Spatial Distribution Pattern of Groundwater Resources and Evaluation of Exploitation Potential in the Heng Shao Drought Corridor of Hunan Province

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ABSTRACT The Heng Shao Drought Corridor in Hunan Province is a critical water-scarce region with significant implications for water-intensive industries. This study evaluates the spatial distribution, exploitable volume, and quality of groundwater by integrating multi-scale hydrogeological data, real-time monitoring observations, and advanced spatial interpolation techniques. Four main groundwater types—loose rock pore water, bedrock fissure water, karst water, and red bed pore fissure water—are characterized in terms of resource modulus, recoverable volume, and mining potential coefficients. Data fusion and equilibrium analysis methods are applied to quantify groundwater recharge, discharge, and exploitation potential across river valleys and mountainous areas. The results indicate that the total groundwater resource is 11.85 billion m3, with 4.454 billion m3 exploitable under sustainable thresholds. Groundwater quality is predominantly Class I–III, with manganese and nitrate as the main influencing factors. The study highlights high-potential zones in the northwestern and western mountainous reaches and identifies regions requiring regulated exploitation. By framing groundwater assessment as a multi-node environmental monitoring and spatial data integration system, the methodology provides an engineering-oriented perspective for sustainable water resource management, planning of extraction strategies, and decision support for industrial applications.

INDEX TERMS groundwater resources, spatial data integration, environmental monitoring, exploitable potential

I. INTRODUCTION

HUNAN Province is in the subtropical monsoon climate zone, and drought is one of the main climate disasters [1,2]. Among them, the Hengyang-Shaoyang mountainous hilly basin area has less precipitation due to the influence of topography and landforms. The annual precipitation is 1100~1300mm, which is 15~25% less than that of non-basin areas at the same latitude in Hunan Province. In addition, limestone is widely distributed in the area, and precipitation seeps rapidly along the surface cracks, making it impossible to effectively conserve water during the rainy season. At the same time, the uneven temporal and spatial climate exacerbates water shortages. The annual precipitation is concentrated in April to June, and periodic or continuous droughts often occur from the end of June to the end of September [3]. It is called the "Hengshao Drought Corridor". The extreme drought in the second half of 2022 caused water shortages in 13 counties and 44 townships, making the regional water shortage problem particularly prominent. At present, the water resource supply of the Hengshao Drought Corridor is mainly surface water, and the development and utilization of groundwater is low. Groundwater resources serve as a critical water source for addressing regional drought challenges and ensuring the reliable operation of the water-intensive industry in the future.

The methods for evaluating groundwater resources can be mainly divided into traditional calculation methods and remote sensing big data analysis methods [4]. Due to the shortcomings of remote sensing technology such as detection accuracy and unstable water balance, traditional methods are still the main methods [5,6], including hydrological analysis method [7], analytical method [8], numerical method [9] and water balance method [10]. In the study of groundwater resource potential and development and utilization, groundwater potential is generally classified by the allowable groundwater extraction volume and the degree of extraction [11-13]. Commonly used groundwater extraction potential evaluation methods include groundwater residual coefficient and extraction potential index [14]. In areas with detailed data, hierarchical analysis method [15] and numerical simulation [16] can also be used to calculate groundwater extractable resources.

Because the Hengshao drought corridor basin is relatively scattered, there is currently little research on it, and the evaluation of groundwater resources and development and utilization potential is insufficient. It is urgent to carry out groundwater resource evaluation research in this area. By systematically calculating groundwater resources and evaluating quality based on observation data from the Heng Shao Drought Corridor, this paper analyzes extraction potential to provide a scientific foundation for regional water planning that supports the sustainable operation of the water-intensive industry. The findings offer a critical reference for balancing the ecological health of the corridor with the high water consumption demands.

