



# Survey of environmental radioactivity at a decommissioned uranium mine in Southern China

Guoxin Qin<sup>1</sup> · Xirui Wang<sup>2</sup> · Dejun Zhao<sup>3</sup> · Honggang Pan<sup>1</sup> · Xu Jia<sup>1</sup> · Yixuan Li<sup>1</sup>

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## Abstract

To gain a deeper understanding of the conditions at decommissioned uranium mines, on-site monitoring of environmental radioactivity was conducted at a decommissioned uranium mine in southern China. The results showed that the average surface  $\gamma$ -ray dose rate in the mining area and surrounding regions ranged from 83.2 to 286.6 nGy h<sup>-1</sup>, and the average concentration of radon and its progeny in the air ranged from 23.1 to 66.5 Bq m<sup>-3</sup> and 30.3 to 112.4 nJ m<sup>-3</sup>, respectively, which are below the national regulatory limits of China. After remediation, the uranium mine did not cause radioactive pollution to spread into the surrounding environment, indicating the effectiveness of remediation efforts over time.

**Keywords** Uranium mine · Environmental radioactivity · Surface  $\gamma$ -ray dose rate · Radon and its progeny · Natural radionuclide

## Introduction

Since the twentieth century, with the expansion of energy structures and the demand for sustainable development, the advantages of nuclear energy have become increasingly important. The stable development of nuclear energy relies on the exploitation of uranium mines, which generate tailings, waste residue, liquid effluents, and gaseous effluents, all of which are radioactive. Their long-term natural deposition negatively affects the surrounding ecological environment, causing the surface  $\gamma$ -ray dose rate and concentration of radon in the surrounding residential areas to substantially exceed normal background values. Consequently, the treatment of radioactive waste produced by uranium mining has become an urgent issue in the field of environmental protection [1–5].

The decommissioning management of uranium mines has a long cycle and requires a large amount of capital investment. Many countries have been conducting research on the environmental monitoring of uranium mines since the 1950s and have developed many effective decommissioning plans, which have achieved significant results in the environmental and ecological restoration of uranium mines [6–10]. In China, due to historical reasons and lack of experience, a "pollute first, manage later" approach has historically been taken in regard to the environmental management of uranium mines, which has led to a noticeable gap between China and international standards in the field of decommissioning and remediation. Since the 1990s, China has successfully implemented decommissioning plans and environmental management measures for a number of resource-exhausted uranium mines. Over time, decommissioned uranium mines may be damaged by human or natural disasters, and the long-term effectiveness of the technologies applied in the decommissioning process remains to be verified [11, 12]. Therefore, understanding the effectiveness of decommissioning management for uranium mines is essential for identifying potential future issues and safety risks. This paper focuses on a decommissioned uranium mine in southern China and thoroughly reviews the domestic and international standards for the decommissioning of uranium mines. We measured the activity concentration of radionuclides in the soil, water, and air surrounding the mine, evaluated the long-term

✉ Guoxin Qin  
qinguoixiu198201@163.com

<sup>1</sup> Shenyang Institute of Engineering, 18 Puchang Dr, Shenyang 110136, Liaoning, China

<sup>2</sup> Department of Ecology and Environment of Liaoning Province, Ecological Environment Monitoring Center, 30 Shuangyuan Dr., Shenyang 110015, Liaoning, China

<sup>3</sup> Science and Technology Center of Ecology and Environment of Liaoning Province, 30 Shuangyuan Dr, Shenyang 110015, Liaoning, China

effectiveness of the decommissioning project, and proposed rectification measures for sources that fail to meet the standards. This research aims to provide insights for long-term environmental radioactivity monitoring of decommissioned uranium mines.

## Materials and methods

### Production process and pollution sources

Located in Hunan Province, China, this mine consists of an eastern and a western mining area. The decommissioned workplaces include opencast mining ruins, an ore dressing plant, a waste rock site, and a wastewater treatment plant (see Fig. 1). Uranium ore is rich in natural radionuclides such as  $^{238}\text{U}$ ,  $^{226}\text{Ra}$  and  $^{232}\text{Th}$ , that generate a significant amount of radioactive waste during the mining, processing, and decommissioning stages. Radioactive materials spread into the environment through diffusion, deposition, percolation, and leaching in the forms of gases, liquids, and solids [13–15]. As shown in Fig. 2, the production process of this mine involves the preliminary screening of uranium ore extracted from opencast mining sites and mine pits, and the separation of low-grade ore with no heap leaching value from high-grade ore, which is then transported to the hydrometallurgical mill. The waste rock and residues produced during mining accumulate in the open air within the mine area. Due to current technological and process limitations, completely separating and extracting these radionuclides remains challenging. The stacking of these solid wastes

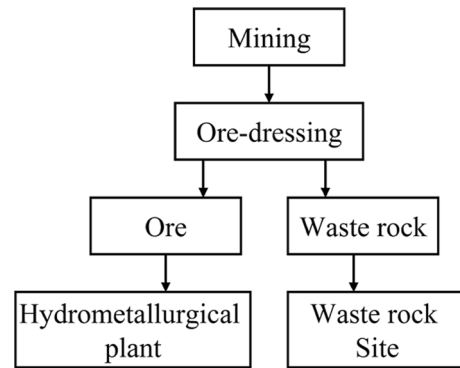


Fig. 2 Production process of the uranium mine

causes radionuclides to migrate continuously through the soil pores.

