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Applying energy theory to understand the relationship between the Yangtze River and Poyang Lake

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Abstract: The complex relationship between the Yangtze River and Poyang Lake controls the exchange of water and sediment between the two, and exerts effects on water resources, flooding, shipping, and the ecological environment. The theory of energy is applied in this paper to investigate the physical mechanisms that determine the nature of the contact between the Yangtze River and Poyang Lake and to establish an energy difference (F_e) index to quantify the interactions between the two systems. Data show that F_e values for this interaction have increased since the 1950s, indicating a weakening in the river effect while the lake effect has been enhanced. Enclosure of the Three Gorges Reservoir (TGR) has also significantly influenced the relationship between the river and the lake by further reducing the impacts of the Yangtze River. The river effect also increases slightly during the dry season, and decreases significantly at the end of the flooding period, while interactions between the two to some extent influence the development of droughts and floods within the lake area. Data show that when the flow of the five rivers within this area is significant and a blocking effect due to the Yangtze River is also clearly apparent, floods occur easily; in contrast, when the opposite is true and the flow of the five rivers is small, and the Yangtze River can accommodate the flow, droughts occur frequently. Construction and enclosure of the TGR also means that the lake area is prone to droughts during September and October.

Keywords: Poyang Lake; Yangtze River; river–lake relationship; Three Gorges Reservoir; characterization index

1 Introduction

The Yangtze River is the longest river in China, and Poyang Lake is the largest freshwater lake. Interactions between the two systems have significantly influenced the natural evolution of the lake (Liu and Ni, 2015), dictating hydrodynamics, sediment transport, and the morphodynamics of this system, which is critical to regional water resources, flood control, irrigation, and the ecological environment (Nakayama and Watanabe, 2008; Wang *et al.*, 2017; Zhang *et al.*, 2017). Interactions between rivers and lakes encompass a range of phys-

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physical processes, including the exchange of water between the two, the natural evolution of riverbeds and lake basins, and the interchange of material and energy (Wan *et al*., 2014).

Previous studies that have addressed the interactions between rivers and lakes have mainly focused on water interactions by addressing the exchange coefficient, as well as the storage and discharge capacity of lakes (Zhao *et al*., 2011; Lai *et al*., 2014; Wang *et al*., 2014). Investigations have also considered the ecological characteristics of these systems by addressing the nature of impacts due to the exchange of water, sand, and dissolved substances on lake quality and ecosystems (Carmack *et al*., 1979; Kneis *et al*., 2006; Elisa *et al*., 2010; Jones *et al*., 2017).

Interactions between the Yangtze River and Poyang Lake can be divided into river and lake effects. Thus, the role of the river mainly includes blocking outflows and backward flowing (river effect) (Guo *et al*., 2011), while the influence of the lake is felt in terms of regulating floods and the water supply to the lower reaches of the Yangtze River (lake effect) (Zhao *et al*., 2011; Fang *et al*., 2012). Characterizing river–lake interactions and their changing mechanisms, and predicting their future development, have attracted substantial research attention.

A number of studies have applied characterization indices to quantify river–lake interactions. In one study, Fang *et al*. (2012) developed an approach based on a judgement of backflow conditions at Hukou Station and a method to calculate flood reservation, while Lai *et al*. (2014) evaluated the discharge capacity of Poyang Lake at different times by investigating hydrological data over years between January and March, 1955–2011. In order to determine the intensity of river–lake interactions, Hu *et al*. (2007) proposed a series of five different conditions; if any of these conditions are met, then the influence of the Yangtze River can be said to be strong, but if none are met, then Poyang Lake is playing a major role. A formula for the water exchange coefficient (I_p) between rivers and lakes based on the water balance equation (which quantifies these interactions) was proposed by Zhao *et al*. (2011), while Dai *et al*. (2015) investigated water level variations within Poyang Lake and utilized the ratio of water level difference to distance between stations (i.e., Duchang–Kangshan, Hukou–Xingzi), to characterize river–lake interactions.

It is generally the case that previous studies in this area have been developed from the perspective of utilizing water interactions to investigate the discharge capacity of Poyang Lake or the backflow and blocking effects of the Yangtze River (Lai *et al*., 2014; Fang *et al*., 2012; Dai *et al*., 2015). To date, no systematic analysis of river–lake interactions has yet been carried out, and the theoretical basis upon which indices can be proposed to quantify river–lake interactions still remains unclear. Indeed, some quantitative results even appear to contradict one another (Hu *et al*., 2007; Zhao *et al*., 2011). Thus, applying the theory of energy, the physical mechanisms that underlie the interaction between the Yangtze River and Poyang Lake are evaluated in this study and a new quantitative index is developed. The results of this study will facilitate the future effective management of rivers and lakes.

