

Isotopic signatures of precipitation, surface water, and groundwater interactions, Poyang Lake Basin, China

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Abstract Poyang Lake, whose hydrological characteristics are impacted by the operation of the Three Gorges Dam, is the largest freshwater lake in China. However, water cycle mechanisms in the Poyang Lake Basin remain poorly understood. In this study, stable isotopes (δD and $\delta^{18}\text{O}$) of water samples (taken in April, July, and November 2013) and hydrological data are used to investigate the interactions between precipitation, river water, lake water, and shallow groundwater in the Poyang Lake region. The isotopic results show seasonal variations in precipitation, surface water, and groundwater, which provides a set of tools to identify waters that have different histories. The similar isotopic compositions of river water and groundwater suggest a close hydrological connection. Hydrological data present a positive correlation between river run-off and precipitation; however, isotopic results show that rivers in the Poyang Lake Basin in different seasons are primarily recharged by subsurface run-off with different proportion between base flow and near-surface quick flow, rather than by surface run-off directly formed by concurrent rainfall. Due to the geological characteristics of stratum in the Poyang Lake Basin, it is easier for precipitation to infiltrate into soil and recharge groundwater than to form direct surface flow that feeds rivers. The groundwater system is like a huge reservoir which can effectively

impound rainfall water, playing an important role in restraining floodwater during the flood season and in ensuring river run-off supply during the dry season.

Keywords Poyang Lake · Deuterium and oxygen-18 · Precipitation · Surface water · Groundwater · Interaction

Introduction

Poyang Lake, the largest freshwater lake in China, is a key tributary of the Yangtze River. In high water-level period, the lake area can reach 4125 km², which is about 13 % of the size of Lake Baikal (31,722 km²). The world's largest dam, the Three Gorges Dam, was built on the Yangtze River in 2003, and its construction and operation has greatly changed the hydrological characteristics of the Yangtze River, and in turn, the Poyang Lake (Zhang et al. 2012a). The impoundment of the dam, beginning around September, significantly reduces run-off in the Yangtze River, resulting in higher lake discharge than lake inflow, thus advancing the lake's dry period and threatening the regional ecological environment (Lai et al. 2014a). In addition, human's reclamation changes parts of the lake into farmland or fishpond, further reducing the water area of Poyang Lake (Zhang et al. 2014). Together with sediment accumulation and soil erosion, the lake's ecological functions are facing great challenges. As a result of these factors, the Poyang Lake Basin now suffers serious hydrological issues, including wetland degradation, water eutrophication, floods, and droughts, all of which cause irretrievable damage to the entire Yangtze River Basin (Huang et al. 2012; Zhang et al. 2012b; Nakayama and Shankman 2013; Ye et al. 2013). In recent years, a controversial proposal to build a floodgate at the mouth of the

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lake has been proposed, with an aim to control the water volume of the lake and solve the problems currently experienced (Jiao 2009). However, due to the new hydrological regime, the current water cycle mechanisms of the Poyang Lake Basin are poorly understood.

Deuterium ($\delta^2\text{H}$ or δD) and oxygen-18 ($\delta^{18}\text{O}$) isotopes are widely used in studies on water cycle processes (e.g. Jeelani et al. 2010; Turner et al. 2010; Yin et al. 2011; Chen et al. 2012; Qian et al. 2014). Large differences are observed in the isotopic compositions of waters that originate from different climate zones, latitudes, and elevations, and among those that have undergone different physical and chemical processes. Therefore, it is possible to use δD and $\delta^{18}\text{O}$ to identify the origins of different hydrological cycle components and to understand their past interactions (Yang et al. 2012; Chiogna et al. 2014). Zhan et al. (2015) investigated the isotopic compositions of hydrological components in the Dongting Lake Basin during different dispatching periods of the Three Gorges Dam, and determined the seasonal relationships between the lake and rivers as well as the influence of the dam's operation on the lake. Bocanegra et al. (2013) used stable isotopes to study the interaction between lake and groundwater in the Pampa Plain of Argentina, and applied these data to provide a quantification of the water balance. Chen et al. (2014) used stable isotopes to disprove the conventional viewpoint that groundwater in Zhangye Basin, China, was recharged by local precipitation and infiltration of Heihe River water. These recent studies illustrate the ability of hydrogen and oxygen isotopes to contribute to groundwater–surface water interaction knowledge.

Most studies of Poyang Lake have focused on water change, sediment distribution, pollution status, and wetland ecosystems (Deng et al. 2014; Gao et al. 2014; Lai et al. 2014b; Han et al. 2015). Some studies have also investigated water cycle processes using traditional hydrological methods (Li et al. 2013b; Sun et al. 2014; Xu et al. 2014a). These studies mainly focus on the numerical simulation based on hydraulic parameters. Due to the difficulties in using traditional hydrological methods to identify different water sources, several questions remain, for example the nature of the transformation mechanisms that convert precipitation to surface water.

In the Poyang Lake Basin, atmospheric precipitation is the ultimate recharge source of lake water. However, the transformation from rainfall to lake water is complex. δD and $\delta^{18}\text{O}$ isotopes are useful tracers for studying water circulation in big drainage basins, such as the Poyang Lake Basin. The use of stable isotopes can yield much information that may not be available via traditional hydrological methods. A previous study (Hu et al. 2013a) analysed the characteristics of the $\delta^{18}\text{O}$ isotope in this

basin and presented a preliminary discussion of the relationship between surface water and shallow groundwater, confirming that surface water in this basin is not only recharged by current precipitation, but also to a great extent by shallow groundwater. However, a detailed investigation of stable isotopes in this area has not been carried out, and the exact water movement mechanism is still poorly understood. This study further investigates the δD and $\delta^{18}\text{O}$ isotopes of the Poyang Lake Basin in different seasons. Using stable isotopes in precipitation as natural tracers, interactions between precipitation, surface water, and shallow groundwater in this area are discussed, and a possible conceptual model of the water movement mechanism is proposed.

