Spatiotemporal Variation Characteristics of Groundwater and Influencing Factors in the Yellow River Irrigation District of Shizuishan City, Ningxia (Postprint)

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Date: 2020-12-17T00:00:00+00:00

Abstract

Taking the Yellow River irrigation area of Shizuishan City, Ningxia as the study area, this research analyzes the spatiotemporal distribution of groundwater depth within the irrigation area based on 76 long-term groundwater monitoring wells, using a combined approach of classical statistics and geostatistics, and identifies influencing factors through partial correlation analysis. The results indicate: (1) Over the past 20 years, groundwater depth has exhibited an overall increasing trend with a total increase of 0.09 m, which can be divided into two stages: 1997-2002 showed a gradually decreasing trend with an average annual decrease of 0.037 m · a-1; 2002-2017 showed an increasing trend with an average annual increase of 0.019 m · a-1; (2) Spatially, groundwater depth displays a fan-shaped distribution, with Dawukou District as the origin and the Yellow River as the arc, gradually decreasing from west to east, where monthly spatiotemporal distribution variations are primarily influenced by regional irrigation levels; (3) The spatial structure of groundwater depth conforms to a Gaussian model, with nugget coefficients ranging from 1.39% to 3.08%, indicating strong spatial autocorrelation. Spatial heterogeneity is mainly affected by factors such as the geological structure of the irrigation area itself, as well as recharge and discharge volumes, with the degree of influence in descending order being: agricultural irrigation water withdrawal from the Yellow River > rainfall > evaporation > artificial extraction.

Full Text

Temporal and Spatial Variation Characteristics of Groundwater and Their Influencing Factors in the Yellow River Diversion Irrigation Area of Shizuishan City, Ningxia

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Abstract

Taking the Yellow River diversion irrigation area in Shizuishan City, Ningxia, as the research object, this study analyzed the spatiotemporal distribution characteristics of groundwater depth based on 76 long-term groundwater monitoring wells using a combination of classical statistics and geostatistics. The influencing factors were identified through partial correlation analysis. The results indicate that: (1) From 1997 to 2017, the groundwater depth showed an overall increasing trend with a total rise of 0.09 m, which can be divided into two distinct stages. From 1997 to 2002, the depth gradually decreased at an average rate of 0.037 $m \cdot a^{-1}$, while from 2002 to 2017, it exhibited an increasing trend at an average rate of 0.019 $m \cdot a^{-1}$. (2) The spatial distribution of groundwater depth presents a fan-shaped pattern, with Dawukou District as the origin and the Yellow River forming the arc, gradually decreasing from west to east. The monthly spatiotemporal variations are primarily influenced by regional irrigation practices. (3) The spatial structure of groundwater depth follows a Gaussian model, with nugget coefficients ranging from 1.39% to 3.08%, indicating strong spatial autocorrelation. Spatial heterogeneity is mainly affected by the geological structure of the irrigation area, as well as recharge and discharge conditions. The degree of influence of various factors follows the order: agricultural irrigation water diverted from the Yellow River > precipitation > evaporation > artificial exploitation.

Keywords: depth to groundwater; temporal and spatial variation; influencing factors; Yellow River diversion irrigation area; Shizuishan City

Introduction

Ningxia is located in the arid and water-scarce region of northwestern China. With the rapid development of the ecological economic belt along the Yellow River, water resources from the Yellow River have become increasingly strained, and drought-induced water shortages have severely constrained economic and social development in the irrigation areas. Shizuishan City experiences the lowest precipitation, strongest evaporation, and most severe salinization in the Yinchuan Plain. Currently, salinized cultivated land covers an area of 4.06$\times 10^{4}$ hm^2, accounting for 48.35% of the total cultivated land area.

The fundamental cause of salinization is the high regional groundwater level, and controlling the groundwater depth at a reasonable level is a crucial approach for preventing soil salinization. Meanwhile, with rapid industrial and agricultural development, industrial transformation and upgrading, and accelerated renovation of old industrial bases, water demand has increased dramatically, leading to gradually expanded exploitation of groundwater resources. Among the four groundwater over-exploitation areas in Ningxia, Shizuishan has the most prominent over-exploitation problem.