2 Study area

The total length of the Yangtze River is about 6300 km; the main stream of this major watercourse flows through 11 provincial-level areas (i.e., Qinghai, Tibet, Sichuan, Yunnan, Chongqing, Hubei, Hunan, Jiangxi, Anhui, Jiangsu, and Shanghai), before discharging into the East China Sea at Chongming Island. As a key component of this system, Poyang Lake provides important water storage within the middle and lower reaches of the Yangtze River; this waterbody is located in the north of Jiangxi Province (Figure 1) at 115°31'E–117°06'E, 28°11'N–29°51'N, and is a typical open and seasonal lake with a basin area of 162,225 km² that exhibits a lake phase at a high water level and a river phase at a low water level. The Ganjiang, Fuhe, Xinjiang, Raohe, and Xiushui rivers all flow into Poyang Lake from the southern, eastern, and western sides respectively. Thus, once regulated by the lake, water flow is then injected into the Yangtze River at Hukou (Du *et al*., 2015). Measurements of water flow and lake sedimentary conditions are recorded at Waizhou, Lijiadu, Meigang, Hushan, Dufengkeng, and Wanjiabu stations (referred as the five rivers and six stations throughout this paper), while Hukou Station (Figure 2) provides the control at the lake exit. In addition, the largest water control project in the world, the Three Gorges Reservoir (TGR), is also located at Yichang in Hubei Province, just 955 km from Hukou Staion; this reservoir has a normal water level of 175 m and a corresponding flood control capacity of 221.5 × 10^8 m^3 (Han *et al*., 2017a; Han *et al*., 2017b). The TGR commenced operations in June 2003 and a 175 m pilot storage trial was initiated in 2008; this trial had a profound effect on erosion and deposition within the middle and lower reaches of the Yangtze River, as well as on the relationship between this watercourse and the lake (Fang *et al*., 2012; Dai and Liu, 2013; Wang *et al*., 2014; Wang *et al*., 2017).

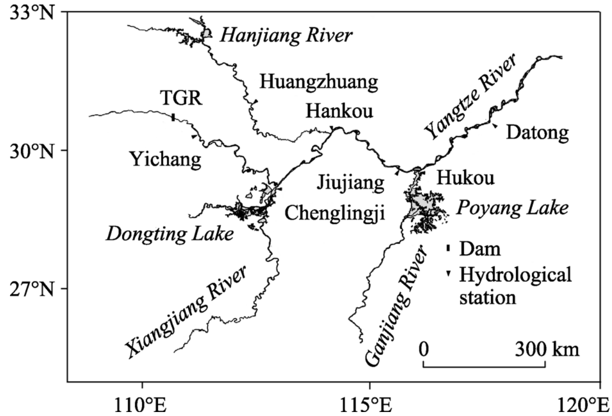

Figure 1 Map showing the location of the study area discussed in this paper

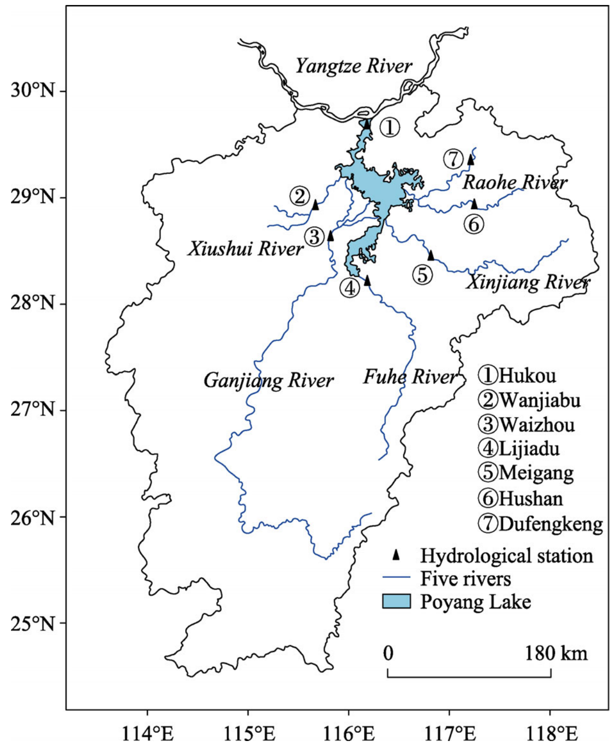

Figure 2 Map showing the location of Poyang Lake and associated hydrological stations

3 Data and methods

3.1 Data

The data analyzed in this study were all collected from hydrological stations within the basin, and were collated by the Jiangxi Provincial Institute of Hydraulic Research and the Jiangxi Bureau of Hydrology. Measurements include water level and flow discharge measured at Hukou Station between 1953 and 2015, as well as those at “the five rivers and six stations”, flow discharge for the period between 1952 and 2015 measured at Hankou Station on the Yangtze River, flow discharge measured at Jiujiang Station in 2011, and water level measured at Xingzi Station in 2011. Notable missing data include flow discharge for December 1966 at Hukou Station, as well as for the period between September 1987 and December 1987 at Dufengkeng Station.