Study area

Poyang Lake, located in northern Jiangxi Province of China ($115^{\circ}47'–116^{\circ}45'\text{E}$, $28^{\circ}22'–29^{\circ}45'\text{N}$), has a catchment area of $1.62 \times 10^5 \text{ km}^2$ (Fig. 1). The Poyang Lake drainage basin accounts for $\sim 9\%$ of the Yangtze River Basin area. The main lake area, which is divided into two parts by Songmen Island, is long and narrow in the northern part, but wide in the south. The southern end of the lake has been widely reclaimed into farmlands or fishponds, resulting in its relatively narrow and closed water area. The lake is primarily recharged from five rivers: the Rao, Xin, Fu, Gan, and Xiu Rivers. The Gan River is the largest river in the basin, with a length of 766 km and a mean annual discharge of $2130 \text{ m}^3/\text{s}$. The Gan, Xin, and Fu Rivers account for $>80\%$ of the total inflow into the lake. The lake has a maximum depth of 29.2 m and a mean depth of 5.1 m. The south part of the lake is shallower than the north part. The lake is a key tributary of the Yangtze River, and flow is the major feature in the lake, especially in the north of the lake. Under normal conditions, the water level in the south is higher than in the north (Feng et al. 2011). Lake water flows from the south and discharges into the Yangtze River through the lake mouth, located at the northern end of the lake. Lake water flows slowly in the south of the lake where the water surface is expansive. In the northern part, the flow velocity is relatively high because of the narrow water channel.

This region has clearly defined rainy and dry seasons, and both the water volume and spatial extent of the lake vary seasonally. During the rainy season, the submerged area of the lake can exceed 4000 km^2 , whereas during the dry season it can fall to $<500 \text{ km}^2$. Lake water level is highest in July and August, and lowest around December. Since the Yangtze River is the only outflow pathway, lake water volume is greatly influenced by the water level of the

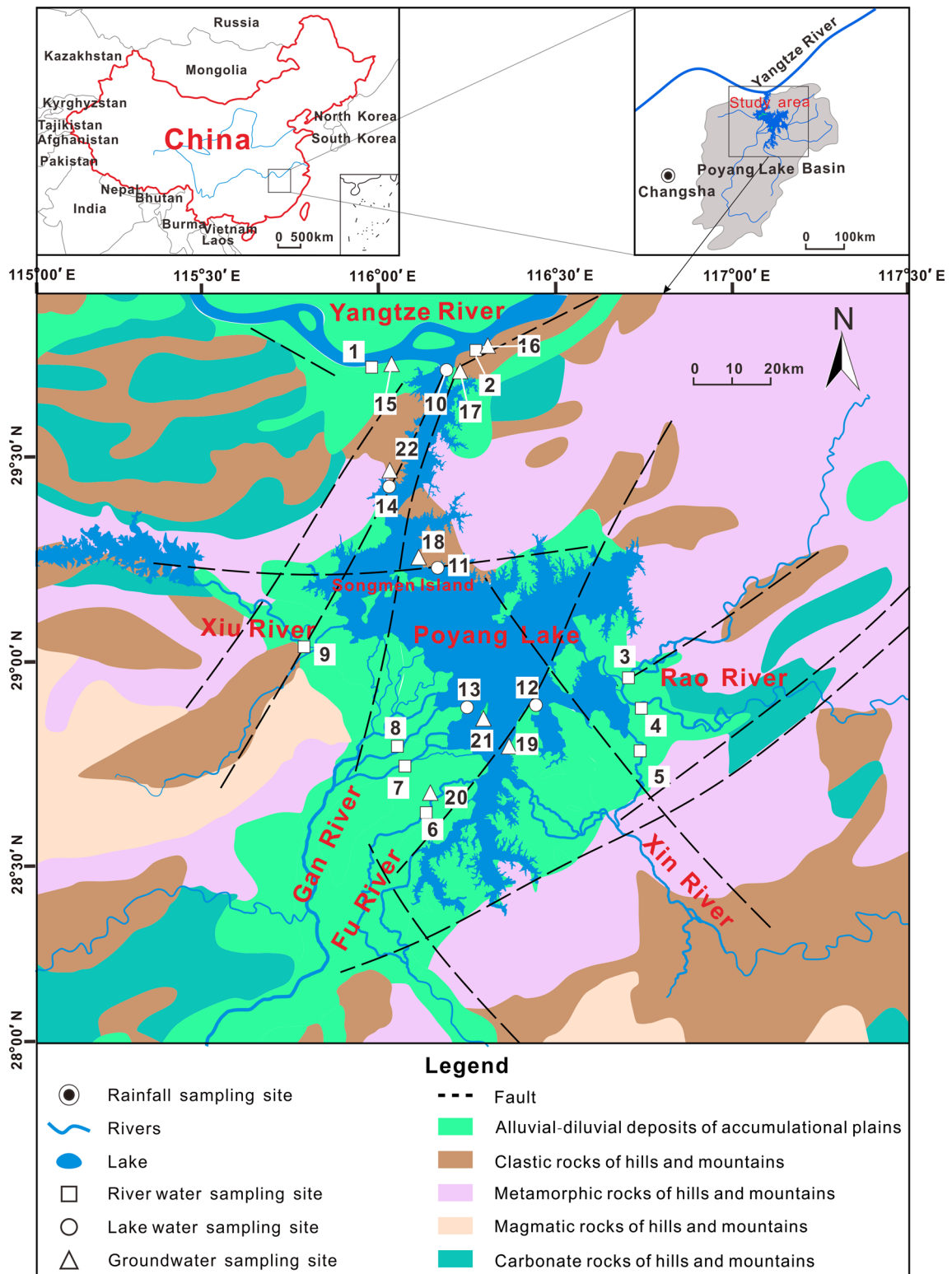


Fig. 1 Simplified geological map of the study area and sampling sites of river water, lake water, and shallow groundwater [geological information is sourced from the 1:6,000,000 scale China hydrogeological map by Zhang (2000) and a survey report by Zhang (1986)]

Yangtze River, increasing when it is high and decreasing when it is low. The rainy season of the Poyang Lake Basin is 1–2 months ahead of the rainy period of the upstream

Yangtze River. When the Yangtze River is in rainy season, its increased discharge raises the river water level at the lake mouth (Hukou) and constrains the drainage of lake

water to the Yangtze River. However, when the Yangtze River has a low water level in dry season, the level difference between the river and the lake mouth promotes the drainage of the lake (Zhang et al. 2012a).

The Poyang Lake Basin has a subtropical monsoon climate, with precipitation mainly controlled by the East Asian monsoon. Precipitation associated with the East Asian monsoon is produced by the interaction along the monsoon front of northward-moving moist summer monsoon air and a northern mass of cooler air (An et al. 2000). Annual precipitation is more than 1500 mm and is distributed unevenly across the year (Ye et al. 2013). Precipitation is usually highest in June and decreases sharply from July to September, with more than half of the annual precipitation concentrated in spring and early summer between March and June. The mean annual temperature is ~ 17.5 °C, and is highest in July or August and lowest in January or February. The mean annual relative humidity is ~ 80 %. Relative humidity usually varies between 70 and 90 %, high in spring and summer, and low in autumn and winter (Seto et al. 2008). The lake supports an extensive wetland area, which is the largest conservation area and habitat for migratory birds in the world.

