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Groundwater Dynamics and Vulnerability Analysis — A Case Study of Xuchang

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ABSTRACT

In recent years, the quantity and quality of water resources play an increasingly important role in economic development, social progress and people's healthy life, etc. The situation of water resources directly affects the scale of urban development and the development pattern of regional economy. Based on the DRASTIC model assessment, the groundwater dynamics and vulnerability in Xuchang City are analyzed. The results show that the change of shallow groundwater level is consistent with the change of precipitation on the whole, and the groundwater level drops due to the excessive exploitation in successive years. The change of middle and deep groundwater level is mainly affected by artificial exploitation, and the water level decreases year by year. Due to the implementation of mining restrictions around 2000, the shallow and middle deep water levels recovered slightly. The groundwater vulnerability level in Xuchang City is poor to good, and the vulnerability zoning results gradually increase from northwest to southeast, which is related to the lithology and permeability coefficient of the vasses zone.

KEYWORDS

Groundwater dynamics; Groundwater vulnerability; DRASTIC evaluation model.

1. INTRODUCTION

The study of groundwater dynamics and equilibrium is of great significance for groundwater research, understanding hydrogeological conditions, evaluating groundwater, and the exploitation and protection of water resources. The study of groundwater dynamics often requires a long period of time to grasp the regularity, so the importance of groundwater dynamics and equilibrium work should be correctly recognized at all stages of groundwater exploration. Margat (1968) first proposed the professional term "groundwater vulnerability". With the continuous deepening of research, the connotation of this term has been continuously enriched and improved by later generations[1]. The research on groundwater vulnerability by international hydrogeologists can be traced back to the 1970s, while domestic research began relatively late, starting in the mid-1990s. Although the research started late, it has developed rapidly. Yan Mingjiang (2006) explored the impact of groundwater vulnerability on human activities in the Hufu Plain of North China[2]. Li Qiao (2014) used groundwater vulnerability assessment to study the spatio-temporal evolution of groundwater quality in the plain area of the Junggar Basin[3]. Li Zijun (2021) conducted a groundwater vulnerability assessment of the Jinghe River Basin and explored the evolution law of regional water resources[4]. This paper mainly analyzes and discusses the groundwater level dynamics and groundwater vulnerability of Xuchang City based on the groundwater monitoring data collected in recent years and starting from the hydrogeological conditions of Xuchang City. Based on the analysis results of groundwater dynamics and vulnerability in the Xuchang area, suggestions for the sustainable utilization and development of water resources in Xuchang are proposed, providing a reasonable scientific basis for the protection of groundwater resources.

2. PHYSICAL GEOGRAPHY

Xuchang is located in central Henan Province. It is located in the Huang-Huai-hai Plain area of Central China, east of Funiu Mountains and east of Songshan Mountains. The main rivers in the city include Yinghe River, Shuangji River and the middle route of the South-to-North water diversion canal. The slope of Xuchang City is generally high in the west and low in the east. The landform is mainly plain, and a few hills are distributed in the west of Xuchang and Xiangcheng and Yuzhou in the northwest. Xuchang City is in the temperate monsoon climate zone, with precipitation concentrated in summer and rare in winter. The average annual rainfall is 700mm. There are four major rivers flowing through the city, namely Yinghe River, Beiru River, Shuangji River and Qingyihe River. The North Ruhe River originates from the western Funiu Mountain region, and the Yinghe River originates from the Songshan region. The outcrop strata in the city are divided into middle Proterozoic, Lower Proterozoic, Cambrian, Carboniferous, Permian, Upper Tertiary and Quaternary. Xuchang City is located in the southwest part of the Middle Chaohuai platform, a grade IV tectonic unit (North China depression tectonic unit), Songjiqiongfold faulted, and its structural features are mainly folds and faults. The groundwater in Xuchang City can be divided into four types: loose rock pore water, carbonate rock karst water, clastic rock fissure water and bedrock fissure water according to the occurrence of groundwater, hydrochemical characteristics, rock mechanical properties and aquifer types and properties.

