Journal of Hydrology 620 (2023) 129507

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Research papers

Spatial-temporal variations of stage-area hysteretic relationships in large heterogeneous lake–floodplain systems

Juan Wu [a,b], Qi Zhang [c,d], Yunliang Li [c], Chong-Yu Xu [e], Xuchun Ye [a,b,*]

[a] Chongqing Key Laboratory of Karst Environment & School of Geographical Sciences, Southwest University, Chongqing 400715, China
[b] Chongqing Jinfo Mountain Karst Ecosystem National Observation and Research Station, Chongqing 400715, China
[c] Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences, Nanjing 210008, China
[d] Yangtze Institute for Conservation and Development, Hohai University, Nanjing 210024, China
[e] Department of Geosciences, University of Oslo, P.O. Box 1047 Blindern, 0316 Oslo, Norway

ARTICLE INFO

Keywords:
Inundation dynamics
Stage-area hysteretic relationship
Hysteresis
Seasonal lakes
Remote sensing
Poyang Lake

ABSTRACT

The hysteretic relationship between the water level and the inundated area is one of the basic non-linear characteristics of lake hydrology. However, it is difficult to obtain this relationship accurately, especially for large floodplain lakes that exhibit time-varying boundaries with rapid water-level fluctuations. Taking the largest lake-floodplain system of the Yangtze River basin – Poyang Lake and its extremely productive wetland – as an example, we investigated the spatial–temporal variation of the stage-area hysteretic relationship in large heterogeneous lake-floodplain systems by adopting the Enhanced Spatial and Temporal Adaptive Reflection Fusion Model (ESTARFM) based on the observed water levels and reconstructed high spatial–temporal resolution inundation datasets using multi-source remote sensing data. The major results indicate that the inundation dynamics in the regions of the main lake and seasonal floodplain lakes are remarkably inconsistent. Concerning the inundation behavior of the river and lake-floodplain, a conceptual model was established to explain the formation mechanism of the counter-clockwise and clockwise stage-area hysteretic relationships in the Poyang lake–floodplain system. Further investigation revealed that seasonal lakes exist widely in floodplain settings and have a crucial impact on increasing the hysteresis of upstream stations and decreasing that of downstream stations. The magnitude and direction of the stage-area hysteretic relationships varied with time in a changing environment. This study extends the understanding of the complexity of hydrological behavior in large heterogeneous lake-floodplain systems, which is of vital importance for lake water resources and ecological management.

1. Introduction

Hysteresis is a non-linear phenomenon characterized by a non-unique relationship between two variables under cyclic variation (Ewing, 1885; Norbiato and Borga 2008). The relationship curve often forms a closed loop because of the different changes in the directions and paths of the variables. Hydrological hysteresis is widely observed in various hydrological processes such as soil moisture retention during wetting and drying cycles (Zhang et al., 2009), saturated soil water content, and subsurface flow during hillslope runoff events (Norbiato and Borga, 2008), and river stage-discharge rating curves (Fread, 2007; Ajmera and Goyal, 2012; Wolfs and Willems, 2014; Sun et al., 2021).

The hysteretic relationship between the water level and the inundated area is one of the basic characteristics of lake hydrology. However, compared to unsaturated zones and riverine situations, studies on stage-area hysteresis in lake hydrology are limited, particularly in large lakes with extensive seasonal floodplain areas (Zhang and Werner, 2015). Such lakes usually have complex hydrological and hydrodynamic processes and large water level fluctuations throughout the year, which makes it difficult to monitor changes in inundated areas (Li et al., 2019a). A common method for obtaining inundated areas of hydrological systems is to perform numerical simulations using physically based models (Koponen et al., 2005; Lai et al., 2012; Tan et al., 2022). However, studies have pointed out that for shallow floodplain lakes with significant time-varying water levels, significant uncertainties may exist in the numerical simulation owing to difficulties in defining lake

* Corresponding author at: 2 Tiansheng Road, Beibei District, Chongqing 400715, China.
E-mail address: yxch2500@163.com (X. Ye).

https://doi.org/10.1016/j.jhydrol.2023.129507
Received 7 April 2022; Received in revised form 28 March 2023; Accepted 6 April 2023
Available online 13 April 2023

boundaries, bathymetric variations, human disturbance, and unconsidered groundwater recharging/discharging (Li et al., 2014; Tan et al., 2019). In addition, numerical models usually have complex structures, strict requirements for boundary conditions, and large basic data requirements, which limit their application to long-term continuous modeling in areas with insufficient data.

With the rapid development of satellite remote sensing technology, multiple sources of remote sensing data have provided important information for inundation monitoring of terrestrial water surfaces in recent years (Feng et al., 2012; Pekel et al., 2016). However, owing to high spatiotemporal heterogeneity, it remains a challenge to capture rapid changes in surface water with fine spatiotemporal resolution in those floodplain lakes (Ye et al., 2019; Tan et al., 2019). For these lakes, remote sensing data with high spatial resolutions (e.g., 30 m of Landsat series) are normally limited in their value for detecting rapid changes in the water surface, due to the long revisit cycles of satellites, frequent cloud contamination, and other poor atmospheric conditions (Zhu et al., 2010). However, satellite remote sensing images with short temporal intervals (e.g., eight days of the MODIS series) do not capture the spatial details of the water surface because of the relatively low spatial resolution (250 m, 500 m, and 1000 m) (Cheng et al., 2020). In this regard, some studies have proposed spatiotemporal fusion technology for remote sensing data (e.g. Zhu et al., 2010, 2016; Chen et al., 2018). By combining the advantages of medium- and high-spatial-resolution remote sensing images with those of high-temporal-resolution remote sensing images, remote sensing images with high spatiotemporal resolution can be obtained, providing a technical guarantee for the study of inundation dynamics in heterogeneous floodplain lakes (Tan et al., 2019).

Located on the south bank of the middle-lower Yangtze River, Poyang Lake is one of the two large lakes that remain naturally connected to the Yangtze River. It is a typical shallow water-carrying lake that plays an irreplaceable ecological service function. The most notable feature of the lake is its high water level fluctuations, resulting in a large floodplain adjacent to the main lake, in which interconnected seasonal lakes are widely distributed (Li et al., 2019a). Zhang and Werner (2015) first explored the hysteresis relationships between the inundated area, water storage, and water level of this lake-floodplain system using a physically based hydrodynamic model (MIKE 21). Zhang et al. (2017) further revealed a three-phase hydrological regime in stage-flow relationships that assisted in developing an improved physical interpretation of stage-area hysteretic relationships. These pioneering studies have highlighted the significance of hysteresis in floodplain lakes and the development of management models.

The reported large uncertainties in water surface simulations from previous studies (e.g., Li et al., 2014; Tan et al., 2019) call for the use of more accurate high spatial–temporal resolution remote sensing data in the investigation of water inundation dynamics and potential hydrological hysteresis in floodplain lakes. Furthermore, the stage-area hysteretic relationships may change in the context of climate change and human impacts, which have not been adequately considered in previous studies. The variability and causes of the stage-area hysteretic relationships in the Poyang Lake floodplain system remain to be explored. This study aims to address these gaps. Specifically, the objectives of this study are: (1) to examine the inundation dynamics of the water surface and its spatiotemporal heterogeneity in the Poyang Lake floodplain system by reconstructing high spatiotemporal resolution (30-m, 8-day) inundated water surface data from 2000 to 2018; (2) to generalize the formation mechanism of stage-area hysteretic relationships and reveal the effect of seasonal lakes in the floodplain; and (3) to explore the interannual variability and causes of stage-area hysteretic relationships in recent years. This study would greatly improve the understanding of the hydrological regimes of large floodplain lakes and promote management practices for shallow lake ecosystems.

