Research Article

Xiao Yu, Yunhui Zhang*, Pei Liu, Haoqing Huang, and Xun Huang

Hydrochemical characteristics and D–O–Sr isotopes of groundwater and surface water in the northern Longzi county of southern Tibet (southwestern China)

<https://doi.org/10.1515/geo-2020-0334>

received September 29, 2021; accepted December 14, 2021

Abstract: The protection of water resource has been the significant mission globally. Hydrochemical compositions and recharge source are the critical tools to analyze the water quality. In this study, 18 surface water and 5 groundwater samples were collected along the Xiongqu and Sequ rivers in the northern Longzi county of southern Tibet. The combination of factor analysis, correlation of major ions, geochemical modeling, and D–O–Sr isotopes were employed to clarify the hydrochemical compositions and recharge source. The concentration of major ions followed the abundance order of $\text{SO}_4^{2-} > \text{HCO}_3^- > \text{Cl}^-$ for anions and $\text{Ca}^{2+} > \text{Mg}^{2+} > \text{Na}^+ > \text{K}^+$ for cations. Ca-HCO_3 and Ca-SO_4 types were identified for groundwater and surface water. Based on ratios of major ions and geochemical modeling, it is proposed that the dissolutions of gypsum, calcite, and dolomite controlled the hydrochemical compositions. D–O isotopes indicated a meteoric origin for surface water and groundwater, with the recharge elevation of 2,519–3,731 m. The $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of groundwater and surface water were compatible with those of sulfate and carbonate minerals, revealing the main type of minerals interacting with water. The achievements of this study can provide a vital reference for groundwater utilization and protection in the Longzi county and adjacent areas in the Tibet.

Keywords: water resource, hydrochemistry, water–rock interaction, recharge source, Longzi county

1 Introduction

Water resource is the important and indispensable natural resource for human survival [1]. With the growing population and increasing economic development, securing the quality of water resource has been the major issue to be addressed around the world [2–4]. The quality of water resource is evaluated by hydrochemical compositions, especially soluble species. It has been believed that hydrochemical compositions are influenced by natural processes and anthropogenic activities [5–8]. Natural processes are dependent on the recharge water and interaction with environment (rocks or soils). Meanwhile, the origin of water is critical to be traced for estimating the reserve volume of water resource. Therefore, understanding the knowledge of water–rock interaction and recharge origin is of significant for the utilization and protection of water resources [9].

The water–rock interaction is literally hard to be ascertained due to complex hydrogeological conditions. Up to date, various approaches have been carried out to clarify the water–rock interaction. Multivariate statistical analysis, including correlation analysis and factor analysis (FA), was used to investigate the possible source of different hydrochemical compositions [10]. Compared with traditional correlation analysis, FA can accurately trace the source of different hydrochemical compositions by dimensionality reduction. Correlation of major ions has been widely discussed to interpret the factors governing the hydrochemical compositions. Gibbs [11] and Gaillardet et al. [12] built the diagrams to prove the main hydrochemical process. Then, the relationship between major cations and anions can be used to analyze the type of mineral dissolution and ion exchange in hydrochemical

* **Corresponding author: Yunhui Zhang**, Faculty of Geosciences and Environmental Engineering, Southwest Jiaotong University, Chengdu 611756, China, e-mail: zhangyunhui0710@163.com, zhangyunhui@swjtu.edu.cn

Xiao Yu: Key Laboratory of Geological Survey and Evaluation of Ministry of Education, China University of Geosciences, Wuhan 430074, China; Research Center of Applied Geology of China Geological Survey, Chengdu 610036, China

Pei Liu, Haoqing Huang: Research Center of Applied Geology of China Geological Survey, Chengdu 610036, China

Xun Huang: Faculty of Geosciences and Environmental Engineering, Southwest Jiaotong University, Chengdu 611756, China

evolution [13]. Moreover, the specific mineral dissolution can be further recognized by saturation indices computed by Phreeqc software [14–16]. D–O isotopes have been believed to be an efficient tool to trace the recharge source of water resource [17–19], while Sr isotope is able to identify the rock type of aquifers [20–22].

