Journal of Groundwater Science and Engineering
ISSN 2305-7068
Indexed by ESCI CABI CSA Scopus GeoRef AJ CNKI

Origin and risk assessment of natural radioactivity in groundwater from the Eastern Gonghe Basin, Tibetan Plateau

Zhao-xuan Niu, Zhi-hui Deng, Xue Niu, Dong-fang Chen, Gui-lin Zhu, Wen-hao Xu, Lin-you Zhang, Qing-da Feng

Citation:
Niu ZX, Deng ZH, Niu X, *et al*. 2025. Origin and risk assessment of natural radioactivity in groundwater from the Eastern Gonghe Basin, Tibetan Plateau. Journal of Groundwater Science and Engineering, 13(3): 301-311.

View online: https://doi.org/10.26599/JGSE.2025.9280056

Journal homepage: http://gwse.iheg.org.cn

Research Article

Origin and risk assessment of natural radioactivity in groundwater from the Eastern Gonghe Basin, Tibetan Plateau

Zhao-xuan Niu[1], Zhi-hui Deng[1*], Xue Niu[1], Dong-fang Chen[1], Gui-lin Zhu[1], Wen-hao Xu[1], Lin-you Zhang[1], Qing-da Feng[1]

[1] *Center for Hydrogeology and Environmental Geology Survey*, *CGS*, *Tianjin* 300304, *China*.

Abstract: This study systematically investigates natural radioactivity in groundwater from the densely populated eastern Gonghe Basin in Qinghai Province, aiming to reveal its spatial distribution, origins, and potential health risks. The characteristics of gross-α and gross-β activities, as well as the concentrations of nuclide including ^{238}U, ^{232}Th, and ^{226}Ra, have been investigated in groundwater samples from 12 groups encompassing various types such as hot springs and artesian wells across different aquifer systems. Correlation analysis and dose estimation models were applied to preliminary estimate the radiation exposure to local residents and to explore the genesis and hazards of natural radioactivity in groundwater. Results indicate that overall groundwater radioactivity in the Gonghe Basin remains within acceptable limits, with mean gross-α and gross-β activity concentrations of 0.32 *Bq/L* and 0.27 *Bq/L*, respectively. Approximately 83.33% of samples comply with relevant national standards. However, two fault-controlled high-temperature spring samples exhibited gross-α activity exceeding regulatory limits, with one also showing elevated gross-β activity surpassing China's Class III groundwater quality standards for radioactivity. Furthermore, single-radionuclide α radioactivity from ^{230}Th, ^{226}Ra, ^{210}Po, and ^{232}Th exceeded regulatory thresholds in some samples, suggesting potential long-term health risks. While most samples complied with effective dose limits, four showed ^{210}Po α radioactivity exceedances within controllable risk ranges. The findings suggest that groundwater radioactivity in the region is primarily controlled by geological structures, lithology, and hydrothermal conditions, with fault zones and high-temperature environments serving as key factors in radionuclide enrichment. This research provides scientific foundation for the sustainable development of geothermal resources and the prevention of radioactive water contamination. Continuous monitoring of high-radioactivity hot springs and prudent resource utilization are recommended.

Keywords: Groundwater radioactivity; Gross-α; Gross-β; Radionuclides; Effective dose

Received: 16 Jul 2024/ Accepted: 23 May 2025/ Published: 20 Jul 2025

Introduction

With the rapid economic development and increasing health awareness, there is a growing concern about the presence of radioactive substances in the environment, particularly in groundwater, and their potential impacts on human health (UNSCEAR, 2016). According to the United Nations Scientific Committee on Radiation Effects, the global average annual radiation dose from natural sources is approximately 2.4 *mSv* per person. Natural background radiation accounts for about 80% of total environmental radiation exposure, estimated at approximately 3.0 *mSv* annually, making it the primary source of human radiation exposure. In China's *Standard for Groundwater Quality* (GB/T 14848–2024), the Class Ⅲ water thresholds for radioactivity are set at gross-α ≤ 0.5 *Bq/L* and gross-β ≤ 1 *Bq/L*. Similarly, the World Health Organization (WHO, 2017) has set a guideline for annual effective dose from drinking water at 0.1 *mSv/a* per person. Radionuclides present in

*Corresponding author: Zhi-hui Deng, *E-mail address*: dzhihui@mail.cgs.gov.cn

DOI: 10.26599/JGSE.2025.9280056

Niu ZX, Deng ZH, Niu X, et al. 2025. Origin and risk assessment of natural radioactivity in groundwater from the Eastern Gonghe Basin, Tibetan Plateau. Journal of Groundwater Science and Engineering, 13(3): 301-311.

groundwater can enter the human body via environmental pathways, and prolonged exposure to elevated levels of natural radiation may pose significant health risks.

