Evidences of hydraulic relationships between groundwater and lake water across the large floodplain wetland of Poyang Lake, China

Yunliang Li, Jing Yao, Guizhang Zhao and Qi Zhang

ABSTRACT

Hydraulic relationship between wetlands and lakes has become an important topic for the scientific and decision-making communities. Poyang Lake, an open freshwater lake in China, and the extensive floodplain wetland surrounding the lake, plays an important role in protecting the biodiversity of this internationally recognized wetland system. This paper is the first field-based study into an investigation of the groundwater dynamics in the floodplain wetland and the associated hydraulic relationship with the lake using hydrological, hydrochemical and stable isotope evidence, as exemplified by Poyang Lake wetland. Results show that groundwater stores within the floodplain wetland exhibit spatial and temporal variability in terms of the magnitudes of groundwater level variations. Floodplain groundwater fluctuations largely reflect patterns of the precipitation and the lake water level; however, the groundwater dynamics are highly affected by the variations in the lake water level, rather than local precipitation. Floodplain wetland is most likely to receive the lake water during spring and summer and may recharge the lake during periods of low lake water level. Additionally, floodplain groundwater displays similar hydrochemical and environmental isotope signatures to that of the lake at different sampling periods, indicating a close hydraulic relationship between groundwater and the lake throughout the year.

Key words | floodplain groundwater, hydraulic relationship, hydrochemistry, lake water, Poyang Lake wetland, stable isotope

INTRODUCTION

Biodiversity is severely threatened across the globe by environmental changes. This specifically applies to wetlands which harbour a high proportion of global biodiversity while deteriorating at an unprecedented pace exceeding that of other ecosystems (Millennium Ecosystem Assessment 2005). The importance of wetlands to biodiversity is now widely recognized and there is growing recognition of the importance of hydrological processes to many of these systems (Murray et al. 2003; Mitsch & Gosselink 2007).

Geographically speaking, floodplain wetlands are a specific subset of wetland systems and are characterized by a seasonal and generally predictable wetting and drying that has important implications for future effects of climate and land use change (Hamilton et al. 2002). This process can range from isolated, very shallow or even desiccated water bodies, to much deeper water bodies with respect to the flow regime of rivers or lakes (Frazier & Page 2006; Townsend 2006). Floodplain wetlands play an important role in flood regulation and attenuation of flood waves by storing and slowing the progress of flood water (Frazier & Page 2006; Dessie et al. 2014). Ecologically, floodplain wetlands may act as sources or sinks of organic matter and...
nutrients, breeding grounds and nurseries for aquatic biota, while also providing a habitat for a diverse range of aquatic and terrestrial plants and animals (Kingsford 2000).

For many large surface water bodies (e.g. rivers, lakes, etc), long-term gauging records provide valuable information about historical flow regimes. However, little is known about the hydraulic relationships between surface waters and their surrounding floodplain wetlands due to difficulties in acquiring data for floodplain systems (Wilcox et al. 2011; Dessie et al. 2014). Hydraulic relationships between surface waters and wetlands can occur via multiple pathways, including but not limited to overland flow (Wilcox et al. 2011), groundwater (Winter & LaBaugh 2005), perched groundwater discharge (Brunner et al. 2009), or through horizontal near-surface flow (Pyzoha et al. 2008). Among these, the connection between floodplain groundwater and surface waters in wetlands has been shown to be a driving factor in biogeochemical processes (Hunt et al. 1999; Woessner 2000) and nutrient retentive processes (Noe & Hupp 2007; Rucker & Schrautzer 2010). Generally, floodplain wetlands receive water during periods of high flow and may recharge the adjacent surface waters by seepage during periods of low flow (Frazier & Page 2006). Additionally, groundwater-surface water connections are variable across spatial and temporal scales, physiographic settings, and ecoregions (Golden et al. 2014). It is therefore important to identify the hydraulic relationship between groundwater and surface water in floodplain systems that determines the nature of the wetland’s physical and ecological function (Jolly et al. 2008; Humphries et al. 2011; Ludwig & Hession 2015).

