Optimization of Well Layout Based on Spatial Variability of Groundwater

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Abstract. Due to the invisibility of the groundwater environment and the anisotropy and heterogeneity of the water medium, its resource environmental functions and pollution issues have long been overlooked and underestimated. Human activities have already had a severe impact on groundwater. To address groundwater issues in Huimin County, Shandong Province, 63 groundwater samples were collected and tested. Kriging interpolation, geostatistical methods, and cluster analysis were used to analyze the statistical characteristics of monitoring data, groundwater chemical types, spatial distribution of groundwater, and influencing factors. In addition, GIS spatial analysis and water quality-water level dynamic methods were combined to assess the suitability of groundwater extraction. The analysis results indicate that the main ions exceeding standards in Huimin County's groundwater are chloride (Cl−), sulfate (SO2−4), and nitrate (NO−3). There is a notable spatial heterogeneity in groundwater quality, with nitrate's spatial variation influenced by structural factors (such as topography and hydrology) and random factors (such as industrial and agricultural activities), among which nitrate's spatial variation is the most significant. Most ion concentrations gradually decrease from northwest to southeast, with overall water quality in the southeastern region being better than in the northwestern region. The spatial distribution of water table depth is influenced by topography, and potential development areas for extraction are primarily located in the western part of Shimiaozhen and parts of Sangluoxu Town, which account for only 12% of the study area. Limited extraction zones are mainly located in the central and northern parts of the study area, making up the largest proportion of the study area at 46.1%.

Keywords: Groundwater, Spatial variability, Mineability.

1. Introduction

Groundwater is the largest available source of fresh water globally [1]and constitutes a significant part of water resources. Human activities have severely impacted groundwater, leading to serious water resource depletion issues in aquifers in regions such as the North China Plain [2]. To address the phenomenon of excessive groundwater extraction in many areas, it is crucial to study the patterns of groundwater change and distribution to understand regional groundwater volume, formulate water resource management policies, and rationally exploit groundwater [3, 4].

Geostatistical methods, based on traditional statistics, examine the spatial distribution and variation of variables. Since groundwater observational data are often spatially dispersed, geostatistical methods are commonly used to analyze the spatial heterogeneity and patterns of groundwater [5, 6]. Many scholars have utilized the combination of GIS and geostatistics to study spatial heterogeneity in vegetation, groundwater, and soil [7-9], especially in arid and semi-arid regions such as the Heihe River Basin, the Sangong River Basin, and the Shiyang River Basin [10-12]. Geostatistical methods have been widely applied in water-scarce regions of northwest China, but there has been limited in-depth research on the spatial heterogeneity, patterns, and changes in groundwater levels in eastern China. Additionally, comprehensive studies on the ecological processes caused by these spatial structures and patterns have not been conducted. Over-extraction of groundwater can lead to the formation of cone of depression zones, causing a series of environmental deterioration issues such as land subsidence, saltwater intrusion, and water quality degradation. It is crucial to clearly understand the current status of groundwater extraction. For instance, Yang Yingjia and others analyzed the spatio-temporal variations of groundwater depth and extractability in the Mihe River Basin, evaluating the suitability of groundwater extraction [13]. Similarly, Li Wenti and others divided groundwater extraction zones in the Hebei Plain region according to different degrees of extraction and analyzed the extent of over-extraction [14]. While many studies have focused on the spatio-temporal variation characteristics of groundwater depth, scientific and rational evaluation of the suitability of groundwater extraction and optimization of well layout in many regions remain underexplored.

This study uses a combination of GIS spatial analysis and geostatistical methods to assess groundwater quality. Based on the spatial variability of groundwater quality and the changes in water table depth, a water quality-water level dynamic coupling method is used to evaluate the suitability of groundwater extraction and optimize the layout of extraction wells in the study area. The goal is to provide scientific evidence for the sustainable use of regional groundwater and the protection of the groundwater environment.

2. Materials and Methods

2.1. Overview of the Study Area

Huimin County is situated between 117°17′ and 117°49′ east longitude and 37°6′ and 37°35′ north latitude (Figure 1). It is located in northern Shandong Province, China, and is part of the western North China Plain, formed by the Yellow River alluvial deposits. The terrain generally slopes from southwest to northeast. The topography features a mix of flat plains, slopes, hills, and low-lying areas, with gentle slopes covering the largest area. Geologically, Huimin County lies in a subsidence zone of the North China Craton. Historical migration and flooding of the Yellow River have led to significant sediment deposition, resulting in loose geological structures (with a permeable surface layer, a water-bearing middle layer, and an impermeable lower layer), providing favorable geological conditions for groundwater storage. The precipitation in Huimin County is characterized by significant interannual variability and uneven distribution throughout the year. The flood season accounts for 63% of the annual precipitation, while the irrigation season accounts for 27%.

2.2. Sample Acquisition

Taking into account groundwater extraction and factors such as rivers and lakes, and adhering to the principle of vertical distribution along the main river, the sampling density in the northern urban area where the industrial park is located was appropriately increased. In March 2023, 63 sets of groundwater samples were collected. Most of them were taken from daily-use wells in shallow groundwater reserves. The samples were collected and immediately sealed with glue, then stored in low-temperature insulated boxes. The distribution of sampling points is shown in Figure 2. The collection of groundwater samples, on-site monitoring, sample management, monitoring projects, analysis methods, laboratory analysis, and quality control strictly follow the "Technical Specification for Groundwater Environmental Monitoring" (HJ/T 164-2004). The detection methods for salt ions (K+, Na+, Ca2+, Mg2+, SO2−4, Cl−, and HCO−3) are titration methods, and the detection method for NO−3 is ion chromatography. The aforementioned analyses and tests were completed in the Shandong Key Laboratory of Water Resources and Water Environment.