Water resources, including groundwater and surface water, are abundant in the Longzi county, which are exploited for domestic and agricultural purposes. However, due to the remote location and high elevation, scarce research was carried out on the water resource. Once water resource is seriously polluted, it is very difficult to proceed with the environmental remediation in such a remote and highland area. Therefore, the hydrochemical composition and recharge sources are yet to be investigated for evaluating the water quality, which is critical to secure water environment in advance.

The main purpose of this study is to assess the water quality based on the hydrochemistry and isotopes of groundwater and surface water in the northern Longzi county of southern Tibet. The water–rock interaction is clarified using FA, correlation of major ions, geochemical modeling, and Sr isotope. Meanwhile, the recharge of groundwater and surface water would be a constraint by D–O isotopes. The knowledge of this study would provide a vital reference for better utilization and protection of water resource in the Longzi county and adjacent areas in the Tibet.

2 Study area

The study area is located in the Longzi county, southern Tibet within the area of N28°07′–28°52′ and E91°53′–93°06′. The climate belongs to plateau temperate continental

monsoon climate with annual average temperate of 5.5°C and annual precipitation of 297.4 mm. The elevation has a large variation of 3,000–6,000 m in the study area, characterized as mountain and valley landform. The Yarlung Zangbo river traverses in the northern study area as regional river. Xiongqu, Sequ, and Jiaqu rivers are situated in the southern study area and utilized as domestic and agricultural purposes (Figure 1). Tectonically, the study area is situated in the Himalayan region [23–25]. Volcanic and igneous rocks are exposed in the regional area. The strata are composed of sandstone and slate in the study area. The structures are dominated by EW- trending and NE-trending faults with minor NW-trending faults [26]. Groundwater resources are abundant and possess $0.5 \times 10^8 \text{ m}^3$ in total. They are reserved as bedrock fissure water and sediment pore water. However, the springs are not commonly exposed in the surface. In statistics, the flow of springs ranges from 0.5 to 3 L/s. The depth of groundwater is generally 0.3–10 m.

3 Groundwater sampling and analytical techniques

Groundwater and surface water were sampled in the July and August of 2020. Total of 18 surface water and 5 groundwater samples were collected along the Xiongqu and Sequ rivers. Surface water samples were collected from the Xiongqu and Sequ rivers and their secondary streams. Groundwater was sampled from all five wells in the study area. The depth of wells ranges from 5–20 m. Each well was pumped out at least half an hour to eliminate stagnant water in the tube. Every bottle was rinsed at least three times by water to be sampled and then sealed with wax. The samples for cation analysis were acidified to $\text{pH} < 2$ by 6 mol re-distilled HNO_3 . The parameters of pH,

Figure 1: Location of study area and groundwater sampling sites.

total dissolved solid (TDS), and temperature were measured in the field. The experiment for hydrochemistry and isotopes were conducted in the laboratory of the Kehui testing Ltd, Beijing. Inductively coupled plasma optical emission spectrometry (ICP-OES) was used for analyzing cation concentration (K^+ , Na^+ , Ca^{2+} , and Mg^{2+}), and ion chromatography (ICS-2100) was employed for measuring anion concentration (Cl^- , SO_4^{2-} , NO_3^- and F^-). HCO_3^- concentration was tested by acid–base Gran titration. D and ^{18}O isotopes were analyzed by LGR liquid water isotope analyzer, and $^{87}Sr/^{86}Sr$ ratio was measured by thermal ionization mass spectrometry (Triton Plus).