2. Study area overview

The Poyang Lake (N28°24′∼29°46′, E115°49′∼116°46′), is the largest freshwater lake in China (Fig. 1a). The lake receives upstream runoff mainly from five tributary rivers (Ganjiang, Fuhe, Xinjiang, Raohe, and Xiushui), and is discharged directly into the Yangtze River after regulation and storage (Fig. 1b). The outline of the lake is similar to a gourd shape, wide in the south, and long and narrow in the north. The lake catchment, covering a drainage area of 162, 225 km^2, belongs to a subtropical monsoon climate zone with an average annual temperature of 17.5 °C and average annual precipitation of 1665 mm.

The hydrological regime of Poyang Lake is affected by both catchment inflow and the Yangtze River discharge, and the water level fluctuates significantly throughout the year (Fig. 1c, 1d). The lake water surface can expand to 4,000 km^2 in the summer wet season (July-September) and shrink to less than 500 km^2 in the winter dry season (December-February), showing the typical hydrological characteristics of "an ocean during the flood season and a stream during the dry season". This huge seasonal fluctuation in lake water surface inundation creates an extensive wetland ecosystem across the floodplain region of some 3, 000 km^2 (Zhang and Werner, 2015). Shallow floodplains provide an excellent place for the reproduction of various animals and plants, as well as a transfer station for many wintering migratory birds (Li et al., 2019c).

Bounded by the Songmen Mountain, the northern lake is narrow and dominated by water channels, whereas the southern lake is flat and broad, where extensive floodplains have developed (Fig. 1b). In floodplain regions, seasonal, shallow, and small lakes with sizes ranging from 1 km^2 to 71 km^2 are distinctive hydrological units. The total water surface area of these seasonal lakes is approximately 767 km^2 (Tan et al., 2020). According to the periphery of the seasonal lakes, the entire Poyang Lake floodplain system can be roughly divided into two regions: the main lake and seasonal floodplain lakes. Topographically, the lake bottom varies from floodplain areas of 30 m to flow channels of approximately 8 m (Yellow Sea datum, China). The bottom elevation of most seasonal lakes varies from 12 to 13 m, which is almost higher than that of the main lake. Because of the changes in hydrologic connectivity throughout the year, the floodplains and their seasonal lakes can be partly or fully coupled to the main lake at high water levels during the summer months (June-October) but become isolated at low water levels during the winter months (December-February) (Li et al., 2019b).

3. Data and method

3.1. Data

The observed daily lake water levels during 2000–2018 were measured at five hydrostations (Hukou, Xingzi, Duchang, Tangyin, and Kangshan) across Poyang Lake. Daily runoff during the same period was recorded from seven hydro-stations (Qiujin, Wanjiabu, Waizhou, Lijiadu, Meigang, Hushan, and Dufengkeng) of the "Five Rivers" in the Poyang Lake catchment. Among the seven hydro-stations, Waizhou, Lijiadu, and Meigang were located at the downstream outlets of the Ganjiang, Fuhe, and Xinjiang rivers, respectively, whereas the Hushan and Dukengfeng, Wanjiabu, and Qiujin stations were located at the branches of the Raohe and Xiushui rivers, respectively. In addition, runoff data from the Hankou hydro-station were collected to represent discharge from the upper-middle Yangtze River. The period of daily runoff at the Hankou hydro-station was 2000–2012, whereas that of annual runoff was from 2000 to 2018. All hydrological data were provided by the Jiangxi Hydrological Bureau and the Hydrological Bureau of the Yangtze River Water Resources Commission. The total drainage area controlled by the seven hydrostations in the Poyang Lake catchment is 137,143 km^2, which is 25,082 km^2 smaller than the entire Poyang Lake catchment. In this study, the total inflow to the entire Poyang Lake catchment was calculated using a simple scaling method

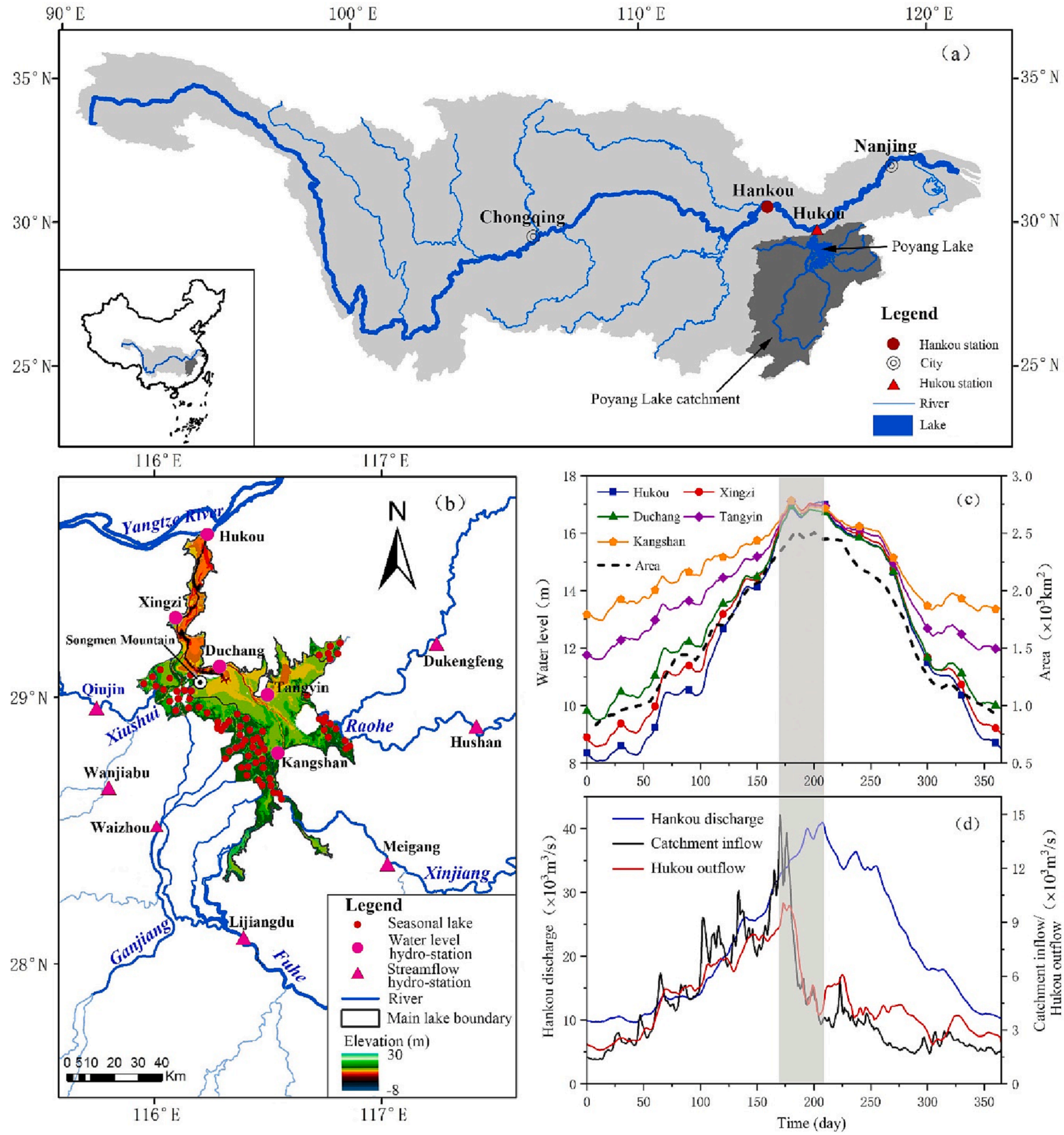


Fig. 1. Overview of the Poyang Lake-floodplain system: (a) location of the Poyang Lake and its catchment in the Yangtze River basin; (b) water system composition of Poyang Lake and seasonal lakes distribution in the lake floodplain; (3) intra-annual variation of lake water level; and (d) flow hydrographs for the Yangtze River (measured at Hankou station), catchment inflow and outflow of the Poyang Lake. The gray area highlights the time lag between the peaks of Yangtze River discharge and catchment inflow.

based on the ratio of the gauged area to the total area.

