast, the area of the 6–8 m range increased by 3.82%, the 12–14 m range increased by 286.96%, the 14–16 m range increased by 517.37%, and the 16–18 m range increased by 1284.57%.2015 vs. 2010 (additional comparison, likely a repeat or correction):Compared with 2010, the area of the 0–2 m range decreased by 27.27%, the 2–4 m range decreased by 29.68%, the 4–6 m range decreased by 57.61%, and the 10–12 m range decreased by 21.28%. Meanwhile, the area of the 8–10 m range increased by 28.96%, the 12–14 m range increased by 0.75%, the 14–16 m range increased by 17.91%, the 16–18 m range increased by 58.11%, and the 20–22 m range increased by 115.78%.

Fig. 4 Spatial variation of groundwater depth from 2000 to 2023



5. ANALYSIS OF DRIVING FACTORS FOR GROUNDWATER SYSTEM EVOLUTION

5.1. Impact of Anthropogenic Factors

Human activities influence the evolution of groundwater systems primarily through groundwater extraction and changes induced by agricultural water diversion for irrigation[16]. Between 2000 and 2023, the total impervious area in the Wuzhi region increased by 71.90 km², with an average annual growth of 3.59 km². Although the volume of water diverted for irrigation showed little change, the overall cultivated area decreased, leading to a continued upward trend in irrigation water use. The redistribution of surface water during irrigation further altered groundwater recharge and discharge. As irrigation water demand increased and surface water became insufficient, groundwater extraction was relied upon to address seasonal water shortages in irrigation areas. Groundwater extraction rose to 150 million m³, representing an increase of 0.08 times compared to 2003, indicating a relatively minor change.