4 Results and discussion

4.1 General hydrogeochemical characteristics

The Schöeller diagram was employed to illustrate the variations in the physicochemical parameters of the groundwater and surface water samples. Groundwater samples possessed pH values of 7.9–9.2 (mean = 8.8) and TDS concentrations of 152–960 mg/L (mean = 358 mg/L). Surface water samples had pH values of 8.1–8.7 (mean = 8.4) and TDS concentrations of 102–413 mg/L (mean = 253 mg/L). Both groundwater and surface water samples displayed weak alkaline affinity in nature and large variation in TDS concentration. The concentration of major ions followed the abundance order of $SO_4^{2-} > HCO_3^- > Cl^-$ for anions and $Ca^{2+} > Mg^{2+} > Na^+ > K^+$ for cations (Figure 2). The pH value and SO_4^{2-} concentration failed to reach the permissible limit of drinking water (Table 1). NO_3^- and F^- of water samples had a range of 0.00–0.77 and 0.03–0.25 mg/L, respectively, markedly lower than the permissible limit of drinking water [28].

Figure 2: Schöeller diagram for groundwater and surface water samples (unit: meq/L).

The cations (Na^+ , K^+ , Ca^{2+} and Mg^{2+}) and anions (Cl^- , SO_4^{2-} and HCO_3^-) were combined in the Piper diagram to identify the hydrochemical type of groundwater and surface water samples. In this study, two hydrochemical types were recognized in the Piper diagram (Figure 3). Groundwater samples showed the hydrochemical type of $Ca-HCO_3$. Surface water samples are plotted in the transited area between $Ca-HCO_3$ type and $Ca-SO_4$ type (Figure 3). The different hydrochemical types would be attributed to their hydrochemical evolution.

4.2 FA

FA has been vastly used in the hydrochemical analysis. It can identify the source of hydrochemical compositions by dimensionality reduction [29–31]. In this study, 11 parameters including pH, TDS, and major ions were involved in FA. Three factors with eigenvalue larger than 1 were extracted, accounting for the 76.633% of the total variance (Table 2). Factor 1 accounted for 43.577% of total variance and has a strong loading of TDS, Ca^{2+} , Mg^{2+} , and SO_4^{2-} . The dissolution of sulfide minerals is the main process dominating the hydrochemical compositions. Factor 2 was responsible for 22.410% of the total variance and displayed medium positive loading of pH, K^+ , Cl^- , NO_3^- and F^- . Considering the absence of Cl and F bearing minerals, the Factor 2 would be affected by anthropogenic activities. Factor 3 contributed only 10.646% of the variances, and it only included a single major species, HCO_3^- . HCO_3^- concentration was probably influenced by the dissolution and precipitation of carbonate minerals (dolomite and calcite).

Table 1: Statistical analysis of hydrochemical parameters of water samples (units of all parameters are mg/L, except pH)

Parameters	Max	Min	Mean	WHO standard [28]	% of SEL
pH	9.20	7.90	8.69	6.5–8.5	25.7
TDS	960.00	102.00	335.17	1,000	0.0
K^+	1.51	0.15	0.58	—	—
Na^+	16.90	0.15	7.19	200	0.0
Ca^{2+}	177.00	24.10	71.46	200	0.0
Mg^{2+}	68.90	5.39	25.28	150	0.0
Cl^-	4.97	0.00	1.12	250	0.0
SO_4^{2-}	679.00	30.30	188.26	250	21.7
HCO_3^-	236.00	67.50	121.04	—	—
NO_3^-	0.77	0.00	0.23	45	0.0
F^-	0.25	0.03	0.11	1.5	0.0

Note: % of SEL, % of samples exceeding acceptable limit.

Figure 3: Piper trilinear diagram for groundwater and surface water samples [27].