3.2 Theory and method

3.2.1 Interaction between the Yangtze River and Poyang Lake

Previous research has shown that the exchange of water between rivers and lakes is a critical component of interaction between the two systems (Ye *et al*., 2012). In this case, once water has been regulated by Poyang Lake, the flow from five rivers enters into the Yangtze River at Hukou and is subject to complicated backwater effects and water exchange processes. Thus, from an energy perspective, there are clear interactions between the Yangtze River and the five tributary rivers; variation in the river–lake relationship is actually the result of these energy changes. In other words, if the inflow discharge of the Yangtze River and its five tributary counterparts remain constants, flow will gradually approach, and then maintain, an equilibrium state that is reflected at Hukou Station. However, if the balance between the rivers becomes unstable, the river–lake interaction will also change (Table 1), as outlined below.

Measurements show that when the flow of the Yangtze River increases, its energy also increases, leading to a water level rise at Hukou Staion. This also causes a corresponding increase in potential energy (E_S), and a reduction in the water slope between the lake area and Hukou Staion which hinders outflow at the mouth. This means that the role of the Yangtze River is characterized by blocking outflow; however, if the flow of this river increases still further, E_S at Hukou Staion also increases rapidly and further enhances the blocking capability of the Yangtze River, and water pours back into Poyang Lake.

In the second possible situation, when the flows of the five rivers increase, energy is also enhanced and the water surface gradient between the lake area and Hukou Station rises, favoring outflow. This also causes a rapid growth in kinetic energy (E_D) at Hukuou Station, which provides the supply to the river reaches below this junction and causes recharging of the Yangtze River from Poyang Lake. An increase in discharge from Poyang Lake also causes a rise in water level at Hukou Station in order to return to the original equilibrium state; this also demonstrates the blocking of Poyang Lake by the Yangtze River to some extent, although in this case, compared to recharging, the effect is relatively minor.

Table 1 Theories and forms of expression of the river–lake relationship

	Effect	Theory	Indication
Yangtze River	Blocking effect	Flow discharge and energy of the Yangtze River increases	Increase in E_S hinders outflow
Poyang Lake	Recharging effect	Flow discharges and energies of the five rivers increase	Increase in E_D favors outflow

A sketch of the interaction between the Yangtze River and Poyang Lake is presented in Figure 3. In this formulation, E_C denotes the energy of the Yangtze River, while E_W refers to that of the five rivers; $E_C = E_W$, and an equilibrium state therefore exists between the Yangtze River and Poyang Lake. Hydraulic theory also suggests the presence of a relationship between different sections, as shown in Equations (1) to (3); in these expressions, Z_i denotes the average water level of section i, v_i denotes the average flow velocity of section i, $h_{wi–j}$ denotes the head loss between sections i to j, C refers to the Chezy coefficient, and R and J denote the hydraulic radius and slope, respectively. Thus, if E_C increases, then z_2 and v_2 increase between section 1–1 and section 2–2 and the backwater effect of the Yangtze River on Poyang Lake is indicated by an increase in $z_2(z_3)$. Similarly, an increase in z_3 reduces the water surface gradient between section 4–4 and section 3–3, which causes an indirect decrease in v_3 (according to the Chezy formula 4), as well as an increase in z_3 and a decrease in v_3 within section 3–3. Therefore, if E_W increases, z_4 and v_4 will increase; as the period featuring strong Poyang Lake effects corresponds to the time when the water level (z_2) of the Yangtze River is relatively low, an increase in z_4 improves the water surface gradient between section 4–4 and section 3–3, and z_3 increases according to the Chezy formula. This means that since Poyang Lake is located between the Yangtze River and the five tributaries, it is functioning as "a weir"; thus, any increase in v_3 will lead to an indirect increase of $z_3(z_2)$. The weir formula shows that v_3 is proportional to $z_3^{1/2}$, rendering any increase in v_3 primarily and any increase in z_3 secondarily. An overall increase in E_C leads to a rise in the water level at Hukou Station, indirectly causing a decrease in flow velocity and an increase of E_S; similarly, an increase in E_W leads to the increased flow rate at Hukou Station, indirectly causing a rise in water level and E_D.