Small mountains surround the Poyang Lake Basin, with elevations decreasing from south to north. The central region of the basin is characterised by valleys and hills, while the north is an alluvial plain related to the Rao, Xin, Fu, Gan, and Xiu Rivers (Fig. 1). The alluvial plain is mainly covered by Quaternary unconsolidated sediments (clay, sand, and gravel) with a thickness of 20–50 m. The Gan River has a major anabranch plain forming the southwestern margin of the lake, which potentially is underlain by a large groundwater system. The major basement complex in the basin consists of metamorphic, clastic, carbonate, and magmatic rocks, and crop out in upstream river catchments. The metamorphic rocks, composed of Cambrian slate, phyllite, and metasandstone, have developed joints and fractures in the weathered layer that has a thickness reaching 35 m. The main clastic rocks are sandstone, conglomerate, and shale from the Palaeozoic and Early Mesozoic period. The carbonate rocks are mainly composed of dolomite and limestone in Palaeozoic and Mesozoic age, with obvious karst development. The magmatic rocks are mainly dominated by granite, with a weathered layer thickness exceeding 20 m (Zhang 1986). The Poyang Lake region has a fault basin structure controlled by 13 geological faults (Fig. 1). The Poyang Lake Basin is extremely abundant in groundwater resources (Fig. 2). Aquifers in this basin can be divided into four types: porous aquifer related to regolith systems, fissured aquifer in bedrocks, karst aquifer in carbonate rocks, and clastic rock pore-fissure aquifer (Hu et al. 2013b). The flow

direction of groundwater is consistent with the decreasing direction of elevation, from the hill and mountain area to the alluvial plain (Fig. 2) (Li et al. 2013a).

Materials and methods

River water, lake water, and shallow groundwater samples were collected in April, July, and November 2013. Samples were taken from 22 fixed sampling sites (Fig. 1), including 9 river water sites (1–9), 5 lake water sites (10–14), and 8 shallow groundwater sites (15–22). Yangtze River water was collected both before and after it is fed by the lake water (sample sites 1 and 2, respectively). Samples 3–9 were taken near the estuaries of the Rao, Xin, Fu, Gan, and Xiu Rivers, respectively. Lake water samples represent most areas of the lake, although residential and industrial areas were avoided. Shallow groundwater samples were taken from drinking wells of local residents living within 1 km of the rivers or the lake. It was learned from the well owners that these wells were 8–15 m in depth and disclosed the sand–gravel layer. Samples from these wells were collected from the well bottom using pumps installed in the wells. However, unforeseen situations meant that some groundwater samples could not be collected for each sampling campaign. For example, sampling site 21 is located on an island that can only be accessed during the dry season. When sampling, the 380-ml plastic sample bottle was first washed three times using sample water. The bottle was then filled with sample water, quickly capped, and tightly sealed with tape to avoid exchange with the atmosphere. A total of 62 samples were collected, including 27 river water samples, 15 lake water samples, and 20 shallow groundwater samples.

The geographical location of every sample was recorded in site using the global positioning system (GPS). Samples were refrigerated and sent to the State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering (Hohai University) for the determination of isotopic concentrations. A MAT253 mass spectrometer was used to measure δD and $\delta^{18}O$ contents of water samples, which are presented as δD and $\delta^{18}O$, following the convention of the international standard of Vienna Standard Mean Ocean Water (VSMOW). Analytical precision was ± 2 ‰ for δD , and ± 0.1 ‰ for $\delta^{18}O$.

We collected available isotopic data for precipitation from the literature published by Huang (2013), who took 336 rainfall samples from January 2010 to December 2012 in Changsha, situated only about 250 km west from the centre of the Poyang Lake Basin (Fig. 1). The average monthly data for δ^2H and $\delta^{18}O$ of a latest three-year time series (2010–2012) in Changsha were used in this study to explain the relationship between rainfall and different

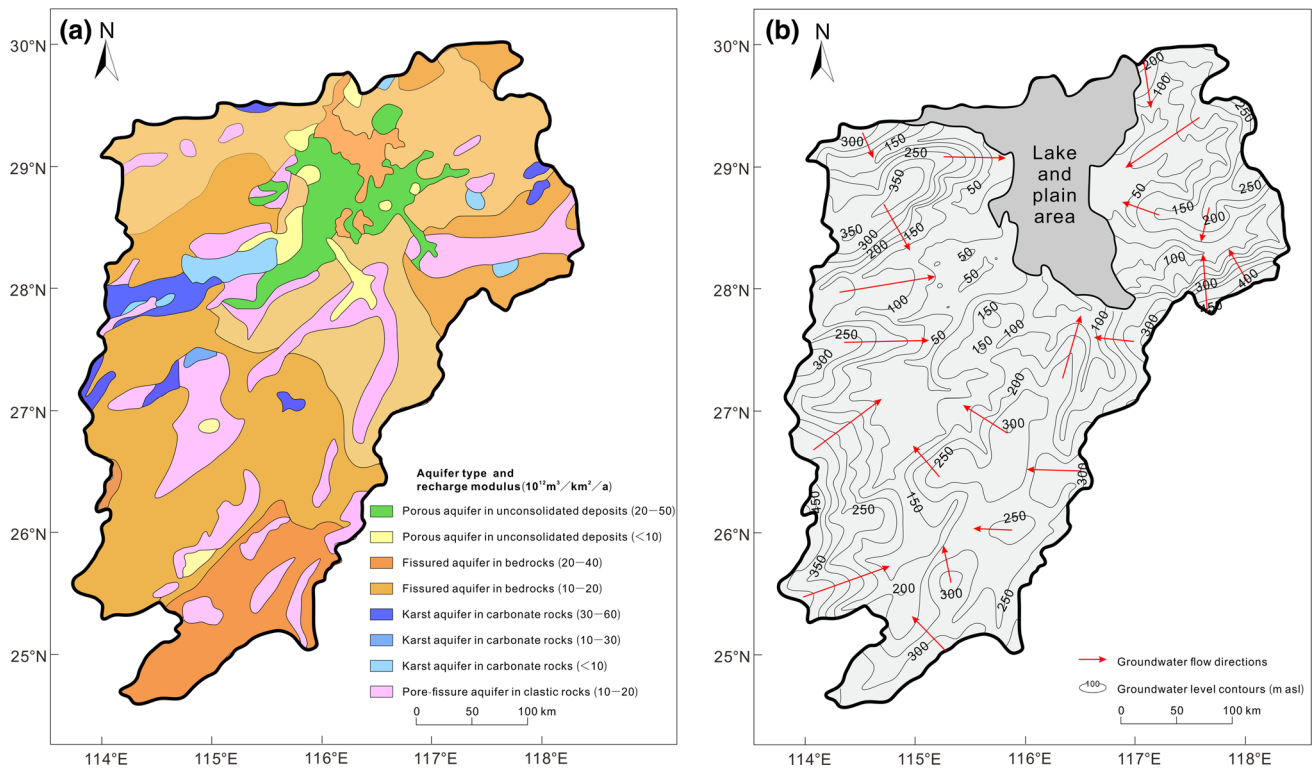


Fig. 2 Groundwater in the Poyang Lake Basin. **a** Aquifer type distribution and corresponding run-off modulus [modified after the 1:12,000,000 scale map of groundwater resources in China published in National Geological Information Data Center, <http://www.ngac.org.cn/Document/Map.aspx?MapId=EC7E1A7A75231954E043010007F182E>.]; **b** groundwater-level contours and flow directions (modified after the numerical simulation result by Li et al. (2013a))