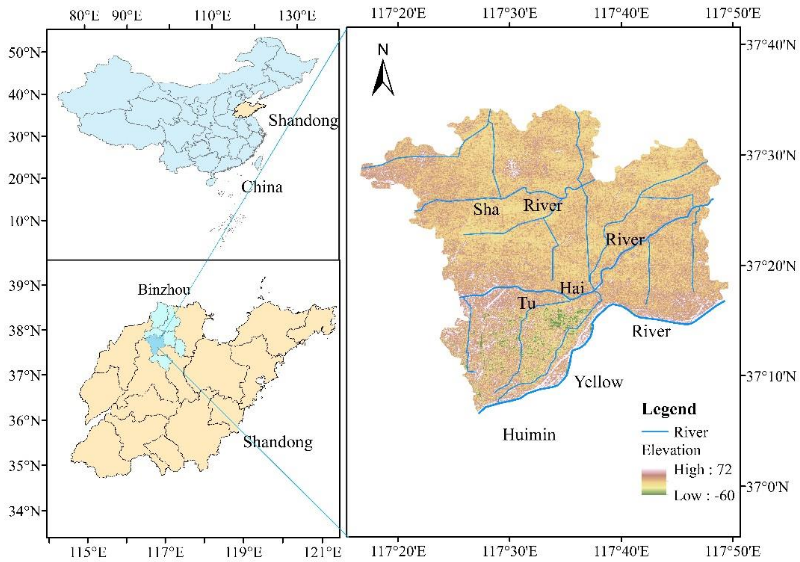

Figure 1. Location of Huimin County

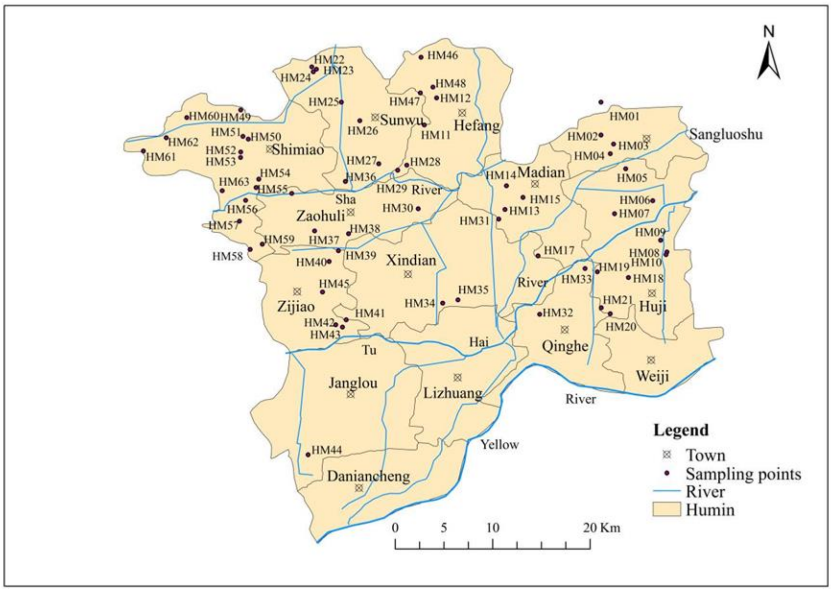

Figure 2. Sampling point distribution map

2.3. Methods

2.3.1. Semivariogram Function

The semivariance function is the most commonly used tool in spatial correlation analysis. It not only reflects the random variation of spatial variables but also their spatial correlated variation [15]. The semivariance function is a function of the spatial distance between data sampling points and their semivariance value. Assuming the regionalized variable satisfies the assumptions of second-order stationarity and intrinsic hypothesis, its calculation formula is as follows:

$$r(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [Z(x_i) - Z(x_i + h)]^2$$

In the formula, r (h) is the semi variance function, h is the spatial distance of the sampling points, Z (xi) is the value of the regional variation Z (x) at spatial position Xi, Z (xi+h) is the sample value of the regional variation Z (x) at spatial position Xi+h, N (h) is the number of sampling points with spatial distance h.

2.3.2. Kriging Interpolation

Kriging interpolation, also known as spatial local interpolation, is based on the theory of variogram and structural analysis, and is a major research focus in geostatistics. Kriging interpolation primarily relies on known observation points within a limited neighborhood of the unknown observation point. It fully considers the shape, size, and orientation of the observation points, as well as the spatial relationship between known and unknown observation points. By leveraging the structural characteristics of the variogram of regional variables, it provides unbiased and optimal estimation for the unknown observation points [16].

2.3.3. Cluster Analysis

Cluster analysis is an unsupervised learning method aimed at exploring the inherent structure in data and discovering patterns and groups in the data without the need for predefined categories. As an effective big data analysis tool, cluster analysis is widely used in fields such as economics, biology, and artificial intelligence [17]. Q-type cluster analysis uses monitoring indicators of each sample as variables to analyze the relationships between samples. Calculations were performed using SPSS Statistics 26.0 software, employing squared Euclidean distance and between-group linkage methods. The clustering index was the groundwater depth at monitoring wells.

2.3.4. Water Quality Water Level Dynamic Coupling Method

Water level dynamic method refers to the division of the suitability of extraction zones based on the annual average rate of decline in groundwater levels and the current year's groundwater depth [18]. The water quality-water level dynamic method involves dividing the suitability of groundwater extraction based on the water level dynamic method and incorporating groundwater indicators, combining water level and water quality changes.

Raster calculation involves performing spatial function analysis on multiple raster data sets; reclassification is the restructuring of original raster data according to new classification standards to produce a set of new values [19]. In this study, the reclassification and raster calculation functions in ArcGIS were used to divide the suitability of extraction zones in the study area. First, the spatial distribution map of groundwater depth in 2020 in the study area was reclassified into three categories: depth <2.0 m, assigned a value of 1; depth between 2.0 m and 3.0 m, assigned a value of 2; and depth >3.0 m, assigned a value of 3.Next, the raster calculator was used to compute the annual average rate of change in groundwater depth in the study area and reclassify it into three categories: areas with a rate of change less than 0 m/year, assigned a value of 4; areas with a rate of change between 0 and 1 m/year, assigned a value of 5; and areas with a rate of change greater than 1 m/year, assigned a value of 6. Finally, the new reclassified raster data were calculated (2020 groundwater depth reclassification data × groundwater depth rate of change reclassification data × Cl^- concentration reclassification data). The new results were then reclassified into four categories to obtain the recommendation map for the suitability of groundwater extraction in the study area.