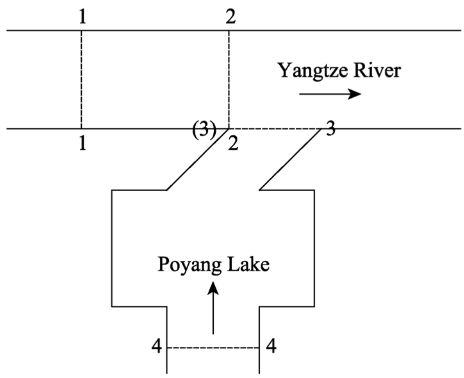

Figure 3 Sketch to show the nature of interactions between the Yangtze River and Poyang Lake

The equations applied in this analysis are as follows:

$$z_1 + \frac{a_1 v_1^2}{2g} = z_2 + \frac{a_2 v_2^2}{2g} + h_{w1-2} \tag{1}$$

$$z_4 + \frac{a_4 v_4^2}{2g} = z_3 + \frac{a_3 v_3^2}{2g} + h_{w3-4} \tag{2}$$

$$z_2 = z_3 \tag{3}$$

$$v = C\sqrt{RJ} \tag{4}$$

3.2.2 A characterization index for river–lake interactions based on energy theory

As noted above, river–lake interactions mainly take the form of energy exchange between the Yangtze River and its five feeder rivers, with the junction at Hukou Station acting as the contact point between the two. The flow and water level at this interface are therefore the result of energy interactions.

Measurements show that the Yangtze River mainly causes an increase in the water flow E_S at Hukou Station, while Poyang Lake mainly causes an increase in the E_D of outflow at the junction. Therefore, E_C and E_W can be replaced in this context by E_S and E_D, calculated using Equation (5) and Equation (6), respectively. However, because energy is always positive, E_D cannot represent situations where water flows backward (i.e., when flow discharge is negative and the velocity direction is oriented back towards the interior of the lake); in this case, energy is computed using Equation (7) and Equation (8) rather than Equation (5) and Equation (6) so that flow direction can also be incorporated.

The equations used for this section of the analysis are as follows:

$$E_S = mgh \tag{5}$$

$$E_D = \frac{1}{2}mv^2 \tag{6}$$

$$e_s = \sqrt{mgh} \tag{7}$$

$$e_d = \frac{\sqrt{m}v}{\sqrt{2}} \tag{8}$$

In order to quantify the energy flow of the Yangtze River and the five tributary rivers, F_e is defined to illustrate the relationship between E_S and E_D at Hukou Station. Equation (9) shows that the interval difference between these two variables ranges between minus one and one for the same quantity of water, $e_s \propto h^{1/2}$. Thus, neglecting bed erosion and deposition, $e_d \propto v \propto Q/h$ and $h \propto z$. In these expressions, Q represents the flow discharge at Hukou Station, z represents the water level, and h denotes water depth. Equation (9) can be transformed into Equation (10), in which f_1 and f_2 are empirical coefficients and f_3 denotes the correction value, as follows:

$$F_e = e_d - e_s \tag{9}$$

$$F_e = f_1 \frac{Q}{z} - f_2 z^{\frac{1}{2}} + f_3 \tag{10}$$

Data show that when flow discharge at Hukou Station increases and water level falls, e_d and F_e increase, and the effect of Poyang Lake is enhanced. Similarly, when the flow discharge at Hukou Station decreases and the water level rises, e_s increases, F_e decreases, and the effect of the Yangtze River is enhanced. The empirical constants f_1, f_2, and f_3 are determined by three distinct conditions in each case, including the initial combination of maximum flow discharge and minimum water level at Hukou Station over a long-term hydrological sequence. This first case assumes that the influence of Poyang Lake is most significant and so e_d will be maximal and F_e is 1. The second case assumes the combination of maximum water level and minimum flow discharge at Hukou Station over a long-term hydrological sequence and considers that the influence of the Yangtze River is the most significant, which means that e_s is maximal and F_e is –1. The third case assumes that river–lake interactions are at a constant state and so F_e is zero after the multi-year process; the empirical values of f_1, f_2, and f_3 in this case are 0.00027, 0.18, and 0.54, respectively.

