Investigation and Analysis of Airborne Gamma Radiation Absorbed Dose Rate of Danjiangkou Reservoir

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Abstract. Airborne gamma-ray spectrometry is widely used in regional nuclear radiation surveys and environmental nuclear radiation pollution assessments. This paper aims at analyzing the status of nuclear radiation in the Danjiangkou Reservoir area by using airborne gamma spectrometry data. Mapping of the gamma radiation air absorbed dose rate in the study area was completed by using the Beck formula and divided into three different grades according to relevant national standards. Based on the survey results, the main sources of high radioactive anomalies in the Danjiangkou Reservoir and surrounding areas were identified. Furthermore, a protection proposal was put forward to guarantee the water quality and safety of residents in the South-to-North Water Diversion Source.

1. Introduction
The natural radionuclide is an important radioactive source that affects the safety of public environmental radiation. The natural radionuclide is unevenly distributed in crustal rocks and poses a regional hazard to the human body. As a basic basis for assessing regional background radioactivity, the gamma air absorbed dose rate (AADR) is used by many countries as an important basis for residential area selection and environmental suitability evaluation [1]. Airborne gamma-ray spectrum measurement has the advantages of large scale, high efficiency, and small influence by factors such as terrain, landforms, and traffic [2-3]. Since the 1980s, with the improvement of public awareness of environmental safety, airborne gamma spectrum measurement has been widely applied in regional nuclear radiation background surveys and regional environmental nuclear radiation pollution assessment. The previous researches on the theory and method of estimating gamma AADR have been relatively mature [4-5]. However, due to the lack of data sources, there are still scarce in application practice and application analysis.

Danjiangkou Reservoir is located in the middle and upper reaches of the Han River, the longest tributary of the Yangtze River. As an important development area of the Yangtze River Economic Belt and the starting point of the Middle Route of South-to-North Water Transfer Project, Danjiangkou Reservoir is of great significance for ensuring water safety in Jing-Jin-Ji region. However, since the completion of the reservoir, it has been scarce to carry out large-scale aerial radioactivity measurement and systematic research.

This paper aims at analyzing the status of nuclear radiation in the Danjiangkou Reservoir area by using 1:50,000 airborne gamma spectrometry data acquired in 2017. Mapping of GRAADR based on
the beck formula and systematic evaluation of the status of the radiation environment in the reservoir and surrounding areas. Combined with field verification results, the impact of natural radionuclides distributed in regional rock formation and radiation anomalies caused by human activities on the environment of the reservoir area is evaluated, providing scientific reference and decision support for a national strategy and local economic development.

2. Study area and data
Danjiangkou Reservoir is the source of water for the Middle Route Project of South-to-North Water Diversion. It provides domestic and production water to more than 20 large and medium-sized cities. Most of the study area is structurally located in the middle-south Qinling section. Various types of magmatic rocks and strata of different ages are widely distributed in the study area. The coverage area of the study area is approximately 14000km².

From 2016 to 2017, 1: 50,000 high-precision aerial radioactivity measurement work was carried out in the Danjiangkou area, by China Aero Geophysical Survey and Remote Sensing Center for Natural Resources. A total of 21 flights of high-precision airborne gamma spectrometry data were acquired, with an average flight altitude of 87m. The aerial measurement uses the GR-820 airborne gamma spectrometer, and the ground verification uses the GS-512i gamma spectrometer.

3. Methods
Processing of airborne gamma-ray spectrometry data includes corrected for live time, Background component correction, Compton scattering correction, highly normalized energy spectrum data, negative value processing, and content conversion in sequence. Background component correction coefficient, Compton scattering coefficient, Altitude attenuation coefficient and Airborne sensitivity coefficient at 120m are listed in Tables 1-4.

| Table 1 Background component correction coefficient |
|-----------------------------------------------|
| Looking upon U | K | U | Th | Tc |
| 1.64 | 25.56 | 6.79 | 2.81 | 188.25 |

| Table 2 Compton scattering coefficient |
|----------------------------------------|
| Th stripping of U | Th stripping of K | U stripping of K | U stripping of Th |
| 0.2620 | 0.3808 | 0.8606 | 0.0745 |

| Table 3 Altitude attenuation coefficient |
|------------------------------------------|
| Tc | K | U | Th |
| 0.0057 | 0.0074 | 0.0061 | 0.0058 |

| Table 4 Airborne sensitivity at 120m |
|-------------------------------------|
| Tc | K | U | Th |
| 119.35 | 66.64 | 7.25 | 4.47 |

Spectrometric surveying is greatly affected by changes in flight altitude, the height attenuation coefficient is calculated by the formula (1). The data is normalized to a height of 120m by formula (2) according to Danjiangkou area flight altitude barometer records.