3. Results and Discussion

3.1. Chemical Types of Groundwater

Through statistical analysis of the chemical analysis results of 63 water samples from Huimin County using a Piper diagram, the major chemical types and compositional characteristics of the groundwater were revealed. The primary types were identified as HCO3•Cl-Ca•Na and HCO3-Ca•Na. These two types dominated the chemical composition of the groundwater, exhibiting relatively complex ion combinations. In these two main types, Ca2+ and Na+ were the predominant cations, present in higher concentrations. This suggests that the groundwater contains significant amounts of calcium and sodium elements, which may be related to the nature and composition of the geological layers the groundwater passes through. In particular, carbonate rocks could be a possible geological layer, as such rocks are typically rich in Ca2+ and HCO3−. These two components may be released into the groundwater through hydrogeological processes and physicochemical reactions, influencing the ion composition of the groundwater. On the other hand, HCO3− and Cl− were the primary anions, with relatively high concentrations. This indicates that the groundwater is rich in bicarbonate and chloride ions, which may be associated with the source of the groundwater, the characteristics of the geological layers it flows through, and interactions between groundwater and subsurface rocks. Notably, the analysis of the Piper diagram also revealed higher concentrations of Na+ and Cl− in some areas of the groundwater, which could indicate the possibility of seawater intrusion. This phenomenon may be caused by the lowering of groundwater levels due to groundwater extraction, leading to seawater infiltrating the groundwater system and impacting the ion composition of the groundwater.

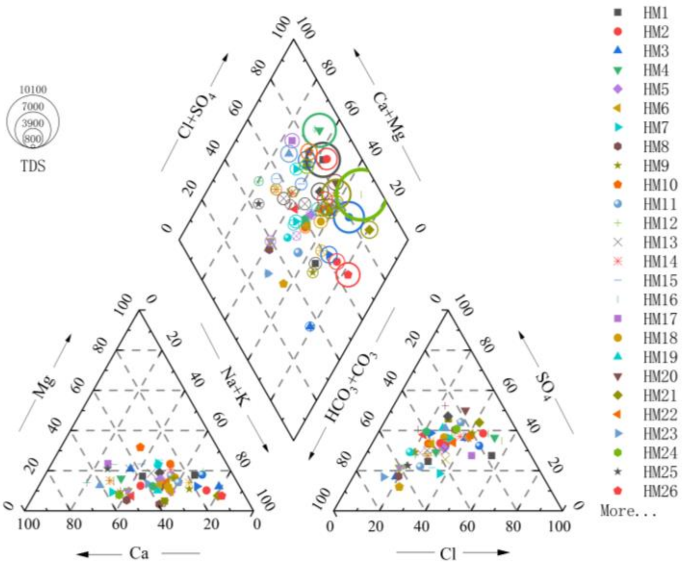

Figure 3. Piper chart of groundwater quality in Huimin County

3.2. The Spatial Variation Characteristics of Groundwater Environmental Indicators

The presence of various elements in groundwater holds significant hydrochemical meaning for water quality. The ions K+, Na+, Ca2+, Mg2+, SO2−4, Cl−, NO−3, and HCO−3 not only indicate the level of mineralization in the groundwater but also reflect key hydrogeological characteristics such as the permeability of aquifers, water residence time, and flow conditions. The relationships among these ions can also serve as key indicators for assessing the extent of groundwater pollution. Through comprehensive data analysis, the main ions in the study area that exceeded water quality standards included Cl−, SO2−4, and NO−3, with NO−3 showing particularly significant variation. The concentrations of ions generally decreased from northeast to southwest, revealing a geographical trend in water quality distribution. The southwestern region demonstrated better water quality compared to the northeastern region. Additionally, fluoride concentrations gradually increased from north to south, which may be associated with an increase in industrial enterprises in the southern region, leading to higher fluoride concentrations in surface wastewater. This fluoridated industrial wastewater percolates downwards through the surface, causing elevated fluoride concentrations in shallow groundwater, thereby affecting the water quality characteristics of the groundwater.