### Decommissioning governance schemes and regulatory limits

The mine was closed in 1995, and its decommissioning work was completed in 2002. The decommissioning efforts mainly included: (1) backfilling opencast mining ruins with waste rock and scattered ore from the surrounding environment to reduce the accumulation of waste rock on the surface, (2) all production equipment was washed with high-pressure water and repurposed for other mining operations, (3) metal parts contaminated with radionuclides were cut off and filled into the opencast mining ruins, (4) after decontamination and ensuring surface radioactivity levels were below  $0.08 \text{ Bq cm}^{-2}$ , the remaining decommissioned equipment

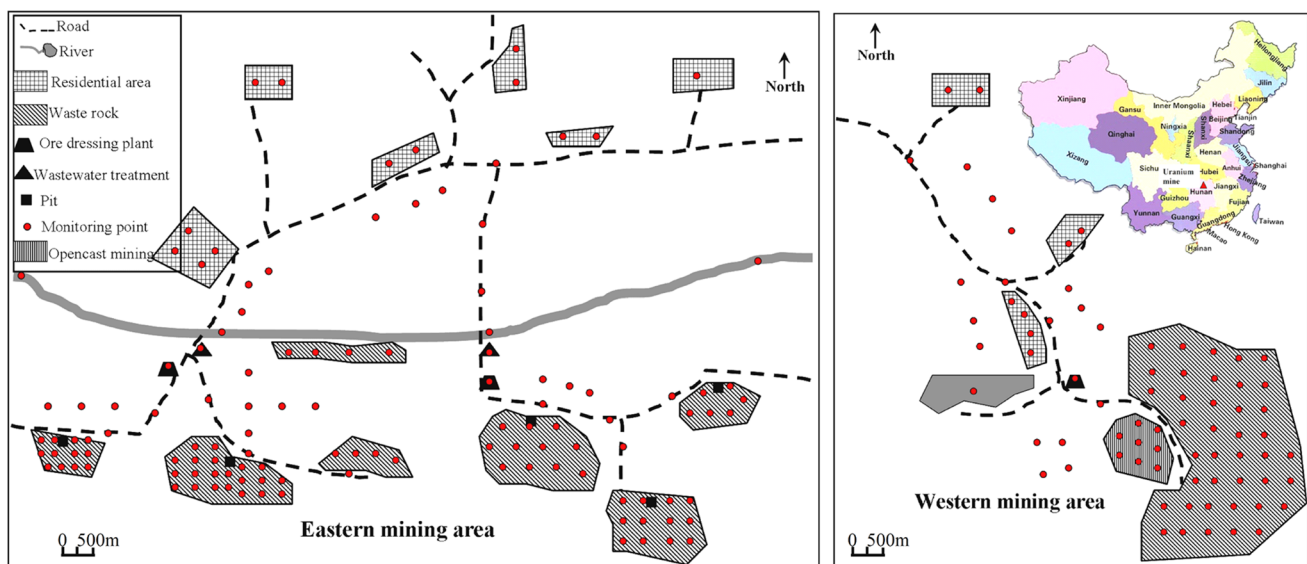


Fig. 1 Arrangement of the monitoring points of the uranium mine

was sent to a smelting plant in Hunan Province, and (5) after all the decommissioned areas were cleaned, leveled and stabilized in situ, low-level radioactive areas nearby were selected as soil excavation sites, and sticky loess was excavated and spread over the decommissioned areas to a thickness of 60–80 cm. This mixture was then mechanically compacted to reduce the surface  $\gamma$ -ray dose rate and suppress the exhalation of radon and its progeny. Finally, grass was planted to restore vegetation.

According to China's "Regulations for Radiation Protection and Radiation Environment Protection in Uranium Mining and Milling" and relevant regulations from other countries on uranium mine decommissioning [16–20], a dose limit of no more than 1 mSv a<sup>-1</sup> is widely adopted worldwide as the main recommended guidance limit for

evaluating uranium mine decommissioning projects. For specific measurement items, the decommissioning regulatory limits for uranium mines we selected are shown in Table 1.

## Survey methods and instruments

From May 2021 to April 2023, in accordance with China's "Regulations for Radiation Environmental Monitoring in Uranium Mine and Mill" [21], measurements were conducted in the eastern and western mining areas of the mine and the surrounding regions. These measurements included the surface  $\gamma$ -ray dose rate, the concentration of radon and its progeny in air, the radon exhalation rate, and the concentration of natural radionuclides in the soil and surface water. To comprehensively and accurately reflect the environmental radioactivity status within the surveyed area, the frequency of monitoring for each measurement target was set at once per month. Multiple measurements were continually performed at each monitoring point, and their average values were taken. Additionally, each monitoring point was measured repeatedly every year during the survey period. To obtain contrast point data, measurements were taken in areas 80 km away, that were unaffected by the production of the mine.

To ensure the accuracy of the measurement results, comprehensive quality assurance measures were adopted for this survey. The collection, processing, and analysis of samples were conducted based on China's national standards. All measuring instruments employed were verified by the China Institute of Metrology. The personnel conducting the measurement analysis received professional training. The instruments and parameters introduced for each monitoring item are listed in Table 2.