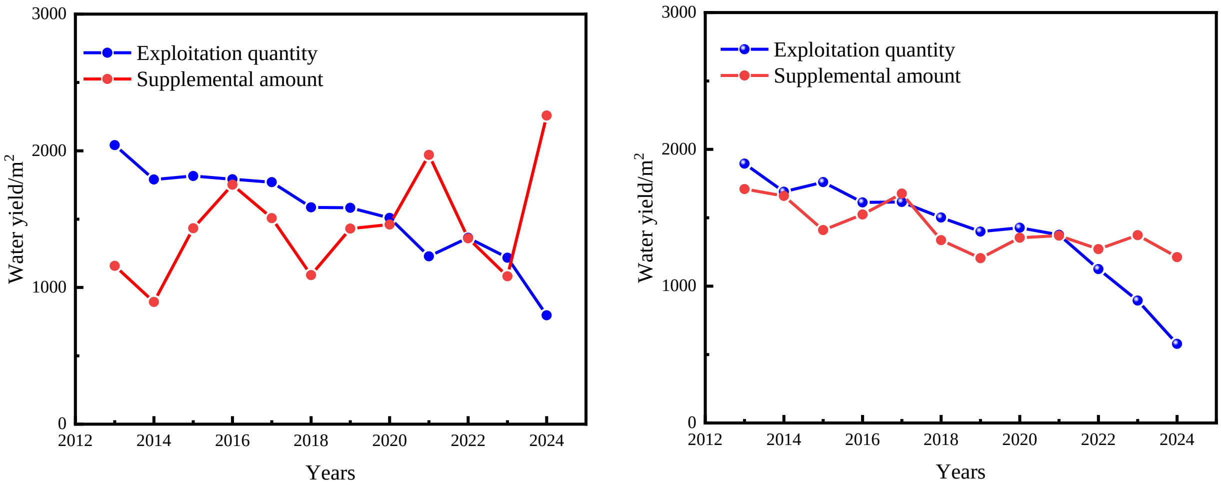
3. DYNAMIC ANALYSIS OF GROUNDWATER LEVEL

According to the annual survey data of buried depth of groundwater level from 2013 to 2024 (Table 1) and the relationship between mined and replenished (Figure 1), the buried depth of shallow groundwater level in dry season is 8 ~ 11m, and that of groundwater level in flood season is 7 ~ 9m, the annual average buried depth is 8.26m, and the maximum buried depth can reach 11m. As can be seen from Table 1, the large-scale development of shallow groundwater from 2013 to 2015 resulted in a significant decrease in water level, which increased from 6.71m buried depth in 2013 to 8.59m in 2015, an increase of 3.17m compared with the maximum depth reduction in 2013. From 2017 to 2020, the amount of extracted water decreased, and the overextracted water value also slightly decreased in general. In 2019, the overextracted water was 1,521,300 m3, which decreased by 3,443,100 m3 compared with 2018. The shallow groundwater has the lowest overextraction in 2020, with an overextraction of 480,800 m^3, and the groundwater level has significantly recovered, but it has not recovered to the level of ten years ago due to continued mining in excess of the maximum limit.

Between 2013 and 2018, there was an overall downward trend in the deep water table, which was caused by the extraction of large quantities of water from deep storage that could not be supplied sustainably. After 2018, the deep groundwater level began to rise year by year, from the annual average water level of 47.71m in 2019 to 52.18m in 2023, with an increase of 9.3%. This is mainly due to the development and utilization of new water sources to alleviate the contradiction between supply and demand of urban water. In 2024, no overmining was found, and the net recharge was 14.6116 million m^3, which caused the groundwater level to recover and rise to the maximum in recent years. From the data of groundwater survey over the years, it can be seen that the buried depth of deep groundwater level is 45 ~ 70m, the maximum buried depth of water level in dry season appeared in 2016, the maximum value was 58.97m, the minimum value was 49.62m in 2019, and the maximum buried depth of water level appeared in 2013, the maximum value was 57.43m. The smallest value occurred in 2019, with a minimum value of 47.63m. In 2016, 2017, 2019, 2021 and 2024, the buried depth of the groundwater table in the dry season is greater than that in the wet season, and the groundwater table in the dry season of other years is higher than that in the wet season. Therefore, it can be seen that the seasonal and multi-year changes of the dynamic changes of the deep water table are not significant.