The remote sensing image data used in this study included Landsat series (including TM, ETM +, and OLI) from 2000 to 2018 (downloaded from http://glovis.usgs.gov) and MODIS surface reflectance data series on the NASA Terra platform (MOD09A1) (downloaded from http://reverb.echo.nasa.gov) (Table 1). Landsat data have a spatial resolution of 30 m and a temporal resolution of 16 d. Owing to the influence of cloud cover, the availability of Landsat data is greatly reduced. During the study period, 275 Landsat data sets were obtained. The MOD09A1 dataset is a composite product of the 500 m surface reflectance of MODIS data every-eight days. A total of 46 images were captured each year. In total, 847 MODIS images were obtained during the study period. All the acquired Landsat and MODIS data were of good quality. Before application, all the image data were subjected to standardized pre-processing on the ENVI platform, including projection transformation, radiometric calibration, and atmospheric correction.

Table 1
Remote sensing images used in this study.

Data type	Sensor	Resolution	Row/column number	Number of images obtained
Landsat	TM	16 d , 30 *m*	121/40	88
Landsat	ETM+	16 d , 30 *m*	121/40	141
Landsat	OLI	16 d , 30 *m*	121/40	46
MOD09A1	TERRA	8 d , 500 *m*	121/40	847

3.2. Water surface extraction

The normalized difference water index (NDWI) (McFeeters, 1996) was used to determine the lake water area. This index was constructed by calculating the ratio of the strong and weak reflection bands and combining it with a certain threshold to extract water information using the following formula:

$$\mathrm{NDWI} = \frac{(\mathrm{DN})_{\mathrm{Green}} - (\mathrm{DN})_{\mathrm{NIR}}}{(\mathrm{DN})_{\mathrm{Green}} + (\mathrm{DN})_{\mathrm{NIR}}} \quad (1)$$

where $(\mathrm{DN})_{\mathrm{NIR}}$ and $(\mathrm{DN})_{\mathrm{Green}}$ indicate the digital number (DN) values in the NIR (Near-infrared) and green bands of remote-sensing imagery, respectively.

Generally, the acquired NDWI ranges from -1 to $+1$. Water features have positive values, whereas soil and terrestrial vegetation features have zero or negative values (McFeeters, 1996). Based on the calculated NDWI images, the inundation and non-inundation areas could be distinguished by setting two different values for the NDWI across the lake floodplain (the inundation area, i.e., NDWI with positive values, was set to 1, and the non–inundation area, i.e., NDWI with zero or negative values, was set to 0).

3.3. ESTARFM fusion framework

The enhanced spatial and temporal adaptive reflectance fusion model (ESTARFM) was applied to reconstruct continuous remote sensing image data with high temporal and spatial resolution. ESTARFM is a data-fusion method based on a moving window that considers the auxiliary information obtained from adjacent pixels with similar spectra and the weights of these pixels themselves (Zhu et al., 2010). The ESTARFM model fuses and reconstructs Landsat images of the current day (L_p) through a MODIS image (M_p) and Landsat (L_a, L_b) and MODIS (M_a, M_b) images of at least two stages before and after the simulation date. The details of the principle of the model can be found in Zhu et al. (2010). A flowchart of the ESTARFM fusion process is shown in Fig. 2.

It should be noted that there are two fusion schemes, BI (Blend-then-Index) and IB (Index-then-Blend) (Abdollah et al., 2014), which differ in the fusion order. A previous study by Kai (2018) indicated that compared to the BI scheme, the IB scheme can weaken the speckle phenomenon caused by cloud interference and can better reflect the fine texture characteristics of real features. Therefore, the IB scheme was selected for image fusion in this study; the input data in the fusion model were the calculated NDWI data images.

This study reconstructed the missing NDWI data of 667 images from 2000 to 2018 using the ESTARFM model and formed a continuous high spatial–temporal resolution (8d, 30 m) NDWI dataset since 2000. The inundated areas of the real Landsat and ESTARFM-fused images were subtracted to verify the accuracy. Statistical analyses showed that the average accuracy of the fused image data in calculating water NDWI was 92.7 % with reference to real Landsat data.

3.4. Measurement of hysteresis

The degree of stage-area hysteresis was quantified by calculating the loop area of the stage-area relationship curve (Norbiato and Borga,

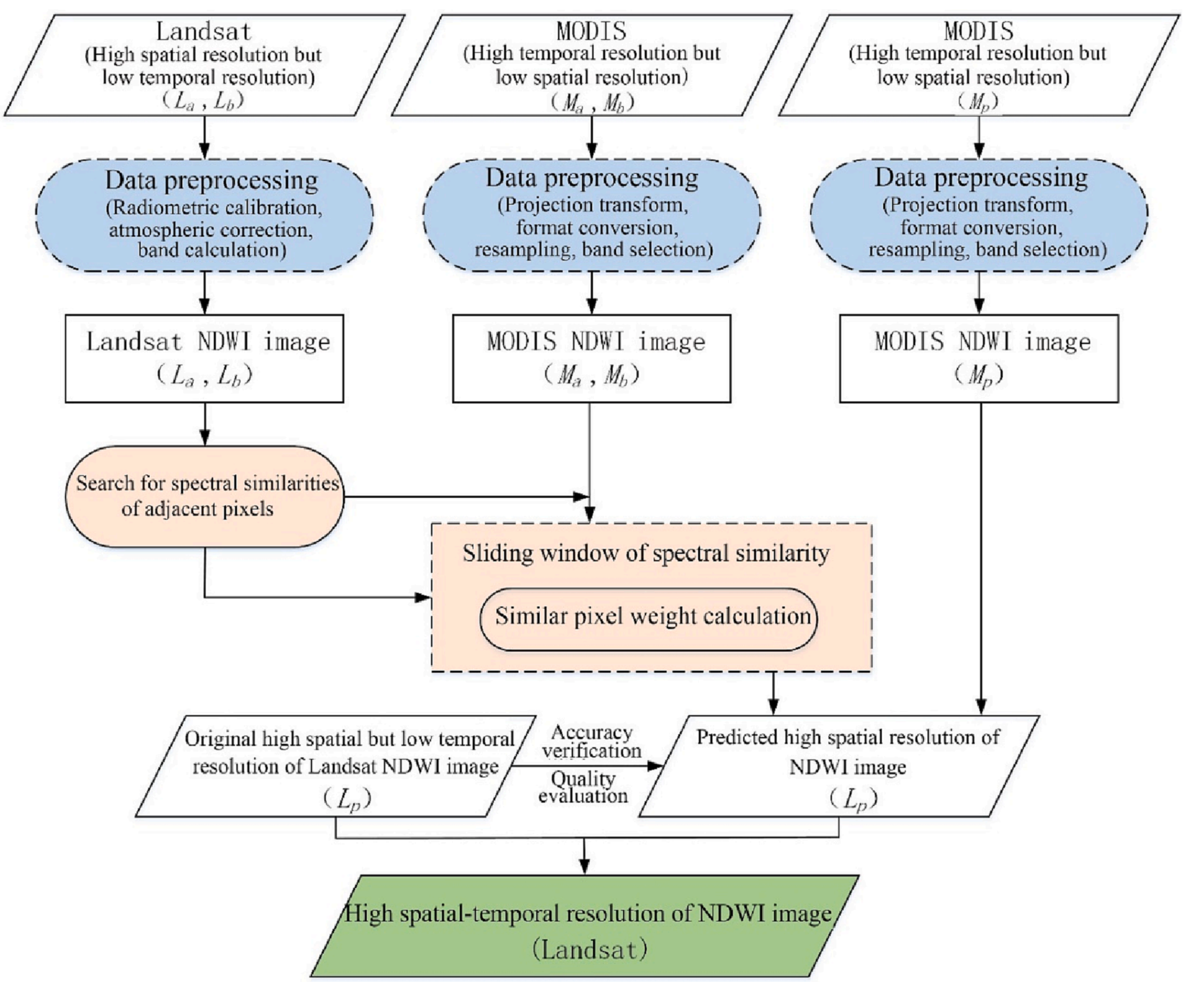


Fig. 2. ESTRAFM flowchart of data fusion.