**Table 1** Radionuclide concentration/dose regulatory limits in soil, water and air

Medium	Measurement item	Regulatory limit
Soil	<sup>226</sup> Ra	180/560 Bq kg <sup>-1</sup> *
	<sup>232</sup> Th	180 Bq kg <sup>-1</sup>
	<sup>238</sup> U	400 Bq kg <sup>-1</sup>
	Radon exhalation rate	0.74 Bq m <sup>-2</sup> s <sup>-1</sup>
Water	<sup>226</sup> Ra	0.37 Bq L <sup>-1</sup>
	<sup>232</sup> Th	0.3 Bq L <sup>-1</sup>
	Total uranium	0.3 mg L <sup>-1</sup>
	Gross $\alpha$	0.5 Bq L <sup>-1</sup>
	Gross $\beta$	1 Bq L <sup>-1</sup>
Air	Surface $\gamma$ -ray dose rate	450 nGy h <sup>-1</sup>
	<sup>222</sup> Rn	100 Bq m <sup>-3</sup>
	Progeny of <sup>222</sup> Rn	0.416 $\mu$ J m <sup>-3</sup>

\* 180 Bq kg<sup>-1</sup> is the regulatory limit for the upper 0–15 cm soil layer, and 560 Bq kg<sup>-1</sup> is the regulatory limit for the 15–30 cm soil layer

**Table 2** Monitoring instruments and their parameters

Medium	Measurement item	Monitoring instrument	Manufacturer	Minimum detectable limit
Soil	<sup>226</sup> Ra	GEM HPGe $\gamma$ spectrometer	AMETEK.Inc	6.5 Bq kg <sup>-1</sup>
	<sup>232</sup> Th			6.8 Bq kg <sup>-1</sup>
	<sup>238</sup> U			10.7 Bq kg <sup>-1</sup>
	Radon exhalation rate	RaD-7 and its soil cover	America Duridge	1 mBq m <sup>-2</sup> s <sup>-1</sup>
Water	<sup>226</sup> Ra	GEM HPGe $\gamma$ spectrometer	AMETEK.Inc	6.2 Bq kg <sup>-1</sup>
	<sup>232</sup> Th			6.5 Bq kg <sup>-1</sup>
	Total uranium	FYWY uranium analyser	FANGYUAN Technology Co., Ltd	0.01 $\mu$ g L <sup>-1</sup>
	Gross $\alpha$	Fj-2604 $\alpha/\beta$ radioactivity monitor	China nuclear control system engineering Co., Ltd	0.02 Bq L <sup>-1</sup>
	Gross $\beta$			0.01 Bq L <sup>-1</sup>
Air	Surface $\gamma$ -ray dose rate	HA1310 high-pressure ionization chamber	Zhonglv Technology Co., Ltd	1 $\times$ 10 <sup>-9</sup> Gy h <sup>-1</sup>
	Radon and its progeny	DHBM-II radon monitor	China Institute for Radiation Protection	Radon: 3.0 Bq m <sup>-3</sup> Progeny: 10 nJ m <sup>-3</sup>

## Results and discussion

### Radioactivity measurement in air

#### Surface $\gamma$ -ray dose rate

The instrument used for measuring the surface  $\gamma$ -ray dose rate is an HA1310 high-pressure ionization chamber (see Fig. 3), which adopts an integrated structure design of the host and detector and has the characteristics of high detection sensitivity, stable performance, long service life, and good energy response. The measurement results of each monitoring point in the mining area are listed in

Table 3. During the measurement, the locations of monitoring points were organized into a grid: a 20 m  $\times$  20 m layout was used within the uranium mine area, and a 50 m  $\times$  50 m layout was used for other areas. If abnormal values were detected, the number of monitoring points was increased. The measuring instruments were placed 1 m above the ground at the centre of each grid. The monitoring results from Table 3 indicate that the average  $\gamma$ -ray dose rates at the decommissioned areas, including open-cast mining ruins, waste rock sites, mine pits, ore dressing plants, and wastewater treatment plants, ranged from 90.2  $\sim$  286.6 nGy h<sup>-1</sup>. This range aligns with the decommissioning management goal of ensuring the environmental surface  $\gamma$ -ray dose rate does not exceed 450 nGy h<sup>-1</sup>.

**Fig. 3** Instruments used for measuring the surface  $\gamma$ -ray dose rate and concentration of radon and its progeny in the air