II. GENERAL INFORMATION OF THE RESEARCH AREA

A. PHYSICAL GEOGRAPHY

The Heng Shao Drought Corridor is located at 109°45'–113°30'E, 25°30'–28°15'N, in the central part of Hunan Province, south of the Xuefeng Mountains and north of the Wuling Mountains, with a total area of approximately 51,200 square kilometers. The administrative divisions include the entire territories of Hengyang City, Shaoyang City, Loudi City, and parts of Yongzhou City. It belongs to the subtropical monsoon climate zone, with uneven rainfall in time and space, and a large gradient of variation [17]. The average annual precipitation is 1377.44 mm, which is lower than the average annual precipitation of the province. The Heng Shao Drought Corridor is a transition zone from hills to plateaus, surrounded by mountains on the east, west, and south. It is a basin and hilly terrain. The overall terrain is high in the southwest and low in the northeast, with gentle undulations and diverse landform types, with more than 65% being hills [18]. The strata are widely distributed, and the exposed rock types are mainly limestone, shale, and red sandstone. According to statistics over the years, four counties including Shaoyang County and Xinning County were the most severely affected by the drought, and the drought area affected 20 counties and districts. The geographical location and distribution map of the drought severity in the Hengshao arid corridor over the years are shown in Figure 1:

B. HYDROGEOLOGICAL CONDITIONS

Based on groundwater occurrence conditions, hydrological properties, and hydraulic characteristics, the groundwater in the region is divided into four main types: loose rock pore water, bedrock fissure water, karst water, and red bed pore fissure water. Loose rock pore water is primarily found along the banks of the Xiangjiang, Leishui, and Zhengshui rivers in the Hengyang Basin, and on terraces along the Zishui River and its tributaries, the Shaoshui and Shimajiang Rivers. It possesses strong to moderate water-yield characteristics. The Quaternary strata in the Hengyang Basin are primarily divided into the Holocene (Q4) and Middle Pleistocene Mawangdui Formation (Qp2m), with aquifers composed of sand, gravel-sand, and sand-gravel. Bedrock fissure water occurs primarily in fissures and tectonic fracture zones of clastic rocks, igneous rocks, and metamorphic rocks. Its water-bearing properties vary widely, but it is generally weak. Karst water is widely distributed in the study area, mainly in the central part of the Heng Shao Drought Corridor. The water-bearing rock groups mainly include Devonian-Carboniferous, Triassic limestone, and dolomite, and are highly waterrich. The red layer pore and fissure water is mainly distributed around the Hengyang Basin. The water-bearing rock groups are mainly Jurassic-Paleogene sandstone and siltstone. The water storage structure is unevenly distributed, and the water-bearing properties vary greatly, with strong to weak water-rich.

C. GROUNDWATER DEVELOPMENT AND UTILIZATION STATUS

According to historical data, mining near Lianyuan City and Loudi City within the study area once destroyed aquifers, leading to regional depressions. However, with the closure of operating mines within the area, groundwater levels have gradually recovered, and there are no over-exploited areas within the study area. According to the Hunan Provincial Water Resources Bulletin, groundwater extraction in the study area remained relatively stable from 2008 to 2019, primarily used for domestic water, industrial water, and artificial ecological environments, with a total extraction volume of 544 million cubic meters per year. In accordance with the requirements of the Hunan Provincial 14th Five-Year Plan for Water Resources Allocation and Supply, the irrigation water utilization coefficient is being improved, the accessibility of tap water is being increased, and the allocation of industrial water resources is being optimized. Consequently, since 2020, the proportion of groundwater used for industrial and artificial ecological environments has decreased significantly, while agricultural water use has increased slightly, with a total extraction volume of 282 million cubic meters per year.

III. RESEARCH METHODS AND DATA SOURCES

A. RESEARCH METHODS

Based on the hydrogeological conditions and the availability of survey data within the study area, the Quaternary-covered area of the Hengyang Basin is divided into river valleys and the rest into mountainous areas. Groundwater resources in the mountainous areas are assessed using the runoff modulus method. The river valleys are assessed using the equilibrium method, using recharge as the groundwater resource volume.