Poyang Lake (28°4′–29°46′N, 115°49′–116°46′E), located on the south bank of the middle reaches of the Yangtze River, is the largest freshwater lake in China (Shankman et al. 2006). The floodplain wetland of Poyang Lake, as one of the world’s six major wetland systems, plays an important role in the protection of biodiversity for the internationally recognized wetland system (Kanai et al. 2002; Wang et al. 2015). The wetland has also attracted considerable public attention during the past decade, as the natural fluctuations of water level in Poyang Lake have been changing dramatically due to climate change and human activities (Zhang et al. 2012; Feng et al. 2013; Lai et al. 2014), including an earlier seasonal drying of a large portion of the wetland area accompanied by longer periods of low water levels in the lake (Mei et al. 2016). Therefore, to the authors’ best knowledge, previous studies have focused on the influences that Poyang Lake water level changes have on the floodplain wetland ecology, using a combination of observations of the lake water levels and remote sensing techniques (e.g. You et al. 2015; Feng et al. 2016a, 2016b; Tan et al. 2016). In addition, some researchers have pointed out that groundwater has remained a major water supply source that affects the ecology of floodplain wetlands in Poyang Lake (Xu et al. 2014; 2015; Deng et al. 2016; Feng et al. 2016b). Therefore, investigation of the groundwater dynamics and the hydraulic relationship with associated lake water level changes is a first important step to understand how the wetland may be potentially affected by the lake and, in turn, how the wetland affects the local hydrology and water balance of the lake. Such an understanding is critical to help flood control, land use planning, and ecological conservation for both the lake and wetland. However, to date, these scientific questions remain poorly understood due to data deficiencies in the floodplain wetland of Poyang Lake.

The specific objectives of this paper are to: (1) investigate the spatial-temporal dynamics of groundwater levels and the associated hydraulic relationship with the lake water level changes in the floodplain wetland of Poyang Lake, using statistical methods; and (2) apply hydrochemistry and stable isotope signatures from water sources (lake water, groundwater, and precipitation) to assess the hydraulic relationship between the floodplain groundwater and lake water.

MATERIALS AND METHODS

Study area

Poyang Lake is located at the south bank of the middle reaches of the Yangtze River, and has a catchment area of \(1.62 \times 10^5 \text{ km}^2\) (Shankman et al. 2006). The lake has a maximum length and width of 173 km and 74 km, respectively (Figure 1(a)). 85% of Poyang Lake has a water depth less than 6 m during flood seasons, indicating that the lake is generally shallow (Li et al. 2016). Poyang Lake receives
inflows predominantly from five major rivers, including the Ganjiang, Fuhe, Xinjiang, Raohe and Xiushui Rivers within its drainage catchment, and it subsequently discharges its water into the Yangtze River through a narrow outlet channel at the northern end of the lake (Figure 1(a)). The lake is in a humid, subtropical monsoon climate zone, with a mean annual precipitation and evapotranspiration of 1,570 and 797 mm/yr, respectively (averaged over the periods during 2000–2010). Surface air temperatures are also highly seasonal, with June–August average of 28.4°C, December–February average of 5.2°C, and annual average of 17.2°C for the periods during 2000–2010 (data obtained from the National Climate Center of China Meteorological Administration).

The hydrological regime of Poyang Lake is controlled both by the catchment rivers and the Yangtze River (Hu et al. 2007; Guo et al. 2012; Zhang et al. 2014; Li et al. 2017). These result in dramatic seasonal water level fluctuations of 8 to 22 m each year, and associated substantially changes in the water surface area. During the late spring and early summer, the water level dramatically increases and the water surface area expands to over 4,000 km², whereas the water level decreases sharply, reaching a surface area less than 1,000 km² in the winter, according to the remote-sensing data (Figure 1(b)). It is a geometrically complex lake with tortuous shorelines and incised bottom morphology, which are shaped by a combination of lacustrine and riverine morphological processes (Gao et al. 2014). Poyang Lake has shrunk in size in recent years, resulting in significant hydrological, ecological and economic consequences (Liu et al. 2013). The lake is characterized by dramatic seasonal fluctuations in water level that favor the development of an approximately 3,000 km² floodplain wetland adjacent to the lake (Feng et al. 2012; Yao et al. 2016). The wetland is home to 310 species of birds (most of which are migratory), of which 16 are listed as threatened by the International Union for the Conservation of Nature. Wetland vegetation in Poyang Lake exhibits zonal distribution from the lake center to the shorelines, including floating vegetation zone, submerged vegetation zone, emergent aquatic vegetation zone, semi-aquatic emergent tall vegetation zone and mesophytic vegetation zone (Tan et al. 2016). Sedges
(Carex spp.) are the main aquatic vegetation in the wetland, dominating areas at an elevation between 14.2 m and 16 m above Wusong datum (Mei et al. 2016).