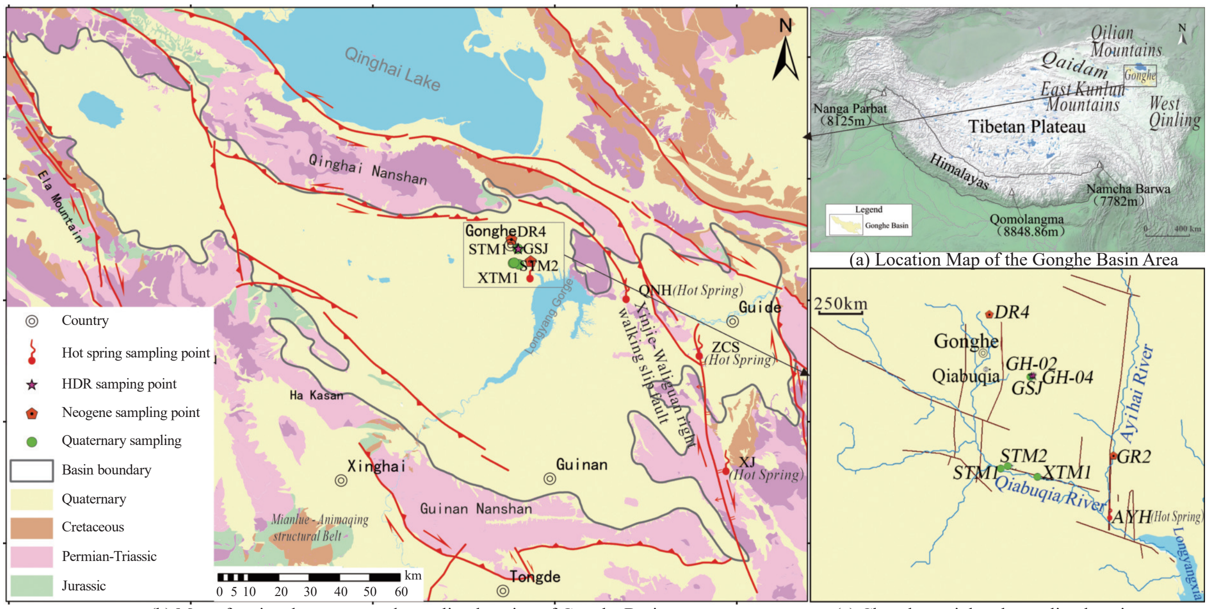
Radionuclides in water bodies primarily originate from natural radionuclides (Fahad I et al. 2020). The activity concentrations in groundwater are influenced by local physicochemical and geochemical conditions, as well as the geological composition of the soil and bedrock (Giuseppe et al. 2021; Contreras et al. 2022). The Gonghe Basin in Qinghai Province is rich in geothermal water resources, with the highest recorded hot spring temperature reaching 96.6°C (Wang et al. 2020). The deep thermal reservoir rocks in the basin are primarily composed of granite, which exhibits naturally elevated levels of radioactivity, slightly above background concentrations for uranium, thorium, and potassium (Zhang et al. 2019). As groundwater flows through granite formations, water-rock interactions promote the leaching of substances from the host rocks into the groundwater. During this process, radioactive elements such as uranium (U), thorium (Th), and potassium (K) are mobilized into the groundwater system. Elevated temperatures further enhance the leaching efficiency of these radionuclides. Once mobilized, they can be transported to the surface through groundwater circulation, potentially posing risks to the local ecological environment and human health (Murad et al. 2014).

Groundwater radioactivity in the eastern Gonghe Basin is influenced by multiple factors and has important implications for both public health and resource development. This study focuses on this region to investigate the spatial distribution, origins, and hazard assessment of radioactive elements in groundwater. The objectives are to identify the controlling factors and processes, evaluate associated health risks, and provide a scientific foundation for sustainable resource utilization and pollution prevention. For the first time, this research integrates geological structures, lithology, and hydrothermal conditions to reveal the enrichment mechanisms of radionuclides in groundwater. A refined dose estimation model was developed, and targeted mitigation strategies were proposed. The findings offer new insights that may be applied to other regions facing similar challenges.

1 Study area

The Gonghe Basin is situated at the northeastern margin of the Qinghai-Tibet Plateau, at the western end of the West Qinling region. It is bordered to the north by the Qilian Mountains and to the west by the Qaidam Basin. The southern boundary is defined by the Guinan Nanshan, while the eastern boundary gradually transitions into the West Qinling tectonic belt (Peng et al. 2016). Specifically, the northern and southern limits are marked by the Qinghai Nanshan and Guinan Nanshan, respectively. The eastern and western boundaries are delineated by the Xinjie-Waliguan right-lateral strike-slip fault and the Ela Mountain. Overall, the basin exhibits a roughly diamond-shaped geometry in plan view (Fig. 1).

The Quaternary fluvial-lacustrine facies, with



(b) Map of regional structure and sampling location of Gonghe Basin
(c) Chapcha peripheral sampling location map

Fig. 1 Geological structure and sampling point location map of the Gonghe Basin thickness ranging from 100 to 1600 meters, are predominantly composed of yellow-green or gray sand and gravel layers. In contrast, the Neogene Guide Group (NG) consists of interbedded mudstone and sandstone, along with fine conglomerate layers, reaching thickness of 1,000 m to 1,900 m thick. Regional groundwater types include pore water in unconsolidated sediments, fracture pore water in clastic rocks, and fracture water in bedrock. These groundwater types are influenced by factors such as topography and lithological composition, resulting in diverse hydrogeological conditions. Numerous fault-controlled hot springs, such as Qunaihai (QNH), Zhacangsi (ZCS), and Xinjie (XJ), are located along the Xinjie-Waliguan right-lateral strike-slip fault zone on the eastern side of the basin. The highest recorded spring temperature in the area reaches 96.6°C. In the Qiabuqia area, groundwater primarily occurs in unconfined and confined aquifers, characterized by moderate to high water abundance and forming dual- or multi-layered aquifer systems. Groundwater is replenished through infiltration from the surrounding high-altitude mountainous regions and transitions from phreatic and semi-confined states to confined conditions as altitude decreases. Correspondingly, groundwater temperature increases, and discharge occurs mainly near the Qiabuqia River and Longyangxia (Niu et al. 2022; Dai, 2020).

2 Sample collection and testing

Twelve groups of water samples were collected from the Gonghe Basin, Qinghai Province, including four groups of Quaternary pore water, two groups of Neogene pore water, two groups of Hot Dry Rock (HDR) recycling produced water, and four groups of hot spring water. The spatial distribution of sampling points is shown in Fig.1. During the sampling process, containers were rinsed with the native water at least three times to avoid contamination. Additionally, the pumping wells were purged and flushed prior to sampling to ensure that the collected water accurately reflected the in-situ chemical characteristics of the aquifers. Water samples were then stored in 10 *L* plastic containers, sealed and transported to the laboratory for testing and analysis.