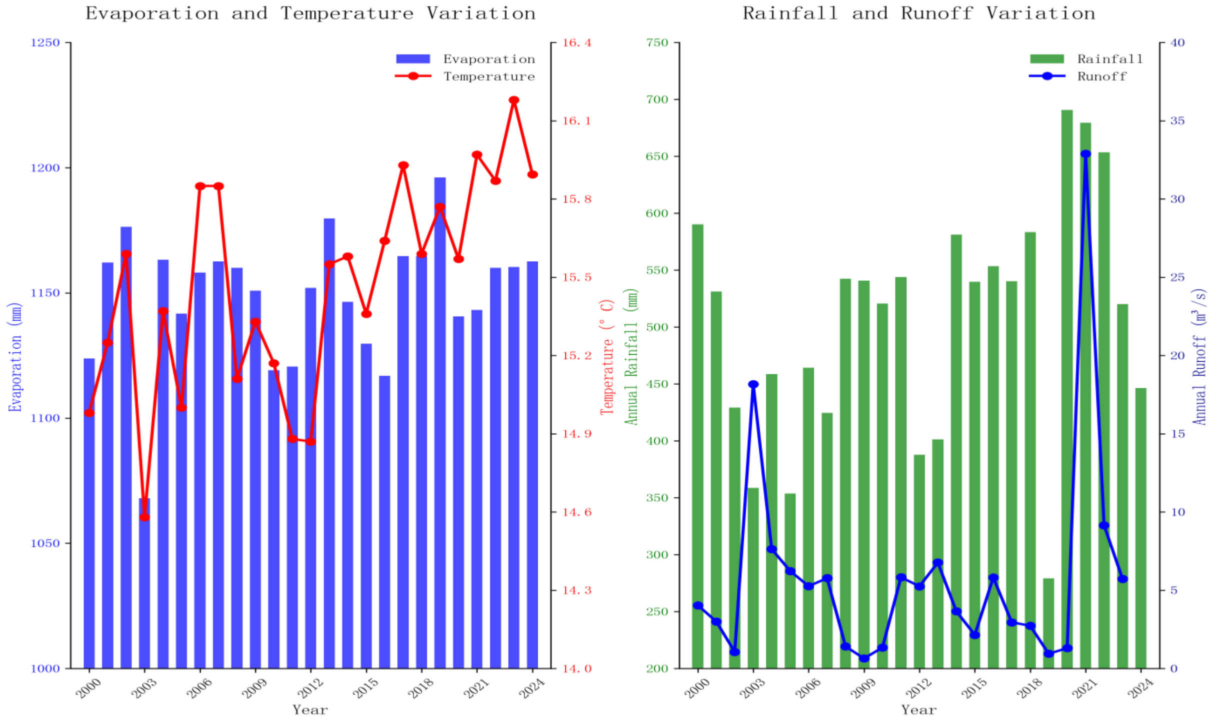


Fig. 5 Annual mean time series of hydrological and meteorological variables

5.2. Degree of Influence of Different Factors

Principal Component Analysis (PCA)[17] was applied to analyze the influence of four meteorological and hydrological factors—temperature, precipitation, evaporation, and average annual runoff—and six human activity factors—irrigation water use, groundwater extraction, total urban and rural water consumption, industrial water use, water supply from diversion projects, and water use for forestry, animal husbandry, and fisheries—on groundwater storage changes from 2000 to 2022. The calculation results indicate that the degree of influence of each factor on groundwater storage changes, in descending order, is as follows: irrigation water use > groundwater extraction > total urban and rural water consumption > industrial water use > average temperature > evapotranspiration > average annual precipitation > water use for forestry, animal husbandry, and fisheries > average annual runoff > water supply from diversion projects. The study area is relatively arid, with most precipitation consumed through evaporation before it can replenish groundwater. The Qin River and the Yellow River are significant sources of groundwater recharge in the region, and they interact with groundwater through repeated exchanges along their courses. However, due to the rapid economic, agricultural, and urban development in the study area, groundwater levels have declined sharply. Additionally, water diversion through canal systems and groundwater extraction have altered the natural recharge processes of groundwater. The findings demonstrate that anthropogenic factors exert a greater influence on groundwater balance changes than meteorological factors.