Table 2: Factor loadings and eigenvalues of the 11 extracted factors

Scaled coordinates	Factor 1	Factor 2	Factor 3
pH	0.278	0.677	-0.413
TDS	0.977	-0.16	-0.083
K ⁺	0.479	0.719	-0.221
Na ⁺	0.617	0.402	0.401
Ca ²⁺	0.976	-0.089	-0.06
Mg ²⁺	0.923	-0.276	0.021
Cl ⁻	-0.116	0.715	-0.452
SO ₄ ²⁻	0.922	-0.227	-0.184
HCO ₃ ⁻	0.607	0.283	0.502
NO ₃ ⁻	0.018	0.565	0.444
F ⁻	-0.339	0.506	0.302
Eigenvalues	4.794	2.465	1.171
Variance (%)	43.577	22.410	10.646
Cumulative (%)	43.577	65.987	76.633

4.3 Correlations of major ions

Gibbs diagram has been used to identify the main process (rock weathering, atmospheric precipitation, and evaporation) determining hydrogeochemical compositions [11]. In this study, the concentration ratios of $\text{Na}^+ / (\text{Na}^+ + \text{Ca}^{2+})$ and $\text{Cl}^- / (\text{Cl}^- + \text{HCO}_3^-)$ ranged from 0.08 to 0.39 and from

0.03 to 0.42, respectively. The plots collectively show the source of rock dominance (Figure 4a and b). Of note, the $\text{Na}^+ / (\text{Na}^+ + \text{Ca}^{2+})$ cation weight ratios had a relatively wide variation, supporting the existence of cation exchange in the hydrochemical evolution. Gaillardet et al. [12] proposed a plotting diagram to further constrain the type of aquifer rocks based on the concentrations of Ca^{2+} , Mg^{2+} , HCO_3^- , and Na^+ . The weight ratios of Ca^{2+} , Mg^{2+} , and HCO_3^- , against Na^+ were 5.11–314.33, 1.71–162.28, and 3.46–169.67, respectively. The plots of groundwater and surface water samples were situated in the transited zone between silicate rocks and carbonate rocks (Figure 4c and d). Therefore, carbonate and silicate minerals were the main minerals interacting with groundwater and surface water.

The relationship among major ions can reveal the possible type of minerals involved in the water–rock interaction. The weight ratio of Ca^{2+} and HCO_3^- were used to clarify the dissolution of carbonate minerals. The $\text{Ca}^{2+} / \text{HCO}_3^-$ ratios of 1:1 and 1:2 demonstrated the dissolution of calcite and dolomite, respectively [32]. In this study, the groundwater samples presented the distinguished $\text{Ca}^{2+} / \text{HCO}_3^-$ ratios compared with surface water samples. Groundwater samples followed the $y = x$ equiline, whereas surface water samples had excess

Figure 4: (a) TDS vs $\text{Na}^+ / (\text{Na}^+ + \text{Ca}^{2+})$, (b) TDS vs $\text{Cl}^- / (\text{Cl}^- + \text{HCO}_3^-)$, (c) $(\text{Mg}^{2+} / \text{Na}^+)$ vs $(\text{Ca}^{2+} / \text{Na}^+)$, and (d) $(\text{HCO}_3^- / \text{Na}^+)$ vs $(\text{Ca}^{2+} / \text{Na}^+)$.

concentration and deviated rightward from the $y = x$ equiline (Figure 5a). Hence, the hydrochemical compositions of groundwater samples were determined by calcite dissolution, while the surface water samples would be influenced by the dissolution of gypsum or anorthite. The concentration ratio would be equal to 1, when the hydrochemical compositions are controlled by gypsum dissolution [33]. Groundwater and surface water samples nearly followed the $y = x$ equiline, indicating the dominance of gypsum dissolution (Figure 5b). It is noteworthy that some surface water samples displayed the higher SO_4^{2-} concentration. The extra SO_4^{2-} concentration was possibly derived from the oxidation of metal sulfide. The weight ratio between Na^+ and Cl^- would be 1 when the hydrochemical compositions are mainly affected by halite dissolution. In this study, most of groundwater and surface water samples were distributed below the $y = x$ equiline and showed a rightward deviation. The excess Na^+ concentration would be originated by silicate minerals

and cation exchange (Figure 5c). One surface sample possessed higher Cl^- concentration than Na^+ concentration. Previous studies demonstrated that halite is absent in the strata of southern Tibet [26]. Meanwhile, agricultural activity is common in the study area of field investigation. Hence, the elevated Cl^- concentration is more likely to be polluted by agricultural activity. The weight ratio between Ca^{2+} and SO_4^{2-} would be 1 when the hydrochemical compositions are mainly affected by gypsum dissolution. The bivariate diagram of $(\text{Ca}^{2+} + \text{Mg}^{2+})$ and $(\text{HCO}_3^- + \text{SO}_4^{2-})$ can reflect the main hydrochemical process [34]. In Figure 5d, groundwater and surface water samples plotted along the $y = x$ equiline, indicate that the hydrochemical compositions were controlled by calcite and gypsum dissolution.