HA1310 high-pressure ionization chamber



DHZM-II radon monitor

**Table 3** Surface  $\gamma$ -ray dose rates at the monitoring points

Area	Monitoring point	Decommissioning data		Current data	
		Range (nGy h <sup>-1</sup> )	Average (nGy h <sup>-1</sup> )	Range (nGy h <sup>-1</sup> )	Average (nGy h <sup>-1</sup> )
Eastern mining area	Pithead	99–349	229.2 $\pm$ 61.2	95–334	202.3 $\pm$ 57.5
	Waste rock site	105–255	186.0 $\pm$ 40.8	112–261	171.7 $\pm$ 35.3
	Ore dressing plant	112–233	143 $\pm$ 33.5	92–203	138.2 $\pm$ 21.4
	Wastewater treatment plant	89–225	138.2 $\pm$ 36.3	72–197	122.3 $\pm$ 27.3
	Bus stop	75–186	104 $\pm$ 21.4	63–163	90.2 $\pm$ 19.5
	Outdoor residential area	56–161	84.1 $\pm$ 20.7	53–154	83.2 $\pm$ 21.9
	Indoor residential area	64–182	102.6 $\pm$ 30.3	58–172	97.4 $\pm$ 28.7
Western mining area	Waste rock site	130–261	183.0 $\pm$ 36.7	116–279	182.5 $\pm$ 42.0
	Ore dressing plant	122–244	184.1 $\pm$ 35.5	106–195	141.4 $\pm$ 28.5
	Opencast mining ruin	127–446	293.0 $\pm$ 52.2	145–402	286.6 $\pm$ 54.4
	Outdoor residential area	48–173	88.5 $\pm$ 21.5	55–166	87.7 $\pm$ 20.2
	Indoor residential area	72–202	103.6 $\pm$ 26.6	64–198	102.2 $\pm$ 27.6
Control point	Outdoor residential area			51–141	81.6 $\pm$ 17.8
	Indoor residential area			64–202	96 $\pm$ 21.9

The comparison with the final decommissioning stage revealed a slight reduction in the overall surface  $\gamma$ -ray dose rate. In nearby residential areas, the surface  $\gamma$ -ray dose rates averaged between 83.2 and 102.2 nGy h<sup>-1</sup>, which is within the range of the measurement values for the control point.

The annual effective dose for residents and staff caused by  $\gamma$ -ray was calculated through the dose calculation model recommended in the 1982 report by the United Nations Scientific Committee on Effects of Atomic Radiation (UNSCEAR) [22]:

$$H_{e1} = k \sum_i X_i \cdot T_i \quad (1)$$

where  $H_{e1}$  is the annual effective dose caused by  $\gamma$  ray,  $k$  is the ratio of the effective dose to the surface  $\gamma$ -ray dose rate, with UNSCEAR recommending a value of 0.7,  $X_i$  is the  $\gamma$ -ray dose rate at the  $i$ -th monitoring point, and  $T_i$  is the actual time spent by staff or residents at the  $i$ -th monitoring point. According to UNSCEAR, the occupancy factors for residents indoors and outdoors are 0.8 and 0.2, respectively, which translates to 7008 h spent indoors and 1752 h spent outdoors. For staff who currently reside in the residential area and work in the monitoring area for 2000 h, their time spent indoors and outdoors in the residential area amounts to 5408 h and 1352 h, respectively. The calculations demonstrate that the maximum value of the average annual effective dose caused by  $\gamma$ -ray in the mining area was 0.76 mSv for residents and 1.06 mSv for staff.

### Concentration of radon and its progeny in the air

The layout for monitoring the concentration of radon and its progeny in the air was consistent with that for monitoring the surface  $\gamma$ -ray dose rate. The instrument used for measurement is a DHZM-II radon monitor (see Fig. 3), which uses the double-filter method and can measure the concentration of radon and its progeny in real time. The measurement results are presented in Table 4. According to these results, the concentration of radon and its progeny in the mining area remained at the same level as at the time of decommissioning. The western mining area, which is in a low-lying and relatively enclosed space with poor air circulation, had initially exhibited moderately high concentrations of radon and its progeny. However, when monitoring measurements were compared with the contrast point data, no significant difference was found, which indicates that the potential impact of radon on the public and the environment post-remediation is acceptable.

Based on the dose calculation model proposed in the UNSCEAR 2000 report [23], the annual effective dose caused by the inhalation of <sup>222</sup>Rn and its progeny is calculated as follows:

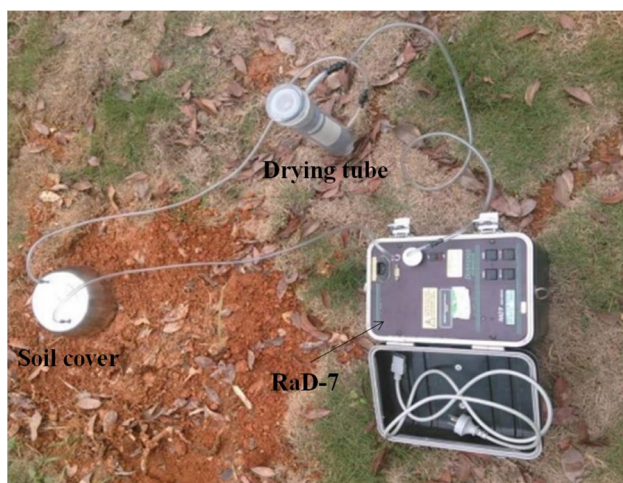
$$H_{e2} = G_R \sum_i 0.180 \cdot D_i \cdot T_i \quad (2)$$

where  $T_i$  is the actual time spent by staff or residents at the  $i$ -th monitoring point, with the specific time distribution consistent with the effective dose calculation for the surface  $\gamma$ -ray dose rate;  $D_i$  is the concentration of radon progeny

