Research on the Water Quality Characteristics and Development Suitability of High-Strontium-rich Groundwater in Qianxinan Prefecture

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Abstract. To scientifically support the refined development of characteristic groundwater resources in karst mountainous areas, 18 high strontium-rich groundwater sites (strontium content ⩾1.0mg/L) in Qianxinan Prefecture were taken as the research objects to systematically analyze their water quality characteristics and development suitability. The results show that strontium content ranges from 1.127 to 11.010mg/L (average 4.23mg/L), mainly occurring in the dolomite and dolomitic limestone of the Guanling Formation and Yelang Formation of the Triassic; The water quality was mainly Class III (83.3%), with only the ammonia nitrogen in the old house gene in the south of Xingren City exceeding Class IV. The water chemical types were mainly HCO_3 -CA and HCO_3 -CA · Mg (91.7%), pH 7.68-8.19, total hardness 257-363mg/L, meeting the standards for drinking natural mineral water. Based on water quality, strontium content and development conditions, three suitable areas were classified, with five preferred suitable development sites including Dujiajing in Afternoon tun, Xingyi City. The research results provide technical support for the precise development of high strontium-rich groundwater in Qianxinan Prefecture and also offer a reference for similar karst areas.

1 Introduction

1.1 Research Background

Strontium is one of the essential trace elements in the human body. It plays a key role in physiological processes such as bone mineralization, osteoblast differentiation, and inhibition of bone resorption. It also participates in the regulation of the cardiovascular system and has the potential to reduce the risk of hypertension and arteriosclerosis. The national standard for drinking natural mineral water (GB 8537-2018) clearly designates strontium as a boundary indicator, specifying that a content of ⩾0.20mg/L can be defined as strontium-type mineral water, while groundwater with a strontium content of ⩾1.0mg/L is regarded as high strontium-rich groundwater. Due to the significantly increased mineral concentration, it has dual development value for high-end drinking and health care, It has become a key development direction for characteristic underground water resources.

Qiannan Buyi and Miao Autonomous Prefecture is located in the core karst area of Yunnan, Guangxi and Guizhou. The exposed area of carbonate rocks accounts for more than 80%, and the lithology of the strata is mainly Triassic Guanling Formation, Yelang Formation dolomite, dolomitic limestone and limestone, with strongly developed karst forming a complex groundwater occurrence and migration system [1]. The groundwater runoff paths in this area are tortuous and the water-rock interaction is full, providing superior geochemical conditions for the selective enrichment of trace elements such as strontium. In recent years, Guizhou Province has fully implemented the "rich Mine Intensive exploitation" strategy, incorporating the refined exploration and high-value utilization of characteristic groundwater resources into the key industrial layout. Qianxinan Prefecture, as a typical karst mountainous area, has the resource endowments and policy opportunities for the development of high strontium-rich groundwater [2].

The Groundwater Management Regulations, implemented in 2021, explicitly propose to strengthen the protection and rational utilization of high-quality groundwater resources and require classified management and precise control of water sources with medical and drinking value [3]. However, in karst mountainous areas, the medium of groundwater is highly heterogeneous, and the degree of strontium enrichment is controlled by multiple factors such as lithological assemblage, depth of water cycle, runoff path and mixing, with significant differences in water quality within the same hydrogeological unit [4]. Existing studies have mostly focused on the formation mechanism and resource quantity evaluation of karst groundwater resources, or only conducted preliminary screening of water sources based on a single indicator (such as strontium content) [5], lacking systematic coupled analysis of water quality characteristics, chemical types, over-limit factors and development potential for high strontium-rich

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groundwater [6]. Due to the imperfect development suitability evaluation system, local authorities face the practical predicament of "unclear resources and unknown target areas" in development site selection, which to some extent restricts the development of high-value-added mineral spring products and the precise industrial layout [7].

Therefore, conducting a systematic study on the water quality characteristics and development suitability of high strontium-rich groundwater in Qianxinan Prefecture is both a practical response to the implementation of the national policy of refined management of groundwater resources and a key scientific and technological support for the transformation of characteristic groundwater resources in karst areas from "resource census" to "targeted development". This study can provide a scientific basis for the identification and graded utilization of priority development areas of high strontium-rich groundwater in the region, and also provide a technical model for the efficient and sustainable development of similar characteristic groundwater resources in the karst areas of Yunnan, Guangxi, Guizhou and Southwest China [8].

1.2 Research Content and Technical Routes

This study focused on 18 high strontium-rich groundwater source points in Qianxinan Prefecture, and analyzed strontium content distribution, conventional water quality indicators and water chemical characteristics; Construct a three-dimensional evaluation system of "strontium content - water quality category - development conditions" to classify development suitability grades; Put forward specific suggestions for graded and classified development, water source protection and technology optimization. The technical route covers four links: data organization, feature analysis, suitability evaluation and countermeasure suggestions.