Data available and sample collection

The national gauging stations of Hukou, Xingzi, Duchang, Tangyin and Kangshan, located from the downstream outlet to the most upstream end of the lake (Figure 2(a)), were adopted to provide routine observations of Poyang Lake water levels (Wusong datum) and meteorological data on a daily basis (Figure 2(a)). Within the seasonal floodplain wetland of the lake, the monitoring wells of Wucheng (Wusong datum 19.0 m), Banghu (16.7 m), Nanji (15.1 m), Ksx1 (13.7 m) and Ksx2 (14.2 m), located from the northern region to the southern region of the wetland (Figure 2(a)), were installed during the dry season on 20th-21st December, 2013 and expected to represent spatial and temporal variations in groundwater levels. The water-table depth below soil surface, as a surrogate for the groundwater level, were monitored automatically and recorded hourly using Solinst 3001 Levelogger (Canada) with an accuracy of 0.01 m. Additionally, the field-survey along one transect illustrates the sedimentary successions in the floodplain wetland show varying combinations of sand, silt and clay (Figure 2(b)). The depth of the monitoring wells is around 10–15 m below the soil surface with sand aquifer (i.e. shallow groundwater). Then entirety of the hydrometeorological data within Poyang Lake is available for 2014 and was used to perform statistical analysis. The lake water levels and bathymetry data (see Figure 2(a)) were obtained from the Hydrological Bureau of Jiangxi Province and the

Figure 2 | (a) Spatial distribution of hydrometeorological observations and sampling points within Poyang Lake; (b) A–A’ represents the wetland transect around the Wucheng gauging station surveyed on 16th March, 2014.
Hydrological Bureau of the Yangtze River Water Resources Commission of the Ministry of Water Resources of China, respectively.

Precipitation samples were collected adjacent to the Xingzi gauging station (Figure 2(a)) during the period from 20th March, 2014 to 18th March, 2015, while water samples were collected three times from lake and groundwater sources during February (winter), April (spring) and June (summer) 2014. Lake water samples were collected at nine locations across the lake’s main flow channels (L1–L9; Figure 2(a)). The samples were collected into pre-cleaned bottles hand dipped approximately 0.5 m below the lake water surface to avoid contamination by floating pollutants. Groundwater was pumped directly from the five monitoring wells in the wetland (G1–G5; Figure 2(a)) and the samples were collected after measurements of electrical conductivity (EC) and pH were stabilized. The EC (mS/cm; YSI Pro 2030, USA) and pH (YSI Pro 10, USA) of the water samples were measured in situ using a handheld meter with a probe. All water samples were stored in 50 mL-volume amber-glass vials with screw tops for isotopic analysis and 500 mL bottles for hydrochemical analyses. The samples for anion and isotope testing were transported with ice bags and then refrigerated at approximately 4 °C until laboratory analysis.

**Laboratory test and analysis**

The oxygen and hydrogen isotope compositions were analyzed during April 2015 using the Picarro L2120-i water isotope analyzer at the Stable Isotope Laboratory, Key Laboratory of Agriculture Water Resources, Chinese Academy of Sciences. Isotopic values were expressed in delta (δ) units (‰) relative to the international Vienna Standard Mean Ocean Water (VSMOW standard; Gonfiantini 1978): 

\[
\delta_{\text{sample}} = \left( \frac{R_{\text{sample}} - R_{\text{VSMOW}}}{R_{\text{VSMOW}}} \right) \times 1,000, \quad \text{where} \quad R = \frac{^{18}\text{O}/^{16}\text{O}}{^{1}\text{H}/^{2}\text{H}} \quad \text{for} \quad \delta^{18}\text{O} \quad \text{and} \quad \delta^{2}\text{H}. \]

When δ is positive, it indicates enrichment in the heavy isotope. A negative δ sample indicates depletion in the heavy isotope. The precision was ±0.07‰ for oxygen and ±0.2‰ for hydrogen.

The samples’ hydrochemical analyses were performed during June 2014 at the Analytical Laboratory, State Key Laboratory of Lake Science and Environment, Chinese Academy of Sciences. The analysis of anion (Cl−, SO2−4, NO3−, F−) and major cation (Na+, K+, Ca2+, Mg2+) concentrations (mg/L) was performed using an ion chromatography system (Dionex ICS-2000, USA).

**Statistical analysis**

Cross-correlation functions were adopted in this study to establish relationships between the input and output time series, and can be written as (Box et al. 1994):

\[
C_{xy}(k) = \begin{cases} 
1 & L - h \sum_{l=1}^{L-h} (x_l - \bar{x})(y_{l+h} - \bar{y}) \quad k = 0, 1, 2, \ldots \\
1 & L - h \sum_{l=1}^{L-h} (y_l - \bar{y})(x_{l-h} - \bar{x}) \quad k = 0, -1, -2, \ldots 
\end{cases}
\]

\[
r_{xy}(k) = \frac{C_{xy}(k)}{\sigma_x \sigma_y} \quad k = 0, \pm 1, \pm 2, \pm \ldots
\]

where k is the time lag, L is the length of the time series, x and y 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, \( \sigma_x \) and \( \sigma_y \) 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). The relationship between the groundwater levels and the lake water levels (or precipitation) were computed and implemented in MATLAB® using this method.