4 Results

4.1 Interannual changes

Energy difference (F_e) was calculated using average flow discharge and water level measurements made at Hukou Station between 1953 and 2014. These data are presented in Figure 4 and Table 2 and show an overall increase in F_e variation over time (Figure 4); this result suggests that the effect of the Yangtze River has grown weaker while the effect of Poyang Lake has continuously increased over time. Decadal-level results show that the mean F_e value in the 1980s was –0.014, the smallest recorded over the course of this study. Thus, alongside changes in the inflow of the Yangtze River and five feeder rivers (Figure 5), inflow discharge from the former has been larger over the time period of this study and has exerted a stronger influence than its five counterparts. In contrast, mean F_e was 0.003 in the 1970s, suggesting that Poyang Lake played a major role at this time. This can be explained by the fact that abundant rainfall provided substantial flow to the five feeder rivers in the 1970s and therefore indirectly enhanced the role of Poyang Lake (Hu *et al*., 2007).

Table 2 F_e values over the time period of this study

Date	F_e	Date	F_e	Date	F_e	Date	F_e	Date	F_e
1953	0.009	1967	–0.011	1980	–0.022	1993	–0.012	2006	0.062
1954	–0.025	1968	–0.024	1981	–0.009	1994	0.014	2007	0.009
1955	–0.009	1969	0.006	1982	–0.027	1995	0.013	2008	0.010
1956	0.002	1970	0.005	1983	–0.030	1996	–0.017	2009	0.010
1957	0.004	1971	–0.004	1984	–0.010	1997	0.026	2010	0.025
1958	0.005	1972	0.019	1985	–0.015	1998	–0.006	2011	0.030
1959	0.025	1973	0.005	1986	0.005	1999	0.009	2012	0.020
1960	0.018	1974	–0.018	1987	–0.009	2000	–0.010	2013	0.029
1961	0.016	1975	0.000	1988	0.010	2001	0.015	2014	0.009
1962	0.012	1976	0.010	1989	–0.029	2002	0.006	2015	0.028
1963	–0.028	1977	–0.002	1990	–0.029	2003	–0.014		
1964	–0.049	1978	0.014	1991	–0.032	2004	–0.008		
1965	–0.025	1979	0.002	1992	0.024	2005	–0.005		

Records show that the intensity of river–lake interactions has also fundamentally influenced the frequency of drought and flood-related disasters within the area of Poyang Lake across all the decades of this study. Gou *et al*. (2012a) considered flooding during the summer of the 1990s as one example; these workers compared the flow discharge of the Yangtze River and five feeder rivers and determined that values for the latter were relatively large at this time. Indeed, data show that flow discharges from the five rivers during the 1990s were 1.14 times higher than the multi-year average, while those of the Yangtze River throughout this period were 1.02 times higher than the corresponding value. At the same time, however, the average F_e value for this period was –0.001, which indicates that when the flow discharge of the five rivers is large, the role of the Yangtze River is correspondingly relatively strong, and

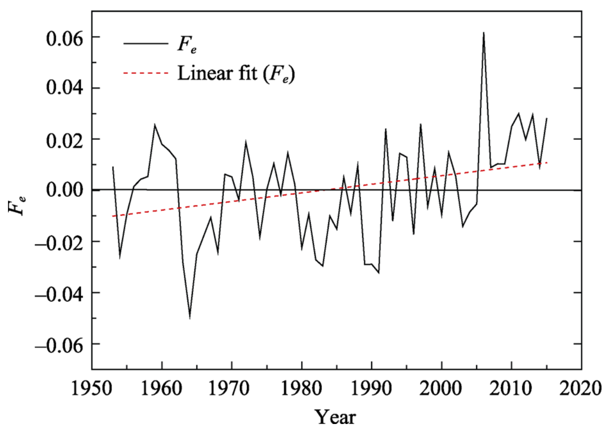

Figure 4 Graph showing F_e variation between 1953 and 2015

Poyang Lake will be prone to flooding. Drought disasters are known to have occurred within the lake area in both the 1960s and 2000s, with drought that occurred during the latter period the more serious of the two (Zhang *et al.*, 2015). These events were largely the result of relatively small flow discharges from the five rivers at this time, just 0.87 and 0.88 times its multi-year average in the 1960s and 2000s, respectively. The average F_e value in the 2000s was 0.009, however, the largest recorded throughout this study; this indicates that more water is supplied to the Yangtze River when the flow of the five rivers is insufficient, and further illustrates an enhanced role for Poyang Lake.