Analytical testing was conducted by the Analysis and Testing Research Center of Beijing Research Institute of Uranium Geology, China National Nuclear Corporation. The following instruments and methods were employed:

• A Z-2000 Graphite Furnace-Flame Atomic Absorption Spectrophotometer for measuring ^{40}K

• An ELEMENT XR Inductively Coupled Plasma Mass Spectrometer (ICP-MS) for determining ^{238}U and ^{232}Th

• An MPC9604 Low Background α-β Counter for gross-α and gross-β activities

• A PC-2100 Radium and Radon Analyzer for measuring ^{226}Ra

For uranium (U) and thorium (Th) analysis, parallel duplicate samples and spike recovery tests were conducted. For ^{226}Ra and ^{40}K, analysis included parallel duplicates along with the insertion of quality control reference materials. In the gross-α and gross-β analysis, routine background checks, efficiency monitoring, and quality control charts were implemented to ensure measurement precision and accuracy.

3 Results and discussion

3.1 Gross-α and gross-β radioactivity levels of groundwater

The results of the radioactivity detection are summarized in Table 1. The gross-α activity concentrations in the 12 groundwater samples ranged from 0.06 *Bq/L* to 1.19 *Bq/L*, with an average value of 0.32 *Bq/L*. Similarly, the gross-β activity concentrations ranged from 0.06 *Bq/L* to 1.26 *Bq/L*, with an average value of 0.27 *Bq/L*. Notable variations in gross-α and gross-β radioactivity levels were observed across the sampled wells, which can be attributed to differences in the lithological composition of the aquifers and surrounding strata. In particular, the QNH and ZCS samples, both high-temperature spring waters sourced from granite lithology, exhibited significantly elevated gross-α and gross-β radioactivity levels compared to other samples. On the other hand, the remaining water samples were predominantly derived from aquifers composed of Quaternary loose sandy sedimentary layer, Neogene strata, or Triassic metamorphic sandstone and slate, resulting in generally lower levels of radioactivity. These findings align with the recently updated *Standard for Groundwater Quality* (GB/T 14848–2024) and the *Standards for Drinking Water Quality* (GB 5749–2022), which both specify the same limits for gross radioactivity in Class III water and drinking water: gross-α ≤ 0.5 *Bq/L* and gross-β ≤ 1 *Bq/L*.

The assessment of natural radioactivity in water has been extensively studied worldwide to evalu-

Table 1 Measured active concentration of gross-α, gross-β, and associated radionuclide contents in groundwater samples from the Gonghe Basin

Field number	pH	T	U	Th	^{226}Ra	^{40}K	gross-α	gross-β
		°C	*μg/L*		*Bq/L*			
GR-2	8.36	19.2	0.209	0.005	0.008	0.166	0.079	0.141
AYH	7.35	30.9	0.098	0.008	<0.008	0.159	0.064	0.143
XTM-1	8.48	27.8	1.06	0.006	0.009	0.079	0.206	0.116
STM-1	8.23	25.4	2.01	0.003	<0.008	0.069	0.262	0.089
STM-2	8.17	17.1	4.55	<0.002	0.008	0.083	0.151	0.114
DR-4	-	-	0.045	0.005	<0.008	0.252	0.069	0.152
GSJ	-	-	6.48	<0.002	<0.008	0.099	0.097	0.136
GH-02	-	-	0.076	0.008	0.04	0.795	0.191	0.146
GH-04	-	-	0.006	0.001	<0.008	0.5	0.067	0.064
QNH	5.59	70.3	0.038	0.003	<0.008	1.59	1.19	1.26
ZCS	5.19	72.8	0.164	0.004	0.809	0.66	1.13	0.613
XJ	5.74	55.6	0.044	0.015	<0.008	0.219	<0.036	0.213

ate the suitability of water for drinking and irrigation purposes. Table 2 presents a comparative analysis of gross-α and gross-β activity concentrations in groundwater from the Gonghe Basin and those reported in other countries and regions around the world.

According to Table 2, the overall groundwater radioactivity in the Gonghe Basin is relatively low. The main groundwater radioactivity levels in the basin are comparable to those reported for groundwater and drinking water samples from countries such as Germany (Beyermann et al. 2010), Italy (Jia et al. 2009), Serbia (N Todorović et al. 2012), Turkey (Turhan et al. 2013), Brazil (Bonotto et al. 2008), Ghana (Darko et al. 2015), and the southwestern Caspian region (Jowzaee, 2013). However, it is noteworthy that significantly higher gross-α and gross-β activity concentrations have been observed in groundwater from Nigeria (Agbalagba et al. 2013; Esi et al. 2021), as well as

Table 2 Comparison of gross α/β activity concentrations in groundwater from this study with values reported in the literature (*Bq/L*)

Country/Region	Type	gross-α	gross-β	References
Nigeria	Drinking water	0.0058–0.174	0.0147–0.2225	Fasae et al. (2013)
Australia	Drinking water	1.40	1.15	Kleinschmidt (2004)
Germany	Drinking water	0.013–0.97		Beyermann et al. (2010)
Italy	Drinking water	0.25–1.1		Jia et al. (2009)
Serbia	Drinking water	0.029–0.21	MDC-0.4	N Todorović et al. (2012)
Singapore	Drinking water	< MDA	0.228–0.258	Ong JX et al. (2024)
Finland	Drilled well water	2.4	1.5	Salonen (1994)
Turkey	Groundwater	0.192	0.579	Turhan et al. (2013)
Brazil (Sao Paulo)	Groundwater	0.001–0.4	0.12–0.86	Bonotto et al. (2008)
Nigeria	Groundwater	0.15±0.003	6.0±0.1	Agbalagba et al. (2013)
Ghana	Groundwater	0.0157–0.198	0.122–0.28	Darko et al. (2015)
Southwestern Caspian	Groundwater	0.016–1	0.022–0.63	Jowzaee (2013)
United Arab Emirates	Groundwater	1.4±4.1	1.5±1.52	Murad et al. (2014)
Aqaba, Jordan	Groundwater	0.64	0.71	Awadallah M et al. (2012)
Saudi Arabia, Hail	Groundwater	2.15	2.60	EI and AA (2014)
Saudi Arabia, North-western	Groundwater	3.15±0.26	5.39±0.44	Alkhomashi et al. (2016)
Saudi Arabia, Northern region	Groundwater	3.51±0.33	3.48±0.36	Fahad I et al. (2020)
Gonghe basin	Groundwater	0.06–1.19	0.06–1.26	Present work

in parts of Saudi Arabia and the United Arab Emirates. Additionally, Table 2 indicates that treated drinking water generally exhibits lower gross-α and gross-β radioactivity compared to untreated groundwater. This highlights the effectiveness of water purification and treatment processes in reducing naturally occurring radioactivity before human consumption.