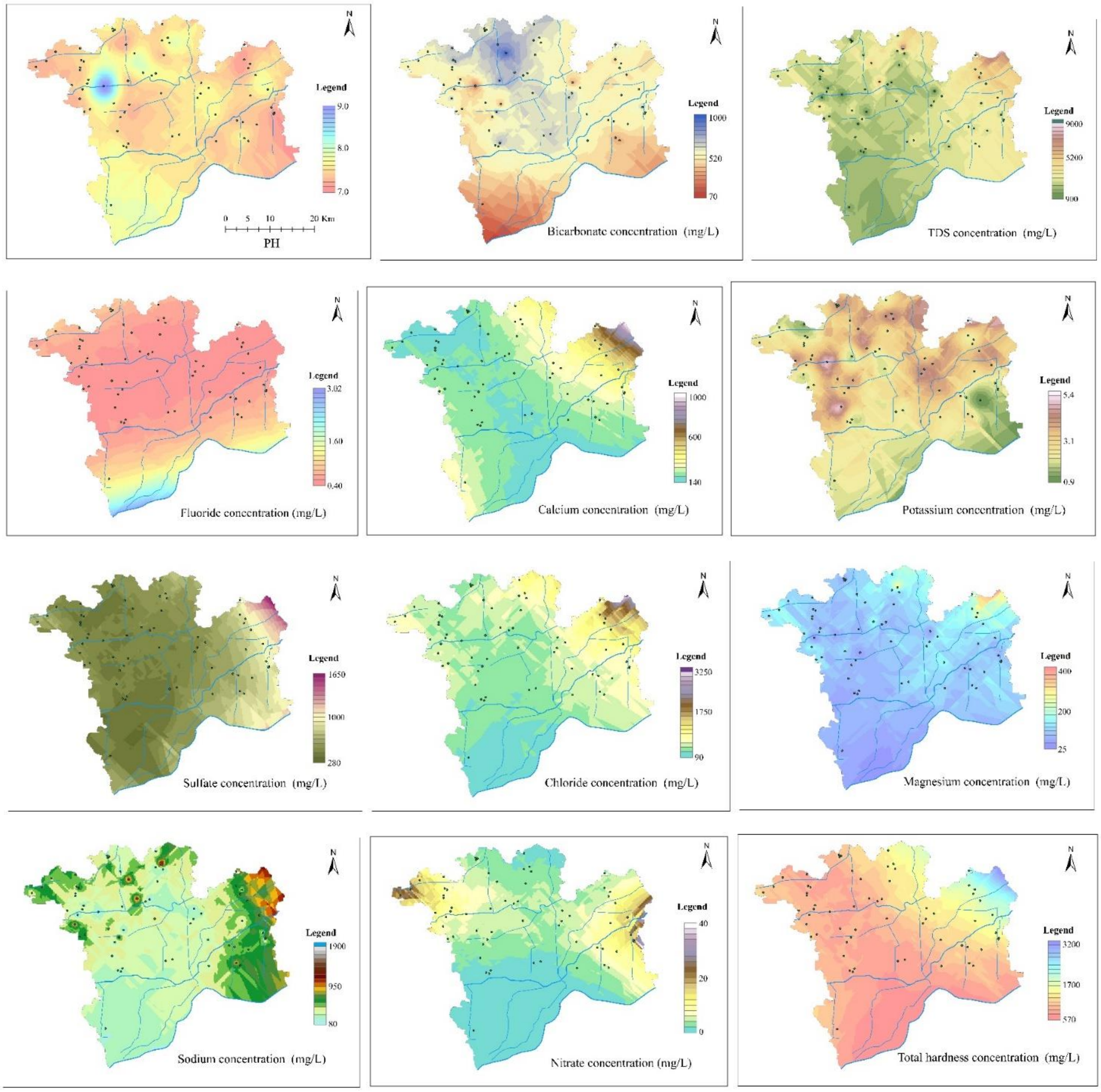

Figure 4. Spatial distribution map of groundwater quality in Huimin County

3.3. Spatial Variation Characteristics of Groundwater Environmental Indicators

Spherical and Gaussian models were used to fit the semivariogram of each water quality indicator. Table 1 lists the semivariogram parameters for each water quality indicator, including the nugget effect (nugget value/base value). The nugget effect represents the degree of spatial variability; a larger nugget value (the non-continuous variation of regionalized variables at scales smaller than the observation scale) indicates a higher degree of spatial variability caused by random factors (such as urban development, farmland, cropping systems, and irrigation intensity), while a smaller value suggests that the spatial variability is primarily due to structural factors (such as topography, geomorphology, hydrology, and soil). Based on the classification of spatial correlation of regionalized variables, when $C_0/(C+C_0)$ is less than 0.25, the spatial variable has strong spatial correlation. When the value is between 0.25 and 0.75, it indicates moderate spatial correlation, while a value greater than 0.75 indicates weak spatial correlation. If $C_0/(C+C_0)$ is close to 1, it suggests that the spatial variability of the variable is stable across the entire scale and has constant spatial variability. From Table 1 and the figures, it can be seen that the nugget values for each water quality indicator are positive, indicating the presence of measurement error, systematic error, short-distance variation, and other random factors causing the nugget effect, although the nugget effect is relatively weak. The ratio for NO−3 falls between 0.25 and 0.75, indicating moderate spatial correlation, with its spatial variation influenced by both structural and random factors. The remaining water quality indicators all have values less than 0.25, indicating strong spatial correlation, with their spatial variability primarily caused by structural factors.

Table 1. Theoretical models and corresponding parameters of semi variogram functions for various water quality indicators

Water quality index	Theory model	Nugget C_0	Partial sill $C+C_0$	Nugget/Partial sill $C_0/(C+C_0)$	Rang
Cl-	Gaussian	0.0430	0.4870	0.0883	883
NO-3	Spherical	0.3200	1.2510	0.2558	1120
SO2-4	Spherical	0.0030	0.3900	0.0077	1250
HCO-3	Gaussian	0.0001	0.1902	0.0005	2234
F-	Gaussian	0.0408	0.2576	0.1584	1888
K+	Spherical	0.0307	0.2904	0.1057	3900
Na+	Spherical	0.0550	0.5170	0.1064	1180
Ca2+	Spherical	0.0001	0.2562	0.0004	1190
Mg2+	Spherical	0.0570	0.5310	0.1073	1930
TDS	Gaussian	0.0377	0.2394	0.1575	1022
Total hardness	Gaussian	0.0295	0.2600	0.1135	1126
COD	Spherical	0.0001	0.2682	0.0004	2440

