

Article

Identification and Quantitative Analysis of Nitrate Sources in Strontium-Rich Mineral Water of Chengde City Based on the MixSIAR Model

Yanliang Zhai ^{1,2}, Jingyi Xie ¹, Ruifeng Wang ^{1,2,*}, Baizhong Yan ^{2,3}, Wenyang Wang ¹, Yuqing Ren ¹, Jiashuai Kang ¹ and Songlong Zhang ¹

¹ The 4th Geological Team of Hebei Geology and Mining Bureau (Water Source Conservation Research Center of Hebei Province), Chengde 067000, China; zhaiyanliang2009@163.com (Y.Z.); xiejingyi20111@163.com (J.X.); wangwy319175851@163.com (W.W.); renyuqing7@163.com (Y.R.); 19031680757@163.com (J.K.); zhangsonglong@163.com (S.Z.)

² Hebei Key Laboratory of Mountain Geological Environment, Chengde 067000, China; jluybz@126.com

³ Hebei Province Collaborative Innovation Center for Sustainable Utilization of Water Resources and Optimization of Industrial Structure, Hebei GEO University, Shijiazhuang 050031, China

* Correspondence: wrfcd@163.com

Abstract

Nitrate is one of the most prevalent inorganic pollutants in groundwater systems. Its concentration directly affects the safety assessment of groundwater quality. To scientifically identify nitrate sources in strontium-rich mineral water and facilitate the protection of mineral water resources, this study selects Chengde City, Hebei Province, as the study area. Nitrate source apportionment was quantified using the MixSIAR model, with uncertainties assessed via cumulative probability distributions. The results show that the nitrate concentration in strontium-rich mineral water of the study area ranges from <0.003 to 70.2 mg/L, with a coefficient of variation of 1.24, indicating high data dispersion. The nitrate sources present a mixed pollution characteristic dominated by natural processes and supplemented by human activities. Nitrification dominates biogeochemical processes of strontium-rich mineral water. Soil nitrogen is the primary contributor to nitrate in mineral water, with an average contribution rate of 70.4%, followed by manure; synthetic fertilizers and rainwater together account for less than 1% of the total. Uncertainty analysis shows that contributions of rainwater, synthetic fertilizer, manure, and soil nitrogen to nitrate in strontium-rich mineral water remain stable ($UI_{95} < 0.15$), verifying reliable results. This study provides guidance for protecting mineral water quality and sustainable resource exploitation.

Keywords: strontium-rich mineral water; nitrate source; MixSIAR model; nitrogen and oxygen isotopes; quantitative analysis

Academic Editor: Alla Khosrovyan

Received: 5 June 2026

Revised: 30 June 2026

Accepted: 7 July 2026

Published: 8 July 2026

Copyright: © 2026 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\) license](https://creativecommons.org/licenses/by/4.0/).

1. Introduction

Water is the source of life. As a source of drinking water essential to human survival, groundwater also supports agricultural irrigation and industrial production. It plays an irreplaceable role in ensuring regional water security, maintaining ecological stability, and promoting the sustainable development of unique mineral water resources. Currently, as the processes of intensive agriculture and urbanization continue to advance

worldwide, large amounts of anthropogenic nitrogen pollutants are being introduced into groundwater systems. Nitrate has become one of the most common inorganic pollutants in global groundwater systems, and nitrate pollution has emerged as a widespread environmental issue affecting groundwater systems worldwide [1–3]. Nitrate accumulation in groundwater has been observed in various regions around the globe, including agricultural areas in Europe and the United States, river valley plains in Asia, and mountainous regions in North Africa [3,4]. Excessive levels of nitrates not only disrupt the ecological balance of groundwater but also pose a threat to human health through drinking water [5–7]. Long-term exposure can lead to methemoglobinemia. Therefore, conducting research to trace the sources of nitrate in groundwater is of great theoretical and practical significance for protecting the region's unique mineral water resources and safeguarding the minimum standards for regional drinking water safety.

The primary sources of nitrate in groundwater include atmospheric precipitation, soil organic nitrogen, inorganic fertilizers, organic fertilizers, livestock manure, and domestic wastewater, among others [1,8,9]. Previous research has primarily relied on methods such as land-use pattern analysis, water chemistry ion ratios, and multivariate statistical analysis to identify nitrate sources [10–12]. However, these traditional tracing methods rely primarily on qualitative analysis and indirect inference, making it difficult to accurately identify the actual contribution of each nitrate source and the nitrogen transformation processes. The molecular form of NO_3^- is not entirely stable in ecosystems and aquatic environments. It is influenced by microbial biogeochemical processes and is also susceptible to disturbances from hydrogeological and hydrogeochemical processes, making it difficult to distinguish between pollution sources with similar isotopic compositions [8,9,13]. Nitrogen and oxygen isotope technology can effectively make up for the deficiencies of traditional hydrochemical methods [9,14]. However, this technique can only qualitatively identify nitrate sources, and it is difficult to quantify the contribution proportion of each pollution source. In addition, isotope fractionation, overlapping endmember values, and other factors tend to bias the results. The isotope mixing model MixSIAR, based on a Bayesian framework, offers high compatibility, comprehensiveness, and flexibility [15–18]. It can accurately quantify the contribution of each pollution source to nitrate levels, addressing the shortcomings of previous research methods and significantly enhancing the scientific rigor and accuracy of nitrate source analysis. It is widely used in estimating nitrate pollution sources both domestically and internationally.

Natural mineral water is a unique water resource formed by groundwater through long-term water-rock interaction [19]. With the rising global demand for high-quality drinking water, natural mineral water has become a research focus in water resource development and protection because it is rich in trace elements beneficial to the human body and possesses natural health properties. As a high-quality type of natural drinking mineral water, strontium-rich mineral water has become an important development resource in the drinking water market owing to the physiological effects of strontium on human bone development and cardiovascular protection [20,21]. At present, scholars both in China and abroad have conducted extensive research on strontium-rich groundwater in various geological settings. These studies mainly focus on the formation, hydrochemical characteristics, and genetic mechanism of strontium-rich groundwater [22–24]. However, there is a particular lack of systematic traceability studies on high-risk contaminants in this specific type of groundwater—strontium-rich mineral water. In particular, research remains relatively limited in areas such as identifying sources of nitrate contamination in strontium-rich mineral water, understanding biogeochemical processes, and analyzing the quantitative contributions of various pollution sources. It is difficult to ensure the safety and sustainable development of the region's strontium-rich mineral water resources.

In order to address this issue, this research uses Chengde City in Hebei Province as a case study (Figure 1). Firstly, the dual nitrate isotope technique is adopted to qualitatively identify nitrate sources in strontium-rich mineral water. Secondly, by comparing the theoretical and measured values of $\delta^{18}\text{O}_{\text{-NO}_3}$ and analyzing the distribution characteristics of isotope correlation, the main biogeochemical processes in strontium-rich mineral water are explored via the relational graph of $\delta^{18}\text{O}_{\text{-NO}_3}$ and $\delta^{18}\text{O}_{\text{-H}_2\text{O}}$, as well as the correlation distribution diagram of pH and dissolved oxygen content. Finally, the Bayesian-based isotope mixing model (MixSIAR) is adopted to quantitatively estimate the contribution proportions of different nitrate sources based on the mass conservation principle. Through this research, we not only fill a gap in the study of nitrate sources in strontium-rich mineral water in the Chengde region but also provide guidance for the scientific development and conservation of these springs.

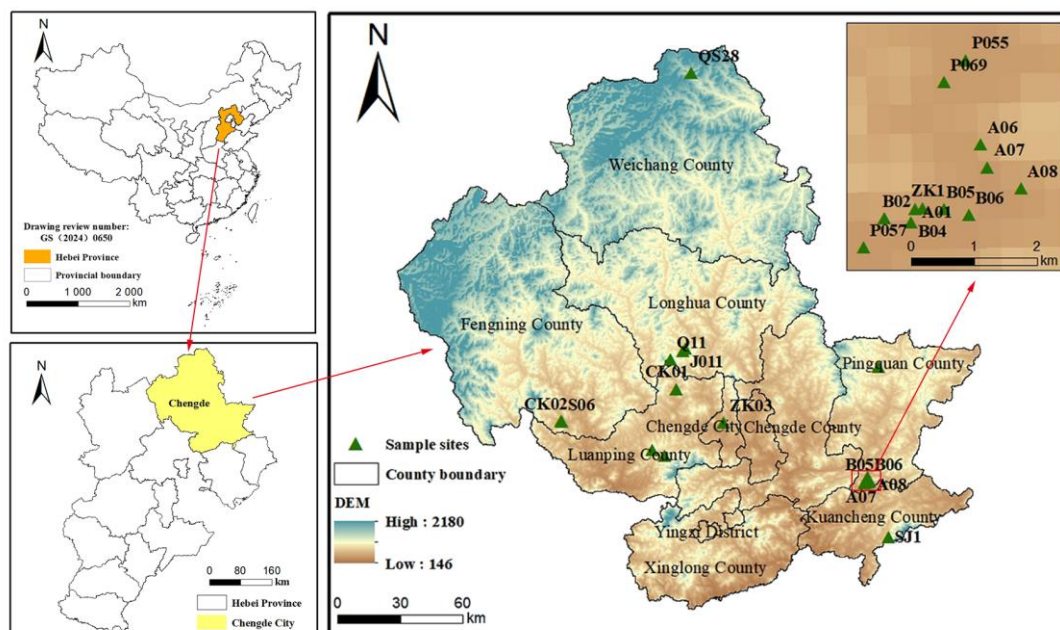


Figure 1. Overview of the study area and spatial distribution of sampling sites.

