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RESEARCH ARTICLE

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Assessing surface water–groundwater interactions in a complex river-floodplain wetland-isolated lake system

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Abstract
Floodplain systems are most often hydrologically complex settings characterized by highly variable surface water–groundwater interactions that are subjected to wide-ranging wetting and drying over seasonal timeframes. This study used field methods, statistical analysis, and the Darcy's law approach to explore surface water–groundwater dynamics, interactions, and fluxes in a geographically complex river-floodplain wetland-isolated lake system (Poyang Lake, China). The floodplain system of Poyang Lake is affected by strongly seasonal shifts between dry and wet processes that cause marked changes in surface water and groundwater flow regimes. Results indicate that wetland groundwater is more sensitive to variations in river levels than the seasonal isolated lakes. In general, groundwater levels are lower than those of the isolated lakes but slightly higher than river levels. Statistical analysis indicates that the river hydrology plays a more significant role than the isolated lakes in controlling floodplain groundwater dynamics. Overall, the river shows gaining conditions and occasionally losing conditions with highly variable Darcy fluxes of up to +0.4 and −0.2 m/day, respectively, whereas the isolated lakes are more likely to show slightly losing conditions (less than −0.1 m/day). Although seasonal flux rates range from 7.5 to 48.2 m/day for surface water–groundwater interactions in the floodplain, the flux rates for river–groundwater interactions were around four to seven times higher than that of the isolated lake–groundwater interactions. The outcomes of this study have important implications for improving the understanding of the water resources, water quality, and ecosystem functioning for both the river and the lake.

KEYWORDS
floodplain wetland, flux rate, isolated lake, Poyang Lake, river flow, surface water–groundwater interaction

1 | INTRODUCTION

Surface water bodies such as rivers, lakes, and wetlands are connected to their underlying groundwater in most types of landscapes (Winter, 1999). Natural exchanges between surface water and groundwater can strongly affect physical hydrological processes (Karan, Sebok, & Engesgaard, 2017; Winter, Harvey, Franke, & Alley, 1998), properties (Hayashi & Rosenberry, 2002; Jin et al., 2018), and the ecological behaviour of both water bodies (Hanrock, Boulton, & Humphreys, 2005; Kaandorp et al., 2018). The potential impacts of climate change and human activities on surface and groundwater resources increase the urgency for reliable assessment of surface water–groundwater interactions (Hutchins et al., 2018; Smerdon, 2017).

The importance of interactions between surface water and groundwater has been widely recognized for many years. However, more knowledge on the interaction processes between the two is still necessary for effective management of water resources (Keery, Binley, Crook, & Smith, 2007). A great many methods have been used to estimate the magnitude and/or direction of surface water–groundwater exchanges, including pressure gradient measurements (Anderson, Wondzell, Gooseff, & Haggerty, 2005; Qu et al., 2017), temperature profile measurements (Hatch, Fisherm, Revenaugh, Constantz, & Ruehl, 2006; Irvine, Lautz, Briggs, Gordon, & Mckenzie, 2015), numerical simulation models (Kalbus, Reinstorf, & Schimer, 2006; Y. Li, Yuan, Lin, & Teo, 2016; Sterte, Johansson, Sjöberg, Karlsen, & Laudon, 2018), geochemical tracers (Jin et al., 2018; J. Li, Li, & Liu, 2017; Zarnetske et al., 2008), and a combination of two or more methods (McCallum, Andersen, Rau, Larsen, & Acworth, 2014). However, all of these approaches suffer from limitations associated with their spatial and temporal scales and underlying assumptions (Cremeans, Devlin, McKnight, & Bjerg, 2018; Hatch et al., 2006). These uncertainties are mainly attributable to disturbance of the flow path, small-scale spatial heterogeneities, and design limitations of measurement devices (Cremeans et al., 2018).

Wetland systems are recognized as key hydrological landscape elements and characteristically have nonnegligible hydraulic relationships with surrounding surface water–groundwater systems (Rains et al., 2016). The interaction between the surface water and groundwater regime has important implications for the effective protection and management of wetland habitat environments (Qu et al., 2017; Turner & Townley, 2006). Floodplain wetlands are a specific subset of wetland systems and exhibit a significant wetting and drying that primarily depend on the hydrological regime of surrounding shallow lakes or rivers (Frazier & Page, 2006; Townsend, 2006). The episodic dynamics of the hydrological regime are likely to have a strong influence on surface water–groundwater interactions across floodplain wetlands (Y. Li, Yao, Zhao, & Zhang, 2018; McDonough, Lang, Hosen, & Palmer, 2015; Wilcox, Dean, Jacob, & Sipocz, 2011). In general, surface water–groundwater interactions provide inputs of matter, energy, and pulses that contribute to temporal change in wetland ecosystems (Gu, Anderson, & Maggi, 2012; Strayer, 2014). It is therefore important to identify the interactions between groundwater and surface water in floodplain systems that determine the nature of the wetland's physical and ecological functions (Jolly, McEwan, & Holland, 2008; Ludwig & Hessionm, 2015).

The floodplain wetland of Poyang Lake in China, an internationally recognized wetland system (Kanai et al., 2002), plays an irreplaceable role in the protection of biodiversity and ecological functions (Z. Hu, Zhang, Liu, Ji, & Ge, 2015; Huang et al., 2018; Yang et al., 2018). The hydrological conditions of the floodplain wetland have attracted considerable public attention during the past decade (Sun, Zhen, & Miah, 2017; Tan et al., 2016; Wang et al., 2012), as the natural fluctuations of the lake water level have been changing dramatically due to climate change and human activities (Q. Zhang et al., 2012, 2014; Li, Tao, Yao, & Zhang, 2016), resulting in significant hydrological, ecological, and economic effects (Mei, Dai, Fagherazzi, & Chen, 2016).

Several studies in Poyang Lake's floodplain wetland highlight the importance of surface water–groundwater dynamics in affecting soil moisture, vegetation distribution, and nutrient transport. For example, Xu, Zhang, Tan, Li, and Wang (2015) used field measurements in 2012–2013 to investigate the relationships between hydrology and vegetation along a typical transect in the lake's floodplain wetland. They found that the groundwater level and soil moisture gradients determine the vegetation community distribution. More recently, Y. Li et al. (2018) used hydrological, hydrochemical, and stable isotope methods to explore the floodplain groundwater dynamics in Poyang Lake, concluding that the lake's hydrology plays a dominant role in affecting the wetland groundwater storage. Similar conclusions were drawn by X. Zhang et al. (2017), using stable hydrogen and oxygen isotopes to investigate the soil–plant–atmosphere continuum in the Poyang Lake floodplain wetland. They found that the seasonal exchanges between river and adjacent floodplain groundwater have significant effects on the water movement in the soil-plant-atmosphere continuum (SPAC) system.