**Table 4** Concentrations of radon and its progeny in the air

Area	Monitoring point	Decommissioning data		Current data			
		Concentration of radon (Bq m <sup>-3</sup> )		Concentration of radon (Bq m <sup>-3</sup> )		Concentration of progeny (nJ m <sup>-3</sup> )	
		Rang	Average	Rang	Average	Rang	Average
Eastern mining area	Pithead	28.6–70.2	47.3 ± 10.3	32.5–67.6	44.5 ± 9.2	51.2–118.5	73.6 ± 18.5
	Waste rock site	21.5–80.6	50.8 ± 15.5	26.5–60.1	41.8 ± 11.0	38.1–101.4	67.3 ± 16.1
	Ore dressing plant	33.5–77.2	44.8 ± 12.6	22.4–66.6	39.5 ± 14.2	28.1–89.6	61.6 ± 19.4
	Wastewater treatment plant	20.7–92.4	43.8 ± 16.4	28.7–58.5	38.9 ± 7.8	36.1–82.7	58.3 ± 15.8
	Bus stop	28.0–51.3	37.2 ± 6.6	19.8–44.9	32.4 ± 8.1	25.9–61.1	41.6 ± 14.2
	Outdoor residential area	15.5–36.6	22.3 ± 6.8	11.6–32.5	21.5 ± 7.3	18.2–45.8	30.3 ± 9.2
	Indoor residential area	22.4–68.3	35.0 ± 8.5	18.2–54.1	32.8 ± 10.1	35.5–98.4	65.8 ± 20.6
Western mining area	Waste rock site	27.2–60.3	47.7 ± 13.3	31.5–62.1	49.3 ± 14.5	41.6–131.3	77.1 ± 23.3
	Ore dressing plant	24.5–88.2	54.7 ± 14.8	28.2–74.6	52.2 ± 17.7	30.4–109.5	62.3 ± 19.8
	Opencast mining ruin	38.6–118.2	69.5 ± 18.8	42.8–92	66.5 ± 15.6	74.6–163.2	112.4 ± 26.6
	Outdoor residential area	12.5–33.2	21.7 ± 6.4	9.2–36.2	23.1 ± 10.4	20.1–92.4	38.6 ± 12.4
	Indoor residential area	25.1–64.5	38.2 ± 8.8	22.7–58.8	35.2 ± 9.7	31.8–115.2	72.2 ± 25.5
Control point	Outdoor residential area			8.6–45.0	18.4 ± 9.3	17.1–87.5	34.2 ± 12.4
	Indoor residential area			11.7–62.9	30.5 ± 12.5	19.6–141.8	68.4 ± 19.9

( $\text{nJ m}^{-3}$ ); and 0.180 is the conversion factor from  $\text{nJ m}^{-3}$  to  $\text{Bq m}^{-3}$ .  $G_R$  is the dose conversion coefficient; according to the UNSCEAR 2000 report, the effective dose conversion coefficient for inhaling the unit equilibrium equivalent radon concentration per unit time is  $9 \text{ nSv (Bq m}^{-3} \text{ h)}^{-1}$ . The calculation results indicate that the maximum annual effective dose caused by the inhalation of radon and its progeny in the mining area was  $1.25 \text{ mSv}$  for residents and  $1.42 \text{ mSv}$  for staff.



**Fig. 4** Measurement device used for determining the radon exhalation rate

## Radioactivity measurement in soil

### Radon exhalation rate

The layout for measuring the radon exhalation rate was consistent with that for the surface  $\gamma$ -ray dose rate. The measurement device is shown in Fig. 4. The RaD-7 radon monitor includes a host, filter, drying tube, and desiccant. It is widely used because of its simple sampling and good stability. To minimize the impact of air humidity fluctuations on measurement accuracy, the measurements were typically conducted between 10 a.m. and 4 p.m. Additionally, field measurements were carried out on clear days and at least 24 h after the last rainfall. Table 5 presents the radon exhalation rates measured in the mining area. The results from Table 5 show that after decommissioning and remediation, the radon exhalation rates measured in the opencast mining ruins ranged from  $123.2$  to  $336.6 \text{ mBq m}^{-2} \text{ s}^{-1}$ , and those in the waste rock sites ranged from  $44.5$  to  $292.7 \text{ mBq m}^{-2} \text{ s}^{-1}$ . The average radon exhalation rates across various monitoring points in other workplaces ranged from  $39.5$  to  $138.6 \text{ mBq m}^{-2} \text{ s}^{-1}$ , which meets the regulatory limits set for decommissioning. Compared with the measurements taken at the final state of decommissioning, there was a significant decrease which indicates that the remediation efforts have been effectively maintained.