Chengde City is located in the northeastern part of Hebei Province, in the heart of the Yanshan Mountains. The regional geology is complex, with well-developed faults and frequent crustal activity. Igneous, volcanic, and metamorphic rocks are widely distributed, and there is ample space for groundwater migration and storage. This provides a rich source of materials and favorable pathways for the formation and migration of strontium-rich mineral water. Strontium-rich groundwater resources are widely distributed throughout Chengde City. Currently, 16 sources of strontium-rich mineral water have been identified, occurring in all 10 counties (districts) within the city. Spatially, these resources are concentrated in the central and southeastern regions, with scattered occurrences throughout the entire area. The proven allowable extraction volume of strontium-rich mineral water has reached 11,776.5 m³/d. Therefore, it can be seen that the Chengde region is endowed with abundant and widely distributed strontium-rich mineral water resources, making it a key area for the accumulation of such resources in northern Hebei. However, in recent years, the nitrate concentration in some strontium-rich mineral water in Chengde City has exceeded the limit of 45 mg/L specified in the National Food Safety Standard—Maximum Levels of Contaminants in Food (GB 2762-2025) [25], nitrate concentrations in some areas are close to the limit of 20 mg/L (as N) for Class III groundwater

specified in China's Quality Standard for groundwater quality (GB/T 14848-2017) [26], resulting in many unsuccessful cases during the exploration and development of strontium-rich mineral water resources. Therefore, conducting a scientific traceability analysis of nitrate contamination in strontium-rich mineral water is of significant practical importance and applied value for ensuring the safety of mineral water quality, promoting its scientific development, and safeguarding its conservation and sustainable use.

2. Materials and Methods

2.1. Study Area

Chengde City is located in the northeastern part of Hebei Province, in the heart of the Yanshan Mountains. It serves as an ecological buffer zone where the North China Plain transitions into the Inner Mongolia Plateau, with a total area of approximately 39,500 km². The terrain is higher in the northwest and lower in the southeast, consisting mainly of low-to-medium-height mountains and hills. The city has a temperate, semi-arid, semi-humid continental monsoon climate. The long-term average precipitation is 500–600 mm. Rainfall and heat occur simultaneously, and evaporation is intense, making it an important water conservation area for the Beijing–Tianjin–Hebei region. Forest land accounts for the largest proportion of the region's land area, with the city's forest coverage rate reaching 60.03%, indicating an overall excellent ecological baseline. Arable land is concentrated in the gentle river valley areas; constrained by the mountainous and hilly terrain, its total area accounts for only 8.2% of the city's total land area. The main crops grown include corn and miscellaneous grains, and urea and compound fertilizers are routinely applied in the fields.

The regional geological structure is complex, with well-developed faults. The strata consist primarily of Archean metamorphic rocks, Proterozoic carbonate rocks, and Mesozoic volcanic and intrusive rocks, featuring a diverse combination of rock types. This provides favorable hydrogeological conditions for the long-term dissolution, filtration, and ion exchange between groundwater and the surrounding rock, making it a typical area in northern Hebei where strontium-rich mineral springs are concentrated. Groundwater in the area consists primarily of bedrock fissure water, karst water, and river valley pore water, replenished mainly through the infiltration of atmospheric precipitation, serving as the core source for the extraction of strontium-rich mineral water. Groundwater is primarily used for daily drinking water for residents, agricultural irrigation, and mineral water extraction. At the same time, due to human activities such as agricultural cultivation and domestic wastewater discharge in rural areas, nitrate pollution in groundwater is a significant problem in some river valleys and foothill areas, highlighting the conflict between water quality safety and resource development.

2.2. Sample Collection

Based on comprehensive geological and hydrogeological investigations, systematic sampling was conducted for strontium-rich mineral water wells in the study area of this research. In particular, well water samples were pumped for at least 4 h prior to on-site testing and sample collection to ensure that the samples were fresh, clean, and free of suspended impurities. Based on hydrogeological conditions and the distribution characteristics of pollution sources, this study selected 24 representative sampling sites for analysis. The sampling point information is shown in Table 1, and the spatial distribution of the sampling points is shown in Figure 1.

Table 1. Sampling point information.

Number	Sampling Point Locations	District/County	Number	Sampling Point Locations	District/County
CK02	Yangjiying Village, Heishanzui Town	Fengning County	A06	Nuanquan Village, Dangba Town	Pingquan City
S06	Yangjiying Village, Heishanzui Town	Fengning County	P069	Qianmeilingzi Village, Dangba Town	Pingquan City
SJ1	Miaoling, Dongchuan	Kuancheng County	ZK01	Jiangzhangzi Village, Liaoheyuan	Pingquan City
QK2-7	Longfengshankou, Lanqi Town	Longhua County	A01	Yong'an Village, Dangba Town	Pingquan City
J011	Laopozigou, Lanqi Town	Longhua County	ZK1	Yong'an Village, Dangba Town	Pingquan City
Q11	Qiansonggou Village, Lanqi Town	Longhua County	P057	Sishimu Di, Yong'an Village, Dangba Town	Pingquan City
CK01	Tazigou Village, Xigou Township	Luanping County	B06	Primary School, Yong'an Village, Dangba Town	Pingquan City
ZK02	Changshanyu Mineral Water Well	Luanping County	B02	Beishangen, Yong'an Village, Dangba Town	Pingquan City
S200	Tieying, Changshanyu Village, Changshanyu Town	Luanping County	B05	West of Yong'an Village, Dangba Town	Pingquan City
P055	Dazhangzi Village, Dangba Town	Pingquan City	B04	Huangjiezi, Yong'an Village, Dangba Town	Pingquan City
A08	Sihedian Village, Dangba Town	Pingquan City	ZK03	Qianying Village, Xidi Town	Shuangluan District
A07	Henan Village, Dangba Town	Pingquan City	QS28	Jiangjiadian Village, Jiangjiadian Township	Weichang County

2.3. Test Methods

Sample testing includes on-site testing and laboratory testing. pH and dissolved oxygen (DO) were determined in situ using an AquaTROLL 400 multi-parameter water quality sonde (In-Situ Inc., Fort Collins, CO, USA). The measuring range of pH was 0–14 with a detection precision of ± 0.1 , and the measuring range of dissolved oxygen was 0–50 mg/L with a detection precision of ± 0.1 mg/L.

Oxygen isotopes in water, nitrate nitrogen and oxygen isotopes, and nitrate concentrations were determined through laboratory analyses. Oxygen isotopes in water samples were collected using 500 mL sampling bottles and analyzed by the Isotope Testing Laboratory, Institute of Hydrogeology and Environmental Geology, Chinese Academy of Geological Sciences, following the standard method Methods for analysis of groundwater quality—Part 77: Measurement oxygen isotope composition CO₂-H₂O equilibration—Isotope ratio mass spectrometry (DZ/T 0064.77-2021) [27]. Analyses were performed using a Thermo Scientific MAT-253 gas isotope mass spectrometer (Thermo Scientific, Bremen, Germany). The instrument has a mass measurement range of 1–150 Da, and the $\delta^{18}\text{O}$ detection accuracy (1σ) is $\pm 0.2\text{‰}$.

Nitrate nitrogen isotopes were collected in 40 mL VOA vials, filtered on-site through a 0.22 μm filter membrane, and then sent to the Environmental Stable Isotope Laboratory, Chinese Academy of Agricultural Sciences, for analysis. The determination was performed using the denitrifying bacteria method, in which denitrifying bacteria (*Pseudomonas aureofaciens*, ATCC 13985) lacking N₂O reductase activity were used to convert nitrate (NO₃[−]) in water samples into N₂O gas. The converted N₂O was purified and concentrated using a trace gas preconcentrator (Precon) and then introduced into a Delta V Plus gas isotope mass spectrometer manufactured by Thermo Scientific (Bremen, Germany) for

analysis. The instrument has a mass measurement range of 1–96 Da, with a detection accuracy of $\pm 0.2\text{‰}$ for both $\delta^{15}\text{N}$ and $\delta^{18}\text{O}$. Data calibration was performed using the USGS32, USGS34, and IAEA-NO-3 international reference materials.