Although the implications of groundwater in Poyang Lake's floodplain wetland have been investigated previously, only limited attempts have been made to assess the surface water–groundwater interactions in terms of water recharge/discharge and water flux. Determining those interactions is critical for flood control and water resource management, as well as for understanding how the floodplain wetland may be potentially affected by the surrounding hydrological regime and how the wetland affects the local hydrology and ecosystem of the lake. These knowledge gaps are even more significant for Poyang Lake regions, where climate patterns are typically highly dynamic, with distinct wet and dry seasons that strongly influence both surface and groundwater flows (Li, Tao, Yao, & Zhang, 2016; Zhan et al., 2017).

The specific objectives of this study are to (a) investigate temporal variations in surface water and groundwater hydrographs and assess regional groundwater flow dynamics based on field measurements in the Poyang Lake floodplain wetland; (b) explore correlations between surface water bodies and floodplain groundwater using several statistical methods; and (c) assess the degree of interactions between groundwater and surrounding surface waters using the Darcy's law approach.

2 | STUDY AREA

Poyang Lake is located at the south bank of the middle reaches of the Yangtze River (Figure 1a) and is one of the few lakes in China that remains naturally connected to surrounding rivers (Q. Zhang et al., 2014). It fulfils industrial, agricultural, urban, and environmental functions for 12.4 million residents (Y. Li, Zhang, Werner, Yao, & Ye, 2017). Poyang Lake is generally shallow, with 85% of the lake less than 6 m deep during the flood season (Y. Li, Zhang, et al., 2017). It receives surface inflows from five large rivers (Figure 1a), and subsequently discharging to the Yangtze River at the northern end of the lake (Q. Hu, Feng, Guo, Chen, & Jiang, 2007; Shankman, Heim, & Song, 2006). Consequently, the hydrology of Poyang Lake is mainly controlled by seasonal fluctuations in both surface river inflows and Yangtze River water levels (Y. Li, Zhang, et al., 2017; Q. Zhang et al., 2014). These result in water level fluctuations of 8 to 22 m each year, and associated dynamics in the water surface area of <1,000 to >3,000 km^2 (Feng et al., 2012). The lake is a prominent example of a highly dynamic system that expands and contracts annually, creating extensive floodplain areas of ~3,000 km^2 (Feng et al., 2012; Y. Li et al., 2018).

The topography of the Poyang Lake floodplain varies from upland areas around the lake's main flow channel at elevations of 29 m (above

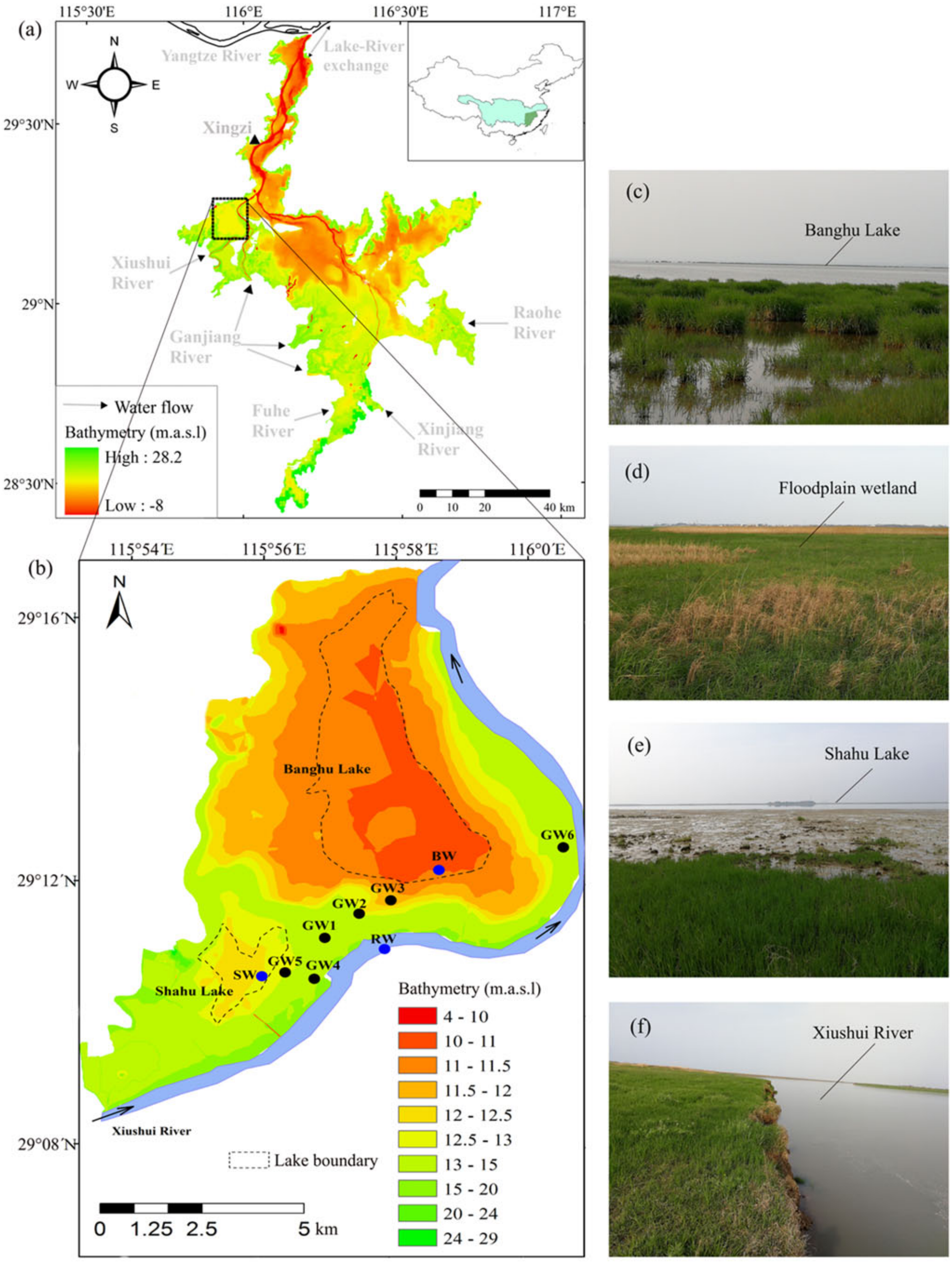

FIGURE 1 (a) Bathymetry of Poyang Lake; (b) spatial distribution of monitoring points of water level/temperature for the surface water (blue circles)–groundwater (black circles) within the lake's floodplain wetland; and (c)–(f) photographs of the floodplain system [Colour figure can be viewed at wileyonlinelibrary.com]