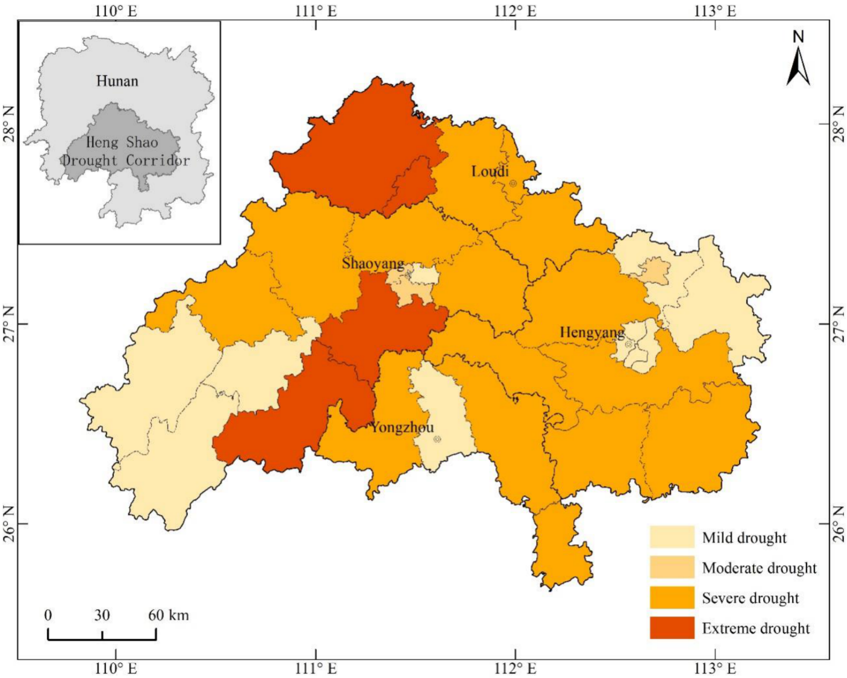

FIGURE 1. Geographical location and distribution map of multi-year drought degree in Heng Shao Drought Corridor

Groundwater equilibrium analysis is performed to validate the calculated results.

Groundwater equilibrium equation in the river valley:

$$\Delta Q = Q_i - Q_e \tag{1}$$

$$Q_i = Q_{pi} + Q_{ii} + Q_{si} \tag{2}$$

$$Q_e = Q_{ee} + Q_{re} + Q_{ve} \tag{3}$$

Where: ΔQ is the change in groundwater resources (m^3/a). Q_i is the total groundwater recharge (m^3/a). Q_e is the total groundwater discharge (m^3/a). Q_{pi} is the precipitation infiltration recharge (m^3/a). Q_{ii} is the irrigation infiltration recharge (m^3/a). Q_{si} is the peripheral lateral recharge (m^3/a). Q_{ee} is the phreatic water evaporation (m^3/a). Q_{re} is the river discharge (m^3/a). Q_{ve} is the artificial extraction volume (m^3/a). Precipitation infiltration recharge is calculated using the infiltration coefficient method. Irrigation infiltration recharge is calculated separately for the irrigation and non-irrigation periods. Peripheral lateral recharge and river discharge are calculated according to Darcy's law. Phreatic water evaporation is converted from meteorological station evaporation data. The amount of artificial mining is taken from the data published by each county and city. Groundwater quality was evaluated in accordance with the Groundwater Quality Standard (GB/T 14848-2017), using a comprehensive evaluation method of multiple indicators. Class IV water was further divided into Class IV-1 and Class IV-2 water considering native high background components.

$$F = \sqrt{\frac{F_{\max}^2 + \bar{F}^2}{2}} \tag{4}$$

Where: F is the comprehensive evaluation score. $\bar{F}$ is the average of the individual component scores F_i. $F_{\max}$ is the maximum value of the individual component scores F_i.

The exploitable amount of groundwater refers to the maximum amount of water that can be obtained from underground aquifers within a certain period of time under the premise of ensuring economic rationality, technical feasibility and no deterioration of the ecological environment [19]. The methods for calculating the exploitable amount of groundwater resources in large areas include the average well distribution method [20], the balance method [21], the exploitable coefficient method, etc [22]. Among them, the average well distribution method determines the yield and influence radius of the exploitation wells based on the hydrogeological conditions of the study area, and calculates the exploitable amount by averaging wells in the area, which has high requirements for data. The balance method is suitable for plain areas with relatively good aquifer exploitation conditions and relatively high exploitation levels. The exploitable coefficient method uses the exploitation coefficient obtained in representative areas and uses it to calculate the exploitable resources in similar areas by analogy, which has low calculation accuracy. In this river valley area, the average well distribution method and the balance method are used to calculate the exploitable amount of groundwater, and the differences in the calculation results of the two methods are compared. In the mountainous area, due to the low level of research, the dry season runoff modulus method is used to calculate the exploitable amount of groundwater.