Nitrate content was determined in accordance with Methods for analysis of ground-water quality—Part 59: Determination of nitrate—Ultraviolet spectrophotometry (DZ/T 0064.59-2021) [28] using a UV-1240 UV-Vis spectrophotometer manufactured (Shimadzu, Kyoto, Japan). The method's measurement range is 0.20–20.0 mg/L, with a limit of quantification of 0.20 mg/L. The analysis was conducted by the Laboratory of the Fourth Geological Brigade of the Hebei Bureau of Geology and Mineral Exploration and Development.

2.4. Data Processing Methods

2.4.1. Dual Stable Isotope Tracing Method

The dual stable isotope tracing method uses nitrogen and oxygen isotopes ($\delta^{15}\text{N}$, $\delta^{18}\text{O}$) as tracing indicators. Isotopic ratios of nitrate in collected strontium-rich mineral water samples were precisely measured [11,29]. Using characteristic isotopic ranges of nitrate from diverse sources, qualitative identification and source analysis of nitrate were performed [30]. To identify the potential sources of NO_3^- in mineral water within the study area, this study selected four typical sources of contamination—rainwater, synthetic fertilizer, soil nitrogen, and manure—based on existing research and field surveys. Qualitative identification is achieved by mapping the distribution of pollution sources using a dual nitrogen-oxygen isotope indicator. Based on previous research, the isotopic ranges for various sources have been systematically summarized and determined, as shown in Table 2 [31].

Table 2. Nitrogen and oxygen isotope ranges for different nitrate sources (‰).

Sources of Nitrate	$\delta^{15}\text{N}_{-\text{NO}_3}$	$\delta^{18}\text{O}_{-\text{NO}_3}$
Rainwater	−13~13	25~75
Synthetic Fertilizer	−4~4	−10~15
Soil Nitrogen	0~8	−10~15
Manure	5~25	−10~15

2.4.2. Nitrification and Denitrification

Nitrification and denitrification are the most important biogeochemical processes involved in the transport and transformation of nitrate in groundwater [32]. In particular, the $\delta^{18}\text{O}_{-\text{NO}_3}$ values produced by nitrification are jointly regulated by the isotopic characteristics of two sources of oxygen: atmospheric oxygen and the surrounding water [33]. Therefore, in terms of mass balance, the theoretical value of $\delta^{18}\text{O}_{-\text{NO}_3}$ formed by nitrification can be calculated using Equation (1):

$$\delta^{18}\text{O}_{-\text{NO}_3} = 1/3\delta^{18}\text{O}_{-\text{O}_2} + 2/3\delta^{18}\text{O}_{-\text{H}_2\text{O}} \quad (1)$$

The $\delta^{18}\text{O}_{-\text{H}_2\text{O}}$ value in environmental water is determined through instrumental analysis, while the $\delta^{18}\text{O}_{-\text{O}_2}$ value in air is relatively stable and is typically taken as 23.5‰ [34].

Nitrification is the key microbial pathway for nitrate formation in aquatic environments. Previous studies have shown that the $\delta^{18}\text{O}_{-\text{NO}_3}$ values resulting from nitrification fluctuate between −2‰ and 6‰, or between <−5‰ and 15‰, or between −10‰ and 10‰ (Table 3) [35,36]. Compare and analyze the theoretical and measured values with previous studies to determine whether nitrification has occurred. Plot the relationship between $\delta^{18}\text{O}_{-\text{NO}_3}$ and $\delta^{18}\text{O}_{-\text{H}_2\text{O}}$ values to determine the correlation lines for the three oxygen sources: (1) The oxygen in nitrate comes entirely from the atmosphere; (2) The oxygen in

nitrate is supplied jointly by oxygen from the ambient water and the atmosphere, in accordance with the theoretical ratio of nitrification; (3) The oxygen in nitrate comes entirely from the ambient water. By assigning values to the $\delta^{18}\text{O}_{-\text{NO}_3}$ and $\delta^{18}\text{O}_{-\text{H}_2\text{O}}$ of nitrate at sampling sites, we can determine whether nitrification has occurred. If the sampling points distribute near the theoretical value line, nitrification is confirmed to occur; otherwise, no nitrification takes place.

Denitrification is a key microbial process for removing nitrate in aquatic environments. Previous studies have shown that during denitrification, the slopes of the linear fitting equations for $\delta^{15}\text{N}_{-\text{NO}_3}$ and $\delta^{18}\text{O}_{-\text{NO}_3}$ in the reaction residue solution fall within a specific range, ranging from 0.48 to 0.77 (Table 3) [37,38]. The fitting of $\delta^{15}\text{N}_{-\text{NO}_3}$ and $\delta^{18}\text{O}_{-\text{NO}_3}$ values of nitrate was conducted, and slope comparison analysis was applied to judge denitrification occurrence. If the slope falls within the theoretical range, denitrification is confirmed; otherwise, it does not occur.

Dissolved oxygen content and pH are key environmental factors governing the biogeochemical processes of nitrate. Previous studies have shown that during nitrification, the dissolved oxygen content in the water is typically >5.5 mg/L, and the optimal pH range for nitrifying bacteria is 6.5–8.0 [39,40]. During denitrification, the dissolved oxygen content in the water is typically <2 mg/L, and the optimal pH range for heterotrophic denitrifying bacteria is 5.5–8.0 (Table 3) [41,42]. By plotting the pH and dissolved oxygen values from each sampling site on a correlation plot of pH versus dissolved oxygen content, the primary biogeochemical processes responsible for nitrate formation at each sampling site can be identified.

The correlation plots above were plotted using Origin 2021.

Table 3. Conditions for biogeochemical processes.

Biogeochemical Processes	$\delta^{18}\text{O}_{-\text{NO}_3}$ Value (‰)	Slope of $\delta^{15}\text{N}_{-\text{NO}_3}$ and $\delta^{18}\text{O}_{-\text{NO}_3}$ Fitting Equation	pH Value	Dissolved Oxygen Content (mg/L)
Nitrification	−2~6/−5~15/−10~10	/	6.5~8.0	>5.5
Denitrification	/	0.48~0.77	5.5~8.0	<2

2.4.3. Analysis of the MixSIAR Model

The isotope mixing model MixSIAR, based on the Bayesian framework, was used to calculate the different sources of nitrate in groundwater [43]. The MixSIAR model runs in an open-source R package. It calculates the contribution ratios of different sources to a mixture by defining isotopic relationships between those sources and the mixture. The model also accounts for the effects of nitrate di-isotopic fractionation. The calculation formula is as follows:

$$X_{ij} = \sum_{k=1}^K P_k (S_{jk} + C_{jk}) + \varepsilon_{jk} \quad (2)$$

$$S_{jk} \sim N(\mu_{jk}, \omega_{jk}^2) \quad (3)$$

$$C_{jk} \sim N(\lambda_{jk}, \tau_{jk}^2) \quad (4)$$

$$\varepsilon_{jk} \sim N(0, \sigma_j^2) \quad (5)$$

where X_{ij} represents the ratio of the j th isotope in the i th sample, where $i = 1, 2, 3, \dots, N$ and $j = 1, 2, 3, \dots, J$; K represents the total number of source elements for nitrate pollution ($k = 1, 2, 3, \dots, K$); P_k represents the contribution percentage of the k th pollution source;

S_{jk} represents the isotopic element value for the k th pollution source, which follows a normal distribution, where μ_{jk} is the mean of the isotopic element for the k th pollution source, and ω_{jk}^2 is the variance of the element value; S_{jk} represents the value of isotope j at the k th pollution source, which follows μ_{jk} normal distribution with mean μ_{jk} and variance ω_{jk} ; C_{jk} represents the isotope fractionation correction term, which is used to characterize the effects of isotope fractionation caused by biogeochemical processes such as nitrification and denitrification; λ_{jk} represents the mean of the fractionation effect; τ_{jk}^2 represents the variance of the fractionation effect; ε_{jk} represents the random error term, and σ_j^2 represents the variance of the error term, reflecting the uncertainties in the isotope testing and model analysis processes.

By calculating the contribution ratios of different nitrate sources and their uncertainty ranges, we can precisely quantify the relative contribution of each pollution source, thereby enabling a quantitative analysis of nitrate sources.