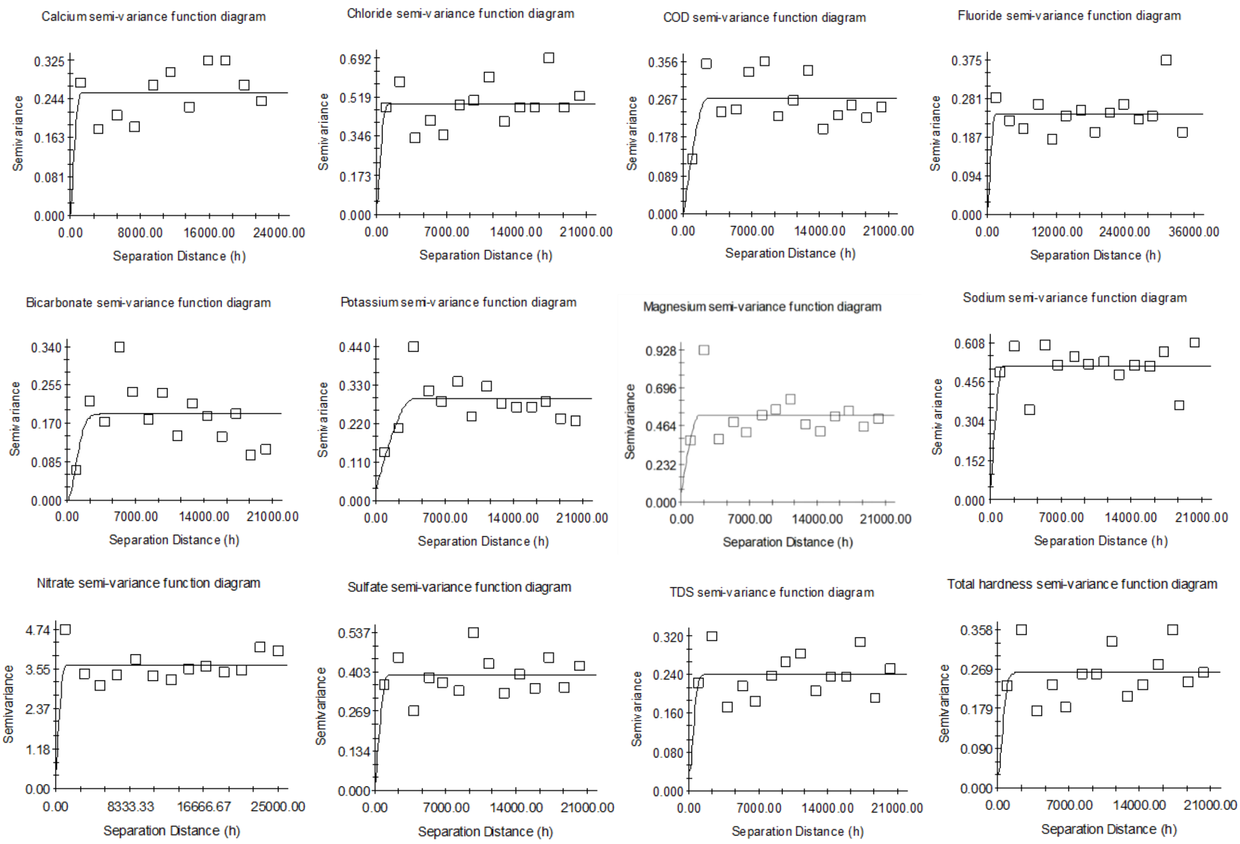

Figure 5. Semi-variogram function of each indicator of groundwater in Huimin County

3.4. Dynamic Variation Characteristics of Groundwater Depth

This study selected groundwater depth data from 29 groundwater monitoring wells in Shandong Province (as shown in the figure) for the period from 2011 to 2020. The control area for each well was calculated using the Thiessen polygon method, and the annual average groundwater depth was obtained by weighting the data and averaging it. Then, the annual variation of groundwater depth over the years, as well as the groundwater extraction volume and precipitation, were plotted. From the figure, it can be seen that the average annual precipitation in Huimin County from 2011 to 2020 was 575.2 mm, with a maximum annual precipitation of 790.1 mm in 2013 and a minimum of 460.4 mm in 2014. The interannual variation in precipitation in Huimin County is characterized by alternating wet and dry years, with a large wet period observed since 2011. The annual average groundwater extraction volume was 1,672.4 mm, fluctuating between 699 mm in 2019 and 2,547 mm in 2018. The annual precipitation shows a very slow upward trend, while the annual extraction volume shows a rapid upward trend, followed by a sharp decline in 2019, likely due to groundwater management measures at the time. Overall, the dynamic changes in groundwater depth across different years in the monitoring wells, in relation to precipitation and extraction volume, can be seen in the figures below. The trend in groundwater depth dynamics in Huimin County is mainly of the type "rise-fall-rise," with a gradual overall increase. The groundwater depth increased from 2.16 m in 2011 to 3.05 m in 2020, with an average rate of increase of 0.089 m/year. Notably, the significant rainfall in 2013 and the lower extraction volume in the plain area led to a rise in water levels. From 2016 to 2020, the groundwater depth ranged between 2.24 and 3.05 m, with a gradually slowing rate of increase. In 2019, the actual extraction volume decreased significantly, leading to a rise in groundwater levels. The changes in groundwater depth are primarily influenced by atmospheric precipitation infiltration, natural evapotranspiration, and artificial extraction, and exhibit a clear seasonal cycle.

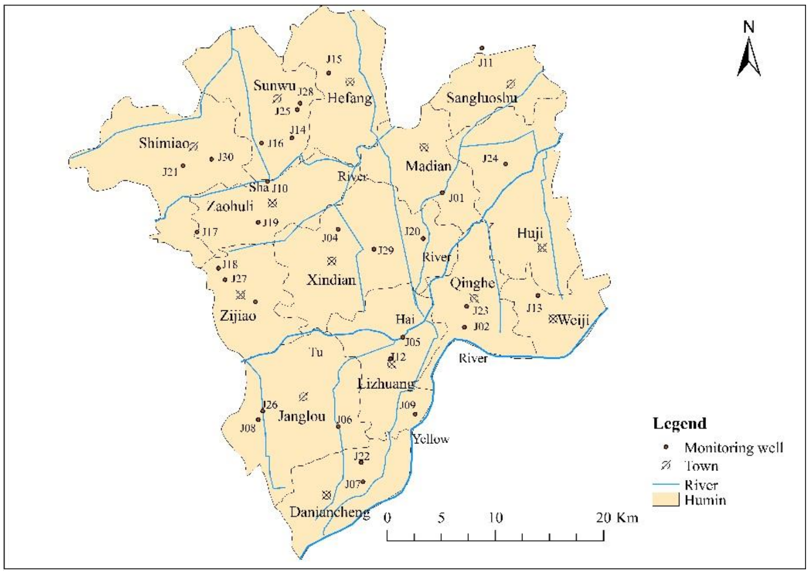

Figure 6. Distribution map of monitoring wells in Huimin County

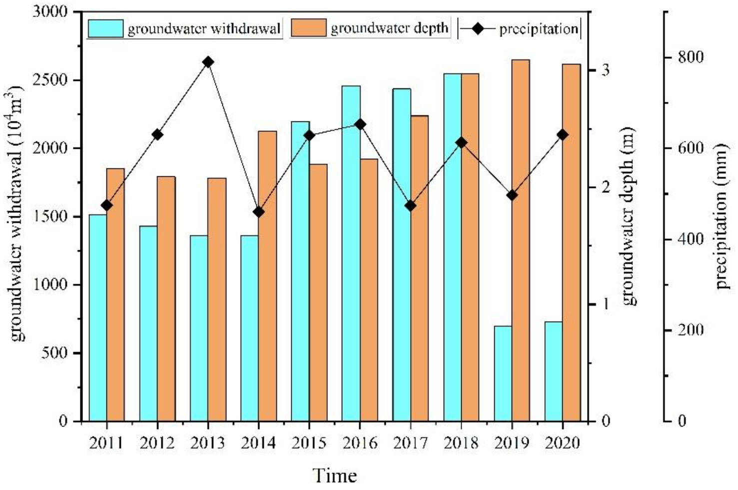

Figure 7. Precipitation - burial depth – mining map in Huimin County

Q-type cluster analysis can be used to analyze groundwater depth by considering water table depth as a variable and comparing the changes in water table depth within the study area across different years. This allows for a clearer understanding of the spatiotemporal distribution characteristics of groundwater depth. By conducting Q-type cluster analysis on groundwater depth in the study area, a cluster analysis dendrogram was obtained.