### Natural radionuclides in soil

Soil samples for this survey were collected from the buried cover layers of the mining area and nearby farmlands. The soil sampling followed a  $10 \text{ m} \times 10 \text{ m}$  grid pattern and utilized a plum distribution method to ensure no fewer than 10 sampling points per grid. After removing all tubers and

**Table 5** Radon exhalation rates from the soil surface

Area	Monitoring point	Decommissioning data		Current data	
		Range ( $\text{mBq m}^{-2} \text{ s}^{-1}$ )	Average ( $\text{mBq m}^{-2} \text{ s}^{-1}$ )	Range ( $\text{mBq m}^{-2} \text{ s}^{-1}$ )	Average ( $\text{mBq m}^{-2} \text{ s}^{-1}$ )
Eastern mining area	Pithead	62.2–322.4	$159.6 \pm 65.8$	61.5–281.1	$138.6 \pm 51.9$
	Waste rock site	82.5–366.2	$237.1 \pm 51.5$	96.6–292.7	$205.5 \pm 64.2$
	Ore dressing plant	40.2–211.6	$131.3 \pm 32.8$	60.5–188.8	$122.7 \pm 24.5$
	Wastewater treatment plant	33.6–125.5	$68.8 \pm 17.6$	34.6–102.2	$63.5 \pm 15.1$
	Bus stop	25.8–89.5	$42.4 \pm 12.4$	21.8–72.2	$39.5 \pm 11.3$
	Residential area	16.3–65.6	$26.2 \pm 7.5$	18.1–58.8	$25.7 \pm 6.8$
Western mining area	Pithead	66.1–192.6	$126.0 \pm 34.4$	36.8–162.5	$101.4 \pm 31.6$
	Waste rock site	54.8–222.4	$140.1 \pm 47.6$	44.5–187.7	$120.5 \pm 35.7$
	Ore dressing plant	33.5–206.8	$116.6 \pm 40.5$	37.2–169.6	$108.7 \pm 33.2$
	Opencast mining ruin	112.4–422.7	$289.5 \pm 76.8$	123.2–336.6	$225.4 \pm 58.5$
	Residential area	17.5–55.8	$25.4 \pm 6.6$	13.1–72.4	$27.9 \pm 8.2$
Control point				14.7–48.8	$23.3 \pm 7.7$

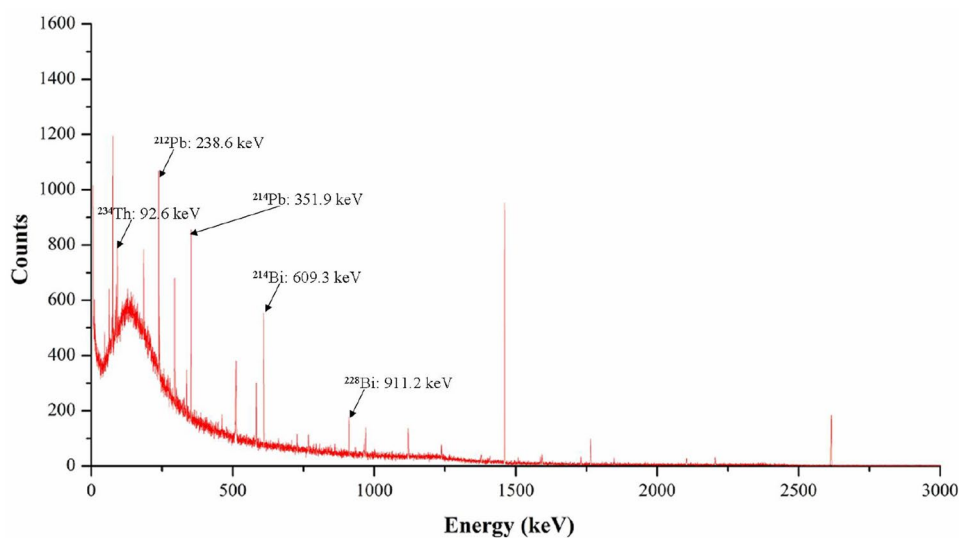
grass layers, samples were mixed on-site, stored in cloth bags labelled with GPS tags, and transported to the laboratory, where they were spread out on enamel trays to dry. The dry samples were then sifted through a 40–60 mesh screen, weighed, sealed in sample boxes, and stored for 5 weeks prior to measurement. The energy resolution of the GEM HPGe  $\gamma$  spectrometer used for measurement (see Fig. 5) is 1.92 keV @ 1332.5 keV, and the relative detection efficiency is 28.3%. Before measuring the samples, the energy and detection efficiency of the  $\gamma$  spectrometer were calibrated using a standard soil source. In the measured energy spectrum data, according to the decay diagrams of  $^{238}\text{U}$ ,  $^{226}\text{Ra}$  and  $^{232}\text{Th}$ , the activity concentration of  $^{238}\text{U}$  was determined by  $\gamma$  photon with an energy of 92.6 keV emitted by  $^{234}\text{Th}$ , the activity concentration of  $^{226}\text{Ra}$  was determined by  $\gamma$  photon

with an energy of 351.9 keV emitted by  $^{214}\text{Pb}$  and  $\gamma$  photon with an energy of 609.3 keV emitted by  $^{214}\text{Bi}$ , and the activity concentration of  $^{232}\text{Th}$  was determined by  $\gamma$  photon with an energy of 238.6 keV emitted by  $^{212}\text{Pb}$  and  $\gamma$  photon with an energy of 911.2 keV emitted by  $^{228}\text{Bi}$ . Figure 6 shows the energy spectrum of a soil sample. The measurement results of the soil samples are shown in Table 6. As shown in Table 6, the measurement results imply that the activities of  $^{238}\text{U}$  and  $^{226}\text{Ra}$  in the soil of the remediated areas, such as the opencast mining ruins and waste rock sites, were slightly greater than those in the farmlands and control points. This likely results from the leaching of  $^{238}\text{U}$  and  $^{226}\text{Ra}$  from buried waste rock into the surface soil. The average activities of  $^{226}\text{Ra}$  in the soil of both the remediated areas and surrounding farmlands were below the levels at the time of decommissioning, which suggests a gradual improvement in the amount of radioactive pollution affecting the farmlands surrounding the mine post-remediation.



