H-O isotope characteristics and hydraulic connections of various waters in the Tai’an pumped storage power station reservoir, Shandong province, China

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Abstract. Reservoir leakage is typically a potential risk to reservoir operation in the world. However, due to the difference of climate, hydrology and geology conditions, the patterns and causes of water leakage in different reservoirs are quite different. This study took the Tai’an pumped storage power station reservoir in Shandong Province as an example to analyze the H-O isotope characteristics of various waters in detail. The results showed that the δ¹⁸O, δ¹⁷O and δ²H values in the reservoir water collected in July were significantly more positive than those in September and October, and other waters also had similar variations. The isotopic difference between September and October was not significant. Isotope analyses showed that water leakage varied with months: in October, well water and leakage water in the right bank gallery and bottom gallery drainage hole 005 did not come from the reservoir, while other waters were closely related to the leakage of reservoir water; in September, well water in the left bank did not originate from reservoir water leakage, while water in the measuring weir behind dam and the right bank gallery drainage hole were closely related to the reservoir water. In July, leakage water in the right bank gallery drainage hole and reservoir water had a close relationship. Our findings are expected to be helpful for guiding the treatment and control of reservoir water leakage.

1. Introduction
There are tens of thousands of reservoirs in China, which play an important role in flood control, power generation and water resources allocation and produce huge social, economic and environmental benefits. In general, there are different degrees of potential risks due to the limitations of construction technology and geological condition after a certain period of reservoir operation. Water leakage is a typical reservoir hazard. It can cause the water to leak, empty the reservoir, and even cause the dam to collapse, bringing the huge loss to the life and the property of people [1]. It was reported that the earth-rock dam accidents caused by water leakage accounted for more than 30% of all accidents in China[2]. In order to prevent the potential risk and avoid the reservoir collapse in time, it is important and urgent to detect water leakage of the reservoir[3].

In natural water, hydrogen has two stable isotopes: ²H and ¹H, and oxygen has three stable isotopes: ¹⁶O, ¹⁷O, and ¹⁸O. These isotopes can be combined in different ways to be different types of water molecules, such as H₂¹⁸O, HD¹⁸O and HD¹⁹O. High-mass water molecules, such as HD¹⁸O, concentrate preferentially in the liquid phase (aqueous phase), while low-mass water molecules, such as H₂¹⁶O, tend to remain in the vapor phase (vapor phase) [4]. Due to mass differences, isotopes
fractionation significantly between the liquid and gas phases. This fractionation is closely related to temperature, evaporation, topography, and distance from the ocean [5]. For example, the $\delta^2$H and $\delta^{18}$O values of meteoric water decrease with increasing latitude and altitude. At the same time, atmospheric precipitation has a significant seasonal effect. In winter or dry seasons, the values of $\delta^2$H and $\delta^{18}$O increase. In summer or rainy seasons, $\delta^2$H and $\delta^{18}$O values decrease. Precipitation is the initial recharge source of surface water (river, lake) and groundwater. In the process of recharging rivers, lakes or groundwater, due to the environmental impact of different regions, water from precipitation is subjected to different degrees of evaporation and mixing, resulting in different H-O isotope compositions of surface water and groundwater[4]. Therefore, this method has great potential in studying the process and mechanism of water cycle [6-9]. In recent years, H-O isotope tracing has become an important tool used for reservoir leakage detection because it can effectively determine water recharge sources and water discharge[10]. It has been widely used in detecting water leakage in many reservoirs such as Xin'anjiang Reservoir, Xiaolangdi Reservoir and Beijiangdi Dike.

The Tai'an pumped storage power station reservoir is an important power station reservoir for peak load regulation of Power Grid in Shandong Province. In recent years, there were several water leakage points for this reservoir, which have been concerned by the local administration section. This study intended to investigate the hydrogen and oxygen isotope compositions of different waters in the reservoir region, and to discuss the hydraulic connections among waters. Our aim was to provide a useful guide for the treatment and control of reservoir water leakage.

2. Study area
The Tai'an pumped storage power station is located at the southwest foot of the Taishan Mountain Scenic Area of Tai'an, Shandong Province, 5 km away from Tai'an Town and 70 km from Jinan Town (figure 1). The Tai'an pumped storage power station undertakes a peak-valley load capacity of $8 \times 10^6$ KW for the Shandong power grid system. This power station consists of the upper reservoir (figure 1b), lower reservoir, water conveyance system and underground power house.