The cross wavelet transform (XWT) of two time series \( x_n \) and \( y_n \) is defined as \( W^{XY} = W^XW^Y \), where * denotes complex conjugation. The theoretical distribution of the cross wavelet power (\(|W^{XY}|\)) of two time series with background \( P_k^X \) and \( P_k^Y \) is given as (Torrence & Compo 1998):

\[
D \left( \frac{W_{n}^{X} (s)W_{n}^{Y*} (s)}{\sigma_X \sigma_Y} < p \right) = Z_v(p) \sqrt{P_k^X P_k^Y}
\]

where s and t are the scale and time parameter, respectively, \( Z_v(p) \) is the confidence level associated with the probability.
where $p, q$ is equal to 1 for real and 2 for complex wavelets (Grinsted et al. 2004).

The wavelet coherence (WTC), which is defined as the coherence of the cross wavelet transform in time frequency space, can be written as (Torrence & Webster 1999; Grinsted et al. 2004):

$$R_n^2(s) = \frac{|S(s^{-1}W_{XY}(s))|^2}{S(s^{-1}|W_n^2(s)|^2) \cdot S(s^{-1}|W_n^2(s)|^2)}$$

$$S(W) = S_{\text{scale}}(S_{\text{time}}(W_n(s)))$$

$$S_{\text{time}}(W)|_{s} = (W_n(s) \ast c_1 2^{s/2} \ast)|_{s},$$

$$S_{\text{scale}}(W)|_{s} = (W_n(s) \ast c_2 \Pi(0.6s))|_{s}$$

where $S$ is a smoothing operator, $S_{\text{scale}}$ denotes smoothing along the wavelet scale axis, $S_{\text{time}}$ represents smoothing in time, $c_1$ and $c_2$ are normalization constants and $\Pi$ is the rectangle function. The factor of 0.6 is the empirically determined scale decorrelation length for the Morlet wavelet (Torrence & Compo 1998). In the current study, the XWT and WTC analysis were implemented in MATLAB$^*$ and used to examine causal relationships in time frequency space between the lake water levels and the groundwater levels.

RESULTS

Hydrological conditions and groundwater level dynamics

Figure 3 shows the hydrological data of Poyang Lake wetland during 2014, including precipitation, lake water level and groundwater level at different gauging stations (see Figure 2 for locations). Precipitation shows significant seasonal variations in the range of 0−61 mm/day (Figure 3(a)). Statistical analysis indicates that precipitation records on the lake surface show distinct wet and dry seasons, with 42% of annual precipitation concentrated in the wet season from April to June, and only 14% of rainfall occurring from September to December, on average (Figure 3(a)). The observed lake water level changes follow similar seasonal variation to the precipitation, including four water level periods (Figure 3(b)): (1) rising water level (March−June), (2) high water level (July−September), (3) falling water level (October−November) and (4) low water level (December−February). The lake water surface elevation has a maximum spatial difference of approximately 5 m in low level periods, whereas the water surface is almost horizontal during periods of high lake level (Figure 3(b)).

Groundwater fluctuations in the floodplain wetland, as shown in Figure 3(c), largely reflect precipitation and lake water level patterns. It would therefore appear that the dynamic of wetland groundwater levels is attributable to the combined effects of seasonal variations in the regional precipitation and lake water level, as expected. Although the precipitation and groundwater from the Poyang Lake catchment may affect the floodplain wetland (Hu et al. 2015), these accompanying factors mainly contribute to the lake water level changes (Chen et al. 2015). Generally, groundwater level rises rapidly from April to May, retains a direct hydraulic connectivity with the lake water during June−September (i.e. the water-table above ground level) and begins to decline in October (Figure 3(c)). Groundwater levels at Wucheng and Banghu gauging stations varied from 0.53 to 10.49 m below ground, and from 8.0 below ground to 2.0 m above ground, respectively, while the groundwater levels have relatively small changes (ranging from 1.6 m below ground to 4.6 m above ground) averaged over Nanji, Ksx1 and Ksx2 gauging stations (Figure 3(c)). These results indicate that groundwater levels at Wucheng and Banghu are much more dynamic than those of the other three gauging stations in terms of the magnitudes of groundwater variations (Figure 3(c)). In addition, the water-table depths throughout the year are close to the soil surface (i.e. approximately <0.5 m) for Nanji, Ksx1 and Ksx2 gauging stations (Figure 3(c)). This is potentially due to the fact that the lake water levels in the middle and upstream sections of the lake are distinctly higher than those downstream (Figure 3(b); Li et al. 2015), possibly inducing a generally shallow groundwater level. The difference between groundwater levels is illustrated further in Figure 3(d) that gives cumulative frequency plots of water-table depths at the five gauging stations with an average spatial difference of approximately 4.9 m (Figure 3(d)), indicating the spatial variability of groundwater level distribution across the floodplain wetland of Poyang Lake.
Hydraulic relationship between lake and groundwater