Average well distribution method:

$$Q_{eg} = 3.65\frac{FQ_{cp}}{4R^2} \times 10^4 \quad (5)$$

Where: Q_{eg} is the recoverable groundwater volume, 10^4 m^3/year. Q_{cp} is the single-well recovery volume, m^3/day. F is the area of the calculation zone, km^2, and R is the radius of influence, m. For this assessment, the river valley was divided into 14 distinct segments, with a total of 32 regionally representative control wells.

Balance method:

$$Q_{eg} = Q_i - Q_{ne} \quad (6)$$

Where: Q_{ne} is the non-extractable discharge, 10^4 m^3/a. This assessment includes river discharge and groundwater extraction.

Groundwater exploitation potential refers to the possibility of expanding groundwater exploitation and the corresponding increment determined by analyzing the difference between the amount of groundwater that can be exploited and the amount that has been exploited in the study area [23]. Analyzing the exploitable potential of groundwater resources can define the exploitation boundary and avoid environmental problems such as aquifer depletion and soil salinization [24]. Groundwater exploitation potential evaluation is carried out in accordance with the "Technical Requirements for Groundwater Potential Evaluation" (GW1-D4):

$$\beta = \frac{Q_{eg}}{Q_{ve}} \quad (7)$$

Where: β is the mining potential coefficient. ≥ 1.4 indicates high potential. 1.2–1.4 indicates relatively high potential. 1.0–1.2 indicates relatively low potential. <1.0 indicates no potential [25].

B. DATA SOURCES

Based on the data from the third groundwater resource assessment, the 1:200,000 hydrogeological survey report and the 1:50,000 hydrogeological survey results conducted since 2000 were compiled to verify and update relevant hydraulic parameters. To address the significant scale discrepancies between historical smallscale reports and recent high-resolution data, a multi-scale data fusion approach was employed. Small-scale parameters (1:200,000) were downscaled and localized using Kriging interpolation, while 1:50,000 data and real-time monitoring results were used as primary constraints to calibrate the regional hydrogeological model. Furthermore, a consistency check and normalization process were applied to all spatial data layers to minimize interpolation errors and ensure that the integration of coarse historical trends with fine-grained current observations remains physically consistent across the study area.

Monthly precipitation and evaporation time series were collected from 43 meteorological stations in and around the study area from 2000 to 2024 through the meteorological department. Water quality monitoring data for 2023 was collected from 30 water quality monitoring points within the study area under the National Groundwater Monitoring Project, 8 water quality monitoring points under the Environmental Protection Department, and 17 water quality sampling points at drought-resistant wells. Data on artificial groundwater extraction in various cities and counties from 2015 to 2019 were collected.

A total of 98 groundwater samples were collected within the study area in 2024, and water quality analysis was commissioned by the Hunan Provincial Geological Experiment and Testing Center.