2 Overview of the Study Area

2.1 Physical Geography and Hydrogeology

Qianxinan Prefecture has a land area of 16,804.4 square kilometers, with karst areas accounting for more than 75% and an average annual precipitation of 1,251.6 mm. The high strontium-rich groundwater in the area is mainly found in the Triassic Guanling Formation (T_2g), Yelang Formation (T_1y) and Jialingjiang Formation ($T_{1-2}j$), with the core lithology being dolomite, dolomitic limestone and argillaceous limestone. The geological structure is dominated by northeast-trending and northeast-trending faults and folds, and the groundwater type is mainly carbonate rock karst water (75%), providing favorable conditions for strontium enrichment.

2.2 Overview of High Strontium-rich Water Source Points

Eighteen high strontium-rich groundwater source points (12 natural springs and 6 Wells) were selected, covering major distribution areas such as Xingyi City, Xingren City, Pu 'an County and Qinglong County. They were classified into three types according to the current development status: domestic water type, industrial development type and undeveloped type, basically covering the core areas rich in strontium in the region.

3 Analysis of Water Quality Characteristics of High Strontium-Rich Groundwater

3.1 Distribution Characteristics of strontium content

The strontium content at 18 water sources ranged from 1.127 to 11.010 mg/L, with an average of 4.23 mg/L. The classification results (Table 1) show that there were 13 sources (72.2%) with strontium content ranging from 1.0 to 3.0 mg/L, 3 sources (16.7%) with strontium content ranging from 3.0 to 6.0 mg/L, and 2 sources (11.1%) with strontium content ⩾ 6.0 mg/L. The highest strontium content (average 5.32 mg/L) was found in Xingyi City, which was closely related to the enrichment of strontium-containing minerals in the dolomitic limestone of the Guanling Formation; Xingren City followed with an average of 3.87 mg/L, while other counties had an average of 1.63 mg/L.

Table 1. Graded Statistics of strontium content at high strontium-rich water sources in Qianxinan Prefecture

Strontium content range (mg/L)	Number of water source points (in)	Proportion (%)	Main distribution area
1.0~3.0	13	72.2	Xingren City, Qinglong County, Pu 'an County
3.0~6.0	3	16.7	South of Xingren City, Sunshine Spring of Xingyi City
⩾6.0	2	11.1	Xingyi City Jinzhou Longquan, Dami Geothermal Well

3.2 Characteristics of conventional water quality indicators

The core routine indicators all meet the requirements of Drinking Natural mineral water (GB 8537-2018) (Table 2). The pH value is weakly alkaline (7.68 to 8.19), which is conducive to the stable occurrence of strontium; The average total hardness is 302 mg/L, which is medium hardness; Average total dissolved solids 346 mg/L; The ammonia nitrogen compliance rate was 94.4%, with only Xingren City Chengnan Laowu Gene Agriculture non-point source pollution causing ammonia nitrogen to exceed the standard (1.412 mg/L); The compliance rates for iron, manganese, chloride, sulfate and other indicators were all 100%.

Table 2. Statistics of Conventional Water Quality Indicators of High Strontium-rich Groundwater in Qianxinan Prefecture (n=18)

Indicator	Range	Average	Standard deviation	Compliance rate (%)	Evaluation criteria
pH (dimensionless)	7.68~8.19	7.92	0.18	100	GB8537-2018 (6.5 to 8.5)
Total hardness (mg/L)	257~363	302	38.6	100	GB8537-2018 (≤450)
Total dissolved solids (mg/L)	220~485	346	82.3	100	GB8537-2018 (≤1000)
Ammonia nitrogen (mg/L)	0.298~1.412	0.436	0.312	94.4	GB/T14848-2017 (Class III ≤0.5)
Iron (mg/L)	<0.03 to 0.24	0.05	0.07	100	GB8537-2018 (≤0.3)
Manganese (mg/L)	<0.01 to 0.14	0.03	0.04	100	GB8537-2018 (≤0.1)
Chloride (mg/L)	3.20~7.24	5.17	1.23	100	GB8537-2018 (≤50)
Sulfate (mg/L)	24.18~93.52	58.36	21.45	100	GB8537-2018 (≤250)

3.3 Toxicological indicators characteristics

The concentrations of toxicological indicators such as chromium (hexavalent), cyanide, fluoride, nitrate, etc. were all below the Class III limits of the Groundwater Quality Standard (GB/T 14848-2017), with a 100% compliance rate, indicating that the overall toxicity risk of the high strontium-rich groundwater in the study area was low and the water quality was safe and reliable (Table 3).