Wetland hydrology and associated groundwater level are inextricably linked to the changes in the dynamic behavior of both precipitation and the lake water level. Cross-correlation analysis shows significant correlation (i.e., the correlation coefficient varies from 0.93 to 0.99) between the lake water levels and the wetland groundwater levels at all five gauging stations, with a time lag of approximately 0 days (Figure 4). A relatively weak correlation (i.e. correlation coefficient <0.2), with a time lag of around 12 days or more is obtained for wetland groundwater level responses to changes in precipitation at all the gauging stations (Figure 4). This coincides with the stable isotope analysis ($\delta^{18}$O) of the Poyang Lake wetland by Deng et al. (2016), who found that the floodplain groundwater may be possibly influenced by precipitation and surface water (i.e. lake and river water). In this study, cross-correlation analysis demonstrates that the groundwater level across the floodplain wetland has a close hydraulic relationship with Poyang
Lake water level, while precipitation has a lagged effect on groundwater level dynamics, even though precipitation is concentrated in the wet seasons (Figure 3(a)). That is, the floodplain groundwater of Poyang Lake is mainly driven, on a seasonal time scale, by the flow regime of the lake rather than meteorological forcings (e.g. rainfall events). It is expected that the differences in water levels of the floodplain wetland and Poyang Lake would represent well the hydraulic relationship between the two (Figure 5). The results reveal that, in general, the lake water may recharge the wetland groundwater during spring and summer (i.e. May–September), while the lake is more likely to discharge the wetland groundwater during other seasons (Figure 5). The seasonal pattern of hydraulic relationship may have important influences on the dynamic water balance for both the lake and wetland.

Figure 6 shows the XWT and WTC results of time-frequency relationships as well as their phase angles using arrows, respectively. The 95% confidence intervals of the relationship are shown within the area surrounded by the
Figure 6 | Cross wavelet transform (XWT) and wavelet coherence (WTC) of the averaged lake water level and wetland groundwater level time series. (a)–(e) represent the XWT (left graphs) and WTC (right graphs) at Wucheng, Banghu, Nanji, Ksx1 and Ksx2 gauging stations, respectively. The relative phase relationship is shown as arrows (with in-phase pointing right and anti-phase pointing left) and the cone of influence (COI) where edge effects might distort the picture is shown as a lighter shade.
thick line. The XWT results show that significant lake water level/groundwater level associations can occur within a wide range of frequencies with periods from approximately 10 days to 64 days (Figure 6(a)–6(e)). Among them, the clear associations at period of 60 days are constantly observed throughout the entire study period for all of the five lake water level/groundwater level pairs, indicating a long-term hydraulic relationship between the two. As the frequency is lower, significantly associated areas are generally increased and observable primarily during the spring and summer (Figure 6(a)–6(e)), which coincides with high lake levels and groundwater levels during these seasons (Figure 5). This is a logical outcome of the need for high Poyang Lake water levels in order for groundwater recharge to occur, suggesting a main determinant of the floodplain wetland. In a similar way to XWT, the WTC results represent significant correlations between the variations of the lake water level and groundwater level at Wucheng and Banghu gauging stations (Figure 6(a) and 6(b)) during the entire study period, relative to the other three stations (Figure 6(c)–6(e)). This result is highly consistent with the cross-correlation analysis (Figure 4). Additionally, the WTC results given in Figure 6 indicate that significantly high correlations are also present for all the gauging stations. The correlation presents stronger seasonality at medium-high frequency (i.e. 8–64 days) for the time series (Figure 6).

**Hydrochemistry and stable isotope characteristics**

Surface water from Poyang Lake and precipitation are the sources of wetland groundwater, which is characterized by relatively low EC during different sampling seasons (Table 1). Overall, groundwater across the floodplain wetland is characterized by similarly low conductivities,