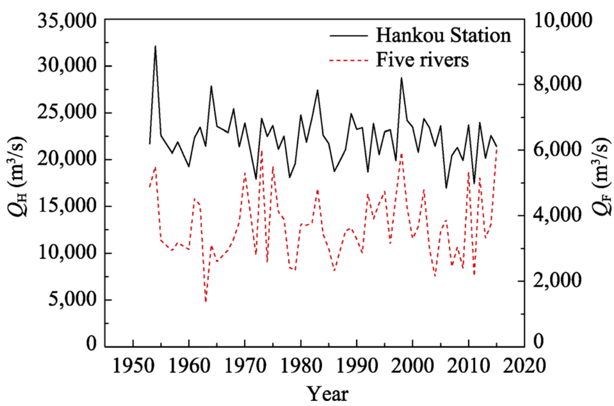

Figure 5 Graph showing variation in annual average discharge between 1953 and 2015

4.2 Average monthly F_e changes

The average monthly F_e values calculated in this study are shown in Figure 6; these data show that values are larger between February and April, before falling between July and September. This change can be explained by the fact that the period between February and April is not flood season, flow discharge is relatively small, and the influence of the Yangtze River is minor. Switching into the flooding season in July (Figure 7a) means that the flow discharge of the main stream increases and Poyang Lake begins to experience a strong backwater effect, including sometimes the phenomenon of backward water flow.

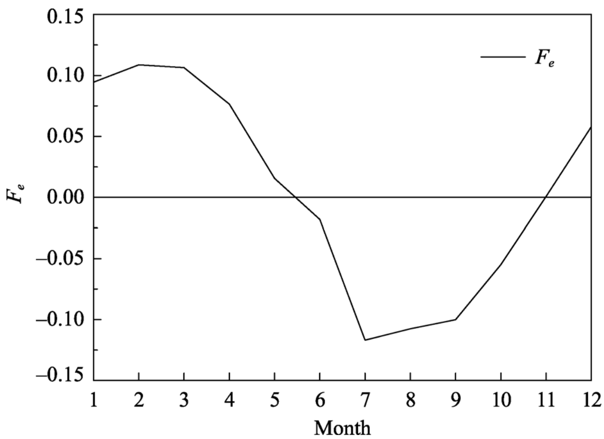

Figure 6 Graph showing average monthly F_e over time

The total number of days when water flows backwards alongside the induced water volume for each month between 1953 and 2015 are presented in Table 3. The highest daily values were seen in September alongside the highest water volume values in July; this indicates the strong effect of the Yangtze River, while corresponding F_e values are small in July and September.

Table 3 Backward flow conditions at Hukou Station between 1953 and 2015

Month	Days	Volume (10^8 m^3)	Month	Days	Volume (10^8 m^3)	Month	Days	Volume (10^8 m^3)
Jan	0	0	May	0	0	Sep	251	454
Feb	0	0	June	13	15	Oct	59	80
Mar	0	0	July	204	540	Nov	14	13
Apr	0	0	Aug	186	336	Dec	2	0.4

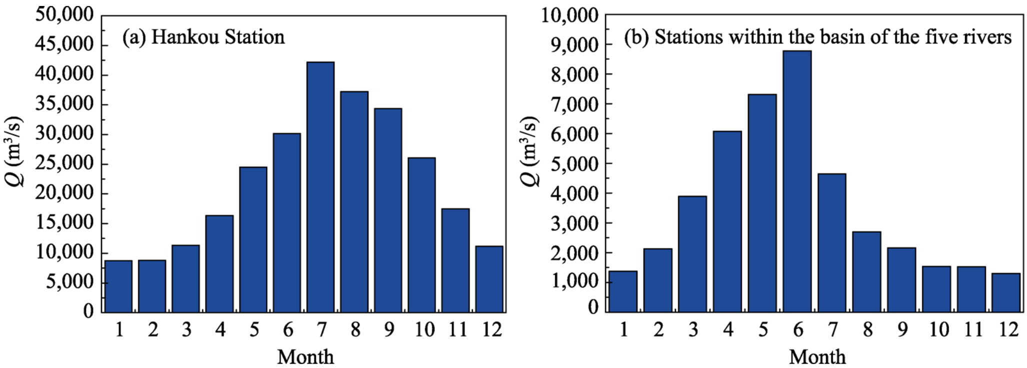

Figure 7 Averaged monthly discharges measured at Hankou Station and the other six stations on the five tributaries of Poyang Lake

River–lake interactions also influence occurrences of droughts and flooding within Poyang Lake area on an annual basis. The data assembled in this study show that most floods within the lake basin occurred between June and August, whereas droughts tend to happen around October (Zhang *et al*., 2015). The flow discharge of the five rivers also tends to increase gradually between June and July; this means that the role played by the Yangtze River is also rapidly enhanced over this period, and remains at a high level between July and August (Figure 6), which facilitates flooding. In contrast, if flow discharge from the five rivers gradually decreases, then the role of the Yangtze River is weakened and the water supply from Poyang Lake increases. All these factors combine to make drought more frequent within the area of the lake.