3.2 Correlation analysis of radioactive content in water samples

The correlation analysis between major radioactive elements, gross-α and gross-β activity concentrations in water samples provide valuable insights into the relationships among radioactive parameters, revealing both similarities and differences in their geochemical behavior and potential sources (Shang et al. 2012; Sadeghi, 2024). Table 3 presents the Pearson correlation coefficients calculated among the radioactive parameters of 12 groups of groundwater samples collected from the Gonghe Basin.

In the study area, gross-α activity in groundwater samples shows a positive correlation with the concentrations of ^{226}Ra, ^{40}K, and Rn. Similarly, the gross-β is positively correlated with ^{226}Ra and ^{40}K, but negatively correlated with Rn. A strong positive correlation is also observed between gross-α and gross-β activities. In addition, significant positive correlations are found between Th and U, ^{226}Ra and ^{40}K, and ^{40}K and Rn, indicating interrelated behavior among these radionuclides. These relationships indicate a degree of geochemical association and shared source among the radioactive elements. Some correlations may also reflect random co-occurrence, pointing to complex interactions in the hydrogeochemical environment.

A significant correlation was observed between gross-α and gross-β in groundwater samples (R=0.911; Fig. 2). This strong association indicates that both gross-α and gross-β activities primarily originate from natural radionuclides within the ^{238}U and ^{232}Th decay chains. Gross-α activity in groundwater is mainly attributed to the decay of uranium isotopes (^{234}U, ^{235}U, ^{238}U) and ^{226}Ra. A key decay product of ^{238}U is radon-222 (^{222}Rn), which can readily escape from rock formations and dissolve into groundwater. However, due to the volatilization of ^{222}Rn during sample evaporation prior to measurement, its contribution is excluded from the reported gross-α activity values. Data on ^{226}Ra (Alshamsi et al. 2013; Uzorka et al. 2024) reveal a strong correlation with gross-α activity in certain groundwater samples (R=0.979), further supporting the interpretation that a substantial portion of gross-α activity is attributable to the decay of the child ^{226}Ra produced by the decay of ^{238}U.

This study investigated the inhibitory effect of pH on gross-α and gross-β activities in groundwater. The pH values of the samples ranged from 5.19 to 8.48 (Table 1), and a negative correlation was observed between gross-α, gross-β, and pH (Fig. 3). pH plays a crucial role in groundwater hydrochemistry, particularly influencing the speciation of chlorine and carboxyl ions. Under alkaline conditions, uranium tends to form carbonate-uranium complexes, such as ($UO_2(CO_3)_2^{2-}$) ions, which increase uranium's solubility and mobility in groundwater, especially within the pH range of 6–8. On the other hand, thorium exhibits greater solubility under acidic conditions. Given the strong negative correlation between pH and radioactivity levels, it is inferred that the contribution of thorium radionuclides to groundwater radioactivity in the Gonghe Basin is significantly higher than that of uranium radionuclide.

Groundwater temperature in the study area varies significantly, ranging from 17.1°C to 72.8°C (Table 1). A strong positive correlation exists between water temperature and both gross-α and gross-β activities, with gross-α exhibiting an especially pronounced correlation (Fig. 4). While

Table 3 Pearson correlation coefficient matrix for radioactive element parameters in groundwater samples from the Gonghe Basin

Item	U	Th	^{226}Ra	^{40}K	Rn	gross-α	gross-β
U	1						
Th	−0.560	1					
^{226}Ra	−0.212	0.023	1				
^{40}K	−0.400	−0.047	0.521	1			
Rn	0.169	0.046	−0.465	−0.706	1		
gross-α	−0.256	−0.062	0.979	0.762	0.719	1	
gross-β	−0.249	−0.074	0.986	0.873	−0.672	0.911	1

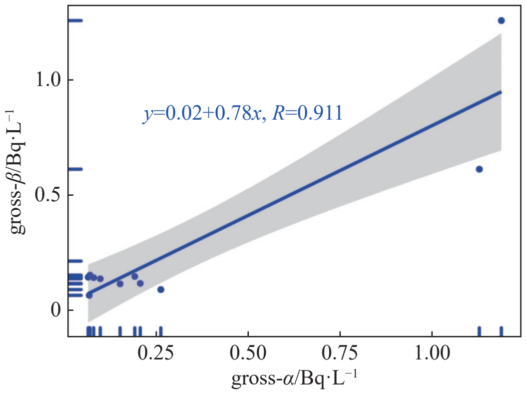


Fig. 2 Relationship between gross-α and gross-β activities in groundwater samples

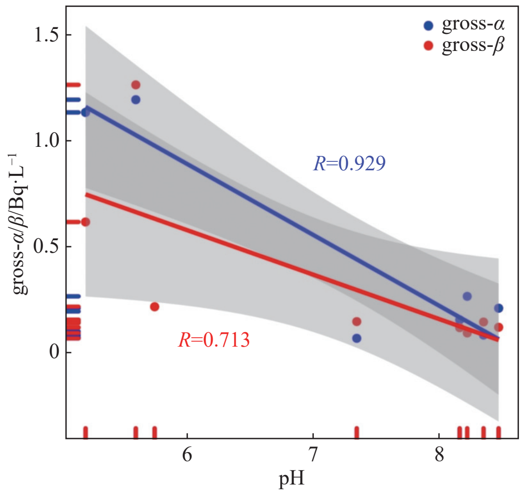


Fig. 3 Relationship between gross-α/gross-β activity concentrations and pH values in groundwater samples from the Gonghe Basin