\[
R_{120}^{20} = R_h \cdot e^{\mu(H-120)} \quad (1)
\]

\[
\mu = \frac{\ln R_{120}^{20} - \ln R_h}{H-120} \quad (2)
\]

\( R_{120}^{20} \) is the count rate values corrected by Compton scattering at an altitude of 120 m, \( R_h \) is computational count rate corrected by Compton scattering at actual flight height h. H is the altitude at normal
atmospheric pressure and temperature. $\mu$ is height attenuation coefficient. The next step is to calculate actual content according to formula (3-5)

$$Q_K = \frac{1}{S_K} \cdot R_{KS} \cdot e^{\mu_K(H-120)}$$  \hspace{1cm} (3)

$$Q_U = \frac{1}{S_U} \cdot (R_{US} - R_{Bi}) \cdot e^{\mu_U(H-120)}$$  \hspace{1cm} (4)

$$Q_T = \frac{1}{S_T} \cdot R_{TS} \cdot e^{\mu_T(H-120)}$$  \hspace{1cm} (5)

$Q_K, Q_U, Q_T$ are the contents of K, U, Th respectively, $R_{Bi}$ is atmospheric radon correction. $S_K, S_U, S_T$ are air system sensitivity respectively. The relationship between the counting rate at a height of 120 meters and the known content on the ground [6].

According to environmental radiation measurement requirements, regional nuclear radiation background expressed as the AADR. The calculation method of AADR is based on Beck formula mentioned in the International Atomic Energy Agency (IAEA) technical report. Results of airborne gamma spectrum measurements are used to calculate the ground (1m height) AADR (formula 6) [7-8].

$$D_{\gamma} = K_K \times A_K + K_U \times A_U + K_{Th} \times A_{Th}$$  \hspace{1cm} (6)

$D_{\gamma}$ is natural gamma AADR, the unit is nGy·h$^{-1}$. $K_K, K_U, K_{Th}$ are the conversion coefficients of $^{40}$K, $^{238}$U, $^{232}$Th, conversion coefficients calculated according to the International Commission on Radiation Protection and Maintenance (ICRP) 1991, and which are shown in Table 5.

| Author   | K    | U    | Th   |
|----------|------|------|------|
| ICRU(1991) | 0.042 | 0.462 | 0.604 |

$A_K, A_U, A_{Th}$ are the specific activities of K, U, Th respectively, the unit is Bq·kg$^{-1}$. Conversion activity and content according to formula (7) in International Atomic Energy Agency (IAEA) Technical Report No. 309.

$$\begin{align*}
1\% K &= 313 \text{ Bq} \cdot \text{kg}^{-1} \\
1 \times 10^{-6} eU &\text{ (g/t)} = 12.35 \text{ Bq} \cdot \text{kg}^{-1} \\
1 \times 10^{-6} eTh &\text{ (g/t)} = 4.06 \text{ Bq} \cdot \text{kg}^{-1}
\end{align*}$$  \hspace{1cm} (7)

4. Results and discussion

4.1. The mapping results

The AADR of the Danjiangkou Reservoir and its surrounding areas can be obtained through the above series of calculations. To better reflect the distribution characteristics of anomalous areas, the results are shown in the form of contour maps (Fig. 1).
Figure 1. The contour map of AADR in Danjiangkou area

The results show that the AADR value range of this area is 0-577.03 nGy/h, which is mainly concentrated between 48-84 nGy/h (Fig. 2) and the average value of the whole area is 77.71 nGy/h. According to the National Air Absorbed Dose Rate Briefing Report issued by the Radiation Environment Monitoring Technology Center of the Ministry of Environmental Protection, the average radioactive AADR in Hubei Province in 2016 was 70.59 nGy/h, which indirectly proved the accuracy of our results.

The regional distribution of AADR values can also be observed from Figure 1. The low-radiation area, with the AADR is 0-60 nGy/h, mainly corresponds to the limestone strata in the middle of the study area and the Danjiangkou reservoir and water system. The east and south are medium radiation area with radiation levels of 60-120 nGy/h. Generally, the radiation level in the high anomaly area is more than three times higher than the average level [9]. With reference to the above principles and the relevant regulations of the State Environmental Protection Administration on radiation protection, we have determined that the delimitation standard for high anomaly areas is 211.8 nGy/h+1mSv. The high anomaly area is mainly distributed on the northeast side of the area that covered about a third of the entire study area. Refer to the above principles and relevant regulations of the National Environmental Protection Agency for radiation protection, the radiation value is concentrated between 120-240 nGy/h, and some areas have abnormally high values of about 500 nGy/h, which may pose a threat to public health.

Figure 2. Frequency diagram of AADR distribution in Danjiangkou area
4.2. Verification

Based on the AADR mapping results, 164 points were selected for field verification. The verification data is in good agreement with the measurement results, which shows the reliability of the mapping results. Due to space limitations, three typical anomalous area were introduced to explain the three main reasons for regional radiation anomalies.