4.3 Influence of TGR operation

Data show that the average F_e value was –0.004 before the enclosure of the TGR (between 1953 and 2002), and then subsequently increased to 0.018 (between 2004 and 2015). This result clearly shows that operation of the TGR has reduced the influence of the Yangtze River, at least to some extent.

Changes in average monthly flow discharge before, and after, the enclosure of the TGR are shown in Table 4, while the data presented in Figure 8 highlight variations in annual F_e calculated using the average monthly water level and flow discharge measured at Hukou Station. Most notably, these data show that F_e values decrease slightly between January and March. This can be explained by the fact that discharge from the TGR during dry seasons has increased the flow at Hukou Station by more than 20% between January and March. It is clear that the advent of the TGR has slightly weakened the influence of Poyang Lake.

Measured F_e values between April and June increase slightly when Poyang Lake is in flood, reflected by an increase in the flow of the five tributary rivers and a decrease in the flow of the Yangtze River, both of which enhance the role of Poyang Lake. Data also reveal a significant decrease in F_e between July and December, largely due to the peak scheduling operation during the flood season and the subsequent water capture of the TGR. These both act to cause drastic reductions in main stream inflow of the Yangtze River and also weaken its supporting effect. The results collated in this study are also consistent with those presented previously (Guo *et al*., 2012b; Hu and Wang, 2014); specifically, the variation in flow rate in October reaches a maximum of –29%, in concert with the largest recorded annual F_e

increase.

Table 4 Comparison of average monthly discharge data for Hankou Station both before (1953–2002) and after (between 1953–2002) construction of the TGR

Month	1953 and 2002	1953–2002	Variation rate (%)	Month	1953–2002	2004–2015	Variation rate (%)
Jan	8,320	10,252	23	July	43,482	37,022	–15
Feb	8,400	10,389	24	Aug	38,137	33,883	–11
Mar	10,737	13,202	23	Sep	34,891	30,003	–14
Apr	16,401	16,296	–1	Oct	27,438	19,588	–29
May	24,585	23,148	–6	Nov	17,827	16,079	–10
June	30,009	30,753	2	Dec	11,045	11,561	5

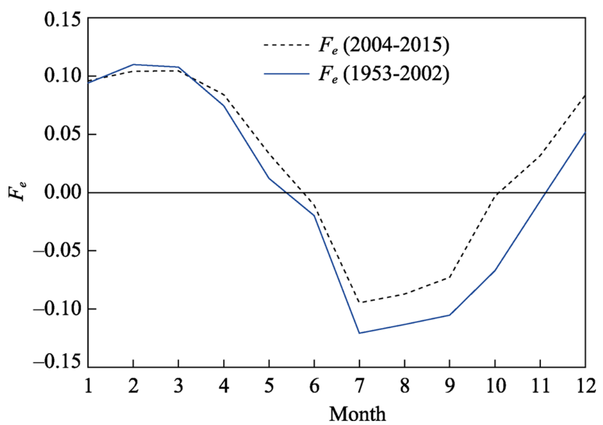

Figure 8 Variations in F_e before, and after, TGR construction and enclosure

Construction and enclosure of the TGR exerted a marked effect on droughts and floods within the area of Poyang Lake. Data show that when flow of the five rivers remains constant between July and August, the backwater effect of the Yangtze River reduces the probability of flooding. Similarly, between September and October, as the role of Poyang Lake is enhanced, its storage capacity and the likelihood of droughts are also reduced (Zhang *et al*., 2014, 2016).

4.4 Rationalizing the characterization indicator

Previous studies that have rationalized the interaction index between Poyang Lake and the Yangtze River have utilized runoff from the latter as well as the five tributary rivers. Then, computing the departure based on the dimensionless runoffs by using Equation (11), a further analysis was performed to compare two runoffs alongside the calculated index. These results, however, suggest that runoff comparisons cannot accurately represent the relative energies of the Yangtze River and Poyang Lake. The measurement data presented in this study demonstrate that though the flows of the five tributary rivers were relatively large during the 1990s, the effect of the Yangtze River was comparatively strong. Similarly, during the 2000s, the flows of the five tributary rivers were small, although those of Poyang Lake remained strong. Improvements need to be made to the rationality assessments of this index in future work.