Figure 5: Correlation diagrams of (a) HCO_3^- vs Ca^{2+} , (b) SO_4^{2-} vs Ca^{2+} , (c) Cl^- vs Na^+ , and (d) $\text{HCO}_3^- + \text{SO}_4^{2-}$ vs $\text{Ca}^{2+} + \text{Mg}^{2+}$.

Figure 6: Saturation indices of calcite, dolomite, gypsum, and halite for groundwater and surface water samples.

4.4 Saturation indices

The saturation indices (SI) are efficient to recognize the equilibrium status of specific minerals in the hydrochemical evolution (Parkhurst and Appelo, 2013). The SI values of four main minerals (calcite, dolomite, gypsum, and halite) were computed using Phreeqc 3.0. Calcite, dolomite, and gypsum showed the oversaturated status with positive SI values, while halite displayed the unsaturated status with negative SI values (Figure 6). Combined with the FA and correlations of major ions, it is proposed that the hydrochemical compositions were primarily controlled by the dissolution of calcite, dolomite, and gypsum and anthropogenic activities.

4.5 Stable isotopes of D, ^{18}O , and $^{87}\text{Sr}/^{86}\text{Sr}$

The δD (‰ Vienna standard mean ocean water (VSMOW)) and $\delta^{18}\text{O}$ (‰ VSMOW) of surface water samples ranged from -96.45 to -133.38 ‰ (mean = 120.69 ‰) and from -14.00 to -17.76 ‰ (mean = 16.47 ‰), respectively. The δD (‰ VSMOW) and $\delta^{18}\text{O}$ (‰ VSMOW) of groundwater samples ranged from -115.92 to -135.22 ‰ (mean = 124.88 ‰) and from -15.66 to -17.06 ‰ (mean = 16.24 ‰), respectively. It is noted that surface water samples showed relatively richer δD and $\delta^{18}\text{O}$ values. Both groundwater and surface water

Figure 7: Plot diagram of δD (‰ VSMOW) and $\delta^{18}\text{O}$ (‰ VSMOW). The solid line is the GMWL (Craig, 1963), while the dashed line is the LMWL (Tan et al., [36]).

Figure 8: Plot diagram of Sr concentrations and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios.

samples were closer to the Global Meteoric Water Line (GMWL) (solid line: $\delta\text{D} = 8 \times \delta^{18}\text{O} + 10$ ‰) [35] and Local Meteoric Water Line (LMWL) (dash line: $\delta\text{D} = 8.2 \times \delta^{18}\text{O} + 14.4$ ‰) [36] (Figure 7). Hence, both groundwater and surface water are recharged by precipitation. As $\delta^{18}\text{O}$ value changes with elevation in a special geographic demarcation, $\delta^{18}\text{O}$ value was employed to calculate the recharge elevation. Herein the function ($-\delta^{18}\text{O} = 0.0031 \times H + 6.19$) was derived from reference [37]. The calculated results of recharge area ranged from 2,519 to 3,731 m.

The Sr concentrations and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of groundwater were 0.13–1.26 (mean = 0.46 mg/L) and 0.710513–0.713763 (0.711918), respectively. The Sr concentrations and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of surface water were 0.13–1.26 (mean = 0.46 mg/L) and 0.710513–0.713763 (0.711918), respectively. The groundwater and surface water displayed similar characteristics of Sr concentrations and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios, indicating the active interaction between groundwater and surface water (Figure 8). The $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of groundwater and surface water were compatible with those of sulfate and carbonate minerals, revealing the main type of minerals interacting with water.