IV. RESULTS AND ANALYSIS

A. GROUNDWATER RESOURCES

The Hengshao Dry Corridor has groundwater resources of 11.85 billion m3. Of this, the river valley area has groundwater resources totaling 107 million m3, with a groundwater resource modulus of 173,000 m3 km-2. While the total groundwater recharge includes various sources, irrigation infiltration — primarily representing the return flow of diverted surface water rather than a natural groundwater resource — accounts for the largest portion of the balance at 53.39%. This highlights the significant influence of human-induced surface water cycles on the local aquifer system. Total discharge is 116 million m3, primarily through evaporation, with artificial extraction accounting for only 7.70%. The relative equilibrium difference (δ) is -8.08%, While this figure technically indicates a negative balance, it falls within the acceptable margin of error ($\pm$10%) for regional groundwater resource assessment. This suggests that the groundwater system is in a state of quasiequilibrium. Therefore, the groundwater regime has remained in a relatively stable natural state for many years, with minimal long-term changes in water levels, reflecting a dynamic balance between recharge and discharge over a multi-year cycle. Groundwater resources in mountainous areas total 11.743 billion m3, with a groundwater resource modulus of 232,200 m3 km-2. Artificial extraction accounts for 544 million m3, or 4.63%, of the total groundwater in mountainous areas. However, as illustrated in Fig. 2, the spatial distribution of the groundwater resource modulus does not strictly follow a simple "mountain vs. valley" dichotomy. While the overall modulus is higher in mountainous regions due to better recharge conditions, there are significant localized variations. These anomalies are primarily attributed to the complex karst systems and tectonic fracture zones prevalent in the central and western parts of the corridor, which create high-modulus "hotspots" even in transition zones. Consequently, the highest values are concentrated in the northwestern and western mountainous reaches, while the middle reaches and southeastern areas exhibit lower values due to tighter geological formations.

In summary, the main mode of groundwater recharge in the study area is precipitation infiltration, and evaporation is the main mode of discharge. The distribution of groundwater resources shows that the highest in the upper and lower reaches, lower in the middle reaches, higher in the northwest and west, and lower in the southeast. The overall groundwater extraction volume accounts for 4.67% of the total discharge volume. Therefore, how to convert the remaining discharge volume into usable water resources is particularly important to solve the water shortage problem in the Hengshao drought corridor in the second half of the year. The balance of groundwater resources in the Hengshao arid corridor watershed is shown in Table 1:

TABLE 1. Balance of groundwater resources in the Heng Shao Drought Corridor valley area

Supply items / 10,000 m^3		Excretion items / 10,000 m^3	
Precipitation infiltration	3199.84	Evaporative excretion	7658.86
Irrigation infiltration	5727.84	River discharge	3043.85
Lateral supply	1800.28	Mining volume	892.30
Total	10727.96	Total	11595.01
Relative balance difference /%			-8.08

The distribution map of groundwater resources is shown in Figure 2:

B. GROUNDWATER QUALITY

The overall groundwater quality in the Heng Shao Drought Corridor is good, with Class IV-V water accounting for 37.91%. Without considering the original high background components, Class IV-V water accounts for 26.14%. The main influencing factors of Class IV-V water quality are manganese and nitrate. From the distribution of Class IV-V water, Class IV-V water is mainly concentrated near urban areas and river valleys. There are three reasons for exceeding the standard. On the one hand, it is caused by the original environment, and the exceeding indicators are iron, manganese, total hardness, and aluminum. The second aspect is due to hydrogeological conditions. Since urban areas and river valleys are mostly located in relatively low-lying areas, they belong to the discharge area of the groundwater flow system, with a long seepage path, and limestone, sandstone, and marl are widely distributed in the study area. As a result, some groundwater has high content of sodium, sulfate, and total dissolved solids. The third aspect is that the region is densely populated and human activities are intense, which can easily cause groundwater pollution. The indicators of human pollution are arsenic, fluoride, iodide, etc.

In summary, the groundwater quality in the study area is good, with Class I to III water accounting for 62.09%. In counties and towns with severe drought, groundwater can be used as domestic water after simple treatment, which can effectively solve the water shortage problem. The evaluation results of groundwater quality are shown in Table 2:

TABLE 2. Groundwater quality assessment results

Data Source	I water	II water	III water	IV-1 water	IV-2 water	V water	Total	Exceeding standard rate /%	Exceeding standard rate /% (excluding native high background components)
National monitoring wells	1	12	0	5	12	0	30	56.67	40
Environmental protection department monitoring wells	3	3	0	2	0	0	8	25	0
Drought-resistant wells	8	6	0	1	2	0	17	17.65	11.76
Other	5	6	51	10	16	10	98	36.73	26.53
Total	17	27	51	18	30	10	153	37.91	26.14

Groundwater quality is shown in Figure 3:

C. GROUNDWATER EXTRACTION POTENTIAL

In the river valley, the average well distribution method calculated the groundwater recoverable volume to be 55.4327 million m3, while the equilibrium method calculated the recoverable volume to be 67.9181 million m3. The two methods provide similar results, but the equilibrium method does not account for excretion caused by plant transpiration, resulting in a slightly higher recoverable volume. The total recoverable groundwater volume in the mountainous area is 4.399 billion m3. This total of 4.454 billion m3 can meet the water demand during droughts within the study area.