1.1 Study Area Overview

Shizuishan City is located in northern Ningxia, within the inland region of northwestern China, between 106°39 E, 39°25 N and 105°58 E, 38°21 N. It borders Inner Mongolia across the Yellow River to the east and lies at the eastern foothills of the Helan Mountains to the west, with terrain gradually descending from west to east. The area includes the Helan Mountain region, plain region, and Ordos Plateau region. The plain region comprises the piedmont alluvial-proluvial fan and the Yellow River alluvial-lacustrine plain. The region has a mid-temperate arid climate, with a multi-year average precipitation of 170.42 mm, primarily concentrated in July-September, which accounts for 76.78% of the total annual precipitation. The average annual evaporation is 1160.59 mm. According to 2017 statistics, Shizuishan City had a total cultivated land area of 8.38×10^{4} hm^2, of which 4.06×10^{4} hm^2 was salinized (48.35% of the total). The total water intake in 2017 was 10.235×10^{8} m^3, including 1.047×10^{8} m^3 of groundwater (11.23% of the total). Precipitation, evaporation, irrigation water volume, and artificial exploitation are considered the main factors affecting groundwater depth in the Yellow River diversion irrigation area, though their relative influence varies across different regions. Currently, few studies have investigated the influencing factors of groundwater depth in Shizuishan's Yellow River diversion irrigation area.

1.2 Hydrogeological Conditions

Shizuishan is situated in the Yinchuan Plain fault basin, where Quaternary deposits are widely distributed. Influenced by basement structures, the thickness of Quaternary deposits gradually thins toward the plain margins. The study area can be divided from west to east into a piedmont unconfined aquifer zone and a central-eastern "dual-layer structure" zone. The unconfined aquifer zone consists primarily of coarse-grained blocks, gravel, pebbles, and sandy clay, with strong aquifer permeability, steep terrain, and active groundwater exchange, mainly receiving recharge from bedrock fissure water and vertical infiltration of perennial surface water flows and floods from mountain valleys. The central-eastern "dual-layer structure" plain has flat terrain, fine-grained aquifer lithology, poor permeability, and slow groundwater runoff, with recharge sources including lateral inflow from upstream groundwater, atmospheric precipitation, and vertical infiltration from Yellow River irrigation.

1.3 Data Sources

Groundwater depth data were provided by the Ningxia Hui Autonomous Region Hydrology and Water Resources Survey Bureau. A total of 76 long-term groundwater monitoring wells were installed in the study area [Figure 2: see original paper]. Measurements were taken monthly using a tape and sounding line on the 5th, 15th, and 25th of each month, with each observation repeated three times. The monthly groundwater depth value was calculated as the average of the three observations. Data from 1997 to 2017 at monthly intervals were used for temporal distribution and influencing factor analysis, while data from 2017 at monthly intervals were used for spatial distribution analysis.

1.4 Analytical Methods

SPSS 19.0 software was used for descriptive statistical analysis of groundwater depth and partial correlation analysis of influencing factors. Semivariogram analysis was completed in GS+9.0 software, and Kriging interpolation was performed in the ArcGIS 10.0 Geostatistical Analyst module.

2.1 Temporal Variation Characteristics

2.1.1 Inter-Annual Variation Based on long-term observation data from the monitoring wells, the annual average groundwater depth from 1997 to 2017 showed obvious inter-annual variation, with an overall increasing trend and a total increase of 0.09 m. The entire time series can be divided into two stages: from 1997 to 2002, the depth gradually decreased by 0.22 m (average annual decrease of 0.037 $m \cdot a^{-1}$); from 2002 to 2017, it showed an increasing trend, rising from 1.26 m to 1.57 m (total increase of 0.31 m, average annual increase of 0.019 $m \cdot a^{-1}$) [Figure 3: see original paper].

2.1.2 Intra-Annual Variation The monthly variation of groundwater depth from 1997 to 2017 shows that March has the maximum depth (2.05 m). As temperatures gradually rise and soil thaws, evaporation capacity strengthens, causing the depth to gradually decrease, though with small amplitude, from 2.05 m to 1.70 m by April. With the onset of spring irrigation in May, the depth rapidly decreases, reaching the annual minimum of 1.11 m in July. After irrigation stops in early August, the depth increases to 1.63 m by September. With reduced field irrigation in October, the depth begins to increase again, then rapidly decreases to 0.64 m in November with winter irrigation, and further decreases to 0.59 m in December [Figure 4: see original paper].