Utilizing average monthly values for 2011, runoff and energy departure values between the Yangtze River and the five tributary rivers were calculated (Table 5). The energy of the Yangtze River can be computed via flow and water-level data from Jiujiang Station, while calculations for this variable for the five rivers can be based on the sum of the inflow of these tributaries as well as Xingzi water levels. Thus, if an anomalous flow rate is used as a

Table 5 Results of a reasonableness analysis for F_e using hydrological data from 2011

Month	I_{FJ}	I_{FW}	F_e	I_{QJ}	I_{QW}	Month	I_{FJ}	I_{FW}	F_e	I_{QJ}	I_{QW}
Jan	0.32	0.39	0.066	0.10*	0.08*	July	0.29	0.09	–0.049	0.73	0.28
Feb	0.31	0.43	0.077	0.04	0.06	Aug	0.52	0.14	–0.065	0.63	0.10
Mar	0.30	0.46	0.091	0.06	0.09	Sep	0.54	0.24	–0.020	0.41	0.07
Apr	0.35	0.44	0.066	0.10*	0.08*	Oct	0.30	0.31	0.026	0.23	0.10
May	0.29	0.46	0.084	0.10	0.12	Nov	0.48*	0.32*	0.019	0.26*	0.07*
June	0.33	0.34	0.023	0.60*	0.37*	Dec	0.34	0.41	0.069	0.05*	0.05*

Abbreviations: I_{FJ}, and I_{FW} denote energy departures between the main stream of the Yangtze River and the five tributary rivers, respectively; I_{QJ} and I_{QW} denote flow departures between the main stream of the Yangtze River and the five tributary rivers, respectively; * refers to results when relative size does not match F_e values.

reference value (Table 5), calculated results for January, April, June, November, and December are inconsistent with F_e values, especially those for April and June. The results calculated show that the flow of the Yangtze River is relatively larger than that of the five tributary rivers; this means that the Yangtze River should be playing a dominant role in river–lake interactions. In practice, however, between April and June the flow of the five rivers has rapidly increased because they remain in flood, whereas the Yangtze River remains within the dry season, and so the influence of Poyang Lake is more marked. It is therefore unreasonable to perform the analysis detailed in this paper using just a comparison between the relative flow discharges of the Yangtze River and the five tributary rivers.

The analysis of computed energy departure values presented in this study exhibits a high degree of consistency, other than for November. Thus, if I_{FJ} is larger than I_{FW}, F_e at Hukou Station will also be negative, and vice versa; this indicates that F_e values calculated on the basis of water level and flow at Hukou Station can be used to accurately demonstrate the relative influences of the Yangtze River and Poyang Lake, as follows:

$$I_{Ji} = \frac{J_i - J_{\min}}{J_{\max} - J_{\min}} \tag{11}$$

5 Discussion and conclusions

This paper has applied energy theory to investigate the physical mechanisms underlying the interaction between the Yangtze River and Poyang Lake and presents a series of characterization index calculations. A number of clear conclusions can be presented on the basis of this analysis.

(1) The interaction between the Yangtze River and Poyang Lake are, in actuality, a reflection of the relationship of energy between the former and the five tributary rivers. The main role of the Yangtze River is to block Poyang Lake, which leads to an increase in E_S at Hukou Station. At the same time, Poyang Lake mainly provides water to the Yangtze River, causing a concomitant growth in E_D at Hukou Station.

(2) Data show that it would not be unreasonable to perform the analysis in this paper via a comparison of respective flow discharges into the Yangtze River and the five tributary rivers as flow discharge cannot represent the overall energy of this system. The concept of F_e proposed in this paper can be utilized to demonstrate the relationship between the E_S and E_D at Hukou Station, and therefore also indirectly reflect the energies of these systems. The con-

cept of F_e is therefore more appropriate for quantifying the river–lake interaction.

(3) Overall, values of F_e have increased since the 1950s and are indicative of an enhanced role for Poyang Lake and a weakened role for the Yangtze River. Data show that the influence of Poyang Lake was the greatest in the 2000s, whereas that of the Yangtze River peaked in the 1980s. In addition, development of the TGR has further demoted the role of the Yangtze River; over the course of a single year, the effect of the Yangtze River has increased slightly over the course of the dry season but has become significantly weakened by the end of the flooding period.

(4) River–lake interactions have also influenced the probability of flooding and drought within the area of the lake. When the flow of the five rivers is large and the role of the Yangtze River is indicative, the lake area is prone to floods. In contrast, when the flow from the five tributary rivers is small and Poyang Lake plays a major role, this area is prone to drought. The enclosure of the TGR has also further weakened the influence of the Yangtze River, making the area of the lake more prone to drought between September and October.

(5) The energy-based index proposed in this study is to characterize the interaction between the Yangtze River and Poyang Lake. It can also be used to investigate these consequences, especially given the fact that similar conditions are shared between the two, and that the water volume of the main stream is much larger than that of the tributary lake.

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