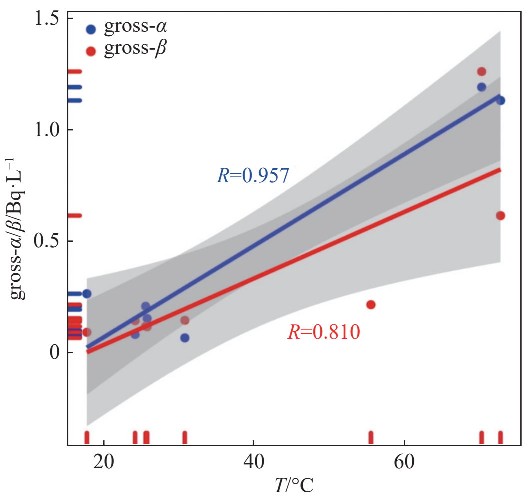


Fig. 4 Relationship between gross-α/gross-β activity concentrations and groundwater temperature in samples from the Gonghe Basin

assessing the precise impact of temperature on radionuclides distribution is complex, it is likely that elevated temperatures enhance the dissolution of radionuclides from aquifer materials into groundwater, thereby contributing to increased gross-α and gross-β activity concentrations.

The concentration of ^{40}K in groundwater samples within the study area ranges from 0.069 Bq/L to 1.590 *Bq/L*, representing a significant contributor to gross-β activity. Variations in potassium levels directly influence gross-β activity. As shown in Fig.5, there is a strong positive correlation (R=0.873) between ^{40}K concentration and gross-β activity concentration, indicating that ^{40}K, along with other naturally occurring β minerals, primarily decay products of ^{238}U and ^{232}Th, contributes substantially to the observed gross-β radioactivity levels. Additional monitoring is recommended to investigate other potential secondary sources of gross-β, such as ^{228}Ra and ^{210}Pb.

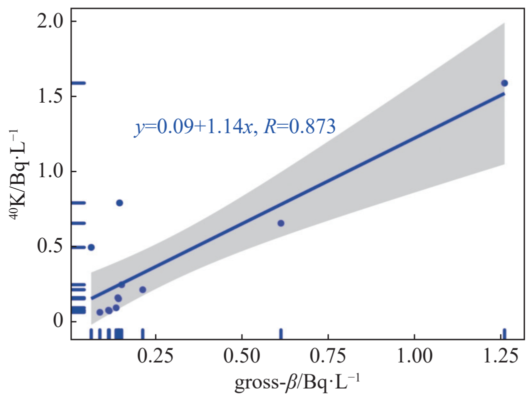


Fig. 5 Relationship between gross-β and ^{40}K concentration in groundwater samples from the Gonghe Basin

3.3 Estimation of population radiation dose due to radioactivity

3.3.1 Annual effective dose estimation method

According to the World Health Organization (2017), the recommended annual effective radiation dose from drinking water for an individual should not exceed 0.1*mSv*. If the gross radioactivity surpasses the screening level, specific radionuclides must be identified, and effective mitigation measures should be implemented to remove the radioactive substances. The natural radioactivity in groundwater primarily originates from naturally occurring potassium, uranium-series, and thorium series radionuclides and their decay products. The α emitters mainly consist of ^{238}U, ^{234}U, ^{230}Th, ^{226}Ra,

^{210}Po, ^{232}Th, and ^{228}Th, while the β emitters mainly include ^{40}K, ^{210}Pb, and ^{228}Ra (Bonotto et al. 2008).

Field investigations revealed no radiation-related industrial activities or contamination sources near the sampling locations, indicating that the radioactivity observed in groundwater samples is of natural origin. Therefore, the estimation of internal radiation dose in this study is based primarily on the contribution from natural occurring α and β radionuclides (Laassiri et al. 2025; María et al. 2022).

Estimation of Annual Effective Dose:

The annual effective dose was estimated using the following formula:

$$AED = A \times V \times C \quad (1)$$

Where:

- AED represents the annual effective dose equivalent (*mSv/a*).

- A denotes the radioactive activity concentration (*Bq/L*).

- V is the annual volume of water consumed by an adult, recommended by the World Health Organization as 730 *L/a*.

- C represents the dose conversion factor (*mSv/Bq*) for ingestion of specific radionuclides by adults.

The dose conversion factor is defined in accordance with the World Health Organization's Guidelines for Drinking Water Quality (4th edition, 2017).

The dose coefficients for radionuclide ingestion by adults, as recommended by the WHO (2017), are as follows:

- α radionuclides: ^{238}U: 4.5×10^{-8} *Sv/Bq*, ^{234}U: 4.9×10^{-8} *Sv/Bq*, ^{230}Th: 2.1×10^{-7} *Sv/Bq*, ^{226}Ra: 2.8×10^{-7} *Sv/Bq*, ^{210}Po: 1.2×10^{-6} *Sv/Bq*, ^{232}Th: 2.3×10^{-7} *Sv/Bq*, ^{228}Th: 7.2×10^{-8} *Sv/Bq*.
- β radionuclides: ^{210}Pb: 6.9×10^{-7} *Sv/Bq*, ^{228}Ra: 6.9×10^{-7} *Sv/Bq*.

3.3.2 Annual effective dose from natural α emitters

The annual effective doses for residents exposed to natural α emitters, ^{238}U, ^{234}U, ^{230}Th, ^{226}Ra, ^{232}Th, ^{228}Th and ^{210}Po, were estimated using the equation AED = A×V×C. The resulting dose were then evaluated against the World Health Organization's recommended limit for annual effective dose for drinking water, which is 0.1 *mSv/a*. If the estimated dose for any specific radionuclide exceeds this threshold, further assessment is required to identify and quantify individual nuclide contributions. This step is essential for determining whether the groundwater is safe for human consumption (Valli et al. 2024).