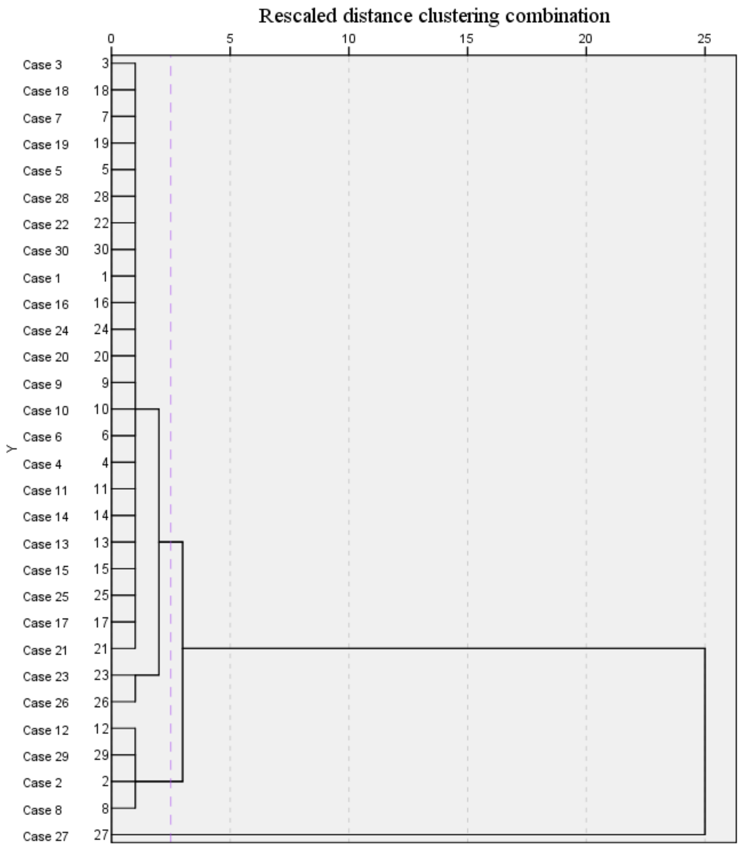

Figure 8. Cluster analysis lineage diagram in Huimin County

The clustering results reflect the differences and similarities in groundwater depth. From the figure 7, it can be observed that when the inter-cluster distance is set to 15, the water table depth is divided into two major categories: I and II. When the inter-cluster distance is set to 8, the first major category can be further divided into I-1 and I-2, and the second major category can be further divided into II-1 and II-2. The second major category includes monitoring wells J06, J12, J21, J27, and J29, while the remaining monitoring wells fall into the first major category. Overall, the groundwater depth in the second major category is greater than that in the first major category, and its annual rate of change in depth is also higher. J27 can be independently classified into its own category, with the corresponding monitoring well located in Lizhuang Town, Huimin County. Monitoring wells J06, J12, J21, and J29 can be grouped into a subcategory, but these monitoring wells are spatially dispersed, with only J06 and J12 being relatively close to each other, located in the southern part of the study area. The rapid rate of change in groundwater depth in this area may be due to its proximity to the Yellow River region, where the water quality is relatively poor, with high salinity and alkalinity, which can lead to soil salinization. High levels of water extraction for nearby agricultural irrigation may also contribute to the large rate of decline in water levels.

Using ArcGIS, the study period from 2011 to 2020 was analyzed to examine groundwater depth and its rate of change from 2011 to 2020. This analysis was used to create a spatial distribution map of groundwater depth and a map showing the rate of change in groundwater depth within the study area. The Thiessen polygon method was employed to calculate areas and create a groundwater map, with monitoring well depth and chloride concentration marked on the map. The specific analysis results can be seen in the figures.

From Figure 9, it is evident that groundwater depths in the Huimin County region are generally greater than 1.6 m, with a small portion of areas having depths ranging from 3.4 m to 7 m. Areas with depths greater than 7 m make up only a small portion of the region and are primarily concentrated in the northwestern part of Shimiaozhen. Figure 10 shows that regions with significant rates of change in groundwater depth in the Huimin County plain area are mainly distributed in the southern part of Lizhuang Town.Figure 11 reveals that regions with potential for exploitation are primarily located in the western part of Shimiaozhen and parts of Sangluoxu Town, accounting for 12.0% of the study area. Suitable extraction zones are mainly in the southwestern part of the study area, including Zijiao Town, Xindian Town, Jianglou Town, and Daanchen Town, as well as parts of Sangluoxu Town.Limited extraction zones are mainly located in the central and northern parts of the study area, including Sunwu Street, Hefang Street, Zaohuli Town, Madian Town, and Hujizhen. These areas constitute the largest portion of the study area, covering 46.1%.In the southeastern part of the study area, mainly including Lizhuang Town, Qinghe Town, and Weiji Town, groundwater extraction should be prohibited, with the closure of some private wells and measures taken to protect and utilize groundwater resources reasonably.

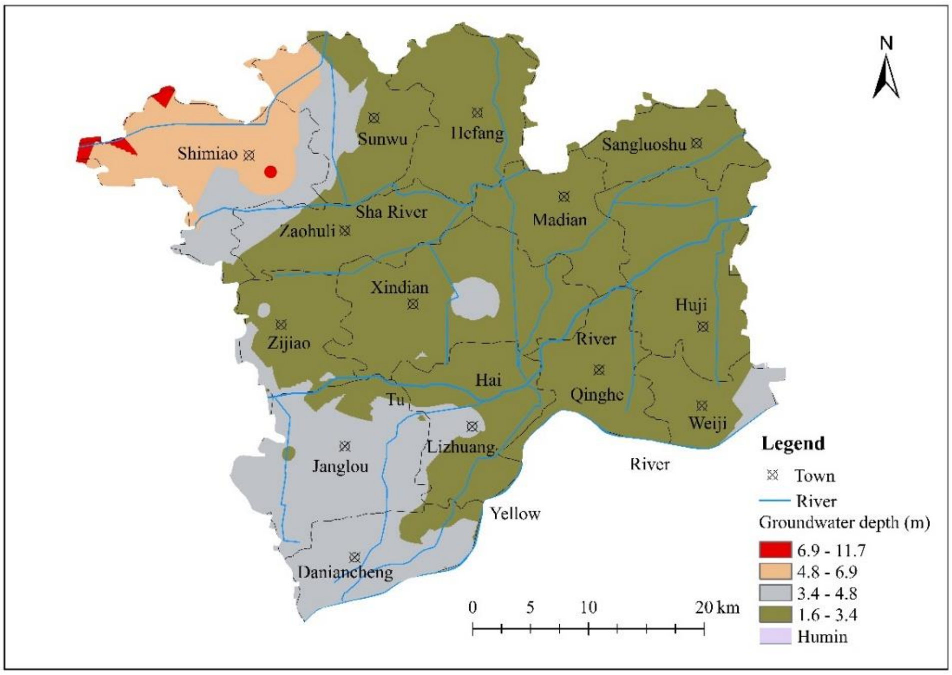

Figure 9. Distribution map of groundwater depth in the current level year (2019)