The upper reservoir is surrounded by mountains on three sides (figure 1b), and the mountain spreads from northwest to southeast. On the other side is a concrete-faced rockfill dam with an elevation of 310-380 m. The mountain is large with a ridge elevation of 500-600 m to the left of this reservoir. The mountain to the right of this reservoir spreads from northwest to southeast with a ridge elevation of 400-500 m. The upper reservoir consists of the concrete-faced rockfill dam, inlet/outlet, reservoir basin and anti-seepage system. The upper reservoir basin area is 1.45 km². The total storage capacity of this reservoir is $1.1681 \times 10^7$ m³ and that of the power generation is $8.9511 \times 10^6$ m³.

There is a temperate monsoon climate with four distinct seasons in the Tai’an region. It is dry and windy in spring, and hot and rainy in summer. The sandy gravel soil and brown loamy soil develop on the mountain slopes to the two sides of the upper reservoir. There is a warm-temperate deciduous broad-leaved forest belt where oak, black pine, thorn are the main plant types. The multi-year average precipitation is 708 mm in the study area. Precipitation mainly concentrates in June to September. In summer, rainstorms often happen with the maximum value of 75 mm/day[14].

Archeozoic complexes and Quaternary deposits outcrop in the power station region. Main rocks include metasomatic granite, migmatitic granite, and plagioclase gneisses. Four regional faults $F_1$, $F_2$, $F_3$ and $F_4$ develop in the power station region, of which, $F_1$ is located in the reservoir bottom (figure 1c) [15].
Figure 1. Map showing the upper reservoir and sampling points.

3. Materials and methods
Field campaigns were separately carried out in July, September, and October, 2019 in the Tai’an pumped storage power station reservoir area. Various water samples were collected, including the leakage water from the right bank gallery, bottom gallery drainage hole, measuring weir behind dam and No. 6 construction hole, the well water from the well in the left bank and wells in the right bank, and reservoir water (Table 1 and Figure 1). Water samples were stored in 500ml PET bottles. Prior to sampling, the sample bottle was cleaned three times by deionized water, and then rinsed three times by water sample to avoid of contamination. At the same time, the sample bottles were fully filled with water samples, and sealed with American Parafilm films for preventing evaporation. For collecting reservoir water and well water samples, a homemade plexiglass sampler was used. The sampler was placed below 10cm of water surface when samples were taken.

After the samples were sent back to the laboratory, the H-O isotope compositions were measured for them using a laser isotope analyzer (LGR9120032) in Isotope Hydrology Laboratory, School of Earth Sciences and Engineering, Hohai University, Nanjing. Before measurement, water samples were filtered with a 0.45μm filter membrane.

The isotopic results are expressed delta (δ) notation as per mil (‰) differences relative to the VSMOW standard (Vienna Standard Mean Ocean Water). The analysis errors for δ¹⁸O and δ²H were 0.2‰ and 1.0‰, respectively. The measurement precision was ± 0.2‰ for δ¹⁸O and ± 1‰ for δ²H. The expressions for the isotope compositions are as follows,
\[
\delta^2H = \left[ \frac{(\delta^2H / \delta^1H)_{\text{sample}}}{(\delta^2H / \delta^1H)_{\text{VSMOW}}} - 1 \right] \times 1000 \\
\delta^{18}O = \left[ \frac{(\delta^{18}O / \delta^{16}O)_{\text{sample}}}{(\delta^{18}O / \delta^{16}O)_{\text{VSMOW}}} - 1 \right] \times 1000.
\]