3. Results

3.1. Sample Analysis Results

The main water chemistry parameters for the study area were obtained through testing (Tables 4 and A1). The pH range of the strontium-rich mineral water in Chengde City is 7.1–8.2, with an average of 7.6 ± 0.3 ($\pm$ standard deviation). Overall, it is slightly alkaline, with a coefficient of variation of 0.04. This indicates that the regional groundwater's pH environment is generally stable and that the strontium-rich mineral water has not been subject to significant acid or alkali contamination or abnormal disturbances. The dissolved oxygen content is in the range of 2.57–16.34 mg/L, with an average of 7.4 mg/L and a coefficient of variation of 0.40. This indicates that there are spatial variations in the redox conditions of the groundwater in the study area, which may influence the processes of nitrogen migration and transformation. The overall concentration of nitrate (NO_3^-) is unevenly distributed, in the range of <0.003 –70.2 mg/L, with a mean of 17.8 mg/L, far exceeding the natural background level (<9 mg/L). The standard deviation is 22.1 mg/L, indicating a high degree of data dispersion. The coefficient of variation is 1.24. Since this value is greater than 1, it is significantly higher than that of conventional ions governed by natural processes. This indicates that there is significant spatial variation in nitrate concentrations, which may be influenced by localized, non-uniform inputs from human activities. Although the average NO_3^- concentration does not exceed 89 mg/L for Class III groundwater specified in the Standard for groundwater quality (GB/T 14848-2017) and 50 mg/L recommended by the WHO, nitrate concentrations at two sampling sites exceed the limit of 45 mg/L stipulated in the National Food Safety Standard—Maximum Levels of Contaminants in Food (GB 2762-2025). This indicates that localized nitrate pollution has already emerged in the region, posing a significant potential threat to human health. The $\delta^{15}\text{N}_{-\text{NO}_3}$ values in the strontium-rich mineral water of the study area were in the range of 0.3–16.8‰, with a mean of 7.7 ± 3.5 ‰. The $\delta^{18}\text{O}_{-\text{NO}_3}$ values were in the range of -1.6 –12.4‰, with a mean of 3.4 ± 3.0 ‰. These data serve as a basis for subsequent qualitative analysis of nitrate sources.

Table 4. Physicochemical parameters of strontium-rich mineral water in Chengde.

Index	Minimum	Maximum	Mean	Standard Deviation	Coefficient of Variation
pH value	7.1	8.2	7.6	0.3	0.04
Dissolved oxygen content (mg/L)	2.57	16.34	7.4	2.9	0.40
NO_3^- (mg/L)	<0.003	70.2	17.8	22.1	1.24

$\delta^{15}\text{N}_{\text{-NO}_3}$ (‰)	0.3	16.8	7.7	3.5	0.45
$\delta^{18}\text{O}_{\text{-NO}_3}$ (‰)	-1.6	12.4	3.4	3.0	0.88

3.2. Qualitative Identification of Nitrate Sources

The nitrate isotope data from strontium-rich mineral water samples collected in the study area were overlaid on the pollution source distribution map (Figure 2). The results indicate that the sources of nitrate in the strontium-rich mineral water of the study area exhibit a pattern of mixed pollution, with natural processes playing the primary role and human activities playing a secondary role. In terms of source distribution, the majority of sampling points—19 in total—were concentrated in the range of manure. This indicates that manure is among the primary sources of nitrate in the study area. It reflects the ongoing impact of decentralized livestock farming and domestic wastewater discharge in the region on the nitrate content of strontium-rich mineral water. All 14 sampling sites fall within the range of soil nitrogen values. This indicates that the mineralization of soil organic nitrogen and subsequent nitrification are the primary sources of nitrate in the study area. In contrast, none of the sample points fall within the rainwater range. At the same time, only 4 sampling sites fall within the range of synthetic fertilizer values. These findings indicate that the direct contribution of rainfall and fertilizer use to nitrate levels in the groundwater of the study area is very limited. The nitrate in the strontium-rich mineral water of the study area primarily originates from soil nitrogen and manure, while the contributions from synthetic fertilizer and rainwater are negligible. This confirms that the source structure of nitrate in the region is characterized by natural processes as the primary source and human activities as a secondary source.

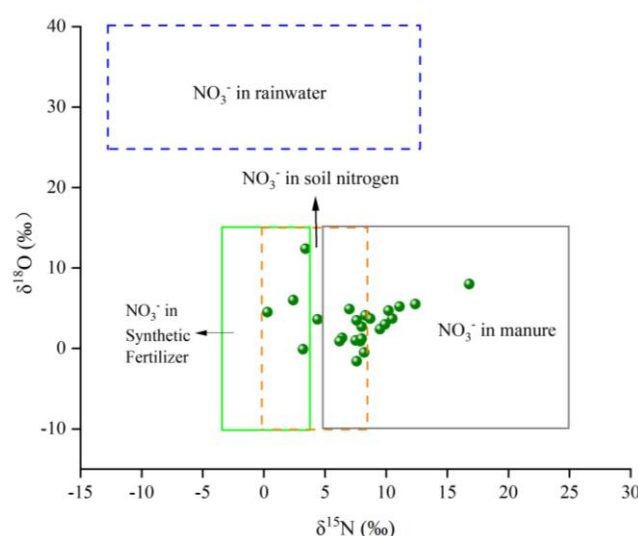


Figure 2. Distribution of $\delta^{15}\text{N}_{\text{-NO}_3}$ and $\delta^{18}\text{O}_{\text{-NO}_3}$ in strontium-rich mineral water.

3.3. Main Biogeochemical Functions of Nitrate

Based on theoretical calculations of nitrification, the theoretical values for $\delta^{18}\text{O}_{\text{-NO}_3}$ formed by nitrification in the study area ranged from -0.8 to 2.6‰ (mean: $1.8 \pm 0.7\text{‰}$), while the measured values ranged from -1.6 to 12.4‰ (mean: $3.5 \pm 3.0\text{‰}$). Compared with previous research findings, the range of both theoretical and measured $\delta^{18}\text{O}_{\text{-NO}_3}$ values for the strontium-rich mineral water in the study area falls within the range of $\delta^{18}\text{O}_{\text{-NO}_3}$ values previously reported to result from nitrification. This indicates that nitrification has occurred in the strontium-rich mineral water of the study area. At the same time, the plot of the relationship between $\delta^{18}\text{O}_{\text{-NO}_3}$ and $\delta^{18}\text{O}_{\text{-H}_2\text{O}}$ shows that the measured $\delta^{18}\text{O}_{\text{-NO}_3}$ val-

ues of the strontium-rich mineral water samples in the study area are predominantly distributed near the theoretical $\delta^{18}\text{O}_{\text{NO}_3}$ line resulting from nitrification (Figure 3). This indicates that the oxygen atoms in the nitrate in the water are primarily derived from a 2:1 ratio of ambient water and atmospheric oxygen, confirming that nitrification has occurred in the strontium-rich mineral water of the study area.

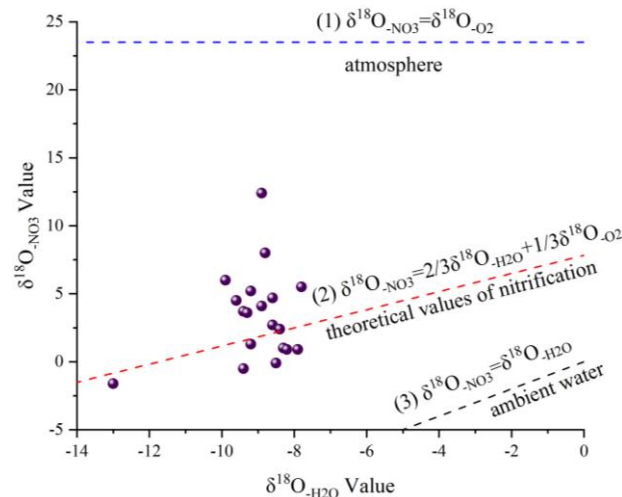
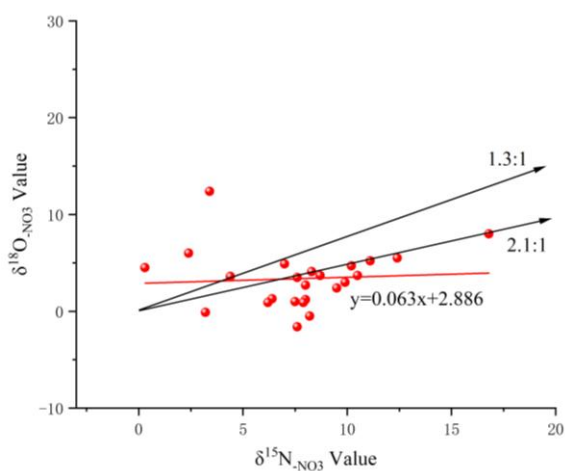
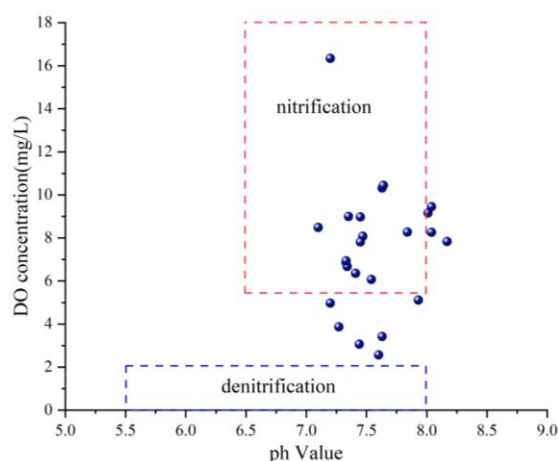


Figure 3. Relationship between measured $\delta^{18}\text{O}_{\text{NO}_3}$ and theoretical nitrification values.