Table 3. Statistics of toxicological indicators of High Strontium-rich Groundwater in Qianxinan Prefecture (n=18)

Indicators	Range	Average	Standard deviation	Standard limits (mg/L)	Compliance rate (%)
Chromium (hexavalent)	<0.004	—	—	≤0.05 (Class III)	100
Cyanide	<0.0025	—	—	≤0.05 (Class III)	100
Fluoride	0.11~0.75	0.38	0.19	≤1.0 (Class III)	100
Nitrate	0.140~4.394	1.86	1.24	≤20 (Class III)	100

3.4 Characteristics of water chemical types

The water chemical types were mainly HCO_3 -CA type (61.1%) and HCO_3 -CA ·Mg type (27.8%) (Table 4), reflecting hydrogeochemical processes dominated by carbonate karst erosion. The groundwater runoff conditions were favorable for the long-term enrichment of strontium and the maintenance of chemical stability.

Table 4. Statistics of hydrochemical types of High strontium-rich Groundwater in Qianxinan Prefecture

Hydrochemical types	Number of water sources (points)	Proportion (%)	Main distribution area	Average strontium content (mg/L)
HCO_3-Ca type	11	61.1	Xingyi City, Xingren City core area	4.57
HCO_3-Ca · Mg type	5	27.8	Pu 'an County, Qinglong County	3.62
HCO_3-Na · Ca type	2	11.1	Anlong County, Ceheng County	2.15

4 Evaluation of Suitability for The Development of High Strontium-Rich Groundwater

4.1 Evaluation System and Grade classification

The Analytic Hierarchy Process (AHP) was used to construct a three-level evaluation system of "target level - criterion level - indicator level" (Table 5). In this paper, the weights of the criterion layer of the analytic hierarchy process are determined through expert consultation and literature review. They are calculated after conducting pairwise comparison and matrix analysis based on the core influencing factors of the suitability of high, rich strontium groundwater development (such as water quality, strontium content, and development conditions). The water quality data mainly come from a one-time centralized sampling activity during the evaluation level year in 2022.The criteria layer includes water quality conditions (weight 0.45), strontium content characteristics (weight 0.35), and development basic conditions (weight 0.20). Each indicator is assigned on a 100-point scale, and the combined score is divided into three suitability grades:

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Priority suitability for development (⩾90 points) : Good water quality, high strontium content, superior basic conditions for development;

Generally suitable for development (80-89 points) : Good water quality, medium strontium content, simple supporting treatment required;

It is suitable for development after treatment (60-79 points) : The water quality is basically up to standard but there are a few factors that exceed the standard. Targeted treatment is required before development.

Table 5. Evaluation Index System and Weights for the suitability of high strontium-rich groundwater Development

Target layer	Criteria Layer	"Weight	Metrics Layer	Weights	Evaluation criteria
Development suitability grades	Water quality conditions	0.45	Water quality category	0.20	Class III = 100 points, Class IV = 60 points
		Rate of compliance with regular indicators	0.15	100%=100 points, 90% to 99%=80 points, < 90%=40 points	
		The rate of compliance with toxicological indicators	0.10	100%=100 points, otherwise = 0 points	
Strontium content characteristics	Strontium content	0.20	⩾3.0=100 points, 1.5-3.0=80 points, 1.0-1.5=60 points		
	Strontium content stability	0.15	Natural spring points = 100 points, well points = 80 points		
Development foundation conditions	Flow rate (L/s)	0.10	⩾10=100 points, 5-10=80 points, < 5=60 points		
	Convenience of transportation	0.10	Suburban = 100 points, town = 80 points, remote = 60 points		

Table 6. DevelopmentEvaluation Results of Priority Water Source Points for Development

Name of water source point	Combined score	Core strengths	Issues to focus on
In the afternoon, Tun Town, Xintun, Dujiajing	95.3	Strontium content 7.557mg/L, water quality good, flow 2.4L/s	Strengthen the prevention and control of surrounding pollution
Quanxin Village, Wantun Town	94.7	Strontium content 1.477mg/L, flow rate 8L/s, rural drinking water infrastructure is good	Maintain existing water source protection
Jinzhou Longquan Natural Mineral Water Co., LTD	93.5	Strontium content 11.010mg/L, stable well, convenient transportation	Regulate the extraction volume and avoid over-extraction
Sunshine Clear Spring Beverage Co., LTD. No. 1 well	92.8	Strontium content 2.669mg/L, with processing facilities available	Optimize the purification process to retain strontium
Dahaizi, Xinfeng Village, Qingshuihe Town	91.2	Strontium content 1.592mg/L, flow 40L/s, abundant water volume	Improve transportation and infrastructure