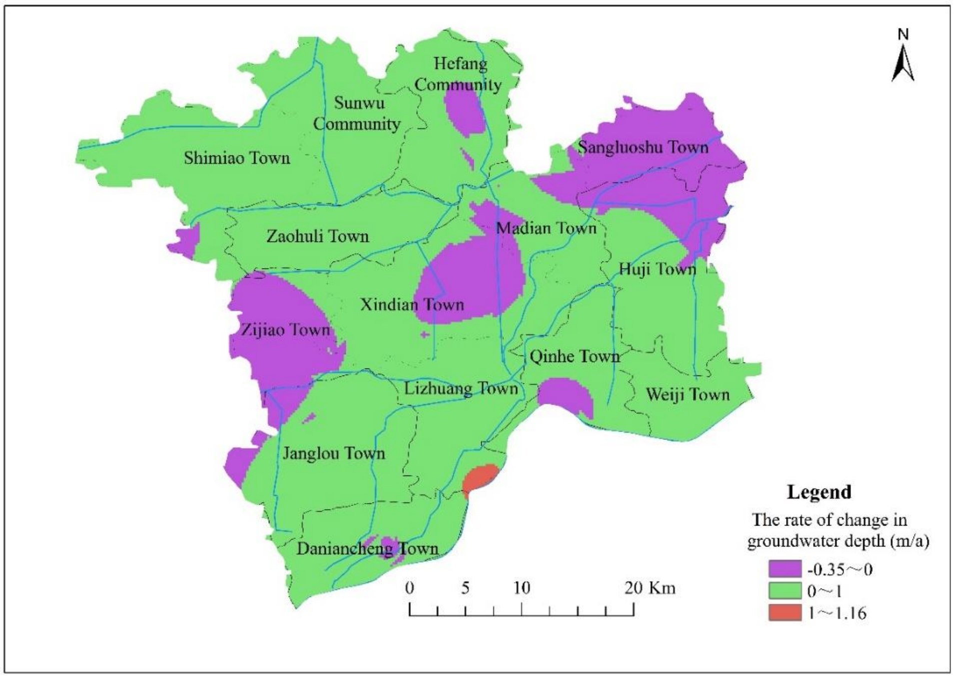

Figure 10. Changes in groundwater depth in Huimin County

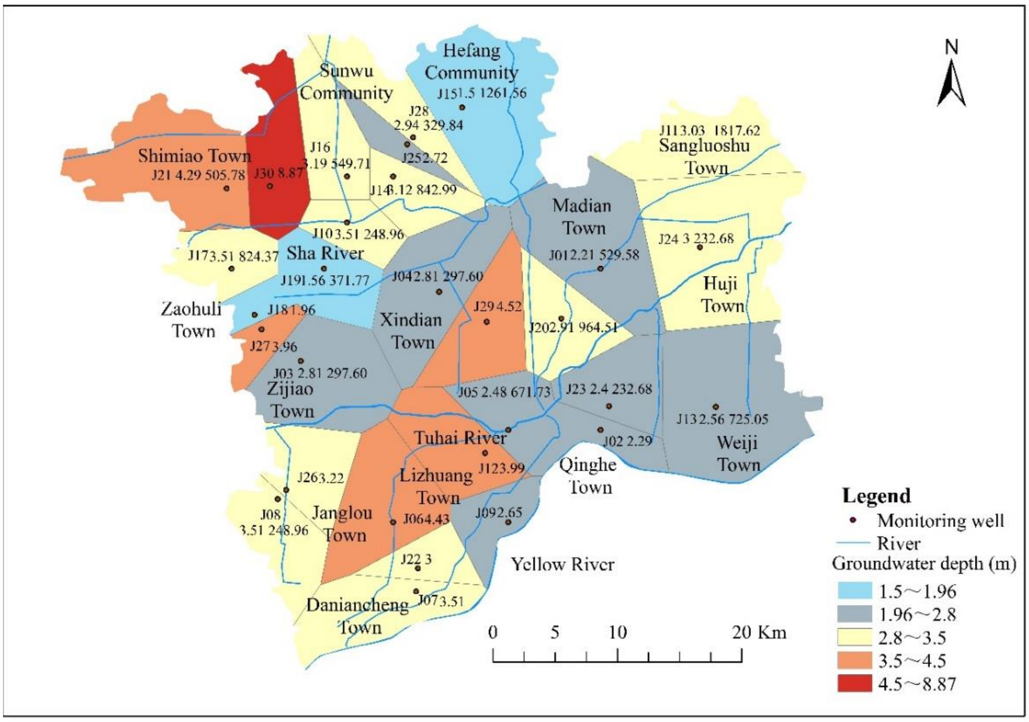

Figure 11. Suggested map of exploitable groundwater in Huimin County

4. Conclusion

This study evaluates the suitability of groundwater extraction in Huimin County by analyzing groundwater chemical types, spatial distribution, and influencing factors, and by combining GIS and water quality-water level dynamic methods to divide suitable extraction zones. The specific conclusions are as follows:

The groundwater in Huimin County mainly exhibits two major chemical types: HCO3•Cl-Ca•Na and HCO3-Ca•Na. The primary cations are Ca^{2+} and Na^{+}, while the primary anions are HCO_3^{-} and

Cl^-. High concentrations of Ca^{2+} and HCO_3^- may be related to the composition of the aquifer groups, particularly carbonate rocks that are rich in Ca^{2+} and HCO_3^-. These components may be released into the groundwater through physicochemical reactions. Additionally, high levels of Na^+ and Cl^- may be associated with seawater intrusion into the groundwater. Overall, the chemical characteristics of Huimin County's groundwater are influenced by geological structures and hydrogeological conditions, which have important implications for the management and protection of groundwater resources.