A linear fit is performed on the $\delta^{15}\text{N}_{\text{NO}_3}$ and $\delta^{18}\text{O}_{\text{NO}_3}$ values of strontium-rich mineral water samples from the study area. The results indicate that the fitting equation is $\delta^{18}\text{O}_{\text{NO}_3} = 0.063\delta^{15}\text{N}_{\text{NO}_3} + 2.886$ (Figure 4a), and the slope does not fall within the characteristic range for denitrification. This shows that denitrification does not occur in the strontium-rich mineral water environment of the study area. At the same time, a plot of the correlation between pH and dissolved oxygen content in strontium-rich mineral water samples from the study area revealed that most water sampling sites fall within the ideal range for nitrification (Figure 4b). This further confirms that nitrification occurs in the strontium-rich mineral water environment of the study area, while denitrification does not.



(a)



(b)

Figure 4. (a) Linear fit of $\delta^{15}\text{N}_{\text{NO}_3}$ and $\delta^{18}\text{O}_{\text{NO}_3}$ values and the range of denitrification; (b) Relationship between pH and dissolved oxygen content in strontium-rich mineral water.

3.4. Quantitative Analysis of Nitrate Sources

The contribution rates for different sources of nitrate in the strontium-rich mineral water of the study area were calculated by MixSIAR. Overall, the contributions of the four different sources to nitrate levels in strontium-rich mineral water are ranked as follows: soil nitrogen > manure > synthetic fertilizer > rainwater, accounting for 70.4%, 28.6%, 0.8%, and 0.2% of the total, respectively (Figure 5). This indicates that soil nitrogen and manure are the primary factors influencing nitrate concentrations in strontium-rich mineral water. Among these, soil nitrogen has the strongest influence, which may be closely related to the high proportion of forest and grassland in land use within the study area. In areas with a healthy ecological environment, the proportion of soil nitrogen sources is higher. This also indirectly confirms that although NO_3^- concentrations in strontium-rich mineral water are elevated in some parts of the study area, the overall ecological environment of the study area remains sound. Manure accounts for the second-largest proportion, which may be related to inadequate local policies supporting the use of reclaimed water, the scattered nature of villages, and inadequate centralized wastewater treatment facilities. The effects of synthetic fertilizer and rainwater are minimal and can be considered negligible. This may be related to the study area's commitment to green development, the significant improvement in air quality, the year-on-year reduction in the application of chemical fertilizers and pesticides, and the low concentration of NO_3^- in rainwater.

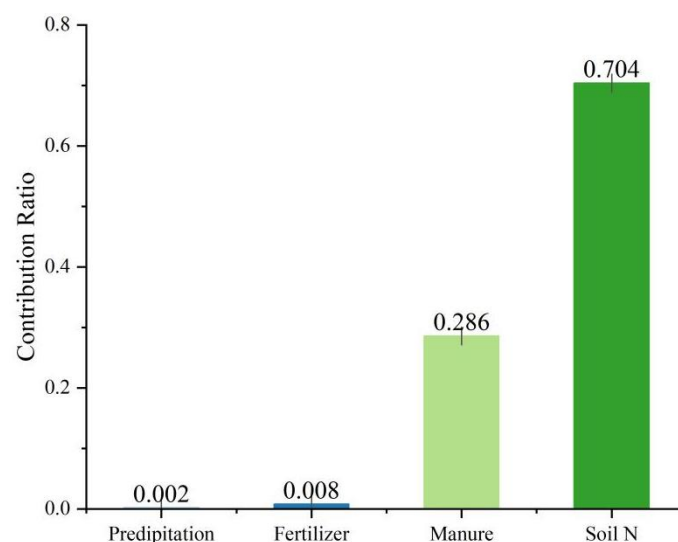


Figure 5. Proportional composition of nitrate sources in strontium-rich mineral water.

4. Discussion

4.1. Uncertainty Analysis in the Quantitative Determination of Nitrate Sources

To assess the reliability and spatiotemporal heterogeneity of the contribution rates of NO_3^- sources in the strontium-rich mineral water of the study area, this study employed a cumulative probability distribution for uncertainty assessment. The uncertainty index (UI_{95}) is calculated using the 95% cumulative probability interval (defined as the difference between the maximum and minimum contribution rates within the 95% cumulative probability range, divided by 0.95) [44]. The UI_{95} value characterizes the stability and spatial heterogeneity of nitrate sources. A lower UI_{95} value indicates that the quantitative results for nitrate sources are more stable and that the spatiotemporal heterogeneity of these sources is smaller; conversely, a higher UI_{95} value indicates that the sources are less stable and that the spatiotemporal heterogeneity is greater. Based on existing research, the following criteria are established: when $\text{UI}_{95} \leq 0.2$, this indicates “low uncertainty and stable

results”; when $0.2 < UI_{95} \leq 0.5$, this indicates “moderate uncertainty”; and when $UI_{95} > 0.5$, this indicates “high uncertainty and significant spatiotemporal heterogeneity” [44–46].

Using the MixSIAR model, we calculate the contribution ratios of various pollution sources to NO_3^- in the strontium-rich mineral water of the study area, along with the corresponding cumulative probability distribution data, and plot the cumulative probability distribution (Figure 6). It can be seen that, within the 95% cumulative probability interval, the contribution rates of the four sources—rainwater, synthetic fertilizer, manure and soil nitrogen—to NO_3^- in the strontium-rich mineral water of the study area are 0–0.8%, 0–2.4%, 21.6–35.5%, and 63.8–77.6%, respectively. The corresponding UI_{95} values for each pollution source are 0.01, 0.03, 0.14, and 0.15, respectively. The UI_{95} values for the contribution rates of the four sources of nitrate pollution are all at low levels, indicating that the contributions of rainwater, synthetic fertilizer, manure, and soil nitrogen to NO_3^- in the strontium-rich mineral water of the study area are stable and exhibit low spatiotemporal heterogeneity. These results validate the scientific validity and reliability of using the MixSIAR model to conduct quantitative analyses of nitrate pollution sources.

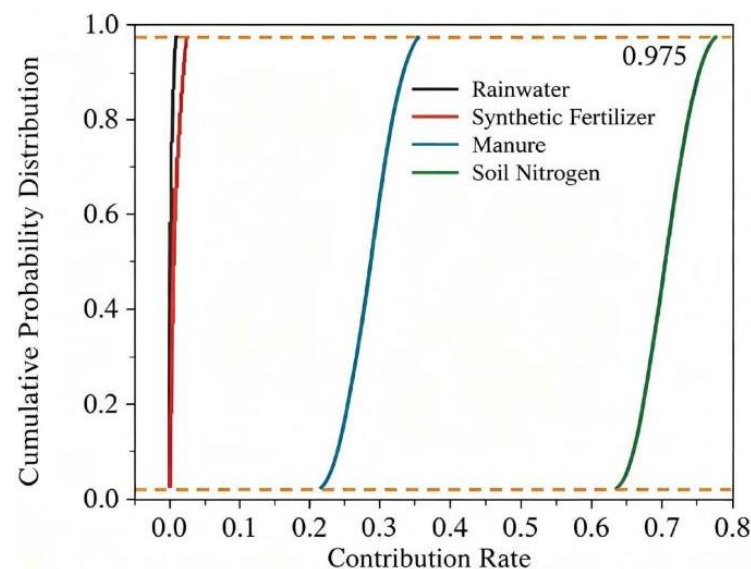


Figure 6. Relationship between nitrate source contribution rate and cumulative probability distribution. (The two horizontal dashed lines represent the 2.5% and 97.5% quantiles, respectively, and together they define the 95% confidence interval).

Research by Sun et al. indicates that nitrate in groundwater in the Luanping Basin of Chengde City primarily originates from mixed pollution from livestock manure and domestic sewage, followed by leaching from chemical fertilizers [47]. These findings are consistent with the source analysis in this study, which identified “soil nitrogen and manure as the primary sources, supplemented by synthetic fertilizer and rainwater”. The UI_{95} values for various pollution sources in the study area generally remained at low levels, which fully demonstrates the reliability of the contributions from different sources of nitrate calculated in this study. This further supports the understanding that denitrification has not occurred in the study area and that the use of synthetic fertilizer in agriculture is relatively limited.

4.2. Contribution Characteristics and Environmental Significance of Nitrate Sources

Based on the quantitative analysis results from the MixSIAR model, the contribution rates of nitrate sources in the strontium-rich mineral water of the study area exhibit significant structural differences, which are highly coupled with the regional environmental context. The results show that soil nitrogen is the primary source, followed by manure,

while synthetic fertilizer and rainwater account for a very small proportion. This distribution pattern is highly consistent with the ecological context of the study area, which is characterized by predominantly mountainous and hilly terrain, high forest cover, low land development intensity, and limited agricultural intensification. The terrain of Chengde City is predominantly mountainous, accounting for as much as 80% of its total area, and exhibits a typical landscape characterized by “nine parts mountains, half water, and half farmland”. The region’s forest coverage rate stands at 60.03%, and it boasts an excellent ecological foundation. At the same time, due to topographical constraints, the overall intensity of land development remains relatively low. The city has only 4.8406 million mu of arable land, accounting for 8.2% of its total area. Therefore, influenced by the regional ecological and environmental context, the natural nitrogen cycle—driven by soil organic nitrogen mineralization and subsequent nitrification—constitutes the primary source of background nitrate levels in strontium-rich mineral water.