4.2 Analysis of Evaluation Results

The comprehensive evaluation results of the 18 water source points showed that 5 points (27.8%) were preferentially suitable for development, with comprehensive scores ranging from 91.2 to 95.3. The core characteristics are detailed in Table 6. There were 11 points (61.1%) generally suitable for development, all of which met the water quality standards, with strontium content concentrated between 1.5 and 3.0 mg/L, medium development conditions, and potential for development after simple purification treatment; Two sites (11.1%) require treatment and are suitable for commercial development: the old house foundation in the south of Xingren City (with excessive ammonia nitrogen) and the geothermal well in Jinzhou Agricultural Park, Anlong County (with high manganese content). Targeted treatment is required before commercial development.

5 Recommendations for Development and Utilization

Graded and categorized development: Prioritize the development of the high-end mineral water industry in suitable areas and extend the "mineral water + health care" industrial chain; Generally suitable areas develop the production of small and medium-sized bottled water in combination with rural drinking water projects; Targeted pollution control and replacement of corroded pipelines in areas requiring treatment.

Strengthen protection and monitoring: Designate protected areas of water sources (first level with a radius of 100 meters, second level with a radius of 500 meters) and strictly control surrounding pollution; Set up automatic monitoring stations at priority suitable development points to monitor core indicators such as strontium content and pH value in real time.

Optimize technology and policy support: Develop high-retention purification processes to prevent strontium loss; Set up special funds to subsidize development projects, establish a water withdrawal permit and total quantity control system, and cultivate the regional public brand of "Qiannan Rich Strontium Mineral Water".

5.1 Grade classificationGraded and Classified development strategy

Based on suitability evaluation results, propose differentiated development paths:
Priority suitable development zones: Focus on developing the high-end mineral water industry, extend the "mineral water + health care" industrial chain, and create regional brand benchmarks;

General suitable development zone: Develop the production of medium and small bottled water, and in combination with the consolidation and improvement project of rural drinking water safety, achieve universal utilization of resources;

Areas requiring treatment: Carry out source tracing and treatment of excessive factors such as ammonia nitrogen and manganese, update old water intake facilities, and access only after meeting the standards.

5.2 Water source protection and monitoring and early warning

Protected area demarcation: In accordance with the "Technical Specifications for the Division of Drinking Water Source Protection Areas" (HJ 338-2018), it is recommended that the radius of the first-level protection area be no less than 100 meters and that of the second-level protection area be 500 meters, with strict control over agricultural non-point sources and domestic pollution.

Dynamic monitoring: Set up automatic water quality monitoring stations at priority suitable development points to conduct real-time monitoring of key indicators such as strontium content, pH, ammonia nitrogen, and manganese, and establish an early warning response mechanism.

5.3 Technical optimization and policy support

Purification process development: Promote efficient retention technologies such as membrane separation and selective adsorption to retain strontium to the greatest extent possible while ensuring water quality safety;
Policy incentives: Establish a provincial special fund for the development of characteristic mineral water, and give preferential policies such as water withdrawal permits and land use quotas to priority development sites;

Brand development: Integrate regional resources to uniformly create the geographical indication brand of "Qiannan Strontium-rich Mineral Water" and promote the implementation of the "rich mineral Water Intensive Development" strategy.

6 Conclusions

The high strontium-rich groundwater in Qianxinan Prefecture is rich in strontium content (1.127-11.010 mg/L), and the water quality is generally good. The water chemical types are mainly HCO_3 -CA and HCO_3 -CA ·Mg. The indicators such as pH, total hardness, and total dissolved solids all meet the standards of "Drinking Natural Mineral water", and the toxicological indicators have a low safety risk. It has a good foundation for development.

The three-dimensional suitability evaluation system of "water quality conditions - strontium content characteristics - development basic conditions" constructed enables precise classification of the development potential of high strontium-rich groundwater. Among the 18 water source points, 5 were preferentially suitable for development, 11 were generally suitable for development, and 2 were suitable for development after treatment, and the identification results were consistent with the on-site investigation.

Comprehensive measures such as graded and classified development, demarcation of water source protection areas, construction of dynamic monitoring networks, research and development of high-retention purification processes and brand cultivation are suggested to provide systematic support for the sustainable development of high-strontium-rich groundwater in Qianxinan Prefecture and the implementation of the "intensive exploitation of rich mines" strategy. This study method can provide reference for the evaluation and targeted development of similar characteristic groundwater resources in the southwest karst area.

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