Table 1. Lists of historical surveys of middle and deep groundwater

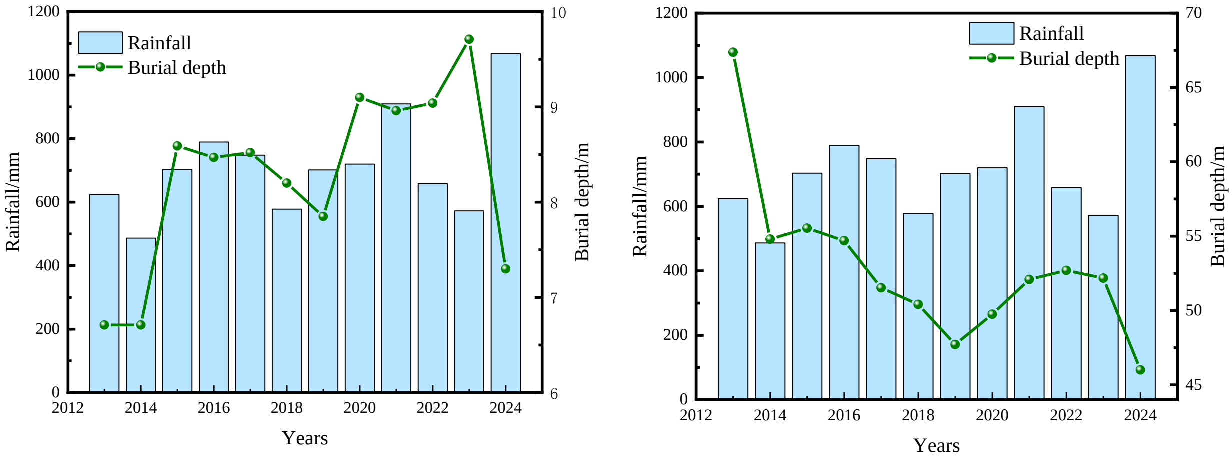
Years	Rainfall /mm	Shallow water			Deep water		
		Buried depth of water level /m					
		Average	Dry season	Wet season	Average	Dry season	Wet season
2013	623.80	6.71	8.79	7.62	67.37	52.25	57.43
2014	486.60	6.71	8.46	8.71	54.80	55.53	56.73
2015	703.20	8.59	8.78	8.60	55.54	57.28	57.38
2016	789.20	8.47	10.08	7.70	54.70	58.97	55.55
2017	748.00	8.52	9.44	7.71	51.53	56.75	54.18
2018	577.90	8.20	8.35	9.11	50.41	51.85	53.44
2019	701.60	7.85	8.33	8.28	47.71	49.62	47.63
2020	719.80	9.10	9.40	8.71	49.75	50.42	50.86
2021	909.50	8.96	11.01	7.20	52.09	55.45	53.85
2022	658.50	9.04	9.05	9.19	52.70	52.70	56.85
2023	572.50	9.71	9.15	9.05	52.18	52.90	53.98
2024	1068.10	7.30	8.46	4.59	46.01	54.58	50.69



(a)Shallow groundwater (b)Deep groundwater

Figure 1. Production-replenishment relationship

Around 2021, due to the control of groundwater exploitation by the Xuchang Municipal government and strict restrictions on over-exploitation, the amount of exploitation has decreased year by year.It can be seen from the figure of precipitation and burial depth of shallow groundwater in Xuchang City (Figure. 2) that the precipitation in 2021 was 909.5mm and dropped to 572mm in 2023, the average groundwater burial depth increased from 8.96m to 9.71m, and the rainfall increased to 1068.1mm in 2024, and the groundwater level also rebounded. According to the data of the past ten years, it can be found that the water level in the high water period is significantly higher than that in the low water period. It can be seen that the average groundwater level changes in the shallow water on the whole are consistent with the precipitation changes, indicating that the dynamic changes of the shallow groundwater are significantly related to the seasons and climate changes. It can be seen from the deep groundwater diving depth map of Xuchang City (Figure. 2) that there is no significant relationship between the deep groundwater level and precipitation. The deep water belongs to the pore water of quaternary loose sediment and is classified as confined water according to burial conditions. The overlying roof hinders the circulation between confined water, atmospheric water and surface water.



