Hydrogeochemical characterization of Tai'an Pumped Storage Power Station reservoir and the implications for Reservoir Water Leakage

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Abstract. Reservoir leakage is typically a potential risk to reservoir operation in the world. In this study, Tai'an pumped storage power station reservoir was selected as an example to analyze the chemical characteristics of various waters in detail. The results showed that silicate rock weathering was the main source of water chemical ions of reservoir water, groundwater and Bashangoue water. Hydrogeochemical analysis showed that the water samples of the right bank gallery and measuring weir behind dam came from the reservoir water leakage, measuring weir of bottom gallery, B2 branch pipe gallery and No.6 construction hole water samples did not originate from reservoir water but from groundwater. The research results are of great guiding significance for guiding the diagnosis and control of reservoir leakage.

1. Introduction

Water leakage is a typical reservoir hazard of the world. It can affect the normal play of the reservoir benefits, and the long-term seepage can take away the fine particles in the cushion material, resulting in increased panel deformation, and then aggravating the leakage, which is extremely unfavorable to the dam safety[1]. Therefore, the research of reservoir leakage is of great practical significance to ensuring the safety of reservoir dam.

In recent years, hydrogeochemical analysis has become one of the important technical means for reservoir leakage detection[2-3]. Song et al. discussed the evolution process of the dam-based groundwater quality in Chencun Hydropower Station, and proposed that there was a very complex hydrogeochemical action of water-rock-dam in the seepage field of the dam site under water storage conditions[4]. Dong et al. used the water chemistry tracing method to analyze the reservoir water leakage situation of the Xiaolangdi left abutment, and found out that the reservoir water seepaged to the back of dam through the crushing zone of the deep fault[5]. Reddy et al. carried out hydrogeochemical monitoring of underground water and surface water and reservoir water from 15 deep wells in Koyana-Warner for 7 years, research showed that there had direct hydraulic connectivity between groundwater and reservoir water[6]. This paper selects Tai'an pumped storage power station in Shandong Province as a case study, to systematically analyze the hydrochemistry characteristics of various water bodies. The results provide theoretical basis for the safe operation of the pumped storage.
power station.

2. Research Area and Project Overview
The Tai'an pumped storage power station is located at the southwest foot of the Taishan Mountain Scenic Area of Tai'an, Shandong Province (figure 1a). The Tai'an pumped storage power station undertakes a peak-valley load capacity of $8 \times 10^5$ 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, 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 main strata exposed in the engineering area of the power station are Taikoo boundary Mount Tai Group and Quaternary, and the bedrock lithology mainly includes metasomatic granite, porphyry mixed rock, mixed granite, black cloud oblique long gneiss mixed with oblique diorite, interspersed with invading diorite vein, diroxenite vein, quartz vein and pegmite vein.

![Figure 1. Sampling Location of the Tai'an Pumped Storage Power Station](image)

3. Materials and methods
There are 8 sampling points (figure 1b) and pH and conductivity were measured on site. Various water samples were collected from 2009 to 2020 year, including surface water of the upper reservoir, lower reservoir, measuring weir behind dam and Bashangou water, with 58 groups of water samples, groundwater samples of the right bank drainage gallery, measuring weir of bottom gallery, B2 branch pipe gallery and No.6 construction hole, with 55 groups of groundwater samples. Testing items for water samples include Ca$^{2+}$, Mg$^{2+}$, K$^+$, Na$^+$, Cl$^-$, SO$_4^{2-}$, HCO$_3^-$. Determination of Ca$^{2+}$ and Mg$^{2+}$ by EDTA titration, K$^+$ and Na$^+$ by calculation method, Cl$^-$ and SO$_4^{2-}$ uses the method of determination of inorganic anions in water (ion chromatography), HCO$_3^-$ by acid indicator titration method, TDS(total dissolved solids) by weight. Test data are shown in table 1.