The overall groundwater recovery potential coefficient for the Hengshao Drought Corridor is 7.96. Except for parts of Changning City, Leiyang City, Qiyang County, and Xintian County in the southern part of the study area, which have no potential, most areas have a recovery potential coefficient greater than 1.4. This indicates significant groundwater recovery potential. Regarding groundwater types, the recovery potential varies significantly across the four identified categories. The potential of karst water areas is the highest due to abundant storage and high permeability, followed by loose rock pore water in the river valleys. In contrast, bedrock fissure water and red bed pore fissure water exhibit relatively lower recovery potential due to their more restricted storage structures and generally weaker water-yielding properties. In terms of distribution, the study area's mountainous areas have greater groundwater potential than its river valleys, and the western part has greater potential than the eastern part.

In summary, the study area's groundwater development and utilization is low, but its potential is high. During droughts, groundwater can be extracted to meet water demand, and then replenished through atmospheric infiltration during the wet season, maintaining regional groundwater reserves. Furthermore, while evaporation is the primary mode of groundwater discharge in the region, converting this "evaporative loss" into "artificial extraction" by lowering the water table must be approached with caution regarding ecological stability. Although reducing evaporation increases the available groundwater potential, excessive drawdown of the water table may negatively impact phreatophytic vegetation and diminish baseflow to local rivers. Therefore, to satisfy the definition of "sustainable exploitation with no ecological deterioration," extraction levels must be