(a)Shallow groundwater (b)Deep groundwater

Figure 2. Relationship between groundwater precipitation and buried depth

4. VULNERABILITY ANALYSIS OF DRASTIC ASSESSMENT MODEL

RASTIC assessment model requires the use of seven indicators for vulnerability assessment, including water level buried depth (D), net recharge (R), aquifer medium (A), soil type (S), ground slope (T), vadiscal lithology (I) and permeability coefficient (C). According to the influence degree of each factor on groundwater vulnerability assessment, a weight size is assigned, and the size range is between 1 and 5. The single factor evaluation of each evaluation index is carried out, and the evaluation range is 1-10. The larger the score, the more likely it is to be polluted. DRASTIC evaluation index is derived from the product of the evaluation results of each individual indicator and each weight. Due to the relationship between climatic types and hydrogeological conditions in Xuchang City, some indexes in DRASTIC assessment model cannot be used as influencing factors in groundwater vulnerability assessment. According to various data monitoring data collected from 2013 to 2018, firstly, Xuchang City is located in the North China Plain, with flat terrain and small variation in topographic slope; Secondly, due to the complexity of soil media data acquisition, it is difficult to collect soil data due to urbanization in important research areas. The net recharge of aquifer needs to consider many factors and is difficult to calculate. Considering the limited data, appropriate evaluation factors will be selected in the study and evaluation of groundwater vulnerability, and soil medium and vasses zone medium will be considered as an index. Since the main recharge mode of shallow aquifer is atmospheric precipitation recharge, the net recharge can be considered as the recharge amount of atmospheric precipitation, which is equal to the atmospheric precipitation multiplied by the rainfall infiltration recharge coefficient. Therefore, in this evaluation, six other indicators except soil medium will be selected as evaluation factors. The characteristic parameters of each district in Xuchang City are shown in Table 2 below.

Table 2. Characteristic parameters

Region	D /m	R /mm	A	T /°	S	C /m*d^{-1}
Xuchang	4~8	61.00	Massive sandstone, limestone, fine sand	0~2	Medium sand	28.5-40.7
Changge	＞8	39.18	Massive sandstone, limestone, fine sand	0~2	Fine sand	12.2-28.5
Yuzhou	2~4	45.92	Fissure does not develop metamorphic rock, clay	2~6	Sub-sandy soil, sub-clay	5～10
Xiangcheng	4~8	68.27	Fissure does not develop metamorphic rock, clay	2~6	Sub-sandy soil, sub-clay	5～10
Yanling	4~8	94.97	Sand conglomerate, coarse sand	0~2	Sand gravel	28.5-40.7

In the DRASTIC model, a fixed weight is given to each factor according to its impact on the degree of vulnerability, and the weight varies from 5 to 1. The greater the proportion of vulnerability index weight, the greater the impact on groundwater vulnerability. In this study, six factors from the DRASTIC assessment model are selected, which are arranged according to the weights of each factor: groundwater level embedment depth, aquifer net recharge, aerated zone lithology, aquifer medium, aquifer permeability coefficient and aerated zone lithology. When the six factors are combined, the product of each factor and weight is the DRATIC index:

$$\text{DRATIC}=5D+4R+3A+T+5I+3C \tag{1}$$

According to the DRATIC index, we can obtain the relative vulnerability of groundwater. The DRATIC index is not a specific value of groundwater pollution, but only represents the relative vulnerability of groundwater distributed in space. The higher the DRATIC index, the more likely the groundwater in the region is to be polluted compared with other regions. According to the groundwater vulnerability index, groundwater vulnerability is divided into the following levels: low, low, medium, high and high, and there are five levels in total: low vulnerability (<70), low vulnerability (70-95), medium vulnerability (95-120), high vulnerability (120-145) and high vulnerability (145-170).

Table 3. Results of groundwater vulnerability assessment in Xuchang City

Region	DRATIC evaluation factor						Comprehensive evaluation result
	D	R	A	T	I	C	
Xuchang	7	3	7	10	7	6	131
Changge	5	1	6	10	6	4	99
Yuzhou	9	1	2	9	3	2	85
Yanling	7	3	8	10	9	6	144
Xiangcheng	7	3	2	9	3	2	83