4. Results and discussion

4.1 Hydrological and geochemical characteristics
As shown in table 1, the pH value range of groundwater is from 7.00 to 8.63, average value is 7.74, surface water pH value range is from 6.80 to 8.64, average value is 7.63, all weak alkaline, the TDS value range of groundwater and surface water is from 138.00 to 422.00mg/L and from 131.00 to 438.00mg/L, average 320.65mg/L and 310.86mg/L, respectively. According on the average
concentration of conventional ions (Table 1), groundwater ions concentration from large to small arrangement is HCO_3^-, SO_4^{2-}, Ca^{2+}, (K^++Na^-), Cl^-, Mg^{2+}; Ca^{2+} is the dominant cation, its content is about 58.17% of total cation, HCO_3^- is the dominant anion, its content accounts for 50.57% of total anion concentration, surface water ions concentration arrangement is HCO_3^-, SO_4^{2-}, Ca^{2+}, Cl^-, (K^++Na^-), Mg^{2+}, Cl^- concentration greater than (K^++Na^-).

Table 1. Statistical Analysis of Water Chemical Parameters (Unit mg/L)

| Water sample type               | pH  | HCO_3^- | SO_4^{2-} | Cl^- | Ca^{2+} | Mg^{2+} | K^++Na^- | TDS       |
|---------------------------------|-----|---------|-----------|------|---------|---------|----------|-----------|
| Cherry ditch Water 1996.9       | 6.97| 61.88   | 53.48     | 8.61 | 23.13   | 3.56    | 19.21    | 169.86    |
| Lower Reservoir Water 1996.9    | 7.62| 100.75  | 53.68     | 16.11| 33.40   | 9.58    | 20.56    | 237.83    |
| Right Bank Fissure Water 1996.9| 6.92| 214.43  | 24.75     | 5.18 | 47.87   | 9.35    | 23.93    | 324.99    |
| Groundwater (n=55)              |     |         |           |      |         |         |          |           |
| Min                             | 7.00| 80.50   | 59.60     | 7.28 | 19.68   | 4.30    | 2.83     | 138.00    |
| Max                             | 8.63| 235.00  | 142.00    | 35.30| 73.40   | 24.00   | 56.70    | 422.00    |
| Mean                            | 7.74| 127.41  | 95.32     | 25.14| 50.42   | 11.43   | 27.02    | 320.65    |
| Surface Water (n=58)            |     |         |           |      |         |         |          |           |
| Min                             | 6.80| 13.70   | 23.10     | 7.80 | 21.60   | 3.40    | 0.03     | 131.00    |
| Max                             | 8.64| 235.00  | 152.00    | 35.10| 73.60   | 27.50   | 48.50    | 438.00    |
| Mean                            | 7.63| 114.48  | 96.65     | 23.51| 50.80   | 12.59   | 22.27    | 310.86    |

Figure 2. Piper Drawing(a) and Durov Drawing(b) of water samples in study area

The Piper graph and Durov graph can intuitively reveal the characteristics of the water chemical composition[7]. As shown in figure 2 (a) and (b): at 25% of the primary ion mg equivalent/liter percent as the boundary, cherry ditch water and lower reservoir water are HCO_3^-SO_4^-Ca type, right bank fissure water chemistry type HCO_3^-SO_4^-Ca-Na in 1996 year. Surface water and groundwater samples are mostly HCO_3^-Ca type, partially HCO_3^-SO_4^-Ca, HCO_3^-SO_4^-Ca-Mg, SO_4^-Ca-Mg in 2009-2020 year, Bashangou water is SO_4^-Ca, SO_4^-Ca-Mg type.