water components in 2013. Under the circumstance without concurrent local rainfall isotopic data, this method has been proved to be acceptable by some researchers (Harrington et al. 2002; Hamed et al. 2010; Beddows et al. 2016).

Hydrological data for the Poyang Lake Basin were collected from the Annual Hydrological Report of the People’s Republic of China. The data on mean monthly precipitation and flow discharge rates (from 2007–2011) of the five rivers and the lake mouth were measured at six hydrological and meteorological stations.

Results

Hydrological characteristics of the Poyang Lake Basin

Due to differences in catchment area (3548–80,948 km²; Table 1), the five recharge rivers show significant variations in annual run-off volume (25.4–578.4 × 10⁸ m³; Table 1). The Gan River, which has the largest run-off volume (accounting for ~63 % of five rivers’ total run-off volume), is the main recharge source of the lake. For each river, there is a positive correlation between mean monthly flow discharge and monthly precipitation (Fig. 3), with

correlation coefficients of 0.908, 0.867, 0.848, 0.782, and 0.818 for the Rao, Xin, Fu, Gan, and Xiu Rivers, respectively. However, at Hukou station, located at the lake mouth, the correlation coefficient is only 0.590. This reflects the fact that not only is the discharge at the lake mouth a combination of five rivers, but it is also influenced by the water-level difference between the lake and the Yangtze River. The different operation modes of the Three Gorges Dam in different seasons have changed the volume of the Yangtze River, thus causing the unnatural variations in lake discharge volume. For the Five Rivers, the positive correlation relationship between river flow discharge and rainfall amount indicates that the rainfall in every catchment can quickly bring an increase in surface run-off within that catchment.

δD and δ¹⁸O in precipitation

As reported by Huang (2013), the local meteoric waterline (LMWL) in Changsha is $\delta D = 8.57\delta^{18}O + 18.55$ ($R^2 = 0.98, n = 336$). The slope of LMWL is bigger than that of the global meteoric waterline (GMWL: $\delta D = 8\delta^{18}O + 10$, Craig 1961), indicating that the condensation of water vapour is under non-equilibrium conditions (e.g. over-saturation) (Liu et al. 2014). The δD and

$\delta^{18}\text{O}$ values of precipitation in the study area show significant seasonal variations (Fig. 4), depleted from June to October, but relatively enriched during other months. This

is consistent with precipitation isotope characteristics across most of southern China (Liu et al. 2008; Wu et al. 2014), which has a typical monsoonal climate controlling the isotopic composition of precipitation (Araguás-Araguás et al. 1998; Xie et al. 2011). In this region, rainfall is brought by different air masses in different seasons. In summer, warm and moist air masses that come from the Pacific Ocean and the Indian Ocean penetrate the continent and bring abundant rainfall that is more depleted in D and ^{18}O isotopes. In other months, precipitation is primarily caused by a northern mass of cold and dry air from high-latitude inland areas (e.g. Siberia), which are enriched in D and ^{18}O . This seasonal variation is a potential signature for this water type, and may be useful for identifying and

Table 1 Hydrological information on the five river catchments that were investigated

River	Hydrological station	Catchment area/km ²	Annual run-off/10 ⁸ m ³
Rao River	Hushan	6374	60.8
Xin River	Meigang	15,535	167.5
Fu River	Lijiadu	15,811	92.9
Gan River	Waizhouzhan	80,948	578.4
Xiu River	Wanjiabu	3548	25.4

Fig. 3 Relationship between monthly mean precipitation and monthly mean flow volume between 2007 and 2011 for Poyang Lake and the five major rivers of the Poyang Lake Basin