2008; Zhang and Werner, 2015). Firstly, both the lake water level and area were normalized, and then the loop area was calculated as the dimensionless hysteresis (η) using the following formula:

$$h_t = \frac{H_t - H_{min}}{H_{max} - H_{min}} \quad (2)$$

$$a_t = \frac{A_t - A_{min}}{A_{max} - A_{min}} \quad (3)$$

$$\eta = \left| \left(\int_0^1 a_{(r)}(h) \bullet dh - \int_1^0 a_{(f)}(h) \bullet dh \right) \right| \quad (4)$$

where H is the observed lake water level (m) at a specific station, and A is the corresponding lake water surface $\left(km^2\right)$ at time t ; the subscripts of min and max represent the minimum and maximum values from time series of H and A; $h(-)$ and $a(-)$ are the normalized variables of lake stage and inundated water surface;$\eta(-)$ is the degree of hysteresis; the subscripts r and f represent the rising and falling stages of the loop of the stage-area hysteretic curve, respectively. The bigger the hysteresis (η), the larger the loop of the stage-area curve, and the greater the fluctuation of lake inundation, and vice versa.

4. Results

4.1. Intra-annual variation in the lake-inundated area

The inundated water surface of Poyang Lake exhibited clear seasonal fluctuations (Fig. 3). On average, the inundated area of the lake increased steadily from January to June, peaking in July. Subsequently, it gradually decreased over subsequent months. During the past 19 years, the maximum inundation was approximately 3000 km^2, whereas the minimum inundation area was less than 600 km^2. The lake surface area varied seasonally, with a maximum in October (2400 km^2) and a minimum in July (990 km^2). Lower variability in the lake water surface mainly occurred during the winter dry season and summer flood season. During this time, the inundated area of the lake typically reached an extreme value and changed only slightly. In contrast, larger variability usually occurred in the spring season (April and May), when the lake water surface expanded rapidly, and in the autumn season, when the lake surface shrank quickly (September and October).

Statistics show that the average annual inundated areas in the main lake and floodplain seasonal lakes are 1232 km^2 and 392 km^2, respectively. Although both had similar seasonal fluctuations throughout the year, the inundation of the seasonal floodplain lakes differed from that of the main lake in certain months. As shown by the gray area in Fig. 4, when the inundated area of the main lake showed an increasing trend at the end of March, a decreasing trend was observed in the regions of the seasonal lake. In addition, during the recession period of Poyang Lake in October, the inundated area in the seasonal lake decreased rapidly and maintained a stable and slow decline subsequently, while the rapid decline of the inundated area in the main lake from October continued until November.

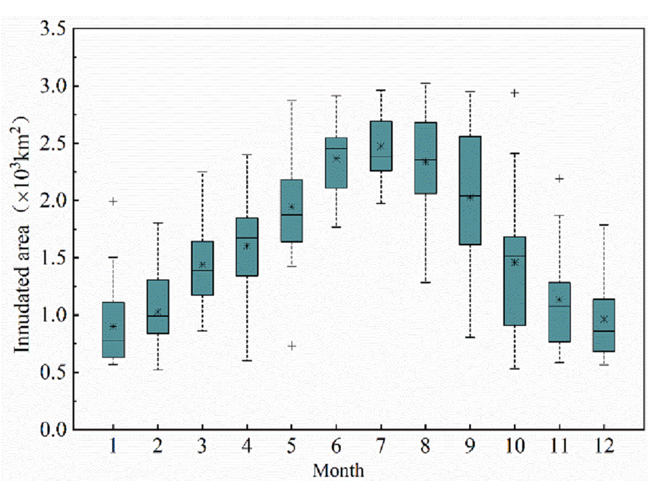


Fig. 3. Average monthly variation in the inundation area in Poyang Lake. The "*" in the box diagram indicates the average value.

4.2. Stage-area hysteretic relationships

The non-linear characteristics of the lake water level (stage) and surface area (inundated area) relationship in the Poyang Lake floodplain system were prominent and showed clear spatial differences. Two different directions of stage-area hysteretic relationships existed in the Poyang Lake floodplain system (Fig. 5). Clockwise hysteresis was observed at the Hukou, Xingzi, and Duchang stations, which are mainly located downstream and in the center of the lake, whereas counterclockwise hysteresis was apparent for the Tangyin and Kangshan stations upstream of the lake. This relationship was most prominent for lake water levels below 14 m at the Hukou and Xingzi stations and between 13 m and 16 m at the Tangyin and Kangshan stations.

The counterclockwise and clockwise stage-area hysteretic relationships of the upstream and downstream stations are further reflected in the statistical differences in lake water levels during the rising and recession periods. The average water levels during the rising period at the Hukou, Xingzi, and Duchang stations were lower than those during the recession period, whereas the opposite was observed at the Tangyin and Kangshan stations (Table 2).

The calculated hysteresis in Fig. 5f indicates the degree of stage-area hysteretic relationships (i.e., the degree of nonlinearity) at different stations. Among the five stations, the hysteresis of the Kangshan station in the southernmost part of the lake was the largest, followed by the Hukou, Xingzi, and Tangyin stations; the Duchang station in the center of the lake had the smallest hysteresis.

As noted in previous studies that the volume of seasonal floodplain lakes accounted for a small part of the whole Poyang Lake in both the high (3.5 % ± 1.9 %) and low (5.6 % ± 2.0 %) water level periods (Li et al 2019b; Tan et al., 2020). On this basis, the influence of seasonal floodplain lakes on lake stage-area hysteretic relationships can be preliminarily evaluated by comparing the stage-area hysteretic relationships for the entire Poyang Lake floodplain and the main lake region without considering the hydraulic connection between seasonal lakes and the main lake. As shown in Fig. 5, the hollow line loops for the main lake at all stations shifted downward to the right without considering the inundated area in the seasonal lake region. For downstream stations (Hukou, Xingzi, and Duchang), the stage-area hysteresis increased,