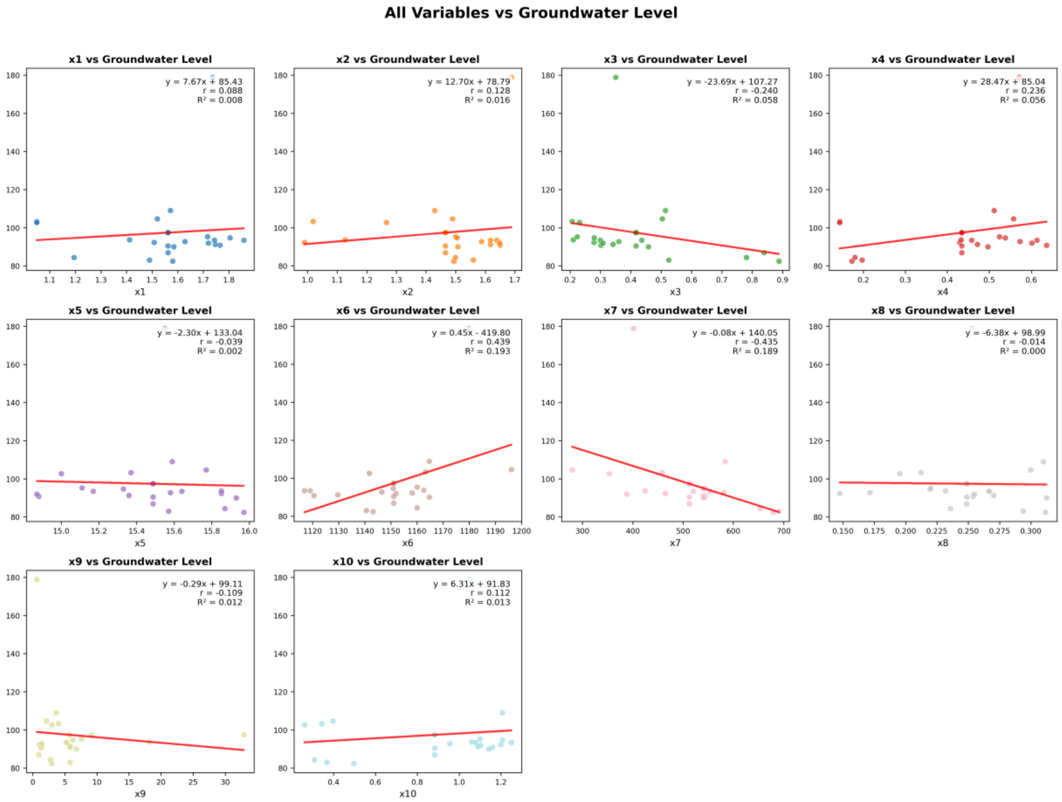


Fig. 6 Correlation matriX of (the) influencing

Based on Figure 6, it can be concluded that among the variables analyzed, evapotranspiration (x6) exhibits the strongest explanatory power, with an R² value of 0.439. This indicates that evapotranspiration alone can account for approximately 43.9% of the variation in groundwater levels. The regression equation reveals a positive correlation between evapotranspiration and groundwater levels, suggesting that for every 1 millimeter increase in evapotranspiration, the predicted groundwater level is expected to rise by about 0.45 meters.

Closely following is annual average rainfall (x7), with an R² value of 0.435, demonstrating explanatory power comparable to that of evapotranspiration. However, the regression equation indicates a counterintuitive relationship: rainfall shows a negative correlation with groundwater levels, meaning that for every 1 millimeter increase in rainfall, the predicted groundwater level actually decreases by about 0.08 meters.

Variables with moderately weak explanatory power include total urban and rural water use (x3, R²=0.246) and industrial water use (x4, R²=0.236). Notably, these two variables exert opposite effects on groundwater levels: an increase in total urban and rural water use leads to a decline in groundwater levels (negative correlation), which aligns with general expectations.

The linear explanatory power of the remaining variables is relatively weak or very limited. Groundwater extraction (x2) has an explanatory power of only 0.138, indicating a weak correlation. Meanwhile, farmland irrigation water use (x1), average temperature (x5), water use for forestry, animal husbandry, and fisheries (x8), water supply from diversion projects (x10), and annual average runoff (x9) all have R² values below 0.1. Among these, runoff has the weakest explanatory power (R²=0.012), suggesting that within a simple linear framework, these variables individually have very limited capacity to explain changes in groundwater levels.

In summary, from the perspective of univariate linear regression, climatic factors (evapotranspiration and rainfall) have the strongest explanatory power for changes in groundwater levels, while the influence of human water use activities is more complex, and the direct linear impact of most individual water use variables is not significant.

Table 4. Eigenvalues and contribution rates of the correlation matriX.

Principal Componet	Eigenvalue	Contribution Rate(%)	Cumulative Contribution Rate(%)
X1	3.25	32.51	32.51
X2	2.37	23.66	56.17
X3	1.42	14.18	70.35
X4	1.13	11.28	81.63
X5	0.89	8.85	90.48
X6	0.36	3.60	94.08
X7	0.26	2.57	96.65
X8	0.20	2.01	98.67
X9	0.08	0.81	99.48
X10	0.05	0.53	100