2.2 Descriptive Statistical Characteristics

The descriptive statistical characteristics of groundwater depth in Shizuishan City are shown in . The minimum depth across all years was 0.99 m, while the maximum reached 12.39 m. The mean depths for each year were 1.71 m, 1.75 m, 1.63 m, 1.74 m, and 1.75 m, respectively. The coefficient of variation

(Cv) reflects the degree of variation among samples within a population, with Cv < 10% indicating weak variability, 10–100% indicating moderate variability, and Cv > 100% indicating strong variability. The annual Cv values ranged from 3.89% to 4.96%, all indicating weak variability, demonstrating that groundwater depth fluctuations in Shizuishan were relatively small in recent years.

Monthly descriptive statistical characteristics show that the Cv in March was 10.2%, indicating moderate variability, while the Cv in July was 18.8%, indicating strong variability. The Cv values for other months were less than 10%, showing weak variability.

2.3 Spatial Structure Characteristics

Following the principle of higher determination coefficient and smaller residuals, semivariogram analysis was conducted using GS+ software . The nugget value (C_0) represents the proportion of spatial variation caused by random factors, reflecting the degree of spatial variation. A nugget coefficient ($C_0/(C_0+C)$) < 25% indicates strong spatial correlation, 25–75% indicates moderate spatial autocorrelation, and > 75% indicates weak spatial autocorrelation dominated by random variation, making spatial interpolation unsuitable. The results show that both monthly and annual groundwater depths follow a Gaussian model, with nugget coefficients ranging from 1.39% to 3.08%, indicating strong spatial correlation. Spatial heterogeneity is primarily caused by autocorrelated factors (geological structure of the irrigation area, recharge and discharge volumes, etc.).

2.4 Spatial Distribution Characteristics

2.4.1 Annual Average Spatial Distribution Based on the optimal variogram model, the spatial distribution of annual average groundwater depth in Shizuishan City for 2017 was analyzed using Kriging interpolation in ArcGIS [Figure 5: see original paper]. The groundwater depth shows a fan-shaped distribution overall, with Dawukou District as the origin and the Yellow River as the fan-shaped arc, gradually decreasing from west to east. Areas with depth > 3 m are mainly distributed in the alluvial-proluvial fan at the front of the Helan Mountains and in Dawukou District, which is Shizuishan' s industrial concentration area and the location of the groundwater depression cone. Areas with depth of 1–2 m are mainly distributed in the Yellow River irrigation zones of Pingluo County and Huinong District, covering about 70% of the total area, where groundwater remains at a high level due to infiltration recharge from Yellow River irrigation. Areas with depth of 2–3 m are distributed in strips between the > 3 m and 1–2 m zones. Areas with depth < 1 m are mainly distributed in river (Yellow River) and lake (Shahu Lake, etc.) regions.

2.4.2 Monthly Spatial Distribution Characteristics The monthly spatial distribution patterns [Figure 6: see original paper] show that from January to March, as temperatures rise and evaporation capacity increases, the area with depth of 2–3 m gradually expands while the 1–2 m area decreases. With the arrival of the irrigation season, the depth gradually decreases and the 1-2 m area expands accordingly. During the main crop growth period (June-September), with cumulative increases in irrigation water, the 1-2 m area gradually expands while the 2-3 m area decreases. In October, with reduced irrigation, the depth begins to increase and the 1-2 m area decreases. With the start of winter irrigation in November, the depth rapidly decreases again and the 1-2 m area expands quickly. In December, the 1-2 m area dominates, with < 1 m areas scattered sporadically.

The > 3 m depth area is concentrated near Dawukou District, with relatively stable spatial distribution that changes little across months. This area has a unconfined aquifer structure in the west that gradually transitions to a multi-layer unconfined-confined aquifer structure to the east, with strong water yield, good water quality, and easy exploitation, making it the current water source area and main concentrated zone for industrial groundwater use in Shizuishan. Long-term exploitation has formed a groundwater depression cone. Since this area receives less recharge from Yellow River irrigation infiltration and is mainly recharged by bedrock fissure water and mountain valley runoff, its distribution shows little monthly variation. This area should prioritize replacing domestic and industrial groundwater sources to address the depression cone problem. The 1-2 m depth area is mainly distributed in the Yellow River alluvial-lacustrine plain with multi-layer aquifer structures, which is Shizuishan' s primary agricultural irrigation zone. Receiving substantial infiltration recharge from Yellow River irrigation, its monthly distribution is affected by irrigation seasons, with groundwater remaining at high levels and prominent soil salinization problems. Therefore, groundwater exploitation should be intensified and well-canal combined irrigation should be developed to reduce Yellow River irrigation volumes.