5 Conclusion

In this study, 18 surface water and 5 groundwater samples were collected along the Xiongnu and Sequ rivers in the northern Longzi county, for FA, correlation of major ions, geochemical modeling, and D–O–Sr isotopes.

- (1) The main anion and cation of groundwater and surface water samples were SO_4^{2-} and Ca^{2+} , respectively. The hydrochemical type was Ca– SO_4 and Ca– HCO_3 . pH value and SO_4^{2-} concentrations exceeded the permissible limit set by WHO for drinking purpose.

- (2) The dissolutions of gypsum, calcite, and dolomite were responsible for hydrochemical compositions based on ratios of FA, major ions, and saturation indices.
- (3) D–O isotopes indicated a meteoric origin for surface water and groundwater. The recharge elevation had a range of 2,519–3,731 m. The $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of groundwater and surface water revealed the dissolution of sulfate and carbonate accounted for hydrochemical compositions in the study area.

Acknowledgements: We thank the editors and reviewers for their helpful comments for improving this contribution. This study was financially supported by the National Natural Science Foundation of China (42072313, 42102334) and Fundamental Research Funds for the Central Universities (2682020CX10 and 2682021ZTPY063).

Conflict of interest: The authors declare that they have no conflicts of interest.

Author contributions: Yu Xiao: investigation, data curation, writing – original draft. Yunhui Zhang: writing – review & editing. Pei Liu: data curation, methodology. Haoqing Huang: conceptualization. Xun Huang: software.

Data availability statement: The data used to support the findings of the present study are available from the corresponding author upon request.