The estimated internal exposure doses from natural α radionuclides are summarized in Table 4. In both the QNH and ZCS high temperature geothermal spring samples, four α radionuclides, ^{230}Th, ^{226}Ra, ^{210}Po, and ^{232}Th, exceed the WHO's recommended annual effective dose limit for drinking water. Specifically, in the QNH sample, the dose contributions from these radionuclides exceed the threshold by 1.8, 2.4, 10.4, and 2.0 times, respectively. Similarly, in the ZCS sample, the exceedances are 1.7, 2.3, 9.9, and 1.9 times, respectively. Additionally, the gross-α activity levels in both QNH and ZCS samples surpass the limits set by the *Sanitary Standard of Drinking Water* (GB 5749–2022) and the *Comprehensive Sewage Discharge Standard* (GB 8978–1996), which define a threshold of 1 *Bq/L*. Although these geothermal springs are not currently used as

Table 4 Estimated annual effective dose of α emitters in groundwater samples from the Gonghe Basin

No.	gross-α	Annual effective dose /*μSv/a*						
	Bq/L	^{238}U	^{234}U	^{230}Th	^{226}Ra	^{210}Po	^{232}Th	^{228}Th
GR-2	0.079	2.60	2.83	12.11	16.15	69.20	13.26	4.15
AYH	0.064	2.10	2.29	9.81	13.08	56.06	10.75	3.36
XTM-1	0.206	6.77	7.37	31.58	42.11	180.46	34.59	10.83
STM-1	0.262	8.61	9.37	40.16	53.55	229.51	43.99	13.77
STM-2	0.151	4.96	5.40	23.15	30.86	132.28	25.35	7.94
DR-4	0.069	2.27	2.47	10.58	14.10	60.44	11.59	3.63
GSJ	0.097	3.19	3.47	14.87	19.83	84.97	16.29	5.10
GH-02	0.191	6.27	6.83	29.28	39.04	167.32	32.07	10.04
GH-04	0.067	2.20	2.40	10.27	13.69	58.69	11.25	3.52
QNH	1.19	39.09	42.57	182.43	243.24	1042.44	199.80	62.55
ZCS	1.13	37.12	40.42	173.23	230.97	989.88	189.73	59.39
ZNH	0.036	1.18	1.29	5.52	7.36	31.54	6.04	1.89

sources of drinking water, and are only utilized for preliminary bathing purposes, the elevated levels of natural radioactivity raise potential long-term health concerns with prolonged exposure. Therefore, regular monitoring of these water sources is recommended. If future plans involve expanded utilization, particularly for residential or recreational purposes, further investigation and detailed risk assessment should be conducted. Moreover, implementing basic water treatment measures prior to large-scale development is advisable to mitigate potential radiological health risks.

The estimated annual effective dose from α radionuclides, ^{238}U, ^{234}U, ^{230}Th, ^{226}Ra, ^{210}Po, ^{232}Th, and ^{228}Th, in the remaining groundwater samples were generally low and did not exceed the WHO's recommended limit of 0.1 *mSv/a* for drinking water. However, the contribution from ^{210}Po was notably higher in several samples. Specifically, the estimated annual doses from ^{210}Po exceeded the WHO guideline in four samples: XTM-1 (1.8 times), STM-1 (2.3 times), STM-2 (1.3 times), and GH-02 (1.7 times). ^{210}Po is a naturally occurring α radionuclide within the ^{238}U decay series. It has a half-life of 138.4 days and an α emission energy of 5.304 MeV. It decays into a stable state of lead (^{206}Pb).

The four groundwater samples with annual effective dose from ^{210}Po exceeding the recommended standard should undergo further radiological screening to identify specific radionuclides and clarify the composition of naturally occurring radioactive materials. Although residential villages are located near the sampling sites, it is important to note that groundwater samples analyzed in this study are not currently used for drinking water purposes Therefore, there is no immediate concern regarding adverse health effects on nearby residents.

3.3.3 Annual effective dose from natural β emitters

Potassium-40 (^{40}K), a primary radionuclide, is widely distributed in nature since the formation of the Earth. The gross-β radioactivity in groundwater primarily originates from the β decay of ^{40}K. However, potassium intake in humans mainly occurs through food consumption, with minimal contribution from drinking water. Moreover, the dose coefficient of ^{40}K (5×10^{-9} *Sv/Bq*) is significantly smaller than that of other natural radionuclides. Therefore, its contribution is excluded from the dose estimation. The annual effective dose from the natural β radionuclides, ^{228}Ra and ^{210}Pb, were calculated and compared with the World Health Organization's recommended personal radiation dose limit for drinking water of 0.1 *mSv/a*. If the activity concentrations of these radionuclides exceed this threshold, further screening is necessary to identify specific radionuclide composition and to evaluate the suitability of the water for drinking purposes.

Table 5 presents the estimated internal exposure dose from natural β radionuclides in groundwater. The annual effective dose for residents due to ^{228}Ra and ^{210}Pb is relatively low and remains below the World Health Organization's recommended personal radiation dose limit for drinking water of 0.1 *mSv/a*.

Table 5 Annual effective dose of β emitters in groundwater of the study area

No.	gross-β	Annual effective dose of β radiation /*µSv/a*	
	Bq/L	^{228}Ra	^{210}Pb
GR-2	0.141	7.10	7.10
AYH	0.143	7.20	7.20
XTM-1	0.116	5.84	5.84
STM-1	0.089	4.48	4.48
STM-2	0.114	5.74	5.74
DR-4	0.152	7.66	7.66
GSJ	0.136	6.85	6.85
GH-02	0.146	7.35	7.35
GH-04	0.064	3.22	3.22
QNH	1.26	63.47	63.47
ZCS	0.613	30.88	30.88
ZNH	0.213	10.73	10.73

4 Conclusions

This study systematically evaluates the natural radioactivity levels and genetic mechanisms of groundwater in the eastern Gonghe Basin, Qinghai Province, highlighting the significant influence of regional geological structures and hydrothermal activities on radionuclide distribution. Based on the findings, health risk prevention recommendations are proposed, with the following key conclusions:

(1) Coupling relationship between groundwater radioactivity and geological structures: The deep thermal reservoir rocks in the Gonghe Basin primarily consist of uranium- and thorium-enriched granites. Groundwater migration along regional fault zones acts as conduits for deep fluids, enhancing water-rock interactions. Under high-temperature conditions, radioactive elements such as uranium and thorium are extensively

released into groundwater through leaching. Although 83.33% of sampled waters meet national standards for gross-α and gross-β activities, the QNH and ZCS high-temperature springs near fault zones exhibit significant exceedances in gross-α activity and specific α-emitters (^{230}Th, ^{226}Ra, ^{210}Po, ^{232}Th), indicating fault zones and high-temperature environments are dominant controlling factors for radionuclide enrichment.