<table>
<thead>
<tr>
<th>Water type</th>
<th>EC (mS/cm)</th>
<th>pH (–)</th>
<th>Na⁺ (mg/l)</th>
<th>K⁺ (mg/l)</th>
<th>Ca²⁺ (mg/l)</th>
<th>Mg²⁺ (mg/l)</th>
<th>Cl⁻ (mg/l)</th>
<th>NO₃⁻ (mg/l)</th>
<th>F⁻ (mg/l)</th>
<th>SO₄²⁻ (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) February 2014</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Precipitation (Xingzi)</td>
<td>0.03</td>
<td>7.11</td>
<td>36.25</td>
<td>1.39</td>
<td>0.33</td>
<td>0.05</td>
<td>9.58</td>
<td>12.12</td>
<td>0.53</td>
<td>19.10</td>
</tr>
<tr>
<td>Lake water (L3)</td>
<td>0.01</td>
<td>7.6</td>
<td>726</td>
<td>0.41</td>
<td>0.001</td>
<td>0.34</td>
<td>7.39</td>
<td>15.17</td>
<td>1.95</td>
<td>29.73</td>
</tr>
<tr>
<td>Lake water (L4)</td>
<td>0.01</td>
<td>6.9</td>
<td>886.0</td>
<td>0.34</td>
<td>0.002</td>
<td>0.18</td>
<td>6.66</td>
<td>10.15</td>
<td>0.33</td>
<td>27.15</td>
</tr>
<tr>
<td>Lake water (L9)</td>
<td>0.01</td>
<td>7.6</td>
<td>606.75</td>
<td>0.47</td>
<td>0.001</td>
<td>0.27</td>
<td>6.73</td>
<td>14.62</td>
<td>0.44</td>
<td>34.66</td>
</tr>
<tr>
<td>Groundwater (G1)</td>
<td>0.03</td>
<td>6.87</td>
<td>712</td>
<td>0.29</td>
<td>0.89</td>
<td>0.69</td>
<td>3.68</td>
<td>5.06</td>
<td>0.35</td>
<td>5.87</td>
</tr>
<tr>
<td>Groundwater (G3)</td>
<td>0.03</td>
<td>6.92</td>
<td>502.5</td>
<td>0.17</td>
<td>0.007</td>
<td>0.51</td>
<td>2.78</td>
<td>5.45</td>
<td>0.41</td>
<td>8.53</td>
</tr>
<tr>
<td>(b) April 2014</td>
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<td></td>
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<tr>
<td>Precipitation (Xingzi)</td>
<td>0.007</td>
<td>6.72</td>
<td>34.15</td>
<td>1.49</td>
<td>0.33</td>
<td>0.44</td>
<td>10.72</td>
<td>9.72</td>
<td>0.47</td>
<td>16.12</td>
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<tr>
<td>Lake water (L2)</td>
<td>0.001</td>
<td>6.9</td>
<td>8.04</td>
<td>0.80</td>
<td>5.94</td>
<td>14.76</td>
<td>6.04</td>
<td>10.59</td>
<td>0.47</td>
<td>19.43</td>
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<tr>
<td>Lake water (L3)</td>
<td>0.099</td>
<td>7.64</td>
<td>38.9</td>
<td>6.95</td>
<td>28.01</td>
<td>6.05</td>
<td>6.78</td>
<td>10.70</td>
<td>0.25</td>
<td>22.24</td>
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<td>6.95</td>
<td>49.0</td>
<td>7.65</td>
<td>32.58</td>
<td>6.25</td>
<td>11.48</td>
<td>10.05</td>
<td>0.20</td>
<td>36.09</td>
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<tr>
<td>Groundwater (G1)</td>
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<td>6.48</td>
<td>39.9</td>
<td>6.45</td>
<td>26.52</td>
<td>5.90</td>
<td>3.33</td>
<td>0.99</td>
<td>0.24</td>
<td>2.65</td>
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<td>0.098</td>
<td>6.38</td>
<td>42.1</td>
<td>6.85</td>
<td>27.89</td>
<td>6.04</td>
<td>0.73</td>
<td>5.31</td>
<td>0.23</td>
<td>3.33</td>
</tr>
<tr>
<td>(c) June 2014</td>
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</tr>
<tr>
<td>Precipitation (Xingzi)</td>
<td>0.004</td>
<td>7.01</td>
<td>462.3</td>
<td>0.63</td>
<td>0.33</td>
<td>0.18</td>
<td>0.77</td>
<td>2.28</td>
<td>0.17</td>
<td>3.39</td>
</tr>
<tr>
<td>Lake water (L1)</td>
<td>0.009</td>
<td>7.28</td>
<td>1.69</td>
<td>0.71</td>
<td>2.62</td>
<td>1.94</td>
<td>4.97</td>
<td>8.06</td>
<td>0.29</td>
<td>20.66</td>
</tr>
<tr>
<td>Lake water (L3)</td>
<td>0.01</td>
<td>7.78</td>
<td>1.42</td>
<td>0.90</td>
<td>4.11</td>
<td>1.72</td>
<td>6.32</td>
<td>9.88</td>
<td>0.31</td>
<td>20.81</td>
</tr>
<tr>
<td>Lake water (L4)</td>
<td>0.03</td>
<td>7.26</td>
<td>10.03</td>
<td>1.08</td>
<td>8.65</td>
<td>7.41</td>
<td>14.99</td>
<td>57.78</td>
<td>0.18</td>
<td>67.96</td>
</tr>
<tr>
<td>Lake water (L5)</td>
<td>0.008</td>
<td>7.33</td>
<td>3.17</td>
<td>0.65</td>
<td>1.82</td>
<td>2.06</td>
<td>5.10</td>
<td>5.16</td>
<td>0.22</td>
<td>19.43</td>
</tr>
<tr>
<td>Lake water (L6)</td>
<td>0.008</td>
<td>7.47</td>
<td>1.07</td>
<td>0.49</td>
<td>1.70</td>
<td>1.69</td>
<td>4.11</td>
<td>2.78</td>
<td>0.19</td>
<td>15.78</td>
</tr>
<tr>
<td>Lake water (L9)</td>
<td>0.008</td>
<td>7.2</td>
<td>0.86</td>
<td>0.67</td>
<td>1.94</td>
<td>0.99</td>
<td>3.73</td>
<td>8.55</td>
<td>0.42</td>
<td>23.40</td>
</tr>
<tr>
<td>Groundwater (G1)</td>
<td>0.030</td>
<td>6.82</td>
<td>1.02</td>
<td>0.62</td>
<td>3.67</td>
<td>3.33</td>
<td>2.19</td>
<td>0.55</td>
<td>0.18</td>
<td>3.07</td>
</tr>
</tbody>
</table>
ranging between 0.03 and 0.098 mS/cm (except for G1 in April; Table 1). Table 1 shows that the order of major ion concentrations is \( \text{Na}^+ > \text{Ca}^{2+} > \text{Mg}^{2+} > \text{K}^+ \) for cations, and \( \text{SO}_4^{2-} > \text{NO}_3^- > \text{Cl}^- > \text{F}^- \) for anions averaged over all the water samples. In addition, the hydrochemical compositions observed in the groundwater samples are more similar to those of the lake water relative to the precipitation, in terms of the magnitude in most of the ion concentrations at different sampling seasons. Although the hydrochemical signatures across the Poyang Lake wetland vary both spatially and seasonally (Table 1), the similarity of groundwater and lake water hydrochemistry appears to provide an important piece of evidence for the hydraulic relationship between the two waterbodies. Extensive sandy soils across the wetland (Figure 2(b)) may play an important role in the hydraulic connection between the two, possibly due to the high permeability of the sand.