4.2. Lithological control of groundwater chemistry

The relationship between the combination ratio Cl^-/(Cl^-+HCO_3^-) and the TDS in water can qualitatively reflect the geochemical evolution of natural water during the process of rock weathering, evaporation and crystallization[8]. The Draw Gibbs diagram was showed in figure 3, Cl^-/(Cl^-+HCO_3^-) ratio (0.10-0.35) and TDS value (131.00 mg/L-438.00 mg/L) of reservoir water and groundwater, Cl^-/(Cl^-+HCO_3^-) ratio less than 0.5. According to Gibbs' s discussion of the control factors in the water chemical evolution, rock weathering is the main source of water chemical composition of the reservoir water and groundwater[9]. The Cl^-/(Cl^-+HCO_3^-) ratio of Banshangou water varies with TDS value,
indicating that Bashangou water chemistry was double controlled by rock weathering and precipitation.

As shown in (Ca$^{2+}$+Mg$^{2+}$) vs (HCO$_3^-$+SO$_4^{2-}$) figure (figure 4a), the reservoir water and groundwater samples fall between lines 1:1 and 1:2, and most samples (Ca$^{2+}$+Mg$^{2+}$) to (HCO$_3^-$+SO$_4^{2-}$)>0.5, (HCO$_3^-$+SO$_4^{2-}$) concentration is greater than (Ca$^{2+}$+Mg$^{2+}$) concentration, indicating that the hydrolysis reaction of silicate rocks occurred[10,11]. Except for a set of water samples, Bashangou water samples basically fall near Line 1:1, and have a low TDS value (changes range between 165.00mg/L to 276.00mg/L), indicating that Bashangou water is controlled by rock weathering, but also controlled by atmospheric precipitation, with atmospheric precipitation mixed without adequate water rock. Figure 4 (b) draws the concentration change relationship between (Na$^+$+K$^+$) and TZ$^+$/((Ca$^{2+}$+Mg$^{2+}$), the (Na$^+$+K$^+$) represents the weathering of silicates in the study area, and the coordinate TZ$^+$/((Ca$^{2+}$+Mg$^{2+}$) reflects the relative composition of cations in the water body. Reservoir water, groundwater and Bashangou water samples showed a significant positive correlation, indicating that silicate rock weathering is the main source of reservoir water, groundwater and Bashangou water chemical ions[12]. Ca$^{2+}$, Mg$^{2+}$, (Na$^+$+K$^+$), and HCO$_3^-$ ions are mainly derived from the dissolution reactions of oblique feldspar and alkaline feldspar[13], this corresponds with the lithological characteristics of the study area. Compared with the water fitting line slope of reservoir water and groundwater in the power station reservoir area, Bashangou water fitting line slope is low, which indicates that the weathering degree of the Bashangou is weaker than that in the upper reservoir area, and the revealed content complies with the geographical location of the Bashangou.

4.3 Implications for Reservoir Water Leakage

From the main molar ratio figures 4 (a) and (b), the right bank gallery, measuring weir behind dam water samples and upper reservoir samples mostly overlap in the reservoir water area, it indicates that right bank gallery and measuring weir behind dam water are leakage of reservoir water, rather than groundwater; measuring weir of bottom gallery, B2 branch pipe gallery and No.6 construction hole are significantly different from the reservoir water and are groundwater source. The comparison of isotope data analyzed by Zhang et al.[14] shows that the comparison between water chemistry and hydrogen-oxygen isotope results have good consistency: δ$^{18}$O and δ$^2$H value of the right bank gallery and measuring weir behind dam water samples have similar characteristics to δ$^{18}$O and δ$^2$H value of the upper reservoir samples, and its deuterium surplus value also falls within the range of the upper reservoir water samples, indicating that right bank gallery and measuring weir behind dam water

![Gibbs diagram of Tai'an Pumped Storage Power water samples.](image)
samples come from the reservoir water leakage. Water samples of No.6 construction hole and measuring weir of bottom gallery are significantly different from reservoir water samples both in δ18O, δ2H and deuterium surplus, show that they are not recharged from reservoir water leakage but groundwater.