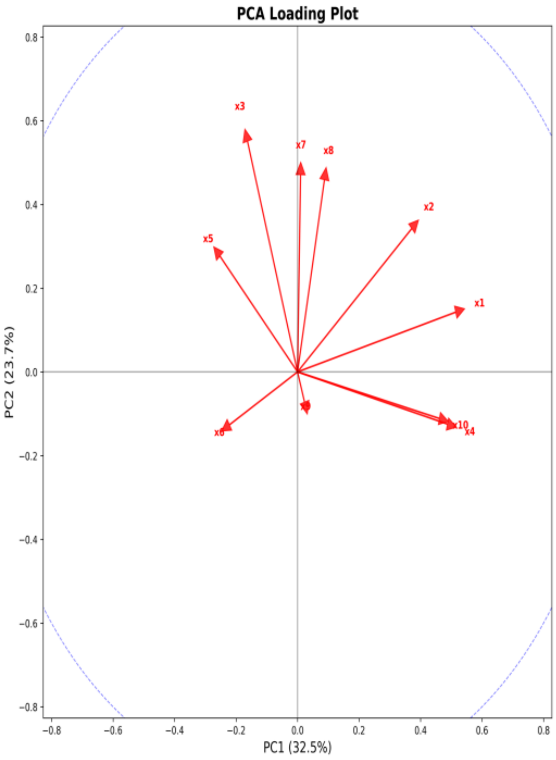


Fig.7 PCA score polt

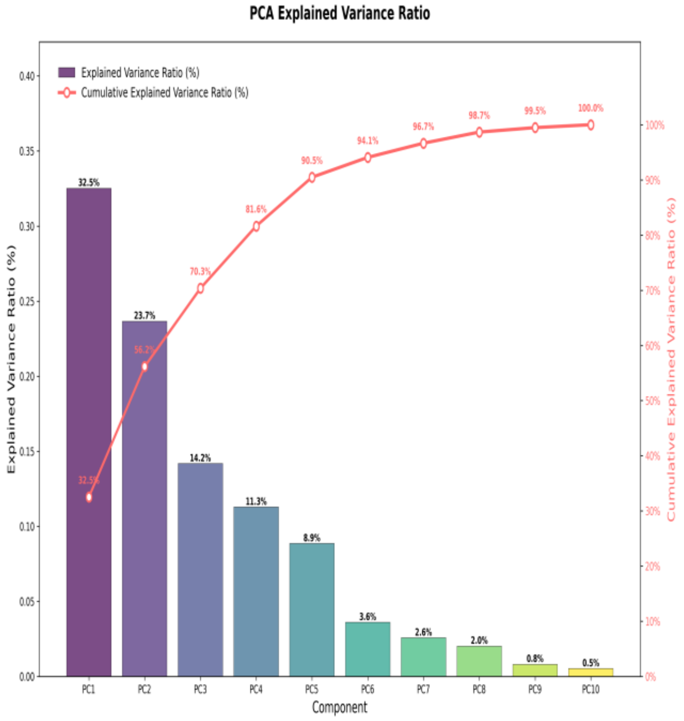


Fig. 8 PCA Explained Variance Ratio

From the above graph(Fig.7andFig.8), the correlation between groundwater levels and influencing factors can be analyzed. Evapotranspiration is the primary influencing factor, exerting a positive correlation with groundwater levels, while annual average rainfall shows a negative correlation, as reduced rainfall leads to a decline in groundwater levels. First Principal Component (PC1: 32.5%): "Human Activity Water Use Intensity"

I. Basic Interpretation: The variance contribution rates are: Z1: 27.84%, Z2: 22.71%, Z3: 16.57%, Z4: 10.36%, Z5: 7.85%. The cumulative contribution rate is 85.33% (the first five principal components together explain 85.33% of the information variation in the original 10 variables, which is a very good result). We assign practical meaning to each principal component based on variables with high loadings (typically absolute value > 0.4).

   1. First Principal Component Z1 (Contribution Rate: 27.84%)

High-loading Variables: X1 Farmland Irrigation (0.5143), X4 Total Urban and Rural Water Use (0.4873), X10 Average Annual Runoff (0.4611).

Designation: "Socioeconomic Water Use and Natural Supply" Composite Component.

Interpretation: This is the most important composite dimension. It shows a positive correlation between core human water use activities (agricultural irrigation, urban and rural domestic use) and the primary natural water resource source (average annual runoff). This reflects a fundamental fact in the study area: socioeconomic water use is highly dependent on the natural supply of surface runoff. A high score for this component indicates a state of "high water demand with relatively abundant water sources".

2. Second Principal Component Z2 (Contribution Rate: 22.71%)

High-loading Variables: X3 Industrial Water Use (0.5513), X7 Evapotranspiration (0.4712), X8 Average Temperature (0.4591).

Designation: "Industry-Climate" Synergy Component.

Interpretation: This is the second largest composite dimension. It closely links industrial water use with climatic factors (high temperature, high evaporation). This strongly suggests that industrial water use in the region (which may include significant cooling water demand) changes synchronously with hot and dry climatic conditions. A high score for this component represents an "industrial water use pattern during hot and dry periods".