The stable isotope contents of various water resources were measured to understand the intricate relationship between these resources within Poyang Lake (Figure 7). The relationship between \( \delta^2\text{H} \) and \( \delta^{18}\text{O} \) in precipitation is defined as a Local Meteoric Water Line (LMWL) at a site. In this study, the resulting stable isotope plot (\( \delta^2\text{H} \) versus \( \delta^{18}\text{O} \)) is measured along with the LMWL for referencing purpose (Craig 1961). The \( \delta^2\text{H} \) and \( \delta^{18}\text{O} \) distributions in the LMWL for the precipitation of Poyang Lake are varied from \(-76.12\%\) to \(16.87\%\) and from \(-9.98\%\) to \(1.27\%\), respectively (see the black dots in Figure 7). The slope of LMWL (8.6; Figure 7) is close to the slopes of meteoric water lines for south China (9.8; Zheng et al. 1983). All slopes are greater than the slope of Global Meteoric Water Line (8.0; Craig 1961), indicating the effects of wet climatic conditions on the lake. The minimum \( \delta^{18}\text{O} \) and \( \delta^2\text{H} \) values measured for precipitation averages \(-9.32\%\) and \(-66.75\%\) in June, while the maximum values were measured for February and December, averaging \(-0.94\%\) and \(3.62\%\), respectively (see the inserted chart in Figure 7), indicating a significant precipitation effect (amount effect) controlled the \( \delta^{18}\text{O} \) and \( \delta^2\text{H} \) levels of Poyang Lake (Hu et al. 2013; Zhao et al. 2015).

The \( \delta^{18}\text{O} \) and \( \delta^2\text{H} \) values of Poyang Lake water, collected from the three time periods, range from \(-6.13\%\) to \(-3.0\%\) and from \(-37.64\%\) to \(-2.45\%\), respectively (Figure 7). The average \( \delta^{18}\text{O} \) value is \(-5.13\%\), and the average \( \delta^2\text{H} \) value is \(-29.32\%) across the lake water samples. The average stable isotope values of wetland groundwater (\( \delta^{18}\text{O} \) and \( \delta^2\text{H} \), \(-5.17\%\) and \(-30.0\%\), respectively) has an isotopic signature almost identical to those of the lake water (Figure 7). That is to say, samples taken from the lake were closely related to those of the wetland groundwater, although the lake water samples during the February plot were relatively isolated from other two