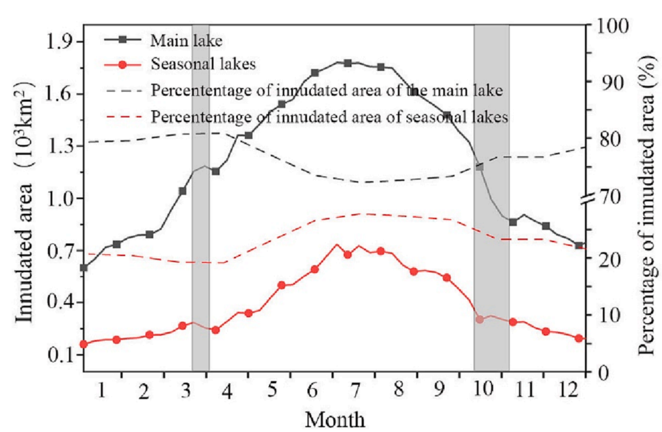
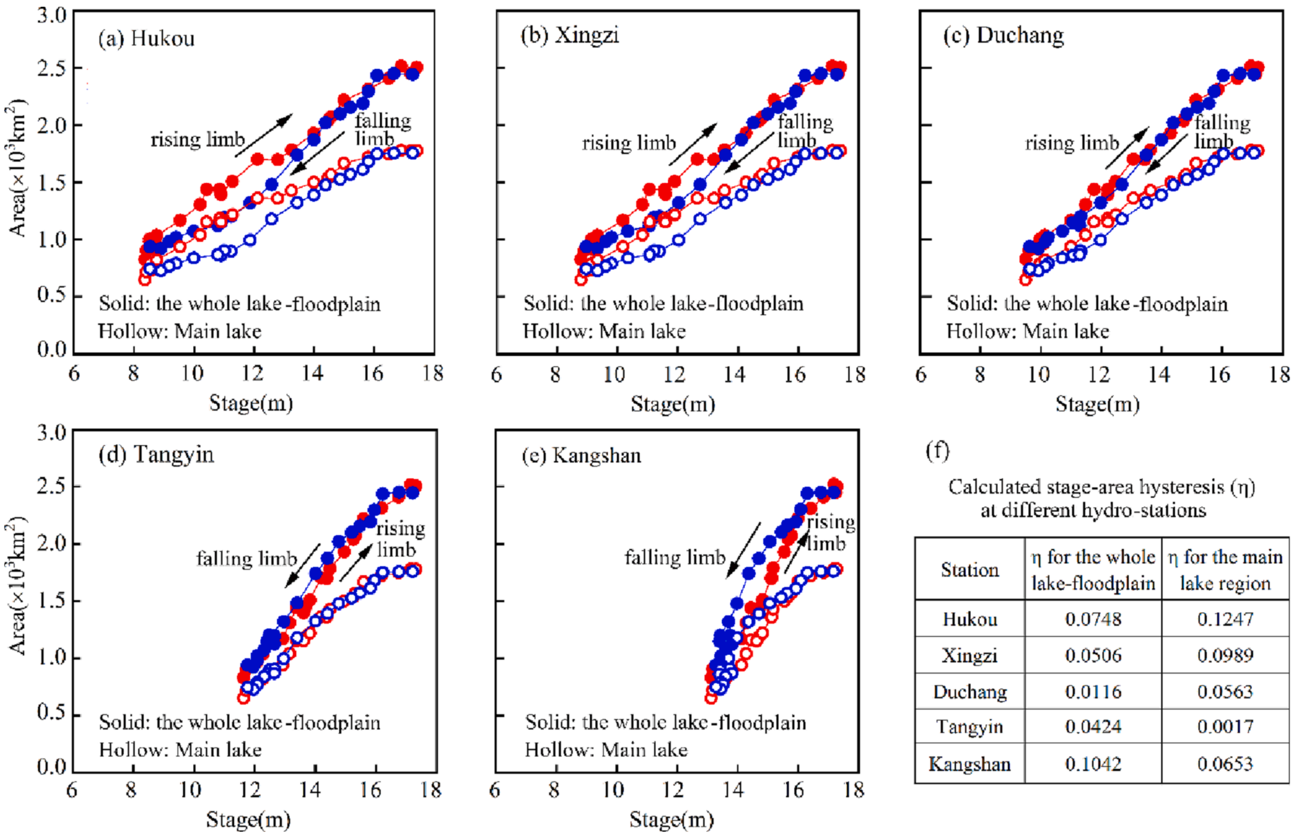


Fig. 4. Intra-annual variation of water surface inundation in the regions of the main lake and seasonal lakes.



Station	η for the whole lake-floodplain	η for the main lake region
Hukou	0.0748	0.1247
Xingzi	0.0506	0.0989
Duchang	0.0116	0.0563
Tangyin	0.0424	0.0017
Kangshan	0.1042	0.0653

Fig. 5. Stage-area hysteresis at different hydro-stations in the Lake-floodplain system (The red and blue lines represent the rising and falling limbs, respectively. The solid points and hollow points represent the stage-area hysteretic curves of the whole lake-floodplain system and the only main lake region, respectively. The arrows show the directions of rising and falling limbs of stage-area hysteretic loops.).

Table 2
Average water levels and their difference at five hydro-stations during the rising and recession periods of the lake.

Item	Hukou (m)	Xingzi (m)	Duchang (m)	Tangyin (m)	Kangshan (m)
Rising period	12.12	12.55	12.92	14.12	14.96
Recession period	12.96	13.15	13.20	14.08	14.73
Difference	−0.84	−0.6	−0.08	0.04	0.23

while it decreased for the upstream stations (Tangyin and Kangshan), which is evident from the calculated η in Fig. 5. For all stations, the relative impact of seasonal lakes on the stage area hysteresis was most prominent at Tangyin.

4.3. *Interannual variability*

The stage-area hysteresis of Poyang Lake changed over time. Fig. 6 shows the calculated hysteresis of the five stations in three different periods before and after the multi-stage experimental impoundment of the Three Gorges Project. It can be seen from the figure that during 2000–2003, the hysteresis of the stage-area relationship at Xingzi station was the smallest, and it increased in turn from Duchang, Tangyin, and Kangshan along the south lake. The Hukou hysteresis at the north end of the lake was greater than that at the Xingzi and Duchang stations. A clockwise hysteretic relationship was observed at Hukou and Xingzi and a counterclockwise hysteretic relationship was observed at the other three stations. In the following period (2004–2009), the hysteresis of the stage-area relationship at the Hukou, Xingzi, and Duchang stations increased significantly and the direction of the hysteretic relationship at

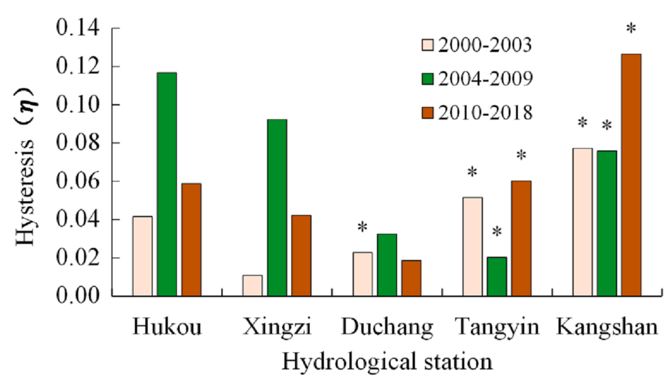


Fig. 6. Changes in stage-area hysteresis at major hydro-stations of Poyang Lake in different periods ("*" indicates counter-clockwise hysteretic relationship).

the Duchang station changed clockwise. In contrast, the hysteresis at the Tangyin and Kangshan stations decreased slightly. During this period, the hysteresis at Tangyin station was the smallest among all stations. The characteristics of the new stage-area hysteretic relationship across the lake emerged from 2010 to 2018. In the former period, the hysteresis of the Hukou, Xingzi, and Duchang stations decreased significantly, whereas that of the Tangyin and Kangshan stations increased significantly. During this period, the hysteresis of the stage-area relationship at Duchang station was the smallest.