Compared with other studies on the origin of nitrate in groundwater, the composition of nitrogen sources in this study area exhibits distinct regional characteristics. Studies in most lowland agricultural areas indicate that nitrate pollution in groundwater is primarily caused by manure and synthetic fertilizer [9,48–50]. In contrast, this study found that soil nitrogen accounted for a significantly higher proportion of nitrate pollution than other sources, while the combined contribution of synthetic fertilizer and rainwater was less than 1%. This difference is primarily determined by the ecological and land-use characteristics of the study area. Soil nitrogen pools in forest and grassland ecosystems are substantial. Under long-term natural hydrological conditions, mineralization and leaching processes continuously supply nitrogen to aquifers, resulting in a nitrate source structure dominated by soil nitrogen. However, compared with some other studies on the sources of nitrate in groundwater, the findings of this study also share notable commonalities, with the contribution rate of manure remaining at a relatively high level. At the same time, we found that the nitrate concentrations at the two strontium-rich mineral water sampling sites, J011 and S200, reached 67.28 mg/L and 70.2 mg/L, respectively, both of which are relatively high (Table A1). Geographically, J011 is located in Laopozi Gou, Lanqi Town, Longhua County, while S200 is located in Tieying, Changshanyu Village, Changshanyu Town, Luanping County (Table 1). Both sites with high nitrate concentrations are situated within mountainous tectonic valleys, in areas with concentrated farmland in villages and towns, and downstream of groundwater runoff. Local agricultural nonpoint source inputs and the convergence effect within the intermountain valleys are the primary factors contributing to the significantly elevated nitrate concentrations at these two sites. Therefore, even in areas with low levels of development, diffuse anthropogenic pollution sources—such as rural domestic sewage and livestock and poultry farming wastewater—remain significant factors influencing groundwater nitrogen levels [18,47]. This reflects the ongoing impact of human activities on the regional groundwater environment.

Based on the characteristics of nitrate sources in strontium-rich mineral water revealed in this study, and taking into account the regional ecological context, targeted management strategies are proposed. The nitrogen cycle in the study area is primarily driven by natural processes, with the mineralization and leaching of soil nitrogen serving as the primary sources of nitrate. Therefore, priority should be given to scientifically demarcating water source protection zones, incorporating areas with stable soil nitrogen pools—such as forested and grassland areas—into the core protection zones, restricting large-scale land development and slope disturbance within these zones, and thereby reducing the accelerated release of soil nitrogen. At the same time, optimize regional agricultural management and reasonably control nitrogen inputs into the soil. Although fertilizer application rates are relatively low in the study area, it is still necessary to promote measures

such as soil-test-based fertilization in agricultural activities to control excess soil nitrogen and to construct soil and water conservation facilities on sloping farmland to reduce the risk of nitrogen leaching. To address secondary anthropogenic sources such as fecal matter, it is necessary to reduce non-point source nitrogen pollution by promoting the resource utilization of fecal waste and constructing small-scale decentralized wastewater treatment facilities. Human activities should be minimized to prevent the exacerbation of nitrate accumulation in the strontium-rich mineral water of the study area. In addition, mineral water extraction companies in the area should regularly inspect the integrity of well casings to prevent stormwater runoff from bypassing the soil filter layer through damaged casings, thereby exacerbating nitrate pollution in groundwater. Finally, a long-term monitoring system for the water quality of strontium-rich mineral water should be established. Particular attention should be paid to nitrate concentrations, nitrogen and oxygen isotope composition, and dynamic changes in hydrogeological conditions. Monitoring should be intensified following disturbances such as extreme rainfall and land-use changes to provide timely warnings of water quality risks driven by both natural processes and human activities.

Therefore, pollution prevention and control in Chengde City must be grounded in the region's ecological characteristics, taking into account both natural processes and human-induced disturbances. Through comprehensive measures such as the demarcation of water source protection zones, nitrogen management in agriculture, treatment of decentralized wastewater, and long-term water quality monitoring, an integrated prevention and control system combining "protection of natural processes—management of anthropogenic pollution—dynamic monitoring and early warning" can be created. This will provide scientific evidence and technical support to ensure water quality and safety and to promote the sustainable development and utilization of Chengde's strontium-rich mineral water resources.

4.3. Limitations and Future Work

Quantitatively identifying sources of nitrate pollution in groundwater is a key issue for ensuring drinking water safety. This study conducts a quantitative analysis of nitrate pollution sources in a specific type of groundwater—strontium-rich mineral water—and combines nitrogen and oxygen isotope data with the MixSIAR model to quantify the contribution rates of each pollution source. The findings provide important guidance for promoting the sustainable development and utilization of regional strontium-rich mineral water resources. The findings of this study can serve as a reference for tracing the sources of nitrate pollution and protecting water quality in similar strontium-rich groundwater systems and mountainous mining areas in the Yanshan Mountains of northern Hebei. However, this study still has several limitations. First, due to the constraints of long-term, continuous sampling in the field, this study collected water samples only once. Since it was not possible to conduct continuous monitoring over multiple time periods to account for seasonal variations, the study falls short in its investigation of the seasonal dynamics of nitrate sources. Secondly, due to the inherent limitations of isotope tracing methods, there is some overlap between the isotopic signature ranges of different nitrogen sources, which may slightly reduce the accuracy of determining the contribution rates of various pollution sources to some extent. In future work, continuous monitoring over multiple quarters can be conducted to further elucidate the patterns of nitrate transport and transformation in conjunction with hydrological processes. At the same time, the regional pollution source element database can be optimized to improve the accuracy of model analysis and more precisely identify the contribution ratios of nitrate pollution sources.

5. Conclusions

This study takes Chengde City, Hebei Province, as its research subject. Using nitrogen and oxygen isotope tracing methods and the MixSIAR model, among other techniques, it conducts a qualitative identification and quantitative analysis of the sources of nitrate in strontium-rich mineral water in the Chengde region, and analyzes their biogeochemical processes. The main conclusions are as follows:

The sources of nitrate in the strontium-rich mineral water of the study area exhibit characteristics of mixed pollution, with natural processes playing the primary role and human activities playing a secondary role. Nitrification is the primary biogeochemical process occurring in the aquifers of the strontium-rich mineral water in the study area.

Soil nitrogen contributes the most to nitrate levels in the strontium-rich mineral water of the study area, accounting for 70.4%. The second-largest source is matter, accounting for 28.6%. The contributions from synthetic fertilizer and rainwater are extremely low, totaling less than 1%.

Efforts to control NO_3^- levels in strontium-rich mineral water in the Chengde region should focus on establishing a coordinated system comprising “protection of natural processes—management of anthropogenic pollution—dynamic monitoring and early warning.” By strengthening the ecological protection of water sources, strictly controlling nitrogen leaching from soil, and addressing diffuse anthropogenic pollution, it is possible to achieve source control of nitrate and establish a long-term early warning system. This will ensure the safe and sustainable use of strontium-rich mineral water resources.

Author Contributions: Conceptualization, Y.Z. and R.W.; methodology, R.W.; software, Y.Z. and R.W.; validation, Y.Z. and R.W.; formal analysis, Y.Z., J.X. and R.W.; investigation, W.W., Y.R., J.K. and S.Z.; data curation, W.W., Y.R., J.K. and S.Z.; writing—original draft preparation, J.X.; writing—review and editing, Y.Z.; visualization, Y.Z. and J.X.; supervision, Y.Z.; project administration, Y.Z. and B.Y.; funding acquisition, Y.Z. and B.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the Open Fund for Hebei Province Collaborative Innovation Center for Sustainable Utilization of Water Resources and Optimization of Industrial Structure (SUTCX20250*).

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Acknowledgments: We are thankful to all those who contributed to this study.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Table A1. Key physicochemical parameters at each sampling point.