sea level) to lowland areas at elevations of about 4 m (Figure 1b). There are around 100 shallow depressions located in Poyang Lake's floodplain wetland, with a total area of ~800 km^2 (Z. Hu et al., 2015). All of these shallow depressions have a saucer-shaped profile, and the maximum water depth is usually less than 2 m (Wu & Liu, 2017). They play an important role in flood mitigation storage and biodiversity protection (Z. Hu et al., 2015; Huang et al., 2018). Generally, these shallow depressions are connected to the main lake during the flood season but become disconnected during the dry season. Hence, these shallow depressions are called "isolated lakes" in the Poyang Lake wetland (Z. Hu et al., 2015). In this study, two typical isolated lakes of the Banghu and Shahu (marked by dashed outlines in

TABLE 1 Main characteristics of the isolated lakes within Poyang Lake's floodplain wetland

Name	Location	Average elevation (m)	Water area (km^2)	Water storage (10^8 m^3)
Banghu Lake	(115.960°, 29.231°)	9.1	73	0.3
Shahu Lake	(115.929°, 29.180°)	12.7	14	0.1

Figure 1b) and their adjacent floodplains were selected as the study area (Figure 1c–f). Table 1 lists the basic characteristics of the two isolated lakes within Poyang Lake.

The floodplain wetland is home to about 310 species of birds, 16 of which are listed as threatened by the International Union for the Conservation of Nature (Huang et al., 2018). Wetland vegetation exhibits zonal distribution from the lake centre to the floodplains, including a floating vegetation zone, a submerged vegetation zone, an emergent aquatic vegetation zone, a semiaquatic emergent tall vegetation zone, and a mesophytic vegetation zone (Tan et al., 2016). Sedges are the main aquatic vegetation in the floodplain wetland affected by the region's hydrological and meteorological conditions (Mei et al., 2016). Precipitation records for the floodplain show distinct wet and dry seasons, with 48% of the annual precipitation concentrated in a wet season that runs from April to June, and about 16% of the rainfall occurring between September and December (Figure 2). January is the coldest month of the year, with an average temperature of 5.7°C, and August as the warmest with an average of 31.2°C (Figure 2). The floodplains experience a subtropical monsoon climate, with a mean annual precipitation and pan evaporation of 1,485 and 1,428 mm/year, respectively (Figure 2).

3 | MATERIALS AND METHODS

3.1 | Field measurements

The gauging station of Xingzi, located in the northern part of Poyang Lake floodplains (Figure 1a), was adapted to provide daily observations of meteorological conditions. The groundwater-surface water exchange monitoring systems were deployed to observe water level and water temperature. The water level and water temperature of Xiushui River and the two adjacent isolated lakes (i.e., Banghu Lake and Shahu Lake) were recorded using a Solinst 3001 Levelogger pressure transducer and recorder (Canada) housed in a 0.05-m-diameter polyvinyl chloride (PVC) driven into the mineral soil beneath the lake bed and the riverbed (Figure 1b). The water level and temperature were monitored automatically and recorded by compensating for barometric pressure, with an accuracy of 0.01 m and 0.05°C, respectively. Within the Poyang Lake floodplain wetland, six Solinst 3001 Levelogger pressure transducers were installed and used to determine spatial and temporal variations in groundwater level and temperature (Figure 1b). All transducers were built inside 0.08-m-diameter PVC, each with 1-m-long screens wrapped in filter cloth. The depth of the groundwater wells ranged from 10.2 to 14.5 m, indicating generally shallow groundwater. In this study, the water level and temperature of surface water and groundwater were continuously recorded at 1-hr intervals from January 15, 2016, to January 17, 2017. Table 2 presents the geological setting of all the monitoring points in the Poyang Lake floodplain wetland.

3.2 | Geophysical investigation

In this study, a geophysical survey using spontaneous potential and resistivity loggings (Anomohanran, Ofomola, & Okocha, 2017; Carrière, Chalikakis, Sénéchal, Danquigny, & Emblanch, 2013) was adopted to estimate the subsurface geological situation for a 400-m-long east/west section between points GW4 and GW5 (Figure 1). The ABEM Terramater SAS 4000 was used with current electrode spacing at 3 m. The data obtained were manually curved matched to derive the values of the apparent resistivity and thickness. The analysis of the resistivity shows that the formation of the floodplain wetland is likely to be the same at the depths less than 15 m (Figure 3 a). The field survey and laboratory tests indicated that the layer at this interval was primarily composed of sand and a smaller proportion of silt (Figure 3b).

3.3 | Statistical analysis

In this study, the relationship between surface water levels (i.e., Banghu Lake, Shahu Lake, and Xiushui River) and the floodplain groundwater levels (GW1–GW6) were computed and implemented in MATLAB® using cross-correlation functions. The mathematical description of the cross-correlation function can be written as (Box, Jenkins, & Reinsel, 1994)

$$C_{xy}(k) = \begin{cases} \frac{1}{L}\sum_{t=1}^{L-k}(x_t - \bar{x})(y_{t+k} - \bar{y}) & k = 0, 1, 2, \ldots \\ \frac{1}{L}\sum_{t=1}^{L+k}(y_t - \bar{y})(x_{t-k} - \bar{x}) & k = 0, -1, -2, \ldots \end{cases}, \tag{1}$$

$$r_{xy}(k) = C_{xy}(k)/\sigma_x\sigma_y \quad k = 0, \pm 1, \pm 2, \pm\ldots, \tag{2}$$

where k is the time lag, L is the length of the time series, x_t and y_t are input and output time series, respectively, $\bar{x}$ and $\bar{y}$ are the means of the input and output series, $r_{xy}(k)$ is the cross-correlation function, σ_x