3. Third Principal Component Z3 (Contribution Rate: 16.57%)

High-loading Variables: X6 Groundwater Extraction (0.6954), X5 Water Supply from Diversion Projects (0.4013), X7 Evapotranspiration (-0.3813).

Designation: Alternative Water Source Development" Component.

Interpretation: This component is centered on groundwater extraction, positively correlated with water supply from diversion projects, and negatively correlated with evapotranspiration. Its physical meaning is very clear: when the climate is dry (strong evaporation) and surface water may be insufficient, the system simultaneously increases groundwater extraction and inter-regional water diversion to compensate for the shortage. This component is an indicator of the "coping strategy" under water resource stress.

4. Fourth Principal Component Z4 (Contribution Rate: 10.36%) High-loading Variables: X9 Average Annual Rainfall (0.7908). Designation: "Pure Rainfall" Component.

Interpretation: This component is almost entirely dominated by average annual rainfall, representing a highly pure climatic input signal. It is independent of other water use activities and represents the most fundamental natural climatic driving factor of the water resource system.

5. Fifth Principal Component Z5 (Contribution Rate: 7.85%)

High-loading Variables: X9 Average Annual Rainfall (0.5283), X8 Average Temperature (0.4852), X5 Water Supply from Diversion Projects (-0.4002), X10 Average Annual Runoff (-0.3505).

Designation: "Climatic Abundance vs. Engineering Dependence" Antagonistic Component.

Interpretation: This component has an interesting structure. One end represents abundant climatic conditions (high rainfall, high temperature possibly promoting snowmelt, etc.), and the other end represents dependence on artificial diversion projects (negative sign). It may reveal two different modes of water resource abundance: one is reliance on natural conditions (good local climate, abundant rainfall and runoff), where the demand for diversion projects is low; the other is average climatic conditions but reliance on engineered water transfer. A high score for this component leans more towards the "climatically abundant" type.

II. Comprehensive Analysis: The Role of Human and Natural Factors

Based on the above interpretation, we can conclude:

1. System drivers are highly coupled: The first three principal components (cumulative contribution rate 67.12%) are not "pure" human or natural components; they are all couplings of human activities and natural conditions. Z1 couples water use with runoff, Z2 couples industry with climate, and Z3 couples groundwater/diversion with climatic aridity. This proves that in the study area, human factors and meteorological factors cannot be viewed in isolation; they jointly shape the state of the water resource system in synergistic or antagonistic ways.
2. "Pure" signals exist in secondary components: The relatively "pure" natural climatic signal (Z4 rainfall) and the complex antagonistic pattern (Z5) appear in the fourth and fifth principal components. The variance they explain (18.21%) is much smaller than that of the first three coupled components. This indicates that individual climate variables or simple patterns are insufficient to explain most of the system's variation.
3. Inference regarding "impact on groundwater level":

If we assume that the variance contribution rate of a principal component approximately represents its influence on the entire system (including groundwater level), then the influence of coupled components is far greater than that of single factors.

Of particular note is Z3 (Alternative Water Source Development). If our goal is to understand changes in groundwater level, Z3 is the most direct indicator because it is directly dominated by groundwater extraction (0.6954), and its formation logic (strong evaporation -> increased extraction) conforms to hydrogeological principles. An increase in the Z3 score likely corresponds directly to a decline in groundwater level.

Z1 and Z2 indirectly affect groundwater extraction decisions by influencing the overall water supply-demand balance, thereby having a secondary impact on groundwater level.

III. Key Conclusions:

1. Dominant Pattern: The core characteristic of the water resource system in the study area (accounting for about 67% of the variation) is the deep coupling between socioeconomic water use and natural climatic conditions, manifested in three main coupling modes: "water use dependent on runoff", "industry linked to hot-dry conditions", and "water shortage triggering alternative sources".
2. Natural vs. Human Role: There is no simple conclusion that "meteorological factors have a greater influence than human factors". The two are intertwined and act together as the main drivers of the system. Human water demand arises within a climatic context, and climatic conditions, in turn, shape human water use behavior by affecting water sources and demand.
3. Key Driver of Groundwater Extraction: Groundwater extraction behavior itself is most strongly associated with the Z3 component. That is, it is a compensatory water source strategy activated in the context of strong evapotranspiration (a drought climate signal) alongside water diversion projects.Therefore, the direct lever for controlling groundwater levels is managing the "drought-contingency extraction" mechanism revealed by Z3.