Figure 4. Moor ratio of (Ca²⁺+Mg²⁺)-(HCO₃⁻+SO₄²⁻) and (Na⁺+K⁺)-TZ⁺/(Ca²⁺+Mg²⁺) of water samples in the Tai'an Pumped Storage Power Station

5. Conclusion
Rock weathering is the main factor in controlling various water bodies in the Tai'an Pumped storage power station. Silicate weathering is the main ions source of reservoir water, groundwater and Bashangou water. Bashangou water is controlled by rock weathering and precipitation, and the weathering degree of Bashangou is weaker than the upper reservoir area. Water chemical analysis showed that the samples of right bank gallery and measuring weir behind dam came from reservoir water leakage, measuring weir of bottom gallery, B2 branch pipe gallery and No.6 construction hole was underground water. The water chemical results compare well with the results of hydrogen and oxygen isotopes. Our research suggests that hydrogeochemical is effective technical means for reservoir leakage detection.

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References
[1] Wei, M., Xu,Y., Chen, X.R. (2020) Multi-source Information Fusion Diagnosis Technology and its Safety Assessment Method. Water Resources and Hydropower Engineering, 51: 106-112. (In Chinese)
[2] Huo, J.X., Song, H.Z., Peng, P., Cao, G.Z. (2011) Hydrochemistry Diagram and Its Application in Evaluation of Dam Foundation. Journal of Hydroelectric Engineering, 30: 73-79. (In Chinese)
[3] Wang, T., Chen, J.S., Li, P., Yin, Y.J. (2019) Natural tracing for concentrated leakage detection in a rockfill dam. Engineering Geology, 249:1-12.
[4] Song, H.Z. (1994) Research on groundwater Chemical Characteristics of Chencun Hydropower Station. Site Investigation Science and Technology, 5:23-27. (In Chinese)
[5] Dong, H.Z., Chen, J.S. (2004) Natural Trer Method of Left Dam Shoulin Xiaolangdi Reservoir. Renmin Yellow River, 26 (004): 43-45. (In Chinese)
[6] Reddy, D.V., Nagabhushanam, P. (2016) Search for hydraulic connectivity between surface reservoirs and surrounding aquifers in the reservoir-triggered seismic environment (Koyna
region, India) using hydrochemical and isotopic signatures. Journal of Seismology, 20:43-62.

[7] Wang, N.F., Qi, J.H., Jia, S.Y. (2007) Water chemistry Characteristics of Dam Area of Dagang Mountain Hydropower Station and its Application in groundwater Research. Design of Hydropower Station, 23: 74-79. (In Chinese)

[8] Xanke, J., Goeppert, N., Sawarieh, A. (2015) Impact of managed aquifer recharge on the chemical and isotopic composition of a karst aquifer, Wala reservoir, Jordan. Hydrogeology Journal, 2015, 23(5):1027-1040.

[9] Gibbs, R.J. (1970) Mechanisms Controlling World Water Chemistry. Science, 170(3962): 1088-1090.

[10] Wang Y., Guo Q., Su C. (2006) Strontium isotope characterization and major ion geochemistry of karst water flow Shentou, northern China. J. Hydrol, 328 (3–4): 592–603.

[11] Wang, Y.N., Rao, W.B., Zheng, F.W. (2020) Chemical characteristics and runoff effect of Ganjiang River. People's Yangtze River, 4:27-34. (In Chinese)

[12] Onwuka, O. S., Omonona, O. V. (2017) Hydrogeochemical characteristics of coastal aquifers from Port Harcourt, southern Nigeria. Environmental Earth Sciences, 76( 17): 176-184.

[13] Shen, Z.L. (1993) Hydrological Geochemistry. Geological Press. (In Chinese)

[14] Zhang, L., Zheng, X.H., Li, G.K. (2020) H-O isotopes composition characteristics and hydraulic connection of various water bodies of Pumped Storage Power Station Reservoir. Nuclear Technology, 6:1-8. (In Chinese)