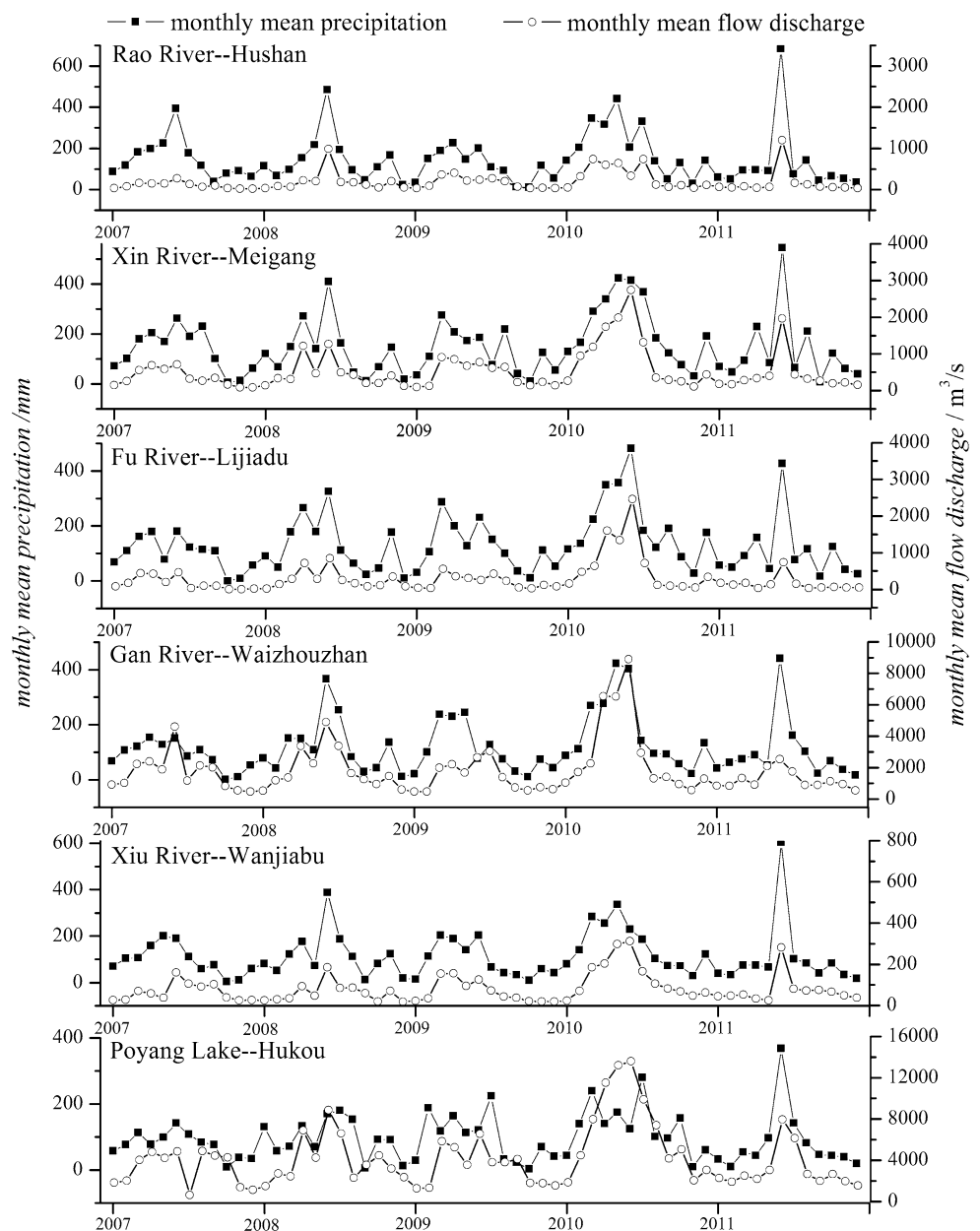
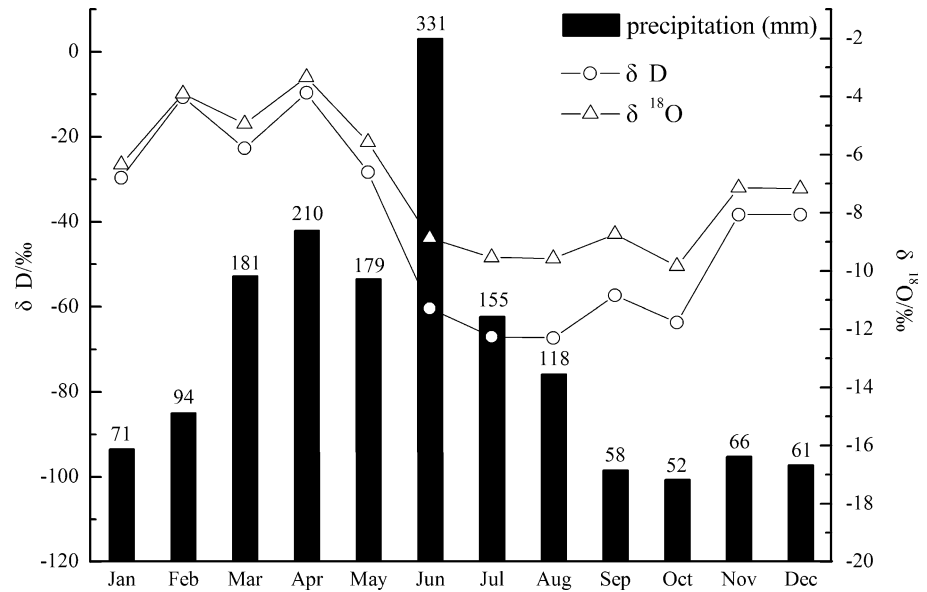


Fig. 4 Monthly values of δD , $\delta^{18}O$, and precipitation for the Poyang Lake Basin. Isotope data for precipitation are collected from Huang (2013) (Changsha 2010–2012), and precipitation is averaged from the data of hydrological and meteorological stations (six stations as shown in Fig. 3, 2007–2011)



quantifying contribution of unmodified rainwater in the Poyang lake system.

δD and $\delta^{18}O$ in river water, lake water, and shallow groundwater

Water sample information and isotopic results are listed in Table 2. In April, the mean δD and $\delta^{18}O$ values of river water, lake water, and shallow groundwater are -30.5 and -5.10 ‰, -22.4 and -4.09 ‰, and -34.4 and -5.73 ‰, respectively. The April samples mainly distribute below the LMWL (Fig. 5), indicating that surface water and groundwater are suffering evaporation, especially for river and lake water. The evaporation line (EL1) can be fitted as $\delta D = 7.19\delta^{18}O + 6.47$ ($R^2 = 0.94$) with river and lake water samples sourced from the Poyang Lake Basin (samples 1–2A and 15–16A are excluded when fitting the evaporation line because of their different water source). The Yangtze River (sample 1A) is the most depleted in heavy isotopes (δD and $\delta^{18}O = -45.8$ and -7.02 ‰, respectively; Table 2), reflecting its origin in a high-altitude inland area. However, after it is fed by the lake (sample 2A), the river becomes much more enriched in D and ^{18}O (δD and $\delta^{18}O = -29.7$ and -5.28 ‰, respectively). Based on the mass balance of deuterium isotope (δD), it is calculated that about 79 % of the downstream Yangtze River water is recharged by the lake water at Hukou. The onset of the rainy season is earlier in the Poyang Lake Basin (starting in March) than it is for the upstream Yangtze River, and the abundant rainfall makes the lake water level higher than that of the river, resulting in lake’s significant discharge. Compared with the river water, the lake water has larger isotopic values that are