5. Discussion

Lake and river floodplains are special underlying surface systems with periodic alternations of dry and wet conditions caused by flood disturbances. Globally, such floodplains cover an area of approximately 80–220 × 10^4 km^2 (Entwistle et al., 2019), including the famous river floodplains of the Nile and Amazon and the lake floodplains of Tonle Sap Lake and Poyang Lake. Because of the significant spatial heterogeneity of the underlying surface, strong openness of the system, and highly dynamic hydrological rhythms, water interactions among floodplains, inflow rivers, and lakes are often complex, leading to prominent non-linear characteristics of hydrological processes (Rudorff et al., 2014; Li et al., 2019b). Our research revealed that within the same open shallow lake-floodplain system, there are two different directions of stage-area hysteretic relationships, indicating that the formation mechanisms behind them are completely different.

The typical lake-floodplain system exhibits obvious fluvial facies during the dry season owing to the extensive exposure of floodplains, and water flows mainly along specific down-cutting channels within the system. Normally, during the rising period of a lake, the rapid rise in the water level in the mainstream channel caused by a large amount of upstream catchment inflow leads to overflow to the floodplains on both sides, forming a typical overbank inundation. In contrast, during the lake recession period, the floodplain water level was higher and drained into the mainstream channel and downstream. These processes are illustrated in the conceptual diagram shown in Fig. 7a. Therefore, compared to the rising period, the inundated area of the lake was larger during the recession period for a given water level, forming a typical counterclockwise stage–area hysteretic relationship, such as the hysteretic relationship presented at the Tangyin and Kangshan stations in the Poyang Lake-floodplain system. The formation mechanism of this hysteretic relationship is similar to the behavior of river floodplains (Rudorff et al., 2014), and its hysteresis is mainly affected by the upstream discharge.

Along the flow direction in an open lake-floodplain system, catchment inflow usually enters the floodplain first and then discharges into the main lake. However, the outflow of the main lake is further affected by the blocking function of its connecting rivers. In this study, because the peak of the Yangtze River discharge was approximately 1–2 months later than that of the Poyang Lake catchment inflow (Fig. 1d), the blocking effect of the Yangtze River on the lake outflow was weak in the first half of the year because of the increasing catchment inflow and relatively low water level of the Yangtze River. At this time, the downstream main lake receives water from the floodplains and can be discharged smoothly. The water level of the entire lake floodplain is mainly affected by the amount of catchment inflow. However, when the catchment inflow decreases rapidly after the peak and the Yangtze River discharge continues to rise, the blocking effect of the Yangtze River on lake outflow becomes obvious and subsequently controls the decline in the downstream lake water level (Hu et al., 2007). Therefore, in contrast to the lake rising period, a time lag can be expected for the drainage of the floodplain and the decrease in the downstream lake water level during the lake recession period. Because of this time lag, the slope of the water surface of the entire lake–floodplain system is clearly different from that in the lake-rising period, and a clockwise stage-area hysteretic relationship can be obtained (Fig. 7b). This clockwise hysteresis is mainly attributed to the floodplain backwater effect in Zhang and Werner (2015) and can be recognized as a typical hydrological characteristic of the lake-floodplain system.

Hydrological processes in large open lake-floodplain systems are highly complex and are related to not only the catchment inflow but also the overall hydrological status of the connected rivers. In this study, changes in the runoff of the lake catchment and the Yangtze River, as well as the alteration in the lake basin topography, were responsible for the interannual variation of stage-area hysteretic relationships in the Poyang Lake-floodplain system. Compared to the period 2000–2003, the mean annual discharge of the Hankou station decreased obviously during–2004–2009 (Fig. 8a). In addition, the operation of the Three Gorges Project has caused riverbed erosion in the middle-lower reaches of the Yangtze River (Ye et al., 2020), and sand mining activities in the lake have enlarged the lake outflow cross-section (Lai et al., 2014). These factors enhance the outflow capacity of Poyang Lake, especially during the recession period (Bing et al., 2017; Zhang et al., 2012; Lai et al., 2014), and shorten the time for catchment inflow to pass through the floodplain and fill the lake. This weakened the backwater effect of the floodplain at downstream stations (northern main lake area), resulting in an obvious reduction in the inundated area during the recession period of the lake and subsequently increasing the stage-area hysteresis. As the outflow channel along the Hukou–Xingzhou–Duchang stations deepened and the topographic gradient decreased (Fig. 8b), the blocking effect of the Yangtze River at the Duchang station strengthened. This is the main reason why the

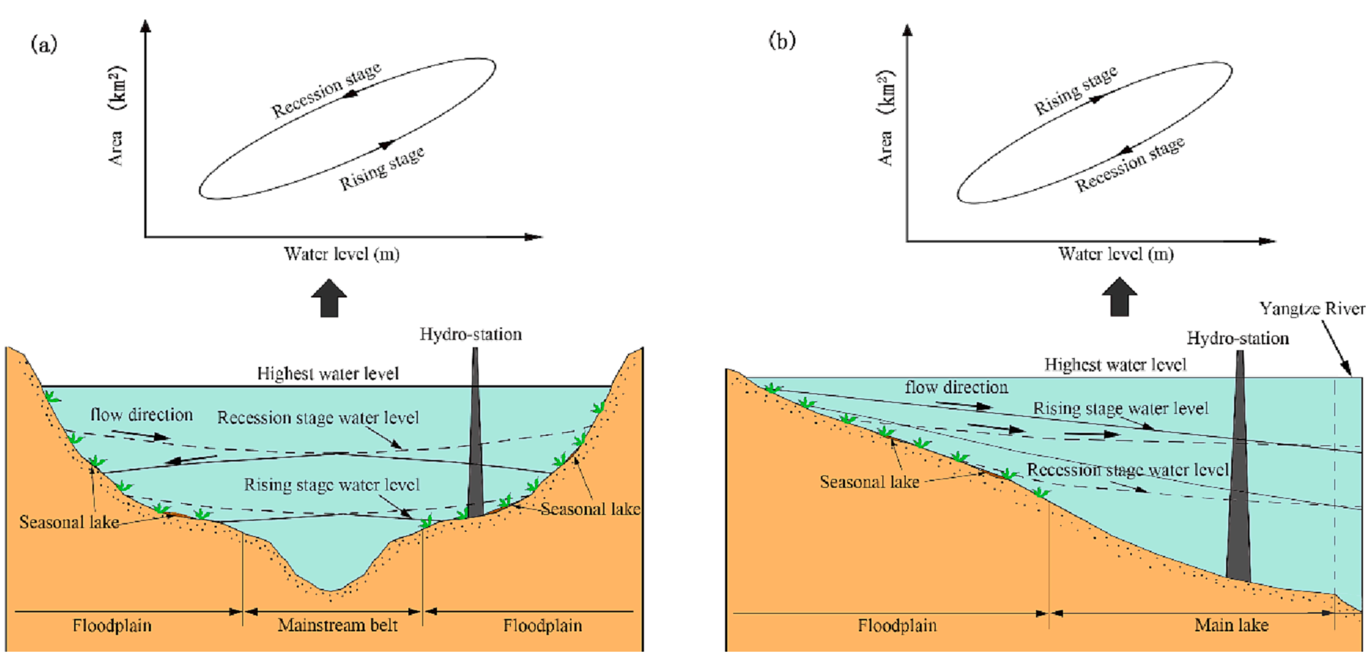


Fig. 7. Conceptual diagram of the formation mechanism of stage-area hysteretic relationships in the lake-floodplain system: (a) counter-clockwise relationship and (b) clockwise relationship.