2.5 Analysis of Influencing Factors

The dynamic variation of groundwater depth in Shizuishan' s Yellow River diversion irrigation area is comprehensively affected by precipitation, evaporation, Yellow River irrigation, and artificial exploitation. Based on partial correlation analysis between groundwater depth and precipitation, evaporation, Yellow River irrigation water volume, and artificial exploitation volume, the influencing factors were determined. In the analysis, groundwater depth was the target variable, while precipitation, evaporation, Yellow River irrigation water volume, and artificial exploitation volume were independent variables . After eliminating the effects of other variables, the partial correlation coefficients between groundwater depth and precipitation, evaporation, Yellow River irrigation water volume, and artificial exploitation volume were 0.126, 0.089, 0.312, and 0.056, respectively, all significant at the 0.01 level. The influence degree follows the order: agricultural irrigation water from the Yellow River > precipitation > evaporation > artificial exploitation.

3 Discussion and Conclusion

Groundwater is an important regional water resource and a key factor affecting the ecology of irrigation areas. Analyzing its spatiotemporal distribution characteristics and influencing factors is crucial for clarifying sustainable groundwater development and utilization and maintaining ecological groundwater levels. The results show that groundwater depth in the irrigation area has increased steadily in recent years, consistent with findings by Xi Wenjuan in this region. The main reason is the reduced infiltration recharge from Yellow River water due to the vigorous development of water-saving irrigation measures. The intra-annual variation characteristics and descriptive statistics of monthly groundwater depth demonstrate patterns consistent with irrigation-type regimes, further proving that irrigation volume is the primary factor affecting groundwater depth.

Spatial distribution results show that groundwater depth decreases from west to east across the irrigation area. Areas with depth > 3 m are mainly distributed in the alluvial-proluvial fan at the front of the Helan Mountains and around Dawukou District, near the mountain front. This zone has a unconfined aquifer structure in the west that transitions eastward to a multi-layer unconfined-confined structure, with strong water abundance and good water quality that is easy to exploit. Consequently, this area serves as Shizuishan' s current water source and main concentrated zone for industrial groundwater use, forming a groundwater depression cone through long-term exploitation. Since it receives less recharge from Yellow River irrigation infiltration and more from bedrock fissure water and mountain valley runoff, its distribution shows little monthly variation. This area should prioritize completing the replacement of domestic and industrial groundwater sources to reduce exploitation and address the depression cone issue. The 1–2 m depth area is mainly distributed in the Yellow River alluvial-lacustrine plain with multi-layer aquifer structures, which is the primary agricultural irrigation zone. Receiving substantial infiltration recharge from Yellow River irrigation, its monthly distribution is affected by irrigation seasons, with groundwater remaining at high levels and prominent soil salinization problems. Therefore, groundwater exploitation should be intensified and well-canal combined irrigation developed to reduce Yellow River irrigation volumes.

Spatial structure analysis indicates that groundwater depth in the irrigation area has strong spatial autocorrelation, with spatial heterogeneity mainly caused by variations in the geological structure and recharge/discharge conditions. The influencing factor analysis shows that the degree of impact follows the order: Yellow River irrigation water > precipitation > evaporation > artificial exploitation. Yellow River irrigation water has the greatest impact while artificial exploitation has the smallest, primarily because Yellow River water is the main water source for the irrigation area, with an annual intake of 9.19×10^{8} m^3 (89.77% of total water use), mainly for agricultural irrigation (8.49×10^{8} m^3). The sum of canal seepage and field infiltration recharge accounts for 76.7% of total groundwater recharge in Shizuishan, while groundwater extraction is only

1.047$\times 10^{8}$ m^3 (10.23% of total water use), and phreatic evaporation accounts for 18.84% of total groundwater discharge. This indicates significant potential for groundwater exploitation. Currently, groundwater extraction accounts for 2.19%, 56.88%, and 91.72% of agricultural, industrial, and urban domestic water use, respectively, showing a small proportion for agriculture. In the future, well-canal combined irrigation should be vigorously promoted to increase groundwater use for agricultural irrigation.

This paper provides relevant recommendations for groundwater resource management in the irrigation area, but these are relatively general. Future research should combine Shizuishan' s economic and social development plans, consider regional water supply security and saline land prevention requirements, and develop a groundwater exploitation zoning plan focused on regional groundwater environmental protection and sustainable utilization.

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Note: Figure translations are in progress. See original paper for figures.