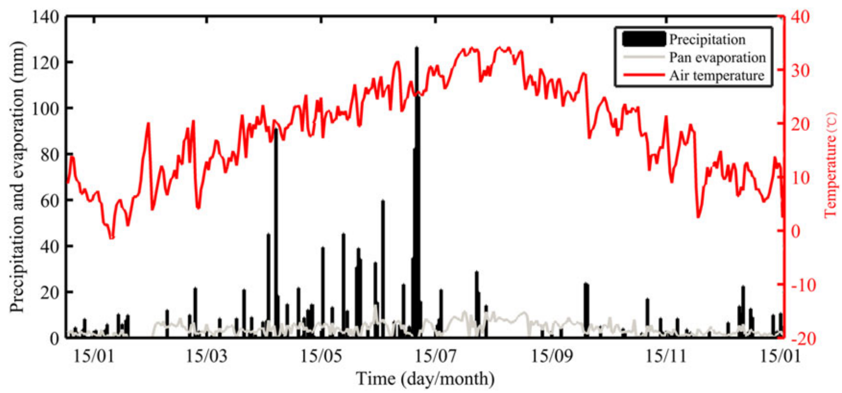

FIGURE 2 Daily meteorological changes (Xingzi gauging station) in the Poyang Lake floodplain wetland from January 15, 2016 to January 17, 2017 [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 2 Locations and simplified geological setting of monitoring points within the Poyang Lake floodplain wetland

Site name	Water type	Observation location	Well elevation (m)	Well depth (m)	Screen midpoint (m)	Geological information[a]
GW1	Wetland groundwater	(115.948°, 29.185°)	13.8	12.7	12.2	Fine sand
GW2	Wetland groundwater	(115.948°, 29.185°)	13.7	12.5	12.0	Coarse sand
GW3	Wetland groundwater	(115.954°, 29.192°)	13.3	10.2	9.7	Fine sand
GW4	Wetland groundwater	(115.950°, 29.175°)	15.0	12.1	11.6	
GW5	Wetland groundwater	(115.945°, 29.207°)	14.1	11.1	10.6	Fine sand and silt deposits
GW6	Wetland groundwater	(116.014°, 29.176°)	14.8	14.5	14.0	Fine sand
BW	Banghu Lake water	(115.980°, 29.198°)	11.7	NA	NA	Fine silt and clay
SW	Shahu Lake water	(115.938°, 29.174°)	13.0	NA	NA	
RW	Xiushui River water	(115.964°, 29.183°)	9.4	NA	NA	Sand and gravel deposits

Note. NA: not available for the surface water observations.

[a]Derived from field sampling and laboratory analysis.

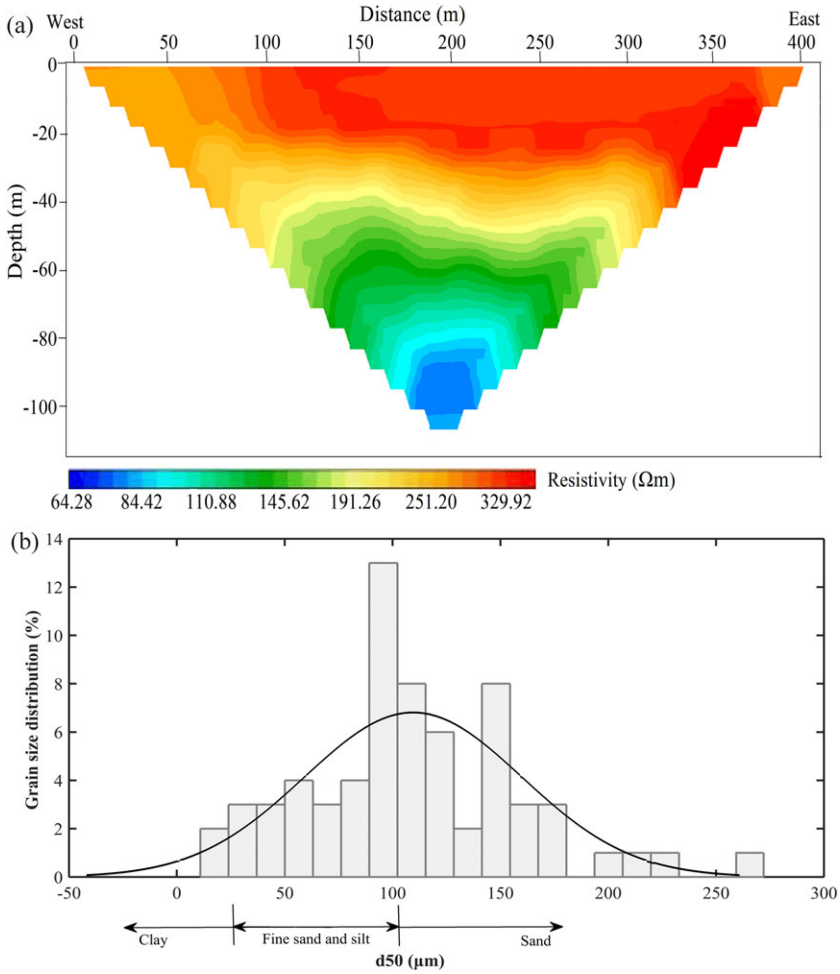

FIGURE 3 (a) Map of the apparent resistivity section in the Poyang Lake floodplain wetland and (b) grain-size distribution of average grain size diameter (d50) with a normal density function for 66 samplings. Note that resistivity values have a negative relationship with underlying water moisture [Colour figure can be viewed at wileyonlinelibrary.com]

and σ_y are the standard deviations of the time series, and $C_{xy}(k)$ is the cross-correlogram (Box et al., 1994). If $C_{xy}(k)$ is not symmetrical and if the maximum or minimum $r_{xy}(k)$ value is obtained for a positive lag, the input signal influences the output signal. The response time is the lag time that corresponds to the maximum $r_{xy}(k)$ value (Box et al., 1994). Additionally, a linear-fitting analysis was implemented to investigate groundwater level responses to surface water and explore relationships between the two.

3.4 | Flux rate calculation

The flux rate between surface water and groundwater was estimated using water levels and Darcy's law (Baxter, Hauer, & Woessner, 2003; Freeze & Cherry, 1979). The Darcy's law approach, based on point measurements, investigates the hydraulic gradient established between groundwater and surface water level, and the hydraulic conductivity of the intervening aquifer and sediment material

(Menció, Galan, Boix, & Mas-Pla, 2014). It can be written as (Freeze & Cherry, 1979; Smerdon, Devito, & Mendoza, 2005)

$$q = -K\frac{dh}{dl}, \tag{3}$$

where q is the flux rate (m/day), K is the saturated hydraulic conductivity (m/day), and dh/dl is the hydraulic head gradient (dimensionless). In this study, the horizontal gradient was determined from the isolated lakes or Xiushui River to the central water table position (averaging over all groundwater points).