As shown in Table 3, the evaluation index of Xuchang City ranges from 80 to 145. The higher the vulnerability evaluation index is, the higher the groundwater vulnerability in the region is and the more susceptible it is to pollution; otherwise, the stronger the regional anti-pollution ability is.According to QGIS mapping results (Figure. 3), it can be seen from the figure that the vulnerability levels of shallow groundwater in Xuchang City are mainly three of the above five levels, and the vulnerability levels are in order from high to low: higher, medium and lower areas. Among them, Yuzhou and Xiangcheng counties in the west belong to the area of low groundwater vulnerability, Changge City in the north belongs to the area of medium groundwater vulnerability, Xuchang City and Yanling County in the middle and west belong to the area of high groundwater vulnerability. It can be seen from the figure that the regional distribution of shallow groundwater vulnerability is basically consistent with the zoning results of lithology and aquifer permeability coefficient of the vasses zone in Xuchang City, and the overall trend is from northwest to southeast, which also indicates the great influence of the vasses zone and permeability coefficient on it. The areas with low vulnerability are mainly distributed in the west and southwest of Xuchang City, including Yuzhou City and Xiangcheng County. Compared with the other three cities (counties), the risk degree of groundwater pollution in this area is lower. The lithology of the vaerated zone in this area is mainly subsandy soil and subclay, the permeability coefficient of rock strata is 5 ~ 10m/d, and the average topographic slope is 3°. The groundwater level in Yuzhou is always higher than that in Xiangcheng County, and the shallow groundwater level is close to the surface with an average groundwater level of 1 ~ 2m. The medium vulnerability area is mainly distributed in Changge City, north of Xuchang City, and the groundwater in this area is relatively medium vulnerable to pollution. The vadose zone in this area is dominated by medium sand and medium fine sand, and the permeability coefficient is 12.2 ~ 28.5, which is higher than that in Yuzhou and Xiangcheng. The annual average groundwater level in Changge City is less than 6m, the groundwater level in some areas is greater than 8m, and the slope is 0 ~ 2°. The areas with higher vulnerability are mainly distributed in Xuchang and Yanling in the central and western parts of China. Compared with Changge, Yuzhou and Xiangcheng, the groundwater is more vulnerable to pollution. The average groundwater level of Xuchang and Yanling counties for many years is 4 ~ 6m, and some of the deepest water level can reach more than 8m. The rock particle size in the region is coarse, mainly medium sand, medium coarse sand and sand gravel, the permeability coefficient is relatively large, and the terrain slope is less than 2°.

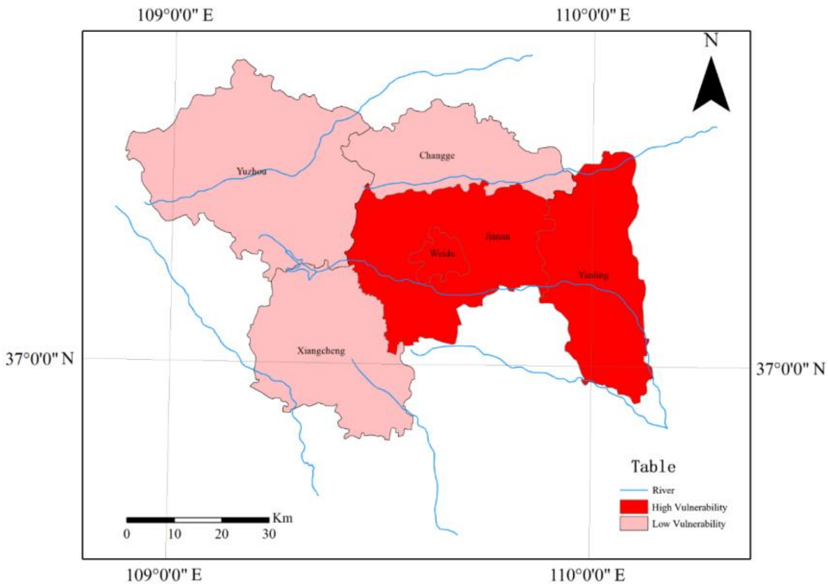


Figure 3. Vulnerability region classification

5. CONCLUSION

By collecting the groundwater level and water quality monitoring data of Xuchang City in recent decades, this paper analyzes the characteristics and conditions of groundwater level in Xuchang City, and draws the following conclusions: the change of shallow groundwater level is consistent with the change of precipitation on the whole, and the groundwater level drops due to excessive mining in successive years. The change of middle and deep groundwater level is mainly affected by artificial exploitation, and the water level decreases year by year. Due to the implementation of mining restrictions around 2000, the shallow and middle deep water levels recovered slightly. The groundwater vulnerability level in Xuchang City is poor to good, and the vulnerability zoning results gradually increase from northwest to southeast, which is related to the lithology and permeability coefficient of the vasses zone.

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