Fig. 5 GEM HPGe  $\gamma$  spectrometer

Fig. 6 Energy spectrum of a soil sample



### Radioactivity measurement in surface water

Water samples were primarily collected from mountain springs, rivers, and residential water sources surrounding the mining area, with focus on the middle of these water bodies for sampling. Polyethylene plastic barrels were chosen as sample containers. Before collection, these barrels were thoroughly cleaned and then rinsed three times with water from the sampling site. Field sampling was conducted on clear days, and the time interval between the last rainfall was at least 48 h. Upon returning to the laboratory, nitric acid was introduced to adjust the pH value of the water samples from each monitoring point to 2. If the water contained suspended particles, it was first filtered through a 0.45  $\mu\text{m}$  membrane filter. The water samples were then saved in sample boxes for measurements. The activity concentrations of

**Table 6** Activity concentration of radionuclides in soil (Bq kg<sup>-1</sup>)

Area	Below ground	Monitoring point	Decommissioning data			Current data		
			<sup>238</sup> U	<sup>232</sup> Th	<sup>226</sup> Ra	<sup>238</sup> U	<sup>232</sup> Th	<sup>226</sup> Ra
Eastern mining area	0–15 cm	Waste rock site	88.2 ± 15.3	68.6 ± 10.6	81.3 ± 13.3	83.5 ± 13.6	71.4 ± 12.8	77.1 ± 11.5
		Ore dressing plant	86.4 ± 13.7	72.1 ± 9.6	77.7 ± 11.6	81.6 ± 14.2	58.5 ± 11.3	74.4 ± 10.2
		Farmland	76.2 ± 11.5	63.9 ± 11.3	69.5 ± 10.1	77.3 ± 12.1	67.2 ± 13.2	65.1 ± 11.7
	15–30 cm	Waste rock site	166.1 ± 18.2	69.1 ± 9.7	142.2 ± 19.4	152.5 ± 15.4	59.3 ± 11.8	127.6 ± 16.2
		Ore dressing plant	131.5 ± 11.5	66.8 ± 12.2	111.3 ± 14.2	133.4 ± 12.4	54.2 ± 15.7	106.5 ± 12.5
		Farmland	73.2 ± 9.1	71.2 ± 12.6	62.4 ± 11.2	76.8 ± 10.5	67.1 ± 9.8	58.6 ± 10.6
Western mining area	0–15 cm	Waste rock site	96.4 ± 19.1	58.3 ± 11.8	84.5 ± 15.8	91.8 ± 20.5	66.5 ± 10.1	80.0 ± 13.1
		Ore dressing plant	92.0 ± 12.3	80.6 ± 11.2	81.1 ± 16.3	88.0 ± 15.6	76.2 ± 14.3	74.3 ± 14.2
		Opencast mining ruin	104.8 ± 17.5	66.6 ± 8.6	98.7 ± 14.2	110.5 ± 15.8	68.2 ± 12.9	92.5 ± 16.5
	15–30 cm	Farmland	89.1 ± 12.2	55.3 ± 16.1	77.5 ± 14.8	85.5 ± 10.4	60.4 ± 15.7	71.2 ± 15.0
		Waste rock site	172.7 ± 21.5	64.4 ± 11.6	150.5 ± 17.3	166.6 ± 22.1	69.0 ± 12.8	135.2 ± 18.4
		Ore dressing plant	136.7 ± 10.3	62.2 ± 14.4	107.1 ± 16.7	140.2 ± 13.5	68.0 ± 16.1	98.5 ± 13.8
Control point	0–15 cm	Opencast mining ruin	207 ± 33.5	73.7 ± 11.6	175 ± 27.4	186.8 ± 25.3	61.6 ± 15.4	142.0 ± 19.5
		Farmland	78.8 ± 10.5	64.4 ± 13.6	67.5 ± 12.9	72.7 ± 11.2	58.8 ± 10.5	61.9 ± 11.5
	15–30 cm					75.8 ± 11.2	60.6 ± 18.3	58.9 ± 9.8
						74.5 ± 10.6	62.4 ± 16.5	56.3 ± 10.2

<sup>226</sup>Ra and <sup>232</sup>Th in the water samples were measured using a GEM HPGe  $\gamma$  spectrometer. The measurement of total uranium was carried out using the FYWY uranium analyser (see Fig. 7). The FYWY uranium analyser uses a new digital laser fluorescence measurement technology, which can easily adjust the measurement parameters according to the actual situation and has a wide range of adaptations. An Fj-2604  $\alpha/\beta$  radioactivity monitor was used for gross  $\alpha$  and gross  $\beta$  measurements. The Fj-2604  $\alpha/\beta$  radioactivity monitor uses a passive implemented planar silicon (PIPS) detector, which is mainly used for radioactivity measurement of low-level environmental samples. The measurement results of the water samples are shown in Table 7. The results reveal that after remediation, the concentrations of nuclides in surface water at various monitoring points were generally lower than those at the time of decommissioning and did not exceed the established regulatory limits, implying the

effectiveness of the decommissioning efforts. The activity concentrations of uranium and radium in the surface water of the residential area in the western mining area are higher than those in the mining area. It can be inferred that uranium and radium in the mining area have migrated. There was no significant difference in the gross  $\alpha$  or gross  $\beta$  values of the drinking water in the residential area compared to those at the control point, which was similar to the results reported by many scientific researchers [24–26].