In this study, the hydraulic conductivities for the lake–groundwater and river–groundwater interactions were obtained by the in situ falling head method (similar to H. Li, Sun, Chen, Xia, & Liu, 2010). The falling head experiment is a commonly used method to determine the hydraulic conductivity. It was conducted at each well on the floodplain wetland to represent the spatial variability of hydraulic conductivity, with K values ranging from 2.3×10^{-6} to 7.1×10^{-3} m/s (from clay to sand deposits). We assumed that the sediments were well sorted and had a uniform distribution (<15 m) across the Poyang Lake floodplain wetland (Figure 3). Therefore, the hydraulic conductivity of the lake bed sediments with fine silt and clay had a mean K of 2.5×10^{-6} m/s, whereas the sandy and gravel materials were estimated to have a mean K of 6.0×10^{-3} m/s for the riverbed sediments and adjacent landscape.

4 | RESULTS AND DISCUSSION

4.1 | Hydrograph analysis and groundwater flow dynamics

The observed water levels for the isolated lakes (BW and SW), the Xiushui River (RW), and the GW1–GW6 are illustrated in Figure 4. Note that all wetland groundwater points exhibit similar water-level responses to the river, relative to variations in the water level of the isolated lakes (Figure 4). The results presented indicate that the river may have a significant influence on the wetland groundwater ($p < 0.05$). It coincides with the fact that streamflow provides energy and pulses for the adjacent floodplain wetland and is expected to enhance groundwater dynamics (X. Zhang et al., 2017). In general, both groundwater and river water levels rise rapidly during the wetter spring months, and in the summer months, the groundwater, the river, and the isolated lakes have nearly the same water levels (~15 to 19 m; see the grey vertical lines in Figure 4), showing a distinct hydrological connectivity between the groundwater and the surface waters. That is, the surface waters enter into the groundwater wells during the Poyang Lake flood period. Groundwater and river water levels exhibit an obvious downward trend during autumn and winter months, whereas the two isolated lakes appear to show smaller magnitudes in water level changes (<0.4 m; see the bold lines in Figure 4). In addition, the time series shows groundwater and river levels that decrease at a more rapid rate in September compared with the isolated lake levels (Figure 4). However, GW3 is an exception and shows a lower rate of decrease. This is possibly due to the effects of Banghu Lake and local geology situation. Generally, temporal variations in the groundwater level are distinctly less than those of the isolated lakes but slightly higher than those of the Xiushui River.

Groundwater and surface water hydrographs indicate that the horizontal hydraulic gradients between the two can reach up to ~4 m during the drier winter months, whereas the hydraulic gradients are close to 0 m during the wetter summer months (Figure 4). It should be noted that there is an average increase in groundwater level (~3 m) during some drier periods (see the time windows in Figure 4). Except for climate variability (no large rainfall event; Figure 2), the anthropogenic causes (e.g., upstream dam operation) appeared to result in an abrupt increase in the Xiushui River discharge and subsequently affected the floodplain wetland, resulting in a higher groundwater levels.

Changes in the horizontal hydraulic gradient between the surface water and groundwater are inextricably linked to wetland groundwater dynamics and the associated flow field. The overall groundwater flow direction in the Poyang Lake floodplain wetland, inferred from the water level difference (as a surrogate for the hydraulic gradient), is shown in Figure 5. From the data available, four distinct groundwater flow fields can be recognized across the study area (see the four time windows in Figure 4). Although groundwater and surface waters

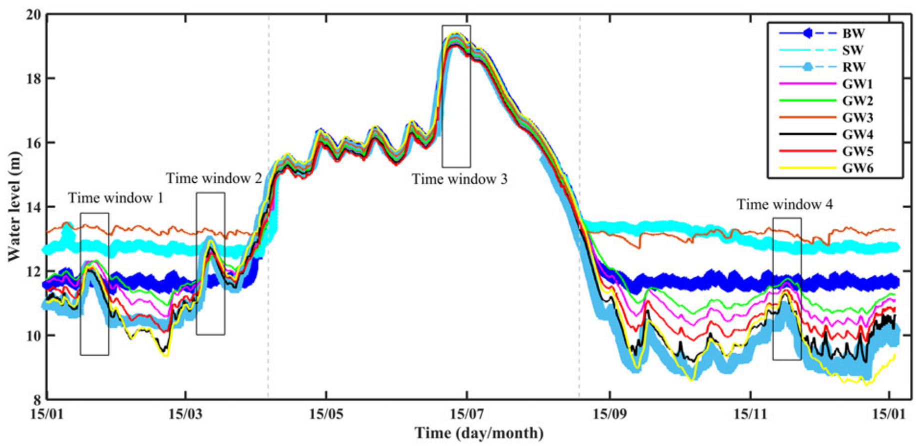

FIGURE 4 Water level time series for surface water (bold lines) and groundwater in the Poyang Lake floodplain wetland from January 15, 2016, to January 17, 2017. Time windows indicate the high groundwater level period, and the grey vertical lines indicate the wetland's flood period [Colour figure can be viewed at wileyonlinelibrary.com]