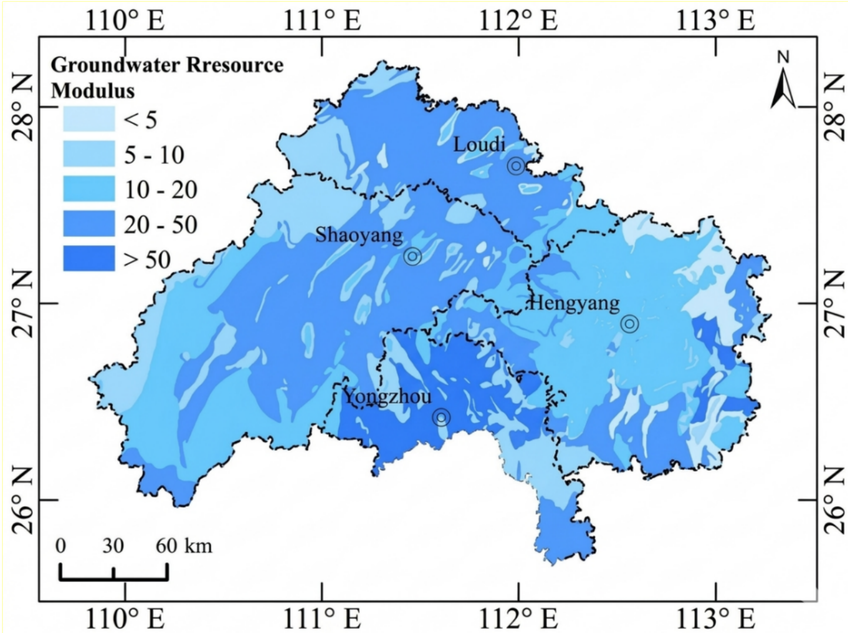

FIGURE 2. Groundwater resource distribution map

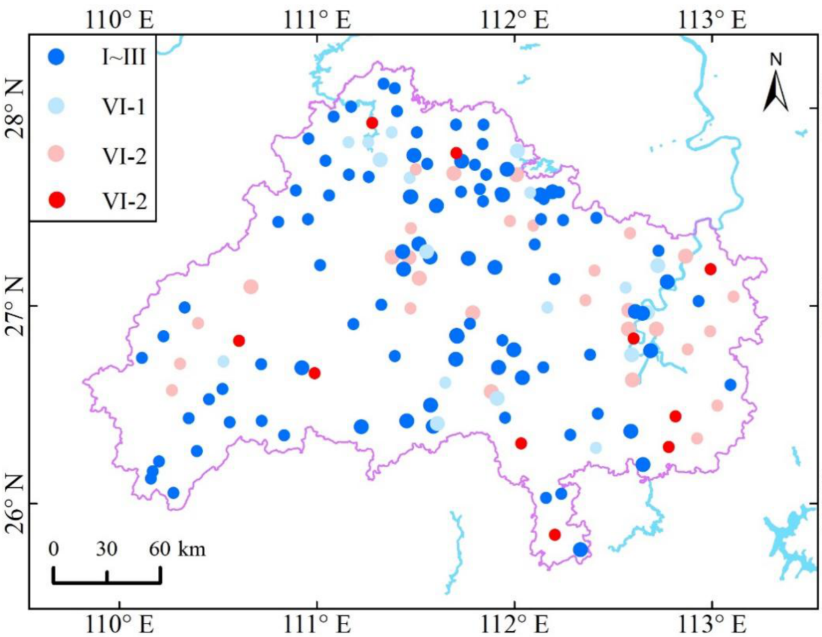

FIGURE 3. Groundwater quality

managed to ensure that the water table remains within a depth that supports both the regional green cover and the hydraulic connection between aquifers and surface water bodies. Therefore, rational groundwater development and utilization can address drought and water shortage issues within the study area. The statistics of groundwater mining output in the basin are shown in Table 3:

TABLE 3. Statistics of mining output of groundwater in valley area

Name	Extractable groundwater volume		
	Well layout method / 10,000 m^3	Balance method / 10,000 m^3	Dry season runoff modulus method / 100 million m^3
River Valley	5543.27	6791.81	–
Mountainous areas	–	–	43.99

The zoning of groundwater exploitation potential is shown in Figure 4:

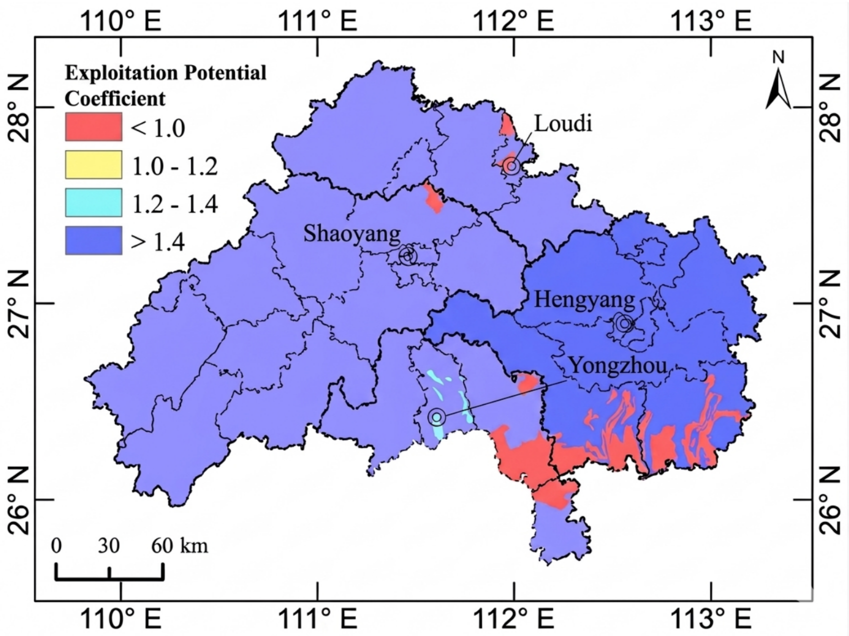

FIGURE 4. Zoning of groundwater exploitation potential

D. COMMENTS ON EXPLOITING THE GROUNDWATER

(1) The groundwater types in Shaoyang County, Xinhua County, Xinning County, Lengshuijiang City and the central part of the study area, where the drought is most severe, are mainly karst water. The groundwater resources are abundant, the groundwater quality is good, and the exploitation potential is large. There are many and scattered groundwater outcrops in the area. The regulation and storage capacity of the karst aquifer should be fully utilized, and it is suitable to expand the karst springs and develop wells. During the drought period, part of the groundwater storage capacity should be temporarily borrowed, and it will be replenished and restored during the flood season and the off-season to achieve multi-year regulation [26].