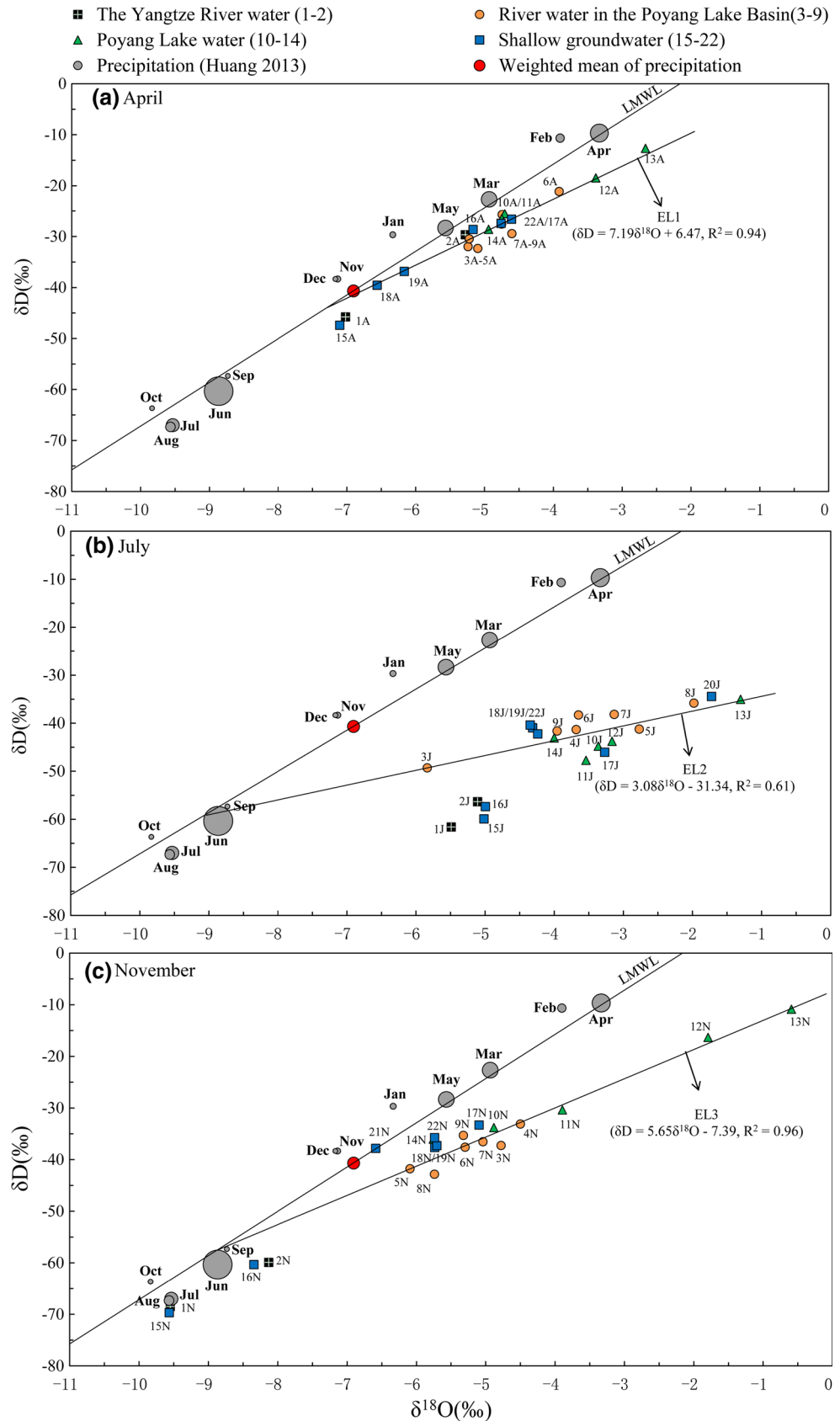
plotted on the right part of the LMWL (e.g. lake water samples 12A and 13A; Fig. 5). Recharged by five rivers, the lake water has a smaller flow velocity, longer water residence time, and thus experiences greater levels of evaporation. The mean isotopic composition of groundwater is similar to that of the rivers, indicating a close contact between river water and groundwater. This would typically be consistent with the rivers being groundwater fed. For example, groundwater samples collected near the Yangtze River (samples 15A and 16A) have similar isotopic values to the corresponding Yangtze River samples (samples 1A and 2A). These isotopic results reflect an obvious bank storage effect of the river, which varies with the permeability of river bank. The high permeability of the stratum in this region results in a close interaction between river water and groundwater. However, although lake water sampling sites 11A and 12A are geographically close to the respective groundwater sampling sites 18A and 19A, the results show a significant difference in isotopic composition, implying a lack of exchange or a mixture of different waters at these sites. Contrastingly, in the northern region of the lake, where the water channel is narrow and flow velocity is relatively big, sets of corresponding lake water and groundwater samples (e.g. 10A and 17A, 14A, and 22A) show similarities in isotopic concentrations, implying a close hydraulic connection between them.

The July sampling campaign coincided with an unusual month-long drought in the Poyang Lake Basin, an event that had the highest temperatures and lowest precipitation since 1951. The temperature was continuously extremely high (>35 °C), with no precipitation during the whole month, which rarely happened in history. The resulting high evaporation is the likely cause of the July relationship

Table 2 Water sample information and isotopic results

Number	Type	Sampling site	Longitude (°E)	Latitude (°N)	April			July			November		
					Number	δD (‰)	$\delta^{18}O$ (‰)	Number	δD (‰)	$\delta^{18}O$ (‰)	Number	δD (‰)	$\delta^{18}O$ (‰)
1	River water	Yangtze River	115.9954	29.7349	1A	-45.8	-7.02	1J	-61.6	-5.49	1N	-68.5	-9.55
2		Yangtze River	116.2446	29.7696	2A	-29.7	-5.28	2J	-56.4	-5.11	2N	-59.9	-8.13
3		Rao River(north)	116.7072	28.9806	3A	-32.4	-5.10	3J	-49.3	-5.84	3N	-37.3	-4.78
4		Rao River(south)	116.7585	28.9159	4A	-32.0	-5.24	4J	-41.4	-3.68	4N	-33.1	-4.50
5		Xin River	116.7497	28.8043	5A	-30.5	-5.22	5J	-41.3	-2.77	5N	-41.8	-6.09
6		Fu River	116.1562	28.6655	6A	-21.1	-3.91	6J	-38.3	-3.65	6N	-37.6	-5.29
7		Gan River	116.0874	28.7709	7A	-27.6	-4.75	7J	-38.2	-3.13	7N	-36.5	-5.04
8		Gan River	116.0817	28.8116	8A	-25.7	-4.74	8J	-35.8	-1.98	8N	-42.9	-5.74
9		Xiu River	115.8112	29.0338	9A	-29.4	-4.60	9J	-41.6	-3.96	9N	-35.3	-5.32
10	Lake water	Hukou	116.2111	29.7404	10A	-25.5	-4.71	10J	-44.8	-3.36	10N	-33.8	-4.88
11		Duchang	116.1839	29.2504	11A	-26.5	-4.75	11J	-47.7	-3.54	11N	-30.4	-3.89
12		Kangshan	116.4924	28.9145	12A	-18.5	-3.38	12J	-43.8	-3.16	12N	-16.4	-1.79
13		Nanjishan	116.3215	28.9020	13A	-12.7	-2.66	13J	-35.0	-1.30	13N	-10.9	-0.59
14		Xingzi	116.0291	29.4537	14A	-28.6	-4.94	14J	-43.1	-4.00	14N	-36.0	-5.75
15	Shallow groundwater	Yangtze River	115.9958	29.7347	15A	-47.4	-7.10	15J	-59.9	-5.02	15N	-69.7	-9.56
16		Yangtze River	116.2455	29.7701	16A	-28.6	-5.17	16J	-57.4	-5.00	16N	-60.4	-8.34
17		Hukou	116.2200	29.7483	17A	-26.6	-4.61	17J	-46.1	-3.27	17N	-33.3	-5.09
18		Duchang	116.1353	29.2650	18A	-39.6	-6.56	18J	-41.0	-4.31	18N	-37.7	-5.73
19		Ruihong	116.3781	28.8170	19A	-36.9	-6.17	19J	-40.4	-4.35	19N	-37.3	-5.70
20		Tangan	116.1637	28.6939	20A	-	-	20J	-34.4	-1.72	20N	-	-
21		Nanjishan	116.3230	28.8940	21A	-	-	21J	-	-	21N	-37.8	-6.58
22		Xingzi	116.0517	29.4475	22A	-27.4	-4.76	22J	-42.3	-4.24	22N	-35.8	-5.73