(2) Genetic mechanisms of radioactivity: The spatial differentiation of radionuclides in groundwater is controlled by lithology, hydrogeochemical conditions, and temperature:

① Lithogenic contributions: Granite formations exhibit uranium and thorium concentrations above regional background levels, with their fracture networks serving as pathways for radionuclide migration and release.

② Hydrogeochemical controls: Alkaline conditions (pH 7.35–8.48) promote uranium mobilization through carbonate complexation, while thorium demonstrates greater mobility under acidic environments.

③ Thermal effects: Elevated groundwater temperatures substantially enhance nuclide leaching, as evidenced by strong positive correlations between gross-α activity and temperature, underscoring hydrothermal circulation as a critical factor driving the migration of radioactive elements.

(3) Health risk assessment: Annual effective dose indicate that most groundwater samples remain below the WHO guideline limit of 0.1 *mSv/a*. However, the QNH and ZCS hot springs exceed this threshold, with the ^{210}Po dose in QNH spring water reaching 10.4 times the recommended limit. This suggests a potential internal radiation hazard from long-term exposure. Special attention should be given to non-drinking exposure pathways, such as recreational bathing and agricultural irrigation in nearby areas.

(4) Recommendations for environmental management and resource development: For water sources with elevated radioactivity, continuous monitoring and cautious development are essential to balance resource utilization and environmental protection. Additionally, public health education and environmental management should be strengthened to raise public awareness about radioactive contamination and enhance community capacity for risk prevention.

References

Agbalagba EO, Avwiri GO, Chadumoren YE. 2013. Gross α and β activity concentration and estimation of adults and infants dose intake in surface and ground water of ten oil fields environment in Western Niger Delta of Nigeria. Journal of Applied Sciences and Environmental Management, 17(2): 267−277. DOI: 10.4314/jasem.v17i2.10.

Alkhomashi N, Al Hamarneh FI, Almasoud IF. 2016. Determination of natural radioactivity in irrigation water of drilled wells in northwestern Saudi Arabia. Chemosphere, 144: 1928−1936. DOI: 10.1016/j.chemosphere.2015.10.094.

Alshamsi DM, Murad AA, Aldahan A, et al. 2013. Uranium isotopes in carbonate aquifers of arid region setting (Article). Journal of Radioanalytical and Nuclear Chemistry, 298(3): 1899−1905. DOI: 10.1007/s10967-013-2558-z.

Awadallah M, Al Hamarneh IF, Al-Abed T, et al. 2012. Natural radioactivity in tap water and associated age-dependent dose and lifetime risk assessment in Amman, Jordan. Applied Radiation and Isotopes, 70(4): 692−698. DOI: 10.1016/j.apradiso.2011.12.002.

Beyermann M, Bünger T, et al. 2010. Occurrence of natural radioactivity in public water supplies in Germany: ^{238}U, ^{234}U, ^{235}U, ^{228}Ra, ^{226}Ra, ^{222}Rn, ^{210}Pb, ^{210}Po and gross α activity concentrations. Radiation Protection Dosimetry, 141: 72−81. DOI: 10.1093/rpd/ncq139.

Bonotto DM, Bueno TO, Tessari BW, et al. 2008. The natural radioactivity in water by gross alpha and beta measurements. Radiation Measurements. 44(1): 92–101. DOI: 10.1016/j.radmeas.2008.10.015.

Contreras VJ, Chávez CM, Onorio CO, et al. 2022. Radiological study of water for human use and consumption in rural areas of the central zone of the State of Veracruz, Mexico. Nature Environment and Pollution Technology, 21(4): 1955−1962. DOI: 10.46488/NEPT.2022.V21I04.050.

Dai M. 2020. Hydrogeochemical characteristics and formation and evolution of geothermal water in Guide area, Qinghai province. China University of Geosciences (Beijing). (in Chinese) DOI: 10.27493/d.cnki.gzdzy.2020.000349.

Darko G, Faanu A, Akoto, O. 2015. Assessment of the activity of radionuclides and radiological impacts of consuming underground water in Kumasi, Ghana. Environmental Earth Sciences, 73(1): 399−404. DOI：10.1007/s12665-014-3433-0.

EI Shabana, AA Kinsara. 2014. Radioactivity in the groundwater of a high background radiation area. Journal of Environmental Radioactivity, 137. DOI：10.1016/j.jenvrad.2014.07.013.

Esi OE, Agbalagba EO, Avwiri G O. 2021. Impact of produced water discharge on the gross alpha and gross beta activity concentrations and radiological health risk on drinking water sources in coastal areas of Nigeria. International Journal of Ambient Energy, 42(1): 18−28. DOI：10.4103/RPE.RPE_24_20.

Fahad I Almasoud, Zaid Q Ababneh, Yousef J, et al. 2020. Assessment of radioactivity contents in bedrock groundwater samples from the northern region of Saudi Arabia. Chemosphere, 242(C). DOI：10.1016/j.chemosphere.2019.125181.

Fasae KP. 2013. Gross alpha and beta activity concentrations and committed effective dose due to intake of groundwater in Ado-Ekiti Metropolis; the Capital City of Ekiti State, Southwestern, Nigeria. Journal of Natural Sciences Research, 3(12): 61−66.