Number	pH	Dissolved Oxygen Content	NO_3^-	$\delta^{15}\text{N}_{-\text{NO}_3}$	$\delta^{18}\text{O}_{-\text{NO}_3}$
CK02	7.54	6.07	39.5	8.3	4.1
S06	7.63	10.32	12.29	8.7	3.7
SJ1	7.93	5.11	2.29	0.3	4.5
QK2-7	7.2	16.34	43.55	3.4	12.4
Q11	7.47	8.08	23.8	7	4.9
J011	7.45	8.97	67.28	8	1.2
CK01	7.41	6.36	15.7	4.4	3.6
S200	7.45	7.81	70.2	9.9	3

ZK02	7.44	3.06	33.91	10.2	4.7
A06	7.33	6.85	0.117	2.4	6
B02	8.04	9.45	0.003	3.2	−0.1
B06	8.01	9.16	0.003	6.2	0.9
P055	7.1	8.49	0.01	6.4	1.3
P069	7.34	6.67	0.12	7.5	1
ZK01	7.6	2.57	17.01	7.6	3.5
B05	8.04	8.26	0.003	7.9	0.9
B04	8.17	7.83	0.18	8	2.7
P057	7.84	8.27	0.004	8.2	−0.5
ZK1	7.64	10.44	39.91	9.5	2.4
A07	7.33	6.94	0.13	10.5	3.7
A01	7.63	3.42	0.003	12.4	5.5
A08	7.27	3.87	0.003	16.8	8
ZK03	7.2	4.97	26.91	11.1	5.2
QS28	7.35	9	34.9	7.6	−1.6

References

- Wang, G.; Gao, H.B.; Long, B.; Wu, J.F. Research progress on nitrate isotope coupled multi-tracer tracing groundwater nitrate pollution. *Chin. J. Appl. Ecol.* **2024**, *35*, 970–984. <https://doi.org/10.13287/j.1001-9332.202404.011>.
- Wick, K.; Heumesser, C.; Schmid, E. Groundwater nitrate contamination: Factors and indicators. *J. Environ. Manag.* **2012**, *111*, 178–186. <https://doi.org/10.1016/j.jenvman.2012.06.030>.
- Guleria, A.; Mehdinejadani, B. Groundwater quality evaluation and human health risk assessment of nitrate using deterministic and probabilistic approaches in Qorveh-Dehgolan region, Kurdistan province, Iran. *Int. J. Environ. Health Res.* **2025**, *23*, 1–23. <https://doi.org/10.1080/09603123.2025.2602754>.
- Oubeid, A.M.A.; Hilal, I.; Kebd, A.; Sadiki, M. Global applications of stable isotopes for identifying nitrate pollution sources in groundwater: A comprehensive review. *Front. Water* **2025**, *7*, 1666498. <https://doi.org/10.3389/frwa.2025.1666498>.
- Heaton, T.H.E. Isotopic studies of nitrogen pollution in the hydrosphere and atmosphere—A review. *Chem. Geol.* **1986**, *59*, 87–102. [https://doi.org/10.1016/0168-9622\(86\)90059-x](https://doi.org/10.1016/0168-9622(86)90059-x).
- Vogiatzi, G.; Lontos, M.; Kostakis, M.; Maragou, N.; Thomaidis, N.S. An updated review on nitrate exposure from drinking water and dietary sources and effects on human health. *Glob. Nest. J.* **2025**, *27*, 13. <https://doi.org/10.30955/gnj.06467>.
- Ward, M.H.; Jones, R.R.; Brender, J.D.; de Kok, T.M.; Weyer, P.J.; Nolan, B.T.; Villanueva, C.M.; van Breda, S.G. Drinking Water Nitrate and Human Health: An Updated Review. *Int. J. Environ. Res. Public Health* **2018**, *15*, 1557. <https://doi.org/10.3390/ijerph15071557>.
- Chen, Q.F.; Chen, A.Q.; Cui, R.Y.; Ye, Y.H.; Min, J.H.; Fu, B.; Yan, H.; Zhang, D. Identification of Nitrate Source and Transformation Process in Shallow Groundwater Around Dianchi Lake. *Environ. Sci.* **2023**, *44*, 6062–6070. <https://doi.org/10.13227/j.hjlx.202211320>.
- Tu, C.L.; Chen, Q.S.; Yin, L.H.; Li, Q.; He, C.Z.; Liu, Z.N. Research Advances of Groundwater Nitrate Pollution and Source Apportionment in China. *Environ. Sci.* **2024**, *45*, 3129–3141. <https://doi.org/10.13227/j.hjlx.202307245>.
- Xi, Y.; Xu, S.S.; Chen, J.J.; Tao, L.; Jing, H.W.; Guo, J.; Tian, Y.; Shen, X.E.; Chen, Q. Identification of Nitrate Sources in Groundwater Based on Multiple Qualitative and Quantitative Statistical Analysis Methods. *Environ. Sci.* **2026**, *47*, 1105–1114. <https://doi.org/10.13227/j.hjlx.202502016>.
- Xu, S.G.; Kang, P.P.; Sun, Y. A stable isotope approach and its application for identifying nitrate source and transformation process in water. *Environ. Sci. Pollut. Res. Int.* **2016**, *23*, 1133–1148. <https://doi.org/10.1007/s11356-015-5309-6>.
- Choi, M.; Lee, C.; Kim, L.H.; Choi, S.H.; Bong, Y.S.; Lee, K.S.; Shin, W.J. Assessing sources of nutrients in small watersheds with different land-use patterns using TN, TP, and NO₃[−]-N. *J. Hydrol.-Reg. Stud.* **2024**, *55*, 13. <https://doi.org/10.1016/j.ejrh.2024.101958>.
- Jiang, S.Y.; Rao, W.B.; Li, T.N.; Song, Z.J.; Li, Z.Y.; Li, X.H.; Rode, M. Identification of transformation and sources of nitrate in a typical agricultural river of South-Central China using hydrochemistry, multiple isotopes and Bayesian model. *J. Environ. Manag.* **2026**, *404*, 15. <https://doi.org/10.1016/j.jenvman.2026.129426>.

14. Chen, R.D.; Hu, Q.H.; Shen, W.Q.; Guo, J.X.; Yang, L.; Yuan, Q.Q.; Lu, X.M.; Wang, L.C. Identification of nitrate sources of groundwater and rivers in complex urban environments based on isotopic and hydro-chemical evidence. *Sci. Total Environ.* **2023**, *871*, 12. <https://doi.org/10.1016/j.scitotenv.2023.162026>.
15. Dong, Z.H.; Zhang, L.; Wang, C.; Zou, Y. Hydrochemical evolution and nitrate contamination sources in Laiwu groundwater: Insights from hydrochemistry and dual-isotope analysis. *Phys. Chem. Earth* **2025**, *141*, 11. <https://doi.org/10.1016/j.pce.2025.104083>.
16. Li, J.N.; Sun, Q.H.; Lei, K.; Cui, L.; Lv, X.B. Using dual stable isotopes method for nitrate sources identification in Cao-E River Basin, Eastern China. *Front. Environ. Sci.* **2023**, *11*, 12. <https://doi.org/10.3389/fenvs.2023.1200481>.
17. Boumaiza, L.; Chesnaux, R.; Stotler, R.L.; Zahi, F.; Mayer, B.; Leybourne, M.I.; Otero, N.; Johannesson, K.H.; Huneau, F.; Schuth, C.; et al. Multiple environmental tracers combined with a constrained Bayesian isotope mixing model to elucidate nitrate and sulfate contamination in a coastal groundwater system. *Sci. Total Environ.* **2025**, *959*, 178265. <https://doi.org/10.1016/j.scitotenv.2024.178265>.
18. Wang, S.; Li, H.; Kang, T.; Li, R.X.; Zhang, C.Z. Resolving Nitrate Sources in Rivers Through Dual Isotope Analysis of $\delta^{15}\text{N}$ and $\delta^{18}\text{O}$. *Water* **2025**, *17*, 22. <https://doi.org/10.3390/w17233370>.
19. Quattrini, S.; Pampaloni, B.; Brandi, M.L. Natural mineral waters: Chemical characteristics and health effects. *Clin. Cases Miner. Bone Metab.* **2016**, *13*, 173–180. <https://doi.org/10.11138/ccmbm/2016.13.3.173>.
20. Neves, N.; Campos, B.B.; Almeida, I.F.; Costa, P.C.; Trigo Cabral, A.; Barbosa, M.A.; Ribeiro, C.C. Strontium-rich injectable hybrid system for bone regeneration. *Mater. Sci. Eng. C* **2016**, *59*, 818–827. <https://doi.org/10.1016/j.msec.2015.10.038>.
21. Tovani, C.B.; Gloter, A.; Azaïs, T.; Selmane, M.; Ramos, A.P.; Nassif, N. Formation of Stable Strontium-Rich Amorphous Calcium Phosphate: Possible Effects on Bone Mineral. *Acta Biomater.* **2019**, *92*, 315–324. <https://doi.org/10.1016/j.actbio.2019.05.036>.
22. Li, G.; Guo, J.; Song, Y.W.; Ma, F.S. Formation Mechanisms and Hydrogeochemical Evolution of a Metasilicate-Strontium Rich Mineral Water in a Subtropical Volcanic Terrain, East China. *Water* **2026**, *18*, 1086. <https://doi.org/10.3390/w18091086>.
23. Liang, C.C.; Wang, W.; Ke, X.M.; Ou, A.F.; Wang, D.H. Hydrochemical Characteristics and Formation Mechanism of Strontium-Rich Groundwater in Tianjiazhai, Fugu, China. *Water* **2022**, *14*, 1874. <https://doi.org/10.3390/w14121874>.
24. Yang, N.; Su, C.L.; Liu, W.B.; Zhao, L. Occurrences and mechanisms of strontium-rich groundwater in Xinglong County, northern China: Insight from hydrogeological and hydrogeochemical evidence. *Hydrogeol. J.* **2022**, *30*, 2043–2057. <https://doi.org/10.1007/s10040-022-02533-1>.
25. GB 2762-2025; National Food Safety Standard—Maximum Levels of Contaminants in Foods. National Health Commission of the People's Republic of China. State Administration for Market Regulation: Beijing, China, 2025.
26. GB/T 14848-2017; Standard for Groundwater Quality. General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China, Standardization Administration of the People's Republic of China: Beijing, China, 2017.
27. DZ/T 0064.77-2021; Methods for Analysis of Groundwater Quality—Part 77: Measurement Oxygen Isotope Composition $\text{CO}_2\text{-H}_2\text{O}$ Equilibration—Isotope Ratio Mass Spectrometry. Ministry of Natural Resources: Beijing, China, 2021.
28. DZ/T 0064.59-2021; Methods for Analysis of Groundwater Quality—Part 59: Determination of Nitrate—Ultraviolet Spectrophotometry. Ministry of Natural Resources: Beijing, China, 2021.
29. Zhang, Y.; Shi, P.; Song, J.X.; Li, Q. Application of Nitrogen and Oxygen Isotopes for Source and Fate Identification of Nitrate Pollution in Surface Water: A Review. *Appl. Sci.* **2019**, *9*, 17. <https://doi.org/10.3390/app9010018>.
30. Chen, R.K.; Wang, Y.G.; Yang, S.; Wang, Y.F.; Zhi, W.H. Source apportionment of nitrate pollution in the reservoir basins based on dual isotopes of nitrogen and oxygen. *J. Contam. Hydrol.* **2026**, *281*, 104980. <https://doi.org/10.1016/j.jconhyd.2026.104980>.
31. Zhang, J.; Li, Y.; Jiang, J.Y.; Li, H.; Min, M. Sources and Health Risks of Nitrate in Shallow and Deep Groundwater Across Different Landform Units Along a Typical Reach of the Middle Yellow River. *Environ. Sci.* **2026**, *47*, 1–20. <https://doi.org/10.13227/j.hjlx.202511362>.
32. Zhang, H.; Xu, Y.; Cheng, S.Q.; Li, Q.L.; Yu, H.R. Application of the dual-isotope approach and Bayesian isotope mixing model to identify nitrate in groundwater of a multiple land-use area in Chengdu Plain, China. *Sci. Total Environ.* **2020**, *717*, 12. <https://doi.org/10.1016/j.scitotenv.2020.137134>.
33. Dispirito, A.A.; Hooper, A.B. Oxygen-exchange between nitrate molecules during nitrite oxidation by nitrobacter. *J. Biol. Chem.* **1986**, *261*, 534–537.
34. Moore, K.B.; Ekwurzel, B.; Esser, B.K.; Hudson, G.B.; Moran, J.E. Sources of groundwater nitrate revealed using residence time and isotope methods. *Appl. Geochem.* **2006**, *21*, 1016–1029. <https://doi.org/10.1016/j.apgeochem.2006.03.008>.
35. Nikolenko, O.; Jurado, A.; Borges, A.V.; Knöller, K.; Brouyère, S. Isotopic composition of nitrogen species in groundwater under agricultural areas: A review. *Sci. Total Environ.* **2018**, *621*, 1415–1432. <https://doi.org/10.1016/j.scitotenv.2017.10.086>.