The first anomaly area is located about 11km west of the reservoir. The value of AADR range from 133.3 to 170.5 nGy/h, and ground measurement results are between 96.5-371.41 nGy/h. The stratigraphic lithology is dominated by Sinian-Cambrian dolomite limestone with carbonaceous slate. The center of the anomalous point is an open-air vanadium mine, with a mining scale of approximately 300 × 300m. Radiation anomalies are caused by the mining of open-air vanadium ore, which exposes radioactive uranium to the air, resulting in a higher AADR. The U content of the carbonaceous slate is (49.50-164.00) × 10^{-6}, and the V content is (0.95-3.74) × 10^{-2}.

The second anomaly is located in Xianghua Town, Xichuan County, 2km west of Danjiangkou Reservoir, and next to a school. As shown in Figure 3, the location of the radiation anomaly has a discontinued steel plant. The average value of AADR in this area is about 111.7 nGy/h, the ground measured AADR close to the ore residue in the plant has reached 758.6 nGy/h, the Th is 268.3× 10^{-6}, and the U content is 15.26× 10^{-6}. It shows that the ore residue is the main source of radiation.

![Figure 3. The second anomalous area in Xianghua Town and field verification](image)

The third anomalous is located northeast of the survey area, 4km southwest of Shuanglong Town, Xixia County, Henan Province. Its natural radioactive AADR ranges from 155.8 to 297.6 nGy/h, and the ground measurement results are between 193.6-371.3 nGy/h. The reason causes the anomaly is that the Paleozoic Yanlinggou Formation feldspar granite was exposed near the area. This rock mass has a high Th content of 115 × 10^{-6}.

4.3. Source of the radiation anomaly

According to the International Atomic Energy Agency 566 technical report, the absorbed natural radioactive material is caused by the natural nuclide potassium, uranium, and potassium on the surface. Reasonably, the AADR is positively correlated with the equivalents of potassium, uranium, and thorium.

The low-radiation area, with AADR range of 0-60 nGy/h, is mainly distributed along the Danjiangkou Reservoir, the surrounding water system, and the Lower Paleozoic limestone distribution area, which corresponds well to the reservoir area and river boundary. In the east, south, and southwest of the survey area, there is a medium radiation field with a radiation level of 60-120 nGy/h. The area of Laohekou-Shigang Town in the east is a quaternary area, and the radioactive materials migrate along the water system to cause an increase in the surrounding radioactive level. The area from the west to the south of Anjiaxiang-Xianxian-Mazhaoling is mainly the meta-acid volcanic group of the Wudang Group, Caused by metamorphic tuff clastic rocks.
The east, west, and south of the study area are medium-radiation areas, and the AADR value is 60-120 nGy/h. The area of Laohekou-Shigang Town in the east is a quaternary area, and the radioactive materials migrate along the water system to cause an increase in the surrounding radiation. The area from the west to the south of Anjiaxiang-Xianxian-Mazhaoling is mainly the meta-acid volcanic rock group of the Wudang Group, caused by metamorphic tuff clastic rocks.

The north of the study area are high-radiation area, the AADR values are concentrated at 380-450 nGy/h. The high-radiation field in the northern Xixia-Qingshan Township is caused by large-scale exposed granite and small-scale gneiss. The high-radioactive boundary coincides well with the stratigraphic boundary of different ages.

5. Conclusions
The airborne gamma-ray spectrum measurement was carried out in the area around the Danjiangkou Reservoir, and a three-component method was used to draw a contour map of the AADR. These work comprehensively explained the background level of radiation in the reservoir area. The result shows that the AADR is distributed in the range of 0-577.03 nGy/h, with an average value of 77.71 nGy/h, and mainly concentrated between 48-84 nGy/h. Concerning national standards and specifications, the regional radiation background is divided into three levels, the characteristics of regional radiation distribution are analyzed, and field verification is performed to verify the reliability of the analysis results. By the analysis of three typical anomalous areas, the three main causes of regional radiation anomalies are explained.

Comprehensively consider the background radiation characteristics and environmental conditions of the study area, and propose the following protection recommendations:

1. For the radiation anomaly caused by illegal mining, illegal activities should be stopped immediately. The ore residues resulting from mining should be moved to a safe and suitable location for landfilling, and greening measures for mine repair should be started as soon as possible.
2. The radiation anomaly on the east side of the Danjiangkou is mainly due to the ore smelting process in Xianghua Town. Considering that it is close to the reservoir and there are residential areas and schools nearby, it is recommended to carry out large-scale radioactive ground measurement in the later stage to further delineate the contaminated area and volume of radioactive ore residue.
3. Local environmental protection departments strengthen supervision and management, implement targeted policies, and protect the water quality safety and ecological environment of Danjiangkou Reservoir.

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