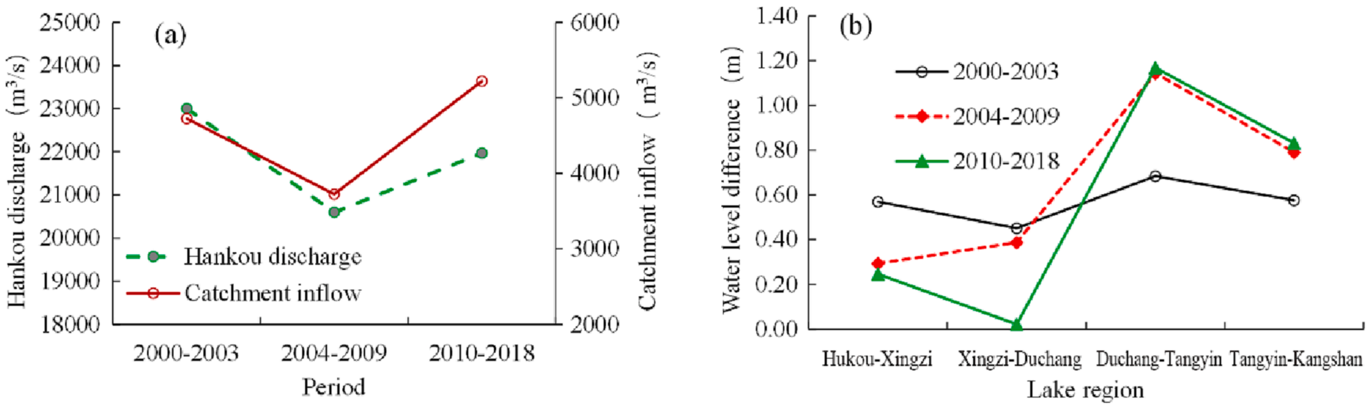


Fig. 8. Changes of (a) Yangtze River discharge and the catchment inflow; and (b) water level difference in the lake at different periods.

hysteresis of the stage-area relationship at the Hukou, Xingzi, and Duchang stations increased significantly, and why the direction of the hysteretic relationship at the Duchang station changed from 2004 to 2009 to. For the Tangyin and Kangshan stations upstream of the lake, the stage-area hysteretic relationships were more affected by changes in catchment inflow. The catchment inflow during 2004–2009 decreased compared with that during 2000–2003 (Fig. 8a); thus, the hysteresis decreased at the two stations. During the period 2010–2018, the average discharge from Hankou station increased significantly compared with that during 2004–2009 (Fig. 8a), resulting in the enhancement of the blocking effect of the Yangtze River and a decrease in the hysteresis at the Hukou, Xingzi, and Duchang stations. Similarly, the significant increase in catchment inflow during 2010–2018 led to an increase in hysteresis at Tangyin and Kangshan stations.

In this study, considering the time-varying boundary of the water surface of a river/lake floodplain system caused by large fluctuations in the water level, a technique for reconstructing a high spatial–temporal resolution inundation dataset based on multi-source remote sensing data and image fusion technology provides an effective way for a detailed examination of the inundation dynamics in these areas. For example, this study revealed that the inundated areas in the two regions of the main lake and the seasonal floodplain lakes in the Poyang Lake floodplain system show obvious intra-annual variations. This result has not been found in previous relevant studies (e.g., Feng et al., 2012; Wu and Liu, 2015; Tan et al., 2019), mainly due to the lack of inundation data with high spatial–temporal resolution. The major reason for this inconsistent intraannual variation is the interference of human activity in floodplain areas. In the Poyang Lake-floodplain system, many seasonal floodplain lakes have been extensively terraced, dammed, and farmed by local fishermen during the recession period of the lake to maintain the water surface, while being released for fishing before the rapid rise of the lake water level, resulting in an abnormal reduction in the water surface (Wang et al., 2016). In addition, based on a high spatiotemporal resolution inundation dataset, the spatial characteristics of inundation frequency, water depth, and hydrological connectivity in these floodplain areas can be calculated, which are important for the prediction of wetland vegetation change and the evaluation of ecosystem stability. Finally, the reconstructed inundation dataset with high spatiotemporal resolution can also be used as a supplement to the numerical simulation, not only to provide accurate water boundary conditions of the complex floodplain areas but also to validate the performance of the hydrodynamic model and improve the model structure.

The findings of this study extend the understanding of the hydrological complexity of large heterogeneous floodplain systems, which have significant implications for relevant floodplain areas worldwide. The main and secondary influencing factors of hydrological processes are intertwined and behave differently in different regions, resulting in obvious spatiotemporal heterogeneity of the inundation dynamics in these floodplain systems. Water resource management and ecological protection plans should be treated differently in different regions, especially in the floodplains and main lake regions. In addition, for large heterogeneous floodplain lakes/rivers, the stage-area hysteretic relationship varies with time and location; therefore, the observed water level at a specific station is not reliable for reflecting or evaluating the inundation dynamics of relevant areas. Lumped-parameter hydrological models that neglect stage-area hysteresis have large simulation errors.

6. Conclusions

Based on the reconstructed high spatiotemporal resolution inundation data of the Poyang Lake floodplain system, this study revealed that inundated areas in regions of the main lake and adjacent floodplain can present inconsistent intra-annual fluctuation. Both clockwise and counterclockwise stage-area hysteretic relationships were observed in the Poyang Lake floodplain system. The downstream stations show clockwise hysteresis, whereas the upstream stations show counterclockwise hysteresis. Stage-area hysteresis occurs because asynchronous inflows and outflows create time-varying gradients across the floodplain-lake complexes. During this process, floodplain settings where seasonal lakes are widely developed have a crucial impact on the formation and magnitude of hysteresis. The magnitude and direction of the stage–area hysteretic relationships also changed with time under the impacts of climate change and human activities in the external environment.

This study highlights the significance of reconstructing high spatiotemporal resolution inundation data based on multi-source remote sensing data in floodplain hydrological research. A better understanding of the spatiotemporal variation in water inundation and stage-area hysteretic relationships provided by this study can be implemented in further research on floodplain areas worldwide.

CRediT authorship contribution statement

Juan Wu: Writing – original draft. **Qi Zhang:** Methodology, Supervision. **Yunliang Li:** Data curation, Validation. **Chong-Yu Xu:** Writing – review & editing. **Xuchun Ye:** Conceptualization, Methodology, Writing – original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

This work was financially supported by the National Natural Science Foundation of China (42071028 U2040205), the Innovation Research 2035 Pilot Plan of Southwest University (SWU-XDZD22003), and the Research Council of Norway (FRINATEK Project 274310). The authors would like to thank expert from Editage (www.editage. cn) for professional editing services for the English language. Cordial thanks also go to the associate editor of the journal and two anonymous reviewers for their valuable comments and suggestions that greatly improved the quality of this paper.

References:

Abdollah, J., Tim, M.V., Thomas, V.N., Irina, E., John, C., Kasper, J., 2014. Blending Landsat and MODIS Data to Generate Multispectral Indices: A Comparison of "Index-then-Blend" and "Blend-then-Index" Approaches. Remote Sensing 6 (10), 9213–9238.

Ajmera, T.K., Goyal, M.K., 2012. Development of stage-discharge rating curve using model tree and neural networks: an application to Peachtree Creek in Atlanta. Expert Syst. Appl. 39 (5), 5702–5710. https://doi.org/10.1016/j.eswa.2011.11.101.

Bing, J., Deng, P., Lv, S., Zhang, X., 2017. The analysis of water exchange regime research on Poyang lake and Yangtze River and driving factors. Scientia Sinica (Technologica). 47, 856–870 (in Chinese).

Chen, B., Chen, L., Huang, B., Michishita, R., Xu, B., 2018. Dynamic monitoring of the Poyang Lake wetland by integrating Landsat and MODIS observations. ISPRS J. Photogramm. 139, 75–87.