## Conclusions

Over the two years, the investigation collected comprehensive environmental radioactivity measurements and assessments of a decommissioned uranium mine and its surrounding area, including soil, surface water, and air, in

**Fig. 7** Instruments used for measuring total uranium, gross  $\alpha$  and gross  $\beta$



FYWY uranium analyzer

Fj-2604  $\alpha/\beta$  radioactivity monitor



**Table 7** Concentrations of radionuclides in water

Area	Monitoring point	Total U ( $\mu\text{g L}^{-1}$ )	$^{232}\text{Th}$ ( $\text{Bq L}^{-1}$ )	$^{226}\text{Ra}$ ( $\text{m Bq L}^{-1}$ )	Gross $\alpha$ ( $\text{Bq L}^{-1}$ )	Gross $\beta$ ( $\text{Bq L}^{-1}$ )
<i>Decommissioning data</i>						
Eastern mining area	Mining area	$6.5 \pm 1.7$	$0.25 \pm 0.04$	$19.6 \pm 2.5$	$0.21 \pm 0.03$	$0.33 \pm 0.06$
	Downstream of the discharge (500 m)	$2.8 \pm 1.2$	$0.23 \pm 0.03$	$12.8 \pm 0.9$	$0.12 \pm 0.02$	$0.24 \pm 0.05$
	Residential area	$2.1 \pm 0.8$	$0.22 \pm 0.04$	$8.2 \pm 0.4$	$0.08 \pm 0.03$	$0.14 \pm 0.03$
Western mining area	Mining area	$11.2 \pm 2.8$	$0.26 \pm 0.05$	$34.2 \pm 7.3$	$0.28 \pm 0.05$	$0.45 \pm 0.08$
	Residential area	$8.8 \pm 1.3$	$0.24 \pm 0.04$	$23.4 \pm 5.1$	$0.21 \pm 0.04$	$0.35 \pm 0.07$
	Pond	$23.3 \pm 5.4$	$0.24 \pm 0.03$	$61.0 \pm 8.7$	$0.38 \pm 0.06$	$0.64 \pm 0.12$
<i>Current data</i>						
Eastern mining area	Mining area	$4.6 \pm 1.2$	$0.24 \pm 0.03$	$15.0 \pm 1.8$	$0.18 \pm 0.05$	$0.27 \pm 0.06$
	Downstream of the discharge (500 m)	$2.4 \pm 0.6$	$0.23 \pm 0.03$	$8.4 \pm 0.7$	$0.10 \pm 0.03$	$0.21 \pm 0.07$
	Residential area	$1.8 \pm 0.5$	$0.25 \pm 0.04$	$6.3 \pm 0.5$	$0.08 \pm 0.02$	$0.13 \pm 0.06$
Western mining area	Mining area	$8.2 \pm 1.6$	$0.26 \pm 0.03$	$27.0 \pm 5.2$	$0.23 \pm 0.04$	$0.38 \pm 0.06$
	Residential area	$8.9 \pm 2.2$	$0.26 \pm 0.04$	$29.2 \pm 6.3$	$0.24 \pm 0.05$	$0.38 \pm 0.08$
	Pond	$18.0 \pm 5.6$	$0.24 \pm 0.04$	$45.0 \pm 5.4$	$0.32 \pm 0.05$	$0.56 \pm 0.11$
Control point		$1.5 \pm 0.4$	$0.25 \pm 0.04$	$8.6 \pm 1.5$	$0.06 \pm 0.02$	$0.13 \pm 0.03$

southern China. The findings indicate that after years of decommissioning efforts, the surface  $\gamma$ -ray dose rate and concentrations of radon and its progeny in the air are all below the regulatory limits. There is a significant reduction in the radon exhalation rate, and the concentrations of radionuclides, such as uranium, thorium, and radium, in the soil and surface water are low which demonstrates that management has been effective. The maximum annual effective dose due to internal and external radiation for the staff was 2.48 mSv, which was lower than the management limit of China (5 mSv). For residents living around the mine, after subtracting the background dose (data from the contrast point), the maximum annual effective dose due to internal and external radiation was 0.18 mSv, which was also below the management limit of 1 mSv.

The comparison of the environmental radioactivity measurements from the current survey to those at the time of the final decommissioning phase illustrates the positive correlation between the radon exhalation rate of the soil and the activity concentrations of uranium and radium. Following remediation efforts, there has been a significant improvement in the environment surrounding the mine. Radon exhalation rates and surface  $\gamma$ -ray dose rates have fallen below the regulatory limits, thereby significantly reducing the impact of the mine on nearby communities. However, data analyses suggest that after decommissioning, the main route of radioactive influence on surrounding areas is attributed to the migration of radionuclides facilitated by the permeation of groundwater and surface water, which emphasizes the necessity for intensified monitoring of these aspects in the future.

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## Declarations

**Conflict of interest** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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