4. Results and discussion

4.1. H-O isotope characteristics of various waters in October

As shown in Table 1, the \(\delta^{18}O\) and \(\delta^{17}O\) values of reservoir water varied from -5.37‰ to -6.48‰, and from -2.58‰ to -3.23‰ with the mean values of -5.94‰ and -2.89‰, respectively. The \(\delta^2H\) value varied from -45.4‰ to -46.6‰ with the average value of -46.04‰. The \(\delta^{18}O\) and \(\delta^{17}O\) values of leakage water in the right bank gallery varied from -4.86‰ to -4.87‰, and from -3.24‰ to -3.37‰, with the mean values of -4.86‰ and -3.31‰, respectively. The \(\delta^2H\) value varied from -46‰ to -46.6‰ with the average value of -46.32‰. The \(\delta^{18}O\) and \(\delta^{17}O\) values of well water varied from -7.58‰ to -8.97‰ and -4.12‰ to -4.80‰ with the mean values of -8.15‰ and -4.39‰, respectively. The \(\delta^2H\) value varied from -51‰ to -59.7‰, with an average value of -55.29‰. The \(\delta^{18}O\) and \(\delta^{17}O\) values of leakage water in the drainage hole of the bottom gallery, right bank tunnel and measuring weir behind dam ranged between -5.43‰ and 6.45‰, and between -2.76‰ and -3.59‰ with the mean values of -5.79‰ and -3.12‰, respectively. The \(\delta^2H\) value varied from -44.4‰ to -50.5‰ with the average value of -46.67‰.

Table 1. The sampling information and isotope compositions of various water samples from the reservoir area of the Tai'an pumped storage power station.

| No. | Sampling date (Y/M/D) | Sampling location | Sample type | \(\delta^{18}O\)±Std. | \(\delta^2H\)±Std. | \(\delta^{17}O\)±Std. |
|-----|----------------------|-------------------|-------------|-----------------------|-------------------|---------------------|
| 1   | 2019/10/10           | Right bank gallery drainage ditch | Leakage water | -4.86±0.12 | -46.6±0.2 | -3.37±0.06 |
| 2   | 2019/10/10           | Right bank gallery drainage hole | Leakage water | -4.87±0.08 | -46.0±0.3 | -3.24±0.06 |
| 3   | 2019/10/17           | The well in the left bank | Well water | -7.58±0.05 | -55.2±0.1 | -4.25±0.05 |
| 4   | 2019/10/13           | Taking samples 49 m deep from the well in the right bank | Well water | -8.97±0.09 | -59.7±0.3 | -4.80±0.11 |
| 5   | 2019/10/13           | Taking samples 23 m deep from the well in the right bank | Well water | -7.88±0.07 | -51.0±0.2 | -4.12±0.11 |
| 6   | 2019/10/14           | Bottom gallery drainage hole 003 | Leakage water | -5.56±0.06 | -44.9±0.5 | -3.07±0.08 |
| 7   | 2019/10/14           | Bottom gallery drainage hole 005 | Leakage water | -6.45±0.09 | -50.5±0.2 | -3.59±0.09 |
| 8   | 2019/10/16           | Right bank tunnel drainage hole | Leakage water | -5.43±0.06 | -44.4±0.3 | -2.76±0.07 |
| 9   | 2019/10/17           | Measuring weir behind dam | Leakage water | -5.73±0.03 | -46.8±0.3 | -3.07±0.05 |
| 10  | 2019/10/15           | 3 m away from No.13 panel | Reservoir water | -6.31±0.07 | -45.4±0.1 | -2.66±0.04 |
| 11  | 2019/10/15           | 2 m away from No.3 panel | Reservoir water | -5.87±0.10 | -46.6±0.4 | -2.87±0.12 |
| 12  | 2019/10/15           | 8 m away from No.4 panel | Reservoir water | -6.48±0.10 | -46.1±0.1 | -2.58±0.03 |
|   | Date       | Location                          | Type                        | Isotope Value |
|---|------------|-----------------------------------|-----------------------------|---------------|
| 13| 2019/10/15 | 10 m away from No.11 panel        | Reservoir water             | -5.37±0.08    |
| 14| 2019/10/15 | 20 m away from No.8 panel         | Reservoir water             | -5.78±0.11    |
| 15| 2019/10/15 | 20 m away from No.5 panel         | Reservoir water             | -5.61±0.05    |
| 16| 2019/10/15 | 20 m away from No.1 panel         | Reservoir water             | -5.98±0.13    |
| 17| 2019/10/15 | 8 m away from No.4 panel          | Reservoir water             | -5.81±0.11    |
| 18| 2019/10/15 | 4 m away from No.8 panel          | Reservoir water             | -6.21±0.11    |
| 19| 2019/9/5   | The well on the left bank         | Well water                  | -5.15±0.04    |
| 20| 2019/9/5   | Reservoir water                   | Well water                  | -5.70±0.07    |
| 21| 2019/9/5   | Measuring weir behind dam         | Leakage water               | -5.58±0.02    |
| 22| 2019/9/5   | Right bank gallery drainage hole  | Leakage water               | -5.64±0.06    |
| 23| 2019/7/8   | No. 6 construction hole mountain  | Leakage water               | -4.80±0.11    |
| 24| 2019/7/8   | Measuring weir behind dam         | Leakage water               | -4.61±0.08    |
| 25| 2019/7/8   | Reservoir water                   | Reservoir water             | -4.12±0.08    |
| 26| 2019/7/8   | Right bank gallery drainage hole  | Leakage water               | -4.35±0.06    |
| 27| 2019/7/8   | Right bank tunnel mountain seepage| Leakage water               | -4.76±0.14    |