References

- [1] Paul PK, Zhang Y, Mishra A, Panigrahy N, Singh R. Comparative study of two state-of-the-art semi-distributed hydrological models. *Water*. 2019;11(5):871.
- [2] Rashid A, Farooqi A, Gao X, Zahir S, Noor S, Khattak JA. Geochemical modeling, source apportionment, health risk exposure and control of higher fluoride in groundwater of sub-district Dargai, Pakistan. *Chemosphere*. 2020;243:125409.
- [3] Gao X, Li X, Wang W, Li C. Human activity and hydrogeochemical processes relating to groundwater quality degradation in the Yuncheng Basin, Northern China. *Int J Environ Res Public Health*. 2020;17(3):867.
- [4] Li C, Gao X, Liu Y, Wang Y. Impact of anthropogenic activities on the enrichment of fluoride and salinity in groundwater in the Yuncheng Basin constrained by Cl/Br ratio, $\delta^{18}\text{O}$, $\delta^2\text{H}$, $\delta^{13}\text{C}$ and $\delta^7\text{Li}$ isotopes. *J Hydrol*. 2019;579:124211.
- [5] Zhang Y, Li X, Luo M, Wei C, Huang X, Xiao Y, et al. Hydrochemistry and entropy-based groundwater quality assessment in the suining Area, Southwestern China. *J Chem*. 2021;2021:5591892–11.
- [6] Zhang Y, He Z, Tian H, Huang X, Zhang Z, Liu Y, et al. Hydrochemistry appraisal, quality assessment and health risk evaluation of shallow groundwater in the Mianyang area of Sichuan Basin, southwestern China. *Environ Earth Sci*. 2021;80(17):576.
- [7] Zhang Y, Dai Y, Wang Y, Huang X, Xiao Y, Pei Q. Hydrochemistry, quality and potential health risk appraisal of nitrate enriched groundwater in the Nanchong area, southwestern China. *Sci Total Environ*. 2021;784:147186.
- [8] Liu H, Guo H, Pourret O, Wang Z, Sun Z, Zhang W, et al. Distribution of rare earth elements in sediments of the North China Plain: a probe of sedimentation process. *Appl Geochem*. 2021;134:105089.
- [9] Liu H, Guo H, Pourret O, Wang Z, Liu M, Zhang W, et al. Geochemical signatures of rare earth elements and yttrium exploited by acid solution mining around an ion-adsorption type deposit: role of source control and potential for recovery. *Sci Total Environ*. 2022;804:150241.
- [10] Zhang Y, Xu M, Li X, Qi J, Zhang Q, Guo J, et al. Hydrochemical characteristics and multivariate statistical analysis of natural water system: a case study in Kangding County, Southwestern China. *Water*. 2018;10(1):80–96.
- [11] Gibbs RJ. Mechanisms controlling world water chemistry. *Science*. 1970;170(3962):1088–90.
- [12] Gaillardet J, Dupré B, Louvat P, Allègre CJ. Global silicate weathering and CO_2 consumption rates deduced from the chemistry of large rivers. *Chem Geol*. 1999;159(1):3–30.
- [13] Li X, Huang X, Zhang Y. Spatio-temporal analysis of groundwater chemistry, quality and potential human health risks in the Pinggu basin of North China Plain: evidence from high-resolution monitoring dataset of 2015–2017. *Sci Total Environ*. 2021;800:149568.
- [14] Xiao Y, Liu K, Hao Q, Li J, Zhang Y, Cui W, et al. Hydrogeochemical features and genesis of confined groundwater and health perspectives for sustainable development in Urban Hengshui, North China Plain. *J Chem*. 2021;2021:5578192–15.
- [15] Luo Y, Xiao Y, Hao Q, Zhang Y, Zhao Z, Wang S, et al. Groundwater geochemical signatures and implication for sustainable development in a typical endorheic watershed on Tibetan plateau. *Environ Sci Pollut Res*. 2021;28:48312–29.
- [16] Adimalla N. Application of the entropy weighted water quality index (EWQI) and the pollution index of groundwater (PIG) to assess groundwater quality for drinking purposes: a case study in a rural area of Telangana State, India. *Arch Environ Contam Toxicol*. 2021;80:31–40.
- [17] Li X, Huang X, Liao X, Zhang Y. Hydrogeochemical characteristics and conceptual model of the geothermal waters in the Xianshuihe Fault Zone, Southwestern China. *Int J Environ Res Public Health*. 2020;17(2):500–14.
- [18] Jiang W, Wang G, Sheng Y, Shi Z, Zhang H. Isotopes in groundwater (^2H , ^{18}O , ^{14}C) revealed the climate and groundwater recharge in the Northern China. *Sci Total Environ*. 2019;666:298–307.
- [19] Yang N, Zhou P, Wang G, Zhang B, Shi Z, Liao F, et al. Hydrochemical and isotopic interpretation of interactions between surface water and groundwater in Delingha, Northwest China. *J Hydrol*. 2021;598:126243.
- [20] Mao C, Tan H, Song Y, Rao W. Evolution of groundwater chemistry in coastal aquifers of the Jiangsu, east China:

- insights from a multi-isotope ($\delta^2\text{H}$, $\delta^{18}\text{O}$, $^{87}\text{Sr}/^{86}\text{Sr}$, and $\delta^{11}\text{B}$) approach. *J Contam Hydrol.* 2020;235:103730.
- [21] Stewart-Maddox NS, Frisbee MD, Andronicos CL, Genereux DP, Meyers ZP. Identifying the regional extent and geochemical evolution of interbasin groundwater flow using geochemical inverse modeling and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in a complex conglomeratic aquifer. *Chem Geol.* 2018;500:20–9.
- [22] Qu S, Wang G, Shi Z, Xu Q, Guo Y, Ma L, et al. Using stable isotopes (δD , $\delta^{18}\text{O}$, $\delta^{34}\text{S}$ and $^{87}\text{Sr}/^{86}\text{Sr}$) to identify sources of water in abandoned mines in the Fengfeng coal mining district, northern China. *Hydrogeol J.* 2018;26:1443–53.
- [23] Zhang Y-H, Wang Y-S, Wang W-S, Liu J, Yuan L-L. Zircon U-Pb-Hf isotopes and mineral chemistry of Early Cretaceous granodiorite in the Lunggar iron deposit in central Lhasa, Tibet Y, China. *J Cent South Univ.* 2019;12:3457–69.
- [24] Zhang Y-H, Cao H-W, Hollis SP, Tang L, Xu M, Jiang J-S, et al. Geochronology, geochemistry and Sr-Nd-Pb-Hf isotopes of the Early Paleogene gabbro and granite from Central Lhasa, southern Tibet: petrogenesis and tectonic implications. *Int Geol Rev.* 2019;61:1–27.
- [25] Cao H-W, Zhang Y-H, Santosh M, Zhang S-T, Tang L, Pei Q-M, et al. Mineralogy, zircon U-Pb-Hf isotopes, and whole-rock geochemistry of Late Cretaceous-Eocene granites from the Tengchong terrane, western Yunnan, China: record of the closure of the Neo-Tethyan Ocean. *Geol J.* 2018;53(4):1423–41.
- [26] Cao H-W, Li G-M, Zhang R-Q, Zhang Y-H, Zhang L-K, Dai Z-W, et al. Genesis of the Cuonadong tin polymetallic deposit in the Tethyan Himalaya: evidence from geology, geochronology, fluid inclusions and multiple isotopes. *Gondwana Res.* 2021;92:72–101.
- [27] Piper AM. A graphic procedure in the geochemical interpretation of water-analyses. *Eos, Trans Am Geophys Union.* 1944;25(6):914–28.
- [28] WHO. Guidelines for drinking-water Quality. 4th edn. World Health Organization; 2011.
- [29] Zhou Y, Li P, Xue L, Dong Z, Li D. Solute geochemistry and groundwater quality for drinking and irrigation purposes: a case study in Xinle City, North China. *Geochemistry.* 2020;80:125609.
- [30] He S, Li P, Wu J, Elumalai V, Adimalla N. Groundwater quality under land use/land cover changes: a temporal study from 2005 to 2015 in Xi'an, Northwest China. *Hum Ecol Risk Assess: An Int J.* 2020;26(10):2771–97.
- [31] Adimalla N, Qian H, Li P. Entropy water quality index and probabilistic health risk assessment from geochemistry of groundwaters in hard rock terrain of Nanganur County, South India. *Geochemistry.* 2020;80(4, Supplement):125544.
- [32] Xiao Y, Hao QC, Zhang YH, Zhu YC, Yin SY, Qin LM, et al. Investigating sources, driving forces and potential health risks of nitrate and fluoride in groundwater of a typical alluvial fan plain. *Sci Total Environ.* 2022;802:149909.
- [33] Luo YF, Xiao Y, Hao QC, Zhang YH, Zhao Z, Wang SB, et al. Groundwater geochemical signatures and implication for sustainable development in a typical endorheic watershed on Tibetan plateau. *Environ Sci Pollut Res.* 2021;28:48312–29.
- [34] Chang XW, Xu M, Jiang LW, Li X, Zhang YH. Hydrogeochemical characteristics and formation of low-temperature geothermal waters in Mangbang-Longling area of Western Yunnan, China. *J Chemsitry.* 2021;2021:1–13.
- [35] Craig H. The isotopic geochemistry of water and carbon in geothermal areas. In: Tongiorgi E, editor. *Nuclear geology on geothermal areas.* Spoleto, Italy: Consiglio Nazionale Delle Ricerche (CNR), Laboratorio Di Geologia Nucleare; 1963. p. 17–54.
- [36] Tan H, Zhang Y, Zhang W, Kong N, Zhang Q, Huang J. Understanding the circulation of geothermal waters in the Tibetan Plateau using oxygen and hydrogen stable isotopes. *Appl Geochem.* 2014;51:23–32.
- [37] Yu JS, Zhang HB, Yu FJ, Liu DP. Oxygen and hydrogen isotopic composition of meteoric waters in the eastern part of Xizang. *Geochemistry.* 1984;3:93–101.