![Figure 7](https://iwaponline.com/ls/article-pdf/18/2/698/206983/ls18020698.pdf)
periods (Figure 7). This result indicates that wetland groundwater has a direct hydraulic connection with the lake, especially during spring (April) and summer (June). This indicates that wetland groundwater is mainly fed by the rapidly rising lake water and large amounts of precipitation during rainy seasons (e.g. April and June; Figure 3). Additionally, the wetland groundwater may contribute to the lake water during the low lake level seasons (e.g. February). Figure 7 also shows that the isotope values of the lake water and wetland groundwater samples analyzed plot close to or on the LMWL indicating their meteoric origin. Additionally, the average isotope values during June are relatively higher than those during April and February, which is consistent with the variations of monthly mean $\delta^{18}O$ and $\delta^2H$ in precipitation (see the inserted chart in Figure 7).

**DISCUSSION**

The floodplain wetland of Poyang Lake provides significant environmental benefits, such as supplying water resources, and maintaining carbon storage and biodiversity (Xu et al. 2015). Particularly, the wetland is crucial for the conservation of the endangered Siberian crane, as more than 95% of its population migrate here during the winter (Wang et al. 2016). The significance of the work described here is that it provides a better understanding of hydrological regime in the floodplain wetland of Poyang Lake, contributing to the integrated management of the wetland and the lake. Although there have been a number of field studies of lakes and wetlands (e.g. Winter & LaBaugh 2005; Frazier & Page 2006; Mendoza-Sanchez et al. 2013; Ludwig & Hession 2015), the use of high resolution (daily and hourly) data, such as employed in the present study, is rare. It is worth noting that, although the groundwater level dynamics in the floodplain wetland of Poyang Lake may display a similar seasonal pattern to other wetland systems, the floodplain groundwater in Poyang Lake appears to exhibit more close relationship with the lake water, partly due to larger lake-wetland water level gradient (i.e., by up to approximately 2.8 m).

The Poyang Lake wetland will be sensitive to any lake management (e.g., proposed hydraulic dam; Li 2009) that might alter the hydrological regime of the lake. Thus, when developing one resource one should consider the impact on the other. Currently, the severe droughts in Poyang Lake have drawn people’s attention to the water resources shortage problem (Zhang et al. 2012, 2014; Liu et al. 2013). If Poyang Lake water level continues to decline at its current rate, the reduction in groundwater stores and associated negative consequences on the floodplain wetland ecosystem could become a serious concern. Additionally, managers and ecologists studying Poyang Lake should consider the role of floodplain groundwater on the already degraded quality of lake water (Zhen et al. 2011), not just on a whole-lake scale, but on a spatial scale. The implications of the work are not limited solely to wetlands but might apply to a range of floodplain environments that are affected more by groundwater or lake water.

The hydrological regime of a wetland is the result of a complex interplay between climate and wetland characteristics (Winter 1998). Long-term monitoring data combined with process-based modeling has the potential to shed light on key processes and how they change over time (Mendoza-Sanchez et al. 2013). Therefore, further work is needed to develop a numerical model so that it includes the floodplain wetland that is adjacent to Poyang Lake, to better simulate local-scale interactions and exchange fluxes between the wetland and the lake. Additionally, future research into the effects of water level dynamics in Poyang Lake should couple ecological models for a more detailed analysis of the influence of lake hydrology on the wetland ecology. For example, the findings in this study could be integrated with the results of hydrochemical investigations to identify ways in which future wetland degradation might alter biogeochemical cycles and impact changes in wetland vegetation communities.

**CONCLUSIONS**

This paper is the first field-based study that investigates groundwater dynamics and responses within the large floodplain wetland system of Poyang Lake (China). The spatial and temporal variations in floodplain groundwater and the associated hydraulic relationship with the lake water were examined using hydrological, stable isotope and hydrochemical evidences.
Groundwater levels across the floodplain wetland of Poyang Lake exhibit spatial variability and distinctly seasonal dynamics in terms of the magnitudes of groundwater level variations. Generally, floodplain groundwater is mainly affected by the rapidly rising lake water level during April–May, retains a direct hydraulic relationship with the lake water during June–September and contributes to the lake water from October to February. That is, floodplain wetland is most likely to receive the lake water during April–September and contributes to the lake during periods of low lake level, indicating a seasonal shift of the lake-groundwater interactions. Although the floodplain groundwater fluctuations largely reflect precipitation and lake water level patterns, statistical results show that the groundwater dynamics are primarily controlled by the variations in the lake water level, rather than local precipitation. Compared to previous studies, our research indicates that both lake and groundwater support important and ecologically sensitive wetland in the floodplain. In addition, floodplain groundwater displays similar hydrochemical composition and environmental isotope signatures as that of the lake at different seasons, providing evidence for the close hydraulic relationship between the two throughout the year.

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