In comparison, the isotope value of well water was significantly lower (figure 2). The oxygen isotope value of leakage water in the right bank gallery was significantly higher than that of reservoir water, while the oxygen isotope values of leakage water in the bottom gallery, right bank tunnel and measuring weir behind dam were not significantly different from that of reservoir water (figure 2a). However, there was little difference between the hydrogen isotope composition of leakage water in the right bank gallery and reservoir water. Nevertheless, there was a significant difference in the hydrogen isotope composition between bottom gallery drainage hole 005 (sample no. 7) and reservoir water (figure 2a).
Figure 2. Spatial distribution of $\delta^{18}$O, $\delta^{2}$H, $\delta^{17}$O and d-excess values for various waters in the Tai'an pumped storage power station in October.

As shown in Figure 2b, the d-excess value of leakage water in the right bank gallery varied from -7 to -8. The d-excess value of well water was above 5, mostly above 12. The d-excess value of leakage water between bottom gallery, right bank tunnel and measuring weir behind dam was between 1 and -1. The d-excess values of reservoir water samples varied greatly, with some above 5 and some below 0. The spatial distribution of the d-excess value corresponded well to those of $\delta^{18}$O, $\delta^{17}$O and $\delta^{2}$H (figure 2), that is, the low $\delta^{18}$O, $\delta^{17}$O and $\delta^{2}$H values corresponded to the high d-excess value, while the high $\delta^{18}$O, $\delta^{17}$O and $\delta^{2}$H values corresponded to the low d-excess value. Comparatively, the leakage water in right bank gallery and well water was quite different from reservoir water.

4.2. Isotopic comparison of water bodies between October and other months

As shown in Figure 3, $\delta^{18}$O, $\delta^{17}$O and $\delta^{2}$H values of various waters varied greatly with month. The $\delta^{18}$O, $\delta^{17}$O and $\delta^{2}$H values of various waters in July were more positive than those in September and October (figure 3a, b, c), which could be caused by higher temperature and stronger evaporation in July. The $\delta^{18}$O, $\delta^{17}$O and $\delta^{2}$H values of well water in the left bank changed significantly between September and October, while the $\delta^{18}$O, $\delta^{17}$O and $\delta^{2}$H values of reservoir water and leakage water in the right bank gallery drainage hole and measuring weir behind dam changed little between the two months (figure 3a, b, c). The d-excess values of various waters varied significantly between July, September and October (figure 3d). Specifically, the d-excess values of water samples from the left bank well and the reservoir were the highest in October and the lowest in July. The d-excess values of the water samples from the right bank gallery drainage hole were the lowest in October and the highest in September. The monthly variation of the isotopic compositions of various waters were tightly related to the local conditions of meteorology, hydrology and hydrogeology.
Figure 3. Comparison of the $\delta^{18}$O, $\delta^{17}$O and $\delta^{2}$H values of various waters in the Tai'an pumped storage power station in July, September and October.