Fig. 5 Relationship between the $\delta^{18}\text{O}$ and δD values of surface water and groundwater in April (a), July (b), and November (c) 2013. The monthly rainfall amount is described by the different sizes of the grey circles



between $\delta^{18}\text{O}$ and δD , which deviates strongly from the LMWL (Fig. 5). Such a small slope of the evaporation line (EL2; $\delta\text{D} = 3.08\delta^{18}\text{O} - 31.34$, $R^2 = 0.61$) in the Poyang Lake Basin is consistent with low air humidity during the drought period (Gat 1971). The mean δD and $\delta^{18}\text{O}$ values of the river water, lake water, and groundwater are -44.9 and -3.96 ‰, -42.9 and -3.07 ‰, and -45.9 and -3.99 ‰, respectively. Since the Yangtze River originates in a different region, its $\delta^{18}\text{O}$ and δD values are not plotted along EL2. However, the isotopes of the Yangtze River also significantly deviate from the LMWL, indicating that the drought has extended to upstream regions of the Yangtze River Basin.

Unlike in April, the isotope concentrations at sampling sites 1J and 2J show only minor differences, suggesting that the influence of the lake water on the Yangtze River is smaller in July. It can be estimated by δD values that the lake water account for only about 31 % of the downstream Yangtze River water at this time. This is consistent with the fact that, during the summer, the Yangtze River has a higher water level than the lake, which reduces the discharge of the lake into the river. Isotopes in the groundwater show that, in addition to the surface water, shallow groundwater also suffered intense evaporation. Greater evaporation occurred in the unsaturated zone of groundwater and probably diminished the amount of recharge. Because of this drought, local residents extracted more water from the wells than usual. Extensive pumping at these wells may promote the recharge from surface water to shallow groundwater in this region, causing the similar isotopic composition of river water and shallow groundwater. However, the wells can still meet the water demand under such extensive pumping. These phenomena imply that there exists a good connection between surface water and shallow groundwater.

In November (dry season in the Poyang Lake Basin), the mean δD and $\delta^{18}\text{O}$ values of river water, lake water, and groundwater are -43.7 and -6.05 ‰, -25.5 and -3.38 ‰, and -44.6 and -6.68 ‰, respectively. Again, the river water and groundwater have similar isotopic compositions. The isotopic data (Fig. 5) show that lake water experiences a greater degree of evaporation than river water, likely because the lake has both a larger area and smaller flow velocity than the rivers. The lake water still discharges into the Yangtze River in significant quantities, as shown by the relative enrichment in heavier isotopes at sampling site 2N, as compared with sampling site 1N. Calculated by δD values using mass balance method, the proportion of lake water in the downstream Yangtze River water is about 25 %, which is a considerable amount for the lake in dry period. This is consistent with the November operation mode of the Three Gorges Dam, the impoundment period, during which there is

significantly reduced water level in the Yangtze River, thus promoting greater lake discharge. At this time, the evaporation line (EL3) of the lake and of the five rivers is fitted as $\delta\text{D} = 5.65\delta^{18}\text{O} - 7.39$ ($R^2 = 0.96$).

Discussion

Isotopic differences between surface water and rainfall

The crossing point of EL1 and LMWL, which represents the isotopic composition of the water source for surface water, is significantly different from the rainfall isotopic values in April ($\delta\text{D} = -9.7$ ‰, $\delta^{18}\text{O} = -3.33$ ‰; Fig. 5), implying that the five rivers are not mainly recharged by recent precipitation. However, the crossing point is close to the volume-weighted mean isotopic composition of annual precipitation, from which it can be hypothesised that rivers are mainly recharged by base flow which is a long-term mixture of rainfall. In July with little rainfall during the drought event, the LMWL and EL1 lines cross at a point close to the isotopic compositions of precipitation in June, suggesting that June precipitation may be the primary source of surface water and shallow groundwater in July. In the dry period with little rainfall, river water and lake water are mainly recharged by shallow groundwater in the surrounding aquifers, and this shallow groundwater dates from previous precipitation events. In November, the water source for surface run-off is much more depleted in heavy isotopes than concurrent rainfall, indicating that rainfall in the end of rainy season (August to October) may still be important recharge for surface run-off at this time.

During the rainy season, the Poyang Lake Basin sees higher precipitation and river water volumes than in previous months. The positive correlation between precipitation and river flow discharge initially suggests that most of the rainfall runs rapidly into the rivers. However, the isotopic composition of the river water in April indicates that rivers are probably mainly recharged by base flow instead of rainfall in the beginning of the rainy season. Therefore, most rainfall water during this period does not directly form surface run-off, but instead infiltrates the soil and recharges the groundwater, which in turn subsequently recharges the rivers. This theory is supported by the considerable river flow observed in July, despite a serious drought, and the isotopic correspondence of July rivers and groundwater with the June precipitation. The same trend in isotopic compositions is again seen in November, when river water and groundwater are different from precipitation in November but close to precipitation from several months previous.

Interaction between surface water and shallow groundwater

The larger-scale hydrological exchange of groundwater and surface water is controlled by (1) the relation between stream stage and the adjacent groundwater level; (2) the hydraulic conductivities within the channel and the alluvial plain sediments; and (3) the geometry and position of the stream channel within the alluvial plain (Woessner 2000). Under conditions of high precipitation, surface run-off and interflow gradually increase, which causes the river to infiltrate its banks and recharging the aquifer. In contrast, under conditions of low precipitation, the surface run-off is recharged by base flow (Brunke and Gonser 1997). The interactions between the surface water and groundwater systems are controlled by the hydraulic properties of stream and lake beds (Sophocleous 2002).