The study reveals significant spatial heterogeneity in the groundwater quality of Huimin County. Among the main ions, Cl^-, SO_4^{2-}, and NO_3^- exceed standards, with NO_3^- showing particularly significant concentration changes. Overall, ion concentrations decrease from northeast to southwest, indicating a decreasing trend in water quality across the geographic space, with better water quality in the southwest compared to the northeast. Moreover, fluoride concentrations gradually increase from north to south, possibly influenced by the increase in industrial enterprises in the southern region, leading to higher concentrations of fluoride in surface wastewater. These fluoridated industrial wastewaters percolate downward, causing elevated fluoride concentrations in shallow groundwater, which impacts groundwater quality characteristics.

Based on the analysis of groundwater depth in Huimin County, the study found clear spatial variability. Regions with potential extraction value are mainly distributed in the western part of Shimiaozhen and parts of Sangluoxu Town, accounting for 12.0% of the entire study area. Suitable extraction zones are mainly distributed in the southwestern part of the study area, including Zijiao Town, Xindian Town, Jianglou Town, and Daanchen Town, with parts of Sangluoxu Town also classified as suitable extraction zones. In contrast, limited extraction zones are primarily located in the central and northern parts of the study area, including Sunwu Street, Hefang Street, Zaohuli Town, Madian Town, and Hujizhen. These zones make up the largest portion of the study area, covering 46.1%. However, in the southeastern part of the study area, including Lizhuang Town, Qinghe Town, and Weiji Town, groundwater extraction is recommended to be prohibited, with some private wells closed and measures taken to reasonably protect and effectively utilize groundwater resources. These conclusions provide useful guidance for the sustainable management of groundwater resources.

Acknowledgments

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References

[1] Taylor R G, Scanlon B, Döll P, et al. Groundwater and climate change [J]. Nature Climate Change, 2013, 3(4): 322-329.

[2] Dalin C, Wada Y, Kastner T, et al. Groundwater depletion embedded in international food trade [J]. Nature, 2017, 543(7647): 700-704.

[3] Hu Ruji. Natural Geography of China Tianshan [M]. Beijing: China Environmental Science Press, 2004. (in Chinese)

[4] Alley W M, Taylor C J. The value of long-term groundwater level monitoring [J]. Ground Water, 2010, 39(6): 801-801.

[5] Pebesma E J, Kwaadsteniet J W D. Mapping groundwater quality in the Netherlands [J]. Journal of Hydrology, 1997, 200: 364-386.

[6] Wang Zhengquan. Geostatistics and Its Application in Ecology [M]. Beijing: Science Press, 1999. (in Chinese)

[7] Li Heng, Liu Hong, Li Youguo, et al. Spatial variability and influencing factors of nutrient elements in purple soil in the Mesozoic red bed area of Xichang [J]. Advances in Earth Science, 2022, 37(6): 627-640. (in Chinese)

[8] Zhang Jingjing, Wei Chuanjiang, Shen Xiaojing, Yao Yizhen, Jia Feng. Spatial heterogeneity analysis of groundwater depth in Jilin City based on GIS [J]. Journal of Water Resources and Water Engineering, 2018, 29(2): 97-103. (in Chinese)

[9] Zhang Zhijian, Liu Yuanqiu, Wu Chunsheng, Li Xiaodong, Liu Liangying, Li Yingwen. Spatial distribution characteristics of forest soil nutrients in Jiangxi Province based on geostatistics and GIS [J]. Research of Soil and Water Conservation, 2018, 25(1). (in Chinese).

[10] Su Litan, Song Yudong, Marina Jumakeld. Influence of groundwater level change on vegetation coverage and their spatial variation in arid regions [J]. Journal of Geographical Sciences, 2004, 14(3): 323-329.

[11] Li Xiaoyu, Song Dongmei, Xiao Duning. Temporal and spatial variation of groundwater mineralization degree in Minqin Oasis downstream of Shiyang River [J]. Acta Geographica Sinica, 2005, 60(2): 319-327. (in Chinese)

[12] Zhao Chuanyan, Li Shoubo, Jia Yanhong, Jiang Yunchao. Coupling simulation of groundwater fluctuation belt and groundwater-vegetation dynamics in the lower reaches of the Heihe River [J]. Chinese Journal of Applied Ecology, 2008, 19(12): 2687-2692. (in Chinese)

[13] Yang Yingjia, Zhang Danrong, Zhuang Huibo, et al. Spatial and temporal variation characteristics and exploitable analysis of groundwater depth in the plain area of the Mihe River Basin [J]. Journal of Water Resources and Water Engineering, 2019, 30(6): 102-108. (in Chinese)

[14] Li Wenti, Liu Xianghua, Feng Qiancheng. Division and analysis of over-exploitation of groundwater in Hebei Province [J]. Water Resources Protection, 2001, 17(4): 26-30 + 72. (in Chinese)

[15] Anctil F, Mathieu R, Parent L É, Viau A, Sbih M, Hessami M. (2002) Geostatistics of near-surface moisture in bare cultivated organic soils [J]. J Hydrol 260(1-4):0-37, 30.

[16] Shi Z, Yan HZ, Bi C, Deng L. (2017) Surface water quality monitoring in town based on Geotatistics-Kriging interpolation [J]. Chin J Environ Eng 11(04):2607–2613 (in Chinese).

[17] Liu Hui, Sun Siao, Wang Jing, et al. Spatial characteristics and factor identification of water quality exceedance in concentrated urban domestic water source areas of the Yellow River Basin [J]. Geographical Research, 2023, 42(12): 3264-3277. (in Chinese)

[18] Guo Xiuhong, Zhao Hui. Discussion on division of over-exploitation areas of groundwater [J]. China Water Resources, 2015(1): 41-43. (in Chinese)

[19] Wu Xiuqin. ArcGIS 9 Geographic Information System Application and Practice [M]. Beijing: Tsinghua University Press, 2007. (in Chinese)