4.3. Isotopic implication for hydraulic connections between different waters

As shown in Figure 4a, well water fell near the lower part of the global meteoric water line (GMWL) in October. This indicated that well water was recharged by precipitation and did not significantly suffer from evaporation. Other types of waters fell below the right of the GMWL in October, suffering varying degrees of evaporation. The right bank gallery leakage water did suffer from stronger evaporation because it’s isotope compositions fell on the evaporation line with a lower slope. The samples from the bottom gallery and measuring weir behind dam were in the range of the reservoir water. It is worth noting that the sample of bottom gallery drainage hole 005 was far away from the reservoir water area (Figure 4a). If the isotope compositions of well water was assumed as those of the initial source precipitation, this sample point was in the same evaporation line with the right bank gallery leakage water, showing the close relationship between both of them (Figure 4a). The $d$-excess value was proposed by Dansgaard (1953) [17], which was defined as $d=\delta^2H-8\times\delta^{18}O$. This parameter mainly reflected the evaporation of the water source area, which was significantly affected by precipitation, temperature, humidity and other parameters[18]. As shown in Figure 4b, the $d$-excess value of the reservoir water in October fell in the range of well water and the right bank gallery leakage water. The leakage water samples of the bottom gallery, the right bank tunnel and the measuring weir behind dam fell within the range of the reservoir water (figure 4b). The $d$-excess values of these samples varied in accordance with the values of $\delta^{18}$O and $\delta^2$H. Based on the above analyses, in October, well water was directly recharged by precipitation rather than lateral seepage of reservoir water whereas leakage water from the right bank gallery leakage water and bottom gallery drainage hole 005 (sample No.7) could be closely linked with well water. The leakage water did seem to have no hydraulic connection with reservoir water while the other waters were tightly associated with the reservoir water, in other words, they was recharged by the seepage of reservoir water.
Figure 4. Relationships between δ¹⁸O, δ²H and d-excess of various water bodies in the Tai’an pumped storage power station. GMWL - Global meteoric water line [16].

The samples collected in July and September fell on the same evaporation line (Figure 4c), indicating that the water bodies were recharged by the same sources and suffered from the same degree of evaporation during the two months. The samples collected in July experienced a longer evaporation period. As shown in Figure 4c, in July, the reservoir water was close in isotopic compositions to leakage water of the right bank gallery drainage hole, but obviously different from leakage water samples collected from other locations. However, as shown in Figure 4d, the reservoir water is different to certain extent from leakage water from the right bank gallery drainage hole, and obviously different from other water samples in July. This suggested that the leakage water did not completely source from the reservoir water. During this period, the mountain seepage water in the construction branch hole no. 6 and right bank gallery drainage hole were close in δ¹⁸O, δ²H and d-excess (Figure 4c and d), indicating that the seepage waters in the two locations had the same sources but had no relation with reservoir water. In September, except well water in the left bank, the reservoir water, leakage water in the right bank gallery drainage hole and the measuring weir behind dam had similar isotope compositions (Figure 4c and d). This result implied that leakage water in the right bank gallery drainage hole and the measuring weir behind dam came from the reservoir water in September.

In brief, the recharge source of leakage water varied with month to some degree, probably related to the meteorological and hydrological conditions, water volume and hydrogeology of the reservoir area.

5. Conclusions
In this paper, the H-O isotope compositions of various water bodies (reservoir water, leakage water and well water) in the reservoir area of the Tai’an pumped storage power station was investigated in detail, and the hydraulic connections among various water bodies were explored in depth. The main findings were as follows:
(1) The δ¹⁸O, δ¹⁷O and δ²H values of various water bodies in the reservoir area varied from -4.12‰ to -8.97‰, -37‰ to -59.7‰, and -2.17‰ to -4.8‰, respectively. The isotopic compositions were different among various water bodies.

(2) The stable isotope compositions of waters varied greatly with month. On the whole, the isotope values of waters were obviously more positive in July than in September and October. Except well water in the left bank, δ¹⁸O, δ¹⁷O and δ²H in other water bodies were not significantly different between September and October. The d-excess values of water bodies also varied with month.

(3) In October, well water, leakage water in the right bank gallery and bottom gallery drainage hole 005 was not recharged by reservoir water, while other leakage waters were closely related to the reservoir water. In September, well water in the left bank did not come from reservoir water, while the leakage water in the measuring weir behind dam and right bank gallery drainage hole was closely related to reservoir water. In July, leakage water in the right bank gallery drainage hole was closely associated with reservoir water. The seepage pathway of reservoir water changed to some extent with month.

Our findings give insights into the water cycle in the reservoir area of the power station and are also helpful for guiding the treatment and control of the reservoir leakage. Further work will be carried out to investigate isotope compositions of well water and reservoir water at different depths, in order to more accurately determine the reservoir leakage area.

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