(2) The groundwater types near the Hengyang Basin are mainly red bed pore fissure water and loose rock pore water. While red bed and bedrock fissure waters have lower individual well yields compared to karst systems, their broad distribution still offers significant cumulative exploitation potential, making them suitable for decentralized drilling and diversion development to support local needs.

(3) In the southern part of the study area, where there is no potential for groundwater exploitation, groundwater exploitation should be stopped, water conservancy projects should be built, and technical means and engineering measures should be taken to reasonably regulate water resources to solve the water use problem during the drought period.

V. CONCLUSION AND ADVICES

(1) The Heng Shao Drought Corridor is rich in groundwater resources. The Heng Shao Drought Corridor has 11.85 billion m3 of groundwater resources and a groundwater resource modulus of 231,400 m3·km-2. Groundwater accounts for 23.35% of the total regional water resources. The groundwater resources in the region are mainly in the mountainous areas. The groundwater resource modulus is highest in the upper and lower reaches and lower in the middle reaches. Overall, the groundwater resource modulus in the river valley is generally lower than that in mountainous areas. Nevertheless, the spatial distribution is highly heterogeneous; the correlation between terrain and modulus is further influenced by regional hydrogeological structures, particularly karst development. This leads to a complex mosaic pattern where high-potential zones are determined by both elevation and favorable geological storage conditions. Precipitation infiltration remains the most critical natural source of groundwater recharge. However, in localized river valley areas, the groundwater balance is heavily influenced by the return flow of surface water irrigation, which must be distinguished from the region's natural renewable groundwater yield.

(2) The overall groundwater quality in the Heng Shao Drought Corridor is good, with Class I to III water accounting for 62.09%. Without considering the primary high background components, Class IV-V water accounts for 26.14%. The water quality in mountainous areas is better than that in river valleys, and the quality of deep water is better than that of shallow water. The extraction potential and water quality follow a distinct hierarchy among groundwater types: Karst water > loose rock pore water > bedrock fissure water > red bed pore fissure water. Class IV-V water is mainly concentrated near urban areas and river valleys. The main factors affecting water quality are manganese and nitrate.

(3) The exploitable groundwater volume in the Heng Shao Drought Corridor is 4.454 billion m3, of which 0.55 billion m3 is in the river valley and 4.399 billion m3 is in the moun-

tainous areas. The current level of groundwater exploitation is low, and there is great potential for exploitation.

(4) The groundwater resources in the Heng Shao Drought Corridor are sufficient, the level of groundwater exploitation is low, and there is great potential for development. In addition, the groundwater quality in most areas is good and meets the relevant drinking water standards. Therefore, while establishing emergency backup water sources is feasible, the exploitation strategy must incorporate an ecological safety threshold. Future groundwater development plans should prioritize a "dynamic balance" that prevents long-term depletion of baseflow and protects moisture-dependent ecosystems. Integrated management must ensure that the transition from natural evaporation to industrial/domestic use does not exceed the ecological carrying capacity of the Heng Shao Drought Corridor.

AUTHOR CONTRIBUTIONS

Conceptualization – Feng Zhao, Liquan Xiao, Senqiu Wang, Zhiqiang Li and Chao Huang; methodology – Feng Zhao, Liquan Xiao, Senqiu Wang, and Chao Huang; investigation – eng Zhao, Liquan Xiao, Senqiu Wang, Zhiqiang Li and Chao Huang; writing-original draft preparation – eng Zhao, Liquan Xiao, Senqiu Wang, Zhiqiang Li and Chao Huang. All authors have read and agreed to the published version of the manuscript.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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