The consistent similarities in isotopic composition between river water and groundwater suggest their close interaction. All of the rivers have relatively larger flow velocities than the lake, producing river bed deposition that primarily involves coarse sand and gravel rather than fine particles. As a result, the river beds maintain high permeability, keeping a good connection with surrounding aquifers (Zhang 2011). When the phreatic water table levels increase, shallow groundwater can be transported into rivers. In contrast, lakes have a relatively small flow velocity from multiple inlets to a single outlet and are characterised by the sedimentation of mainly fine particles. A general lack of exchange through this low permeability medium is supported at Poyang Lake by the difference in isotopic compositions between lake water and groundwater in the lake's southern reaches. However, in the narrow northern end of the lake where water flows relatively fast, exchange between lake water and groundwater is again observed, which is also consistent with the synchronisation between lake level and groundwater level near sampling site 14 found by Xu et al. (2014b).

It is also observed that water samples collected during three sampling campaigns all present a D and ^{18}O enriching order from groundwater to river water to lake water. Isotopic enrichment of continental water is mainly caused by evaporation and water–rock interaction along with the moving process of water. As a result, the heavy isotope enrichment process can also to some degree reflect the recharge relationships among different hydrological cycle components. It can be hypothesised that the rivers are mainly recharged by groundwater, and the lake is mainly recharged by rivers.

Rainfall run-off processes in the Poyang Lake Basin

The river catchments in the Poyang Lake Basin are characterised by mountains and hills, which are primarily

composed of granite or sandstone (Hu et al. 2011; Zhai et al. 2012). In moist, high-temperature climates, the bedrock easily forms a weathered layer. The weathered layer, which may be 20–30 m deep, is always loose and characterised by soil loss and fracture development. The heavily eroded surface soil and the fractures that are developed within the weathered layer allow precipitation to rapidly infiltrate into the aquifers. As a result, most rainfall forms subsurface run-off rather than surface run-off. This conclusion is consistent with the study of Hu et al. (2013a), which pointed out that in the Poyang Lake catchment area, the river water consists of 23 % direct run-off and 77 % base flow. As groundwater levels rise following a rainfall event, stored groundwater from previous rainfall events is discharged towards rivers, which is known as the translator flow or piston flow in water recharge process verified by researches (Buttle 1994; Lischeid et al. 2002; Uchida et al. 2002). Hu et al. (2013a) also found that shallow groundwater in this region is mainly from pre-event precipitation. That is the reason why river water and groundwater have an isotopic composition similar to previous precipitation rather than recent precipitation. The high permeability of the stratum and river bed accounts for the positive correlation between river run-off volume and precipitation.

Although rainfall in the Poyang Lake Basin greatly increases from January to April, most rainwater in the river catchments does not form near-surface quick flow that recharges rivers. After going through the dry period with small rainfall amount, water stored in the unsaturated zone of river catchments has greatly reduced because of evapotranspiration and the discharge of groundwater. In the beginning of the rainy season, the rainfall water needs to infiltrate and recover the soil wetness conditions first before it can form quick flow and recharge surface run-off, and this is called the wetting-up process (Muñoz-Villers and McDonnell 2012). Therefore, water recharge for rivers in April is sustained by base flow in the catchments, with little quick recharge from recent rainfall. Following the increase in rainfall amount and rainfall intensity, the soil moisture conditions gradually meet the formation conditions of near-surface quick flow, causing relatively short travel time of the water from new rainfall to an outflow location (i.e. catchment stream water). Consequently, quick flow recharged by considerable rainfall from June has totally exceeded the base flow and become main water source for rivers and lakes in July. After July, the water yield of quick flow begins to reduce because of the reduction in rainfall. In November, rivers are more likely recharged by both previous rainfall and base flow, and the contribution from the latter may keep increasing until the rainy season comes again. In the Poyang Lake Basin, the groundwater system (base flow and near-surface flow) is like a huge reservoir which can effectively impound

rainfall water. In this way, aquifers surrounding the rivers playing an important role in restraining floodwater during the flood season and in ensuring river run-off supply during the dry season.

Conclusion

Located in a typical monsoon region, precipitation in the Poyang Lake Basin shows significant seasonal variation in δD and $\delta^{18}\text{O}$ isotopes, which are depleted in the summer and enriched in the winter. Recharged by precipitation, surface water and shallow groundwater in the Poyang Lake region also present great seasonal variations. Isotopic compositions reveal a relationship between Poyang Lake and the Yangtze River. During the rainy season of the Poyang Lake Basin, the Yangtze River is significantly recharged by lake. When the Yangtze River is in its flood season, its high water level reduces the lake discharge. During the impoundment process of the Three Gorges Dam, the low water level of the Yangtze River promotes discharge at the lake mouth.

The isotopic compositions of the river water, lake water, and shallow groundwater show that the rivers have a close hydrological connection with the shallow groundwater. The connection between lake water and groundwater is relatively weak, especially in the southern region of the lake. Although hydrological data show a strong correlation between river flow discharge and precipitation, isotope results suggest that rivers in the Poyang Lake Basin are mainly recharged by subsurface run-off (base flow and near-surface quick flow), rather than by surface run-off directly formed by concurrent rainfall. In the beginning of the rainy season, most precipitation infiltrates into the unconsolidated soils and recovers the soil wetness conditions, and rivers during this period are primarily sustained by base flow in the catchments. When the soil moisture conditions meet the formation conditions of near-surface quick flow, rivers become mainly recharged by quick flow that comes from recent abundant rainfall. After the rainy season, rivers receive recharge from both previous rainfall and base flow.

The seasonal variations of δD and $\delta^{18}\text{O}$ isotopes in precipitation provide an effective method to study the real interactions among different hydrological cycle components in large drainage basins. Furthermore, using isotopes in precipitation as natural tracers can yield new findings that may be undetectable by traditional hydrological methods. In this study, the synchronous change between river flow discharge and precipitation observed by hydrological monitoring conceals the fact that river water is mainly recharged by shallow groundwater rather than surface run-off directly formed by concurrent rainfall,

which can be obtained by isotopic methods. Therefore, the isotopic methods applied in this study should be an important auxiliary tool for traditional hydrological methods when studying hydrological processes in large-scale drainage basins such as the Poyang Lake Basin. In this study, isotopic signatures only give a qualitative description that rivers in different seasons are primarily recharged by subsurface run-off with different proportion between base flow and near-surface quick flow. However, to get better understanding of the run-off generation in the Poyang Lake Basin, quantitative hydrograph separation and groundwater residence time estimation which needs concomitant isotopic signal for precipitation and other hydrological compartments should be further investigated.

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