6. CONCLUSION

Based on the Mann–Kendall trend test and geostatistical analysis of groundwater data from 2000 onward in the Wuzhi area, this study concludes that groundwater depth has generally increased, with a steeper rise during dry seasons. Spatially, areas of increasing groundwater depth have gradually shifted from discharge zones toward recharge zones in alluvial–proluvial fans. Since 2000, groundwater depth has risen significantly across most of the region, expanding from alluvial plains to gravelly and fine-soil plains.

The primary driver of groundwater-level variation is climate, particularly precipitation and evapotranspiration. However, human activities—including urbanization, surface-water regulation, groundwater extraction, and land-use change—have increasingly altered recharge mechanisms and intensified groundwater-system stress over the past two decades. These factors complicate surface–groundwater interactions and dominate recent spatiotemporal changes in the groundwater system.Integrated management of surface and groundwater, along with coordinated allocation of land and water resources along river corridors, is essential for ensuring long-term groundwater security in inland river basins such as this study area.

REFERENCES

[1] Liu Jinghang. Hydrological Regime Changes in the Main Stream of the Yellow River and Study on Its Ecological Flow. 2021, North China University of Water Resources and Electric Power.

[2] Wang, H., et al. Combined effects of multiland use decisions and climate change on waterrelated ecosystem services in Northeast China. Journal of Environmental Management, 2022, 315: 115131.

[3] Niu Yuguo & Zhang Jinpeng. Constructing a Yellow River Water Network to Promote Ecological Protection and HighQuality Development of the Yellow River Basin. Water Economy, 2023, 41(2): 14.

[4] Xu Xiong, et al. Environmental Background Values of Shallow Groundwater in the Yellow River Alluvial Plain of Southwestern Shandong. Water Purification Technology, 2023, 42(3): 6774.

[5] Study on Ecological Restoration and Construction Engineering Measures in the Lower Reaches of the Qin River.

[6] Wang, H., et al. Combined effects of multiland use decisions and climate change on waterrelated ecosystem services in Northeast China. Journal of Environmental Management, 2022, 315: 115131.

[7] Analysis of Green Development Level Measurement and Its Evolution Characteristics in the Middle and Lower Reaches of the Yellow River Basin.

[8] Spatial and temporal variation of soil moisture and its influencing factors in Shiyang River Basin under different irrigation scenarios.

[9] Xu Yu, et al. Dynamic Characteristics and Influencing Factors of Shallow Groundwater in the Plain River Network Area of Taihu Basin. Journal of Lake Sciences, 2018, 30(2): 464471.

[10] An Ziyang. Spatiotemporal Variation of Precipitation in Hebei Province Based on Simple Linear Regression and MannKendall Nonparametric Test. Water Resources Science and Cold Region Engineering, 2025, 8(2): 8689.

[11] Spatiotemporal Variation Characteristics of Different Rainfall Levels in Huma County from 1992 to 2020.

[12] Water Quality Assessment of Water Supply Areas Under Interbasin Water Diversion Based on EFDCSWAT Model.

[13] Spatiotemporal Distribution Characteristics of Urban River Water Quality Based on Principal Component Analysis: A Case Study of Cangzhou City.

[14] Groundwater Quality Analysis Based on Principal Component Analysis and ArcGIS.

[15] Multiscale Variation Characteristics of Temperature and Precipitation in Changdu over the Past 40 Years: Interannual, Seasonal, and Monthly Scale Analysis.

[16] Huang He. Study on Spatiotemporal Evolution and Multiobjective Control Management of Groundwater in Jilin Region. 2016, Jilin University.

[17] Du Junpeng, et al. Research on River Water Quality Evaluation Based on Principal Component Analysis and Systematic Clustering Analysis. Technical Supervision of Water Resources, 2022(12): 216220.