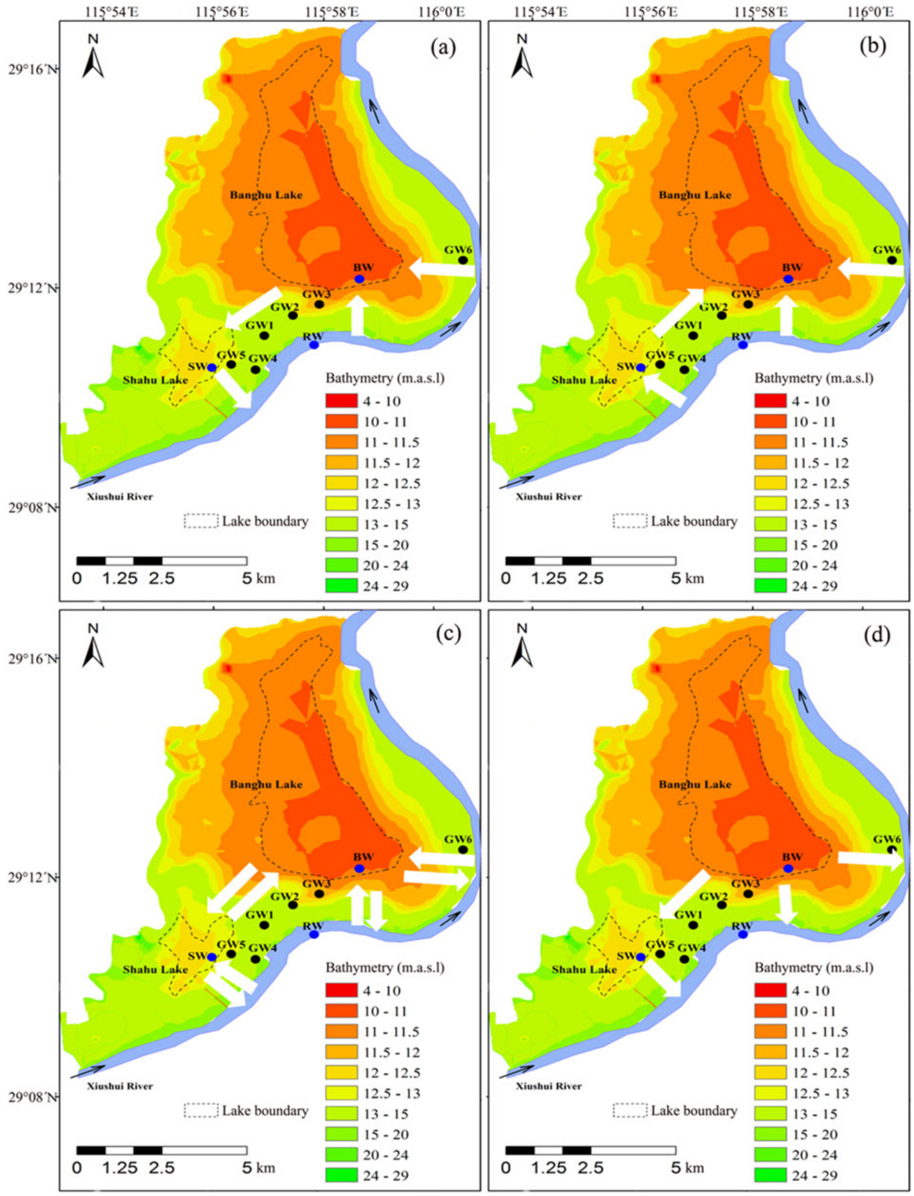

FIGURE 5 (a)–(d) Overall groundwater flow direction (bold white arrows) of the Poyang Lake floodplain wetland, inferred from the water level gradient for the four time windows [Colour figure can be viewed at wileyonlinelibrary.com]

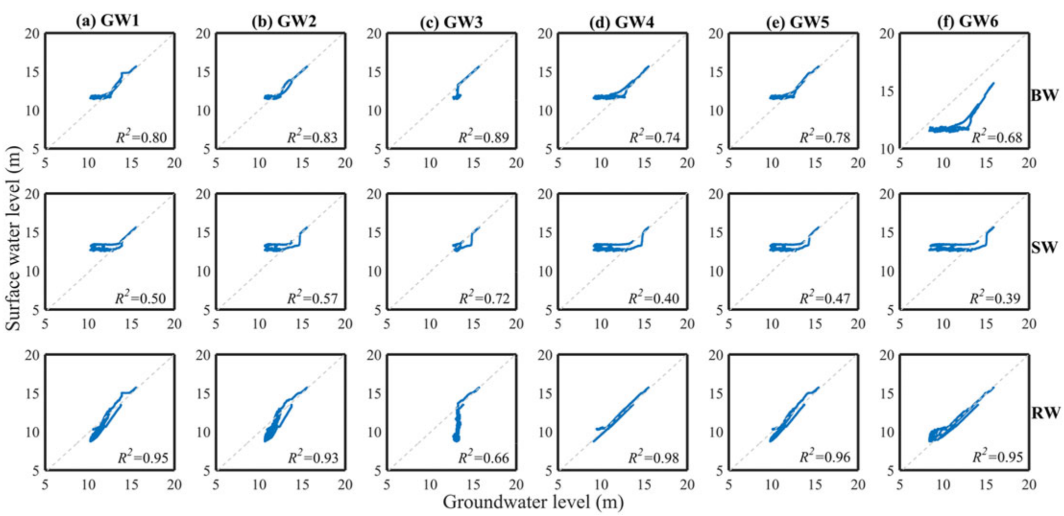

FIGURE 6 Regression analysis for (a)–(f) groundwater and surface water levels with the 1:1 line and the coefficient of determination R^2 [Colour figure can be viewed at wileyonlinelibrary.com]

(i.e., the isolated lakes and river) are more likely to exhibit frequent exchange during the summer seasons (Figure 5c), the spatial variability in groundwater flow directions, based on the observed water-level differences shown in Figure 4, is relatively high (Figure 5a,b,d). That is, the regional groundwater flow directions on the river-floodplain wetland-isolated lake system are highly dynamic and complex, as expected (Figure 5a,b,d). For the majority of the time period, the floodplain groundwater may generally receive water from the isolated lakes (i.e., the lake level is higher than groundwater level) and discharge to the adjacent river (the groundwater level is higher than the river level).

4.2 | Relationship between groundwater and surface water

For the floodplain system, the relationship between surface water bodies (i.e., Banghu Lake, Shahu Lake, and Xiushui River) and groundwater (GW1–GW6), in terms of temporal variations in water level, is illustrated in Figure 6. Compared to the isolated lakes, the closest relationships can be observed between the wetland groundwater and the Xiushui River (RW), as reflected in R^2 values ranging from 0.93 to 0.98 (except GW3). It would therefore appear that wetland groundwater is strongly affected by the river, as was expected given that the floodplain wetland is mainly driven by streamflow in the river. Figure 6 also indicates that groundwater measurements have a stronger relationship with the Banghu Lake level (BW; R^2 in range of 0.68–0.89) than the Shahu Lake level (SW; R^2 in range of 0.39–0.72), using a linear-fitting approach ($p < 0.05$). The results are consistent with the previous findings shown in Figure 4, which indicates that all groundwater observations exhibit similar water-level responses to the river, relative to those of the isolated lakes.