36. Matiatos, I. Nitrate source identification in groundwater of multiple land-use areas by combining isotopes and multivariate statistical analysis: A case study of Asopos basin (Central Greece). *Sci. Total Environ.* **2016**, *541*, 802–814. <https://doi.org/10.1016/j.scitotenv.2015.09.134>.
37. Fukada, T.; Hiscock, K.M.; Dennis, P.F.; Grischek, T. A dual isotope approach to identify denitrification in groundwater at a river-bank infiltration site. *Water Res.* **2003**, *37*, 3070–3078. [https://doi.org/10.1016/s0043-1354\(03\)00176-3](https://doi.org/10.1016/s0043-1354(03)00176-3).
38. Aravena, R.; Robertson, W.D. Use of multiple isotope tracers to evaluate denitrification in ground water: Study of nitrate from a large-flux septic system plume. *Ground Water* **1998**, *36*, 975–982. <https://doi.org/10.1111/j.1745-6584.1998.tb02104.x>.
39. Chang, L.R.; Ming, X.X.; Groves, C.; Ham, B.; Wei, C.F.; Yang, P.H. Nitrate fate and decadal shift impacted by land use change in a rural karst basin as revealed by dual nitrate isotopes. *Environ. Pollut.* **2022**, *299*, 11. <https://doi.org/10.1016/j.envpol.2022.118822>.
40. Buss, S.R.; Herbert, A.W.; Morgan, P.; Thornton, S.F.; Smith, J.W.N. A review of ammonium attenuation in soil and groundwater. *Q. J. Eng. Geol. Hydrogeol.* **2004**, *37*, 347–359. <https://doi.org/10.1144/1470-9236/04-005>.
41. Feast, N.A.; Hiscock, K.M.; Dennis, P.F.; Andrews, J.N. Nitrogen isotope hydrochemistry and denitrification within the Chalk aquifer system of north Norfolk, UK. *J. Hydrol.* **1998**, *211*, 233–252. [https://doi.org/10.1016/s0022-1694\(98\)00245-5](https://doi.org/10.1016/s0022-1694(98)00245-5).
42. Rust, C.M.; Aelion, C.M.; Flora, J.R.V. Control of pH during denitrification in subsurface sediment microcosms using encapsulated phosphate buffer. *Water Res.* **2000**, *34*, 1447–1454. [https://doi.org/10.1016/s0043-1354\(99\)00287-0](https://doi.org/10.1016/s0043-1354(99)00287-0).
43. Luan, B.J.; Wang, A.; Huo, Z.G.; Lin, X.Q.; Zhang, M. Identification of Nitrate Sources in the Upper Reaches of Xin'an River Basin Based on the MixSIAR Model. *Water* **2025**, *17*, 18. <https://doi.org/10.3390/w17243584>.
44. Torres-Martínez, J.A.; Mora, A.; Mahlnecht, J.; Daesslé, L.W.; Cervantes-Avilés, P.A.; Ledesma-Ruiz, R. Estimation of nitrate pollution sources and transformations in groundwater of an intensive livestock-agricultural area (Comarca Lagunera), combining major ions, stable isotopes and MixSIAR model. *Environ. Pollut.* **2020**, *269*, 115445. <https://doi.org/10.1016/j.envpol.2020.115445>.
45. Ji, X.; Xie, R.; Hao, Y.; Lu, J. Quantitative identification of nitrate pollution sources and uncertainty analysis based on dual isotope approach in an agricultural watershed. *Environ. Pollut.* **2017**, *229*, 586–594. <https://doi.org/10.1016/j.envpol.2017.06.100>.
46. Wang, X.H.; Liu, Z.J.; Xu, Y.J.; Mao, B.Y.; Jia, S.Q.; Wang, C.; Ji, X.M.; Lv, Q.Y. Revealing nitrate sources seasonal difference between groundwater and surface water in China's largest fresh water lake (Poyang Lake): Insights from sources proportion, dynamic evolution and driving forces. *Sci. Total Environ.* **2025**, *958*, 178134. <https://doi.org/10.1016/j.scitotenv.2024.178134>.
47. Sun, H.Y.; Wei, X.F.; Jia, F.C.; Li, D.J.; Li, J.; Li, X.; Yin, Z.Q. Source of Groundwater Nitrate in Luanping Basin Based on Multi-environment Media Nitrogen Cycle and Isotopes. *Environ. Sci.* **2020**, *41*, 4936–4947. <https://doi.org/10.13227/j.hjlx.202004142>.
48. Yang, Q.; Li, F.Z.; Zhang, X.H.; Chen, K.; Ding, A.Z. Decadal Hydrochemical Monitoring Reveals Characteristics, Genetic Mechanisms and Health Risks of High-Nitrate Groundwater. *Appl. Sci.* **2026**, *16*, 19. <https://doi.org/10.3390/app16094524>.
49. Li, X.L.; Yang, X.; Zhang, W.Q.; Yang, H.; Huang, X.; Hu, C.Y. Origin and Transformation of Nitrate in Karst Cave Groundwater in the Middle Reaches of the Qingjiang River. *J. Earth Sci.* **2026**, *37*, 241–250. <https://doi.org/10.1007/s12583-023-1844-0>.
50. Zhang, H.; Du, X.Y.; Gao, F.; Zeng, Z.; Cheng, S.Q.; Xu, Y. Groundwater Pollution Source Identification by Combination of PMF Model and Stable Isotope Technology. *Environ. Sci.* **2022**, *43*, 4054–4063. <https://doi.org/10.13227/j.Hjlx.202110174>.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.