Cheng, X., Hong, Y., Chen, J., Ye, B., 2020. A study of the long-term remote sensing dynamic monitoring of inland based on ESTARFM. Remote Sensing for Land and Resources 32 (3), 183–190 in Chinese).

Entwistle, N.S., Heritage, G.L., Schofield, L.A., Williamson, R.J., 2019. Recent changes to floodplain character and functionality in England. Catena 174, 490–498.

Ewing, J.A., 1885. Experimental researches in magnetism. Philos. Trans. R. Soc. Lond. 176, 523–640. https://doi.org/10.1098/rstl.1885.0010.

Feng, L., Hu, C., Chen, X., Cai, X., Tian, L., Gan, W., 2012. Assessment of inundation changes of Poyang Lake using MODIS observations between 2000 and 2010. Remote Sens. Environ. 121 (2), 80–92. https://doi.org/10.1016/j.rse.2012.01.014.

Fread, D.L., 2007. Computation of stage-discharge relationships affected by unsteady flow. J. Am. Water Resour. Assoc. 11 (2), 213–228. https://doi.org/ 10.1111/j.1752-1688.1975.tb00674.x.

Hu, Q., Feng, S., Guo, H., Chen, G., Jiang, T., 2007. Interactions of the Yangtze River flow and hydrologic processes of the Poyang Lake. China. J. Hydrol. 347, 90–100.

Kai, N. 2018. Analysis of vegetation seasonal variation in Yanhe river basin based on spatial and temporal resolution fusion technology. Northwest University (Chine), 2018. (in Chinese).

Koponen, J., Kummu, M., Sarkkula, J., 2005. Modelling environmental change in Tonle Sap Lake, Cambodia. International association of theoretical and applied limnology 29(Pt2):p.1083–1086.

Lai, X., Huang, Q., Jiang, J., 2012. Wetland inundation modeling of Dongting Lake using two-dimensional hydrodynamic model on unstructured grids. Procedia Environmental ences 13 (3), 1091–1098 in Chinese).

Lai, X., Shankman, D., Huber, C., Yesou, H., Huang, Q., Jiang, J., 2014. Sand mining and increasing Poyang Lake's discharge ability: A reassessment of causes for lake decline in China. J. Hydrol. 519, 1698–1706.

Li, Y., Zhang, Q., Yao, J., Werner, A.D., Li, X., 2014. Hydrodynamic and hydrological modeling of the Poyang Lake catchment system in China. J. Hydrol. Eng. 19, 607–616.

Li, Y., Qian, F., Silbernagel, J., Larson, H., 2019a. Community structure, abundance variation and population trends of waterbirds in relation to water level fluctuation in Poyang Lake. J. Great. Lakes Res. 45, 976–985.

Li, Y., Zhang, Q., Cai, Y., Tan, Z., Wu, H., Liu, X., Yao, J., 2019b. Hydrodynamic investigation of surface hydrological connectivity and its effects on the water quality of seasonal lakes: insights from a complex floodplain setting (Poyang Lake, China). Sci. Total Environ. 660, 245–259.

Li, Y., Zhang, Q., Liu, X., Tan, Z., Yao, J., 2019c. The role of a seasonal lake groups in the complex Poyang Lake-floodplain system (China): Insights into hydrological behaviors. J. Hydrol. 578, 124055.

McFeeters, S.K., 1996. The use of the normalized difference water index (NDWI) in the delineation of open water features. Int. J. Remote Sens. 17, 1425–1432.

Norbiato, D., Borga, M., 2008. Analysis of hysteretic behaviour of a hillslope-storage kinematic wave model for subsurface flow. Adv. Water Resour. 31, 118–131.

Pekel, J.F., Cottam, A., Gorelick, N., Belward, A.S., 2016. High-resolution mapping of global surface water and its long-term changes. Nature 540 (7633), 418–422. https://doi.org/10.1038/nature20584.

Rudorff, C.M., Melack, J.M., Bates, P.D., 2014. Flooding dynamics on the lower Amazon floodplain: 1. Hydraulic controls on water elevation, inundation extent, and river-floodplain discharge. Water Resour. Res. 50, 1–16. https://doi.org/ 10.1002/2013WR014091.

Sun, Z., Zhou, X., Fan, J., Xiong, H., Tan, G., 2021. Stage-discharge rating method considering backwater effect in river channel. Advances in Water Science, 32(2), 259–270 (in Chinese).

Tan, Z., Li, Y., Xu, X., Yao, J., Zhang, Q., 2019. Mapping inundation dynamics in a heterogeneous floodplain: Insights from integrating observations and modeling approach. J. Hydrol. 572, 148–159.

Tan, Z., Li, Y., Zhang, Q., Guo, Y., Wang, X., Li, B., Wan, R., Wang, D., Wu, X., 2022. Progress of hydrological process researches in lake wetland: A review. J. Lake Sci. 34 (1) , 18–37 (in Chinese).

Tan, Z., Melack, J., Li, Y., Liu, X., Chen, B., Zhang, Q., 2020. Estimation of water volume in ungauged, dynamic floodplain lakes. Environ. Res. Lett. 15, 054021.

Wang, D., Wang, D., Qi, S., 2016. Analysis of the relationship between water level and natural water surface in Poyang Lake. Resources and Environment in the Yangtze Basin, 25 (S1), 95–102 in Chinese).

Wolfs, V., Willems, P., 2014. Development of discharge–stage curves affected by hysteresis using time varying models, model trees and neural networks. Environ. Modell. Softw. 55, 107–119.

Wu, G., Liu, Y., 2015. Capturing variations in inundation with satellite remote sensing in a morphologically complex, large lake. J. Hydrol. 523, 14–23.

Ye, X., Meng, Y., Xu, L., Xu, C.-Y., 2019. Net primary productivity dynamics and associated hydrological driving factors in the floodplain wetland of China's largest freshwater lake. Sci. Total Environ. 659, 302–313.

Ye, X., Liu, F., Zhang, Z., Xu, C.-Y., 2020. Quantifying the Impact of Compounding Influencing Factors to the Water Level Decline of China's Largest Freshwater Lake. J. Water Resour. Plan. Manag. 146 (6), 05020006.

Zhang, Q., Li, L., Wang, Y.-G., Werner, A.D., Xin, P., Jiang, T., Barry, D.A., 2012. Has the Three-Gorges Dam made the Poyang Lake wetlands wetter and drier? Geophys. Res. Lett. 39, L20402, 7 pp.

Zhang, Q., Werner, A.D., 2015. Hysteretic relationships in inundation dynamics for a large lake–floodplain system. J. Hydrol. 527 (4), 160–171. https://doi.org/10.1016/j.jhydrol.2015.04.068.

Zhang, Q., Werner, A.D., Aviyanto, R.F., Hutson, J.L., 2009. Influence of soil moisture hysteresis on the functioning of capillary barriers. Hydrol. Process. 23 (9), 1369–1375. https://doi.org/10.1002/hyp.7261.

Zhang, X., Zhang, Q., Werner, A.D., 2017. Characteristics and causal factors of hysteresis in the hydrodynamics of a large floodplain system: Poyang Lake (China). J. Hydrol. 553, 574–583.

Zhu, X., Helmer, Eileen, H., Chen, J., Lefsky, M.A., Gao, F., Liu, D. 2016. A flexible spatiotemporal method for fusing satellite images with different resolutions. Remote Sens. Environ. 172, 165–177.

Zhu, X., Jin, C., Feng, G., Chen, X., Masek, J.G., 2010. An enhanced spatial and temporal adaptive reflectance fusion model for complex heterogeneous regions. Remote Sens. Environ. 114 (11), 2610–2623. https://doi.org/10.1016/j.rse.2010.05.032.