Cross-correlation analysis was employed to further explore the relationship between groundwater and surface waters. The result shows the correlation coefficient varies from 0.97 to 0.99 between the river level and the groundwater level at most of the monitoring points, with a time lag of approximately 0–2 days (see the red lines; Figure 7). A relatively weak correlation was obtained for groundwater level responses to changes in the isolated lakes for all points, with the correlation coefficient less than 0.5 (see blue and green lines in Figure 7). It was therefore concluded that the hydrological regime of the Xiushui River is the dominant factor in controlling the floodplain wetland and its groundwater system.

4.3 | Temporal changes in flux rate

The time series of flux rates between surface waters and groundwater were estimated by the Darcy's law approach (Figure 8). It is apparent that differences in the flux dynamic of the river, isolated lake, and groundwater interactions that were observed depended upon the hydraulic gradient and geological conditions (Figure 8a). During spring, autumn, and winter, the Xiushui River showed obvious gaining conditions (RW–GW) with highly variable Darcy flux of up to +0.4 m/day, that is, discharge from groundwater to the river (Figure 8b). During the wetter summer months, the flux results indicated approximately neutral conditions (~0.0 m/day), due to the almost full saturation (~90 days) of the floodplain wetland (Figure 8b). During some short periods in the spring, occasionally losing conditions (less than −0.2 m/day) from the river were observed, that is, discharge from the river to groundwater. The Darcy fluxes for the two isolated lakes (BW–GW and SW–GW) appeared to show similar variation trends throughout the year, and the isolated lakes were more likely to exhibit losing conditions (less than −0.1 m/day). The annual flux rates were 7.5, 12.6, and 48.2 m/day for the interactions of BW–GW, SW–GW, and RW–GW, respectively (Figure 8c). On average, the flux rate for RW–GW is seven and four times higher than for the BW–GW and SW–GW rates, respectively, suggesting the river as the dominant factor in controlling the floodplain groundwater.

4.4 | Implications and future research

Water fluxes into wetland systems have been shown to exhibit long-lasting consequences and can be important for biogeochemical cycling

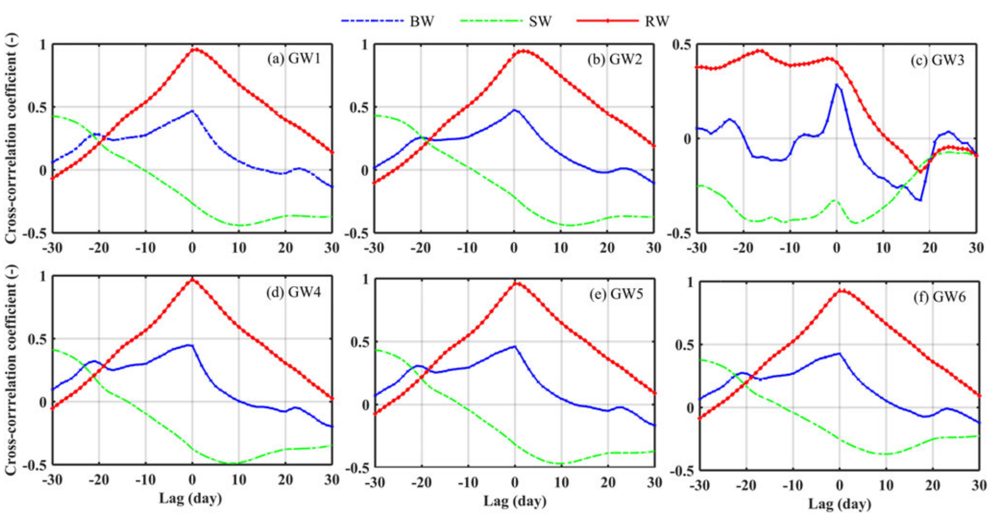

FIGURE 7 Cross-correlation function for (a)–(f) wetland groundwater level responses to the water level of BW, SW, and RW. The maximum cross-correlation coefficient corresponds to the time lag [Colour figure can be viewed at wileyonlinelibrary.com]

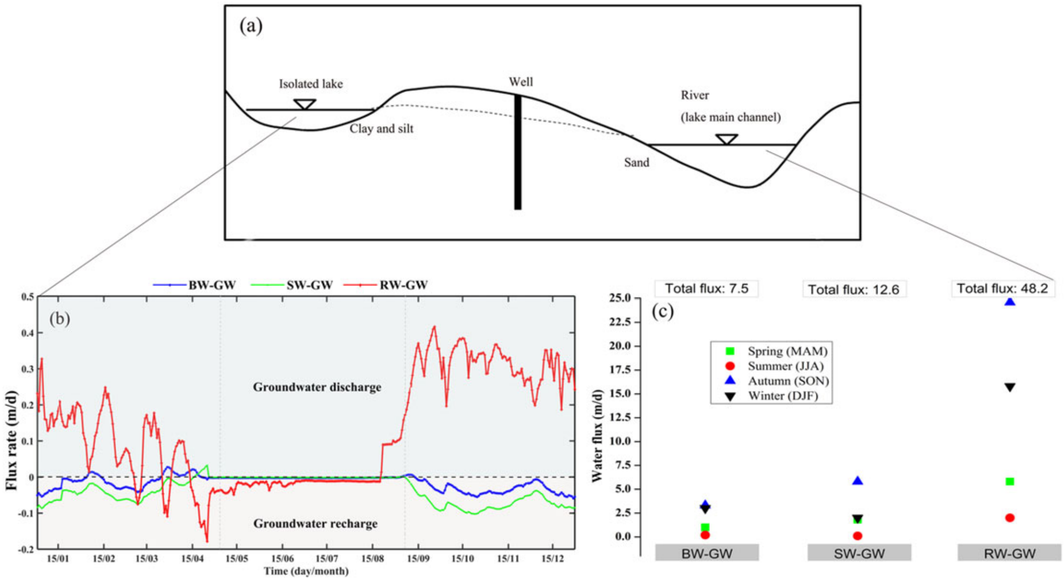

FIGURE 8 (a) Conceptual diagram of the Poyang Lake floodplain; (b) estimated Darcy flux rate using the surface water levels (BW, SW, and RW) and groundwater levels (averaged over GW1–GW6); and (c) corresponding seasonal flux (absolute value) for the interactions between surface waters and groundwater. Positive values indicate the wetland groundwater (GW) discharged to the BW, SW, and RW, and the negative values represent the BW, SW, and RW discharge to the GW. The grey vertical line indicates the wetland's flood period [Colour figure can be viewed at wileyonlinelibrary.com]