General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China. 2024. GB/T 14848–2024. Groundwater quality standard. Beijing: Standards Press of China. (in Chinese)

Giuseppe VL, Valeria A, Vittoria D, et al. 2021. Measurement of natural radionuclides in drinking water and risk assessment in a volcanic region of Italy, Campania. Water, 13(22): 3271−3271. DOI：10.3390/W13223271.

Jia GG, Giancarlo Torri, Leandro Magro. 2009. Concentrations of ^{238}U, ^{234}U, ^{235}U, ^{232}Th, ^{230}Th, ^{228}Th, 226Ra, ^{228}Ra, ^{224}Ra, ^{210}Po, ^{210}Pb and ^{212}Pb in drinking water in Italy: reconciling safety standards based on measurements of gross α and β. Journal of Environmental Radioactivity, 100(11): 941−949. DOI：10.1016/j.jenvrad.2009.07.002.

Jowzaee Sedigheh. 2013. Determination of selected natural radionuclide concentrations in southwestern Caspian groundwater using liquid scintillation counting. Radiation Protection Dosimetry, 157(2): 234−241. DOI：10.1093/rpd/nct132.

Kleinschmidt RI. 2004. Gross alpha and beta activity analysis in water & mdash; a routine laboratory method using liquid scintillation analysis. Applied Radiation and Isotopes, 61: 333−338. DOI：10.1016/j.apradiso.2004.03.004.

Laassiri M, Bouh A H, Ziad N, et al. 2025. Annual effective dose and associated health risk estimation using gross alpha and Beta activity concentrations in bottled mineral water in Morocco. Radiation Protection Dosimetry. DOI: 10.1093/RPD/NCAF019.

María L, Candelaria M, Antonio C, et al. 2022. Estimation of radiation doses due to groundwater intake at a volcanic island: Tenerife (Canary Islands, Spain). Food Control, 135. DOI: 10.1016/J.FOODCONT.2022.108830.

Murad A, Zhou XD, Yi P, Alshamsi D, et al, 2014. Natural radioactivity in groundwater from the south-eastern Arabian Peninsula and environmental implications. Environmental Monitoring and Assessment, 186(10): 6157. DOI: 10.1007/s10661-014-3846-y.

N Todorović, J Nikolov, B Tenjović. 2012. Establishment of a method for measurement of gross alpha/beta activities in water from Vojvodina region. Radiation Measurements, 47: 11−12. DOI：10.1016/j.radmeas.2012.09.009.

Niu ZX, Niu X, Zhang LY, et al. 2022. Chemical characteristics of Neogene groundwater hot water in Qiabuqia area, Gonghe Basin. Science Technology and Engineering, 22(21): 9025−9033. (in Chinese) DOI：10.3969/j.issn.1671-1815.2022.21.003.

Ong JX, Kok JZI, M KK, et al. 2024. Evaluation of tritium, gross alpha and gross beta radioactivity levels in tap and bottled drinking water in Singapore. Journal of Radioanalytical and Nuclear Chemistry, 1–11. DOI：10.1007/S10967-024-09766-2.

Peng Y, Ma YS, Liu CL, et al. 2016. Geological characteristics and tectonic significance of the Indosinian granodiorites from the Zongwulong tectonic belt in North Qaidam. Earth Science Frontiers, 23(2): 206−221. (in

Chinese) DOI：10.13745/j.esf.2016.02.020.

Sadeghi N, Jabbari S, Behzad M. 2024. Gross alpha/beta and radionuclide activity concentrations in soil, plant and some fruits around the Tehran Research Reactor. Applied Radiation and Isotopes, 210111360-. DOI：10.1016/J.APRADISO.2024.111360.

Shang WL, Jin MG. 2012. Preliminary analysis on the evolution of groundwater chemical characteristics at Ceke Port, Ejin Banner, Inner Mongolia. Journal of Inner Mongolia Normal University (Natural Science Edition), 41(3). (in Chinese) DOI: 10.3969/j.issn.1001-8735.2012.03.019.

State Administration for Market Regulation. 2022. GB 5749-2022. Sanitary standard for drinking water. Beijing: Standards Press of China. (in Chinese)

Turhan S, Oezcltak A, Varinlioglu, et al. 2013. Determination of natural radioactivity by gross alpha and beta measurements in ground water samples. Water Research, 47(9): 3103−3108. DOI：10.1016/j.watres.2013.03.030.

UNSCEAR. 2016. Sources, Effects and risks of ionizing radiation. United Nations Publications.

Uzorka A, Olaniyan OA, Akiyode OO, et al. 2024. Evaluation of radioactivity levels and hazard indices of Th-232, Ra-226 and K-40 in sediment and water samples of Lake Victoria, Jinja, Uganda. Discover Environment, 2(1): 120−120. DOI：10.1007/S44274-024-00155-W.

Valli S SN, Raju KM, Satyanarayana V V G, et al. 2024. Assessment of radioactivity levels and dose metrics in coastal drinking water sources of Odisha and Andhra Pradesh, India. Journal of Radioanalytical and Nuclear Chemistry, (prepublish): 1−13. DOI：10.1007/S10967-024-09840-9.

Wang Y, Tong J, Li XL, et al. 2020. Geological characteristics and genetic analysis of Qunaihai hot spring in Qinghai province. Journal of East China University of Technology (Natural Science Edition), 43(03): 248−256. (in Chinese) DOI：10.3969/j.issn.1674-3504.2020.03.006.

World Health Organization. 2017. Guidelines for drinking-water quality: Fourth edition incorporating the first addendum. Geneva: WHO Press.

Zhang LK, Liu X, Sun YJ, et al. 2025. Risks and governance of heavy metals in European soil applied phosphate fertilizers. China Geology, 8(3): 560−572. DOI：10.31035/ cg2023147.

Zhang SS, Zhang L, Tian CS, et al. 2019. Occurrence geological characteristics and development potential of hot dry rock in Gonghe Basin, Qinghai Province. Chinese Journal of Geological Mechanics, 25(04): 501−508. (in Chinese) DOI：10.12090/j.issn.1006-6616.2019.25.04.048.