(Gu et al., 2012). Human activities, such as groundwater abstraction and dam operation, have been shown to have large effects on surface water–groundwater interactions (Francis, Francis, & Cardenas, 2010; Hutchins et al., 2018). In the case of the Xiushui River adjacent to the floodplain wetland of Poyang Lake, the dam operation upstream (~8 km from the study area) causes a significant change in the river level, which alters the hydraulic gradient and results in a dynamic river–groundwater exchange. It is anticipated that the proposed Poyang Lake Dam will be designed across the downstream channel (Jiao, 2009). It is noteworthy that the hydrological regime and associated water level within the lake are more likely to be altered (Y. Li, Zhang, et al., 2017), and hence, the surface water–groundwater interactions within floodplain system will also be affected, which will subsequently affect the wetland ecosystem. Therefore, the results of this study should be considered a preliminary first step towards a fuller understanding of the surface water–groundwater interactions in a complex floodplain system. In addition, the frequent low levels of Poyang Lake have aroused wide concern over the past decade, due to climate change and human activities (Q. Zhang et al., 2014). More importantly, the lake water level may increase during the wet season and decrease in the dry season under future climate change scenarios (Ye, Zhang, Bai, & Hu, 2011), which is more likely to affect the quantity and water quality of surface water–groundwater interactions.

In this study, the groundwater hydrodynamic field is assessed based on limited observation points. This flow field may affect the seasonal water balance of both the lake and the wetland. Further work is needed to develop a combined surface-groundwater model and improved simulation of the flow field using sufficient field observations. It must be acknowledged that our current observations are

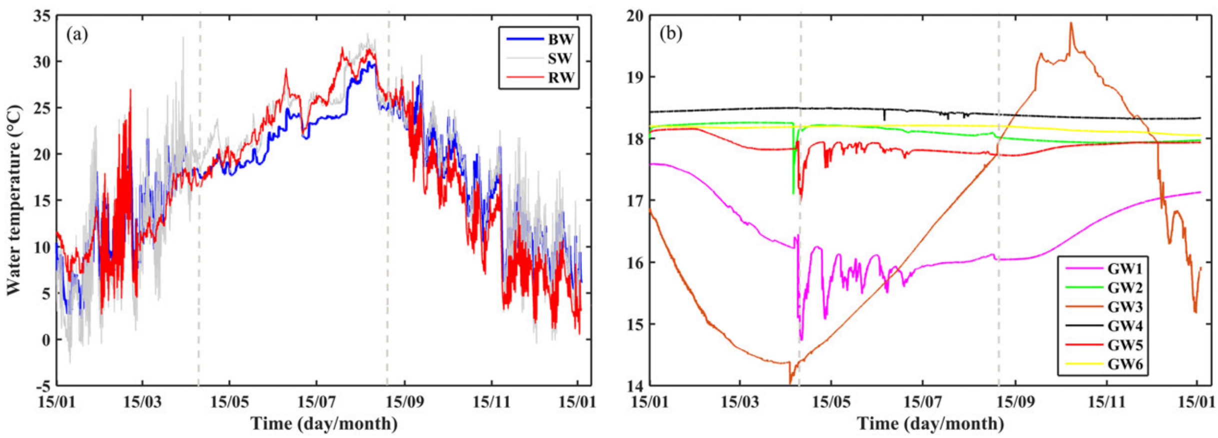

FIGURE 9 Water temperature time series for (a) surface water and (b) groundwater in the Poyang Lake floodplain wetland from January 15, 2016, to January 17, 2017. The grey vertical lines indicate the flood period of the wetland [Colour figure can be viewed at wileyonlinelibrary.com]

limited to shallow groundwater in the floodplain wetland. Fieldwork is also needed to explore the influence of deeper groundwater flows on wetland hydrology, albeit it is a challenging and difficult task. Additionally, an eco-hydrological model may be developed in conjunction with the surface-groundwater model for a better and complete representation of the complex river-floodplain wetland-isolated lake system. The assumption of lateral water flux between surface water and groundwater in the Poyang Lake floodplain system applies to conditions where the vertical exchange is not considered. It is reasonable to predict the magnitude and direction of vertical surface water–groundwater interactions. It can be observed that temperatures in Banghu Lake, Shahu Lake, and the Xiushui River show diurnal and annual changes (−3°C to 32°C; Figure 9a). Temperature oscillations in the surface waters and their underlying sediments provide a mechanism for estimating vertical water fluxes (Keery et al., 2007). However, the current temperature observations in the groundwater well (14–19.8°C; Figure 9b) cannot be used as a valid estimation. As such, a temperature thermal profile approach will improve our ability to extend the current study.

5 | CONCLUSIONS

The floodplain system of Poyang Lake (China) has a large water storage capacity, where surface water–groundwater interactions play an important role in affecting its hydrological and ecological functioning for both the lake and wetland. The current study is the first to investigate the surface water–groundwater dynamics, interactions, and flux rates in the complex river-floodplain wetland-isolated lake system, using field methods, statistical analysis, and the Darcy's law approach. Our results show that, in general, the wetland groundwater levels are lower than those of the isolated lakes in the floodplain system but slightly higher than the river, mainly due to the topographical features. Wetland groundwater exhibits similar water level responses to the river, relative to variations in the water level of the isolated lakes. Statistical analysis indicates that the wetland groundwater dynamics are mainly controlled by the river (R^2 = 0.93–0.98), rather than the isolated lakes (R^2 = 0.39–0.89), demonstrating that the river is a dominant factor in controlling adjacent floodplain groundwater levels.

The combined effect of hydraulic gradient and geology of the floodplain determine the differences in the flux dynamic between the river, isolated lakes, and groundwater interactions. In most cases, the river shows gaining conditions and occasionally losing conditions, with highly variable Darcy fluxes up to +0.4 and −0.2 m/day, respectively. The seasonal isolated lakes appear to exhibit similar flux variations and are more likely to show losing conditions up to −0.1 m/day, as expected. The accumulated flux for the interactions between surface waters and groundwater exhibits distinctly seasonal variations. The seasonal flux rates for the surface water–groundwater interactions range from 7.5 to 48.2 m/day, whereas the flux rate for river–groundwater interactions was around four to seven times higher than that of the isolated lake–groundwater interactions. These findings provide useful information for the future lake–wetland management of not only Poyang Lake but also of other similar floodplain systems worldwide.

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