Journal of Hydrology 578 (2019) 124055

Contents lists available at ScienceDirect

Journal of Hydrology

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

Research papers

The role of a seasonal lake groups in the complex Poyang Lake-floodplain system (China): Insights into hydrological behaviors

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ARTICLE INFO

This manuscript was handled by Huaming Guo, Editor-in-Chief, with the assistance of Sánchez-Pérez José Miguel, Associate Editor

Keywords:
Seasonal lake groups
Hydrodynamic model
Hydrological behavior
Bathymetry changes
Floodplain management
Poyang Lake

ABSTRACT

Seasonal lakes that exist in floodplain settings have significant effects on hydrological and ecological processes and are highly susceptible to various changes; however, they are rarely investigated, mainly because of the large extent and remoteness of floodplains. This study uses physically based hydrodynamic modeling in combination with a bathymetry adjustment approach to investigate the coupling effects of 77 seasonal lakes (defined as the seasonal lake group) on hydrological behaviors within the Poyang Lake-floodplain system (China) from a systemic perspective. Elucidation of the role of seasonal lake groups could benefit from hydrodynamic modeling, which enables complex lake-floodplain simulations and comparison analyses of natural (original bathymetry) and hypothetical conditions (adjusted bathymetry). In the present study, the simulation results showed that the temporal influences of the seasonal lake group on water levels, lake outflows, and inundation dynamics were greater during dry seasons than wet seasons for both the dry (2006) and wet years (2010). The spatial effects of the seasonal lake group on the hydrology of the lake's floodplains were stronger than those of the main lake for both hydrological years. The findings demonstrate that the seasonal lakes are likely to have very limited effects on the main lake and the associated flood levels. On average, the role of the seasonal lake group during the dry seasons was around several times stronger than that during flood seasons in terms of the magnitudes of hydrological responses. Additionally, it is expected that the seasonal lake group may exert an important role in influencing the surface hydrological connectivity and associated dry-wet hydrological shift across lake-floodplains, indicating a dominant role of the floodplain bathymetry changes. Overall, the results of this study will support management and planning of Poyang Lake and other similar floodplain regions with numerous small, shallow, and seasonal lakes by providing more reliable information regarding bathymetry changes, water management and lake-floodplain interactions to decision-makers for improved floodplain protection strategy.

1. Introduction

Floodplains are hydrologically dynamic systems characterized by highly complex surface hydrodynamics that are subjected to wide-ranging wetting and drying over seasonal timeframes (Bonnet et al., 2008; Thomas et al., 2015; Li et al., 2019a). It is estimated that there are between 0.8 million and 2.2 million km^2 of rivers and lake-related floodplains worldwide (Entwistle et al., 2019). Floodplains are hotspots of biodiversity and ecosystem services that are naturally productive and valuable (Dudgeon et al., 2006), providing a range of hydrological and ecological functions, including flood regulation, water purification, nutrient retention, critical wildlife habitats, and agriculture and livestock products (Robinson et al., 2015; van der Most and Hudson, 2018; Funk et al., 2019). However, floodplain areas have long been recognized as globally threatened ecosystems that are presently highly sensitive to anthropogenic interventions and climate change (Karim et al., 2015; van der Most and Hudson, 2018; Entwistle et al., 2019).

Seasonal lakes are numerous and interconnected, but may be typically small in depth and area (Hayashi and van der Kamp, 2000; Li et al., 2019a; Tan et al., 2019). They are hydrologically and geomorphologically similar to depressional wetlands (Maia et al., 2018). The formation of these seasonal lakes is caused by variations within floodplain topography, which influence hydrological and hydrodynamic processes across floodplains (Hu et al., 2015). Seasonal lakes are most likely to play key roles as natural retarding pools that attenuate flood waves and suppress flood peaks in the earth's land surface (Yamazaki et al., 2011). These lakes serve to retain water during the period of flood recession and hold significantly lower water volumes than other

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https://doi.org/10.1016/j.jhydrol.2019.124055
Received 1 April 2019; Received in revised form 11 August 2019; Accepted 19 August 2019
Available online 20 August 2019

large lakes and wetlands; accordingly, their hydrology and ecology are highly sensitive and respond more rapidly to variations in the surrounding floodplain setting (Evenson et al., 2015; Lee et al., 2018; Li et al., 2019a). Seasonal lakes are considered vital contributors to the overall ecological health of their floodplains, and they also have rich natural diversity (Hu et al., 2015). Given these backgrounds, knowledge of seasonal lakes can substantially aid in the assessment of their hydrological and ecological importance for scientists and managers.

Despite the multiple ecosystem services provided by seasonal lakes, they have not been adequately characterized with respect to their hydrological behaviors. In addition, although many human efforts are made to preserve the conditions of seasonal lakes, they still receive less attention than large surface water bodies (Yu et al., 2015). To the best of our knowledge, many previous investigations of river- and lake-floodplain systems focused on either rivers or lakes, while the roles of small, seasonal lakes within their floodplains on the hydrological behaviors have received little attention. The large extent and remoteness of the majority of floodplains across the world have limited the establishment of a dense network of field-based monitoring, resulting in investigations of individual seasonal lakes being technically difficult and time consuming (Karim et al., 2015; Ovando et al., 2018; Khaki and Awange, 2019). In recent decades, much of the knowledge regarding floodplain lakes and their associated hydrological behaviors has been acquired via application of remote sensing techniques along with in-situ observational information (Trigg et al., 2012; Park and Latrubesse, 2017; Ovando et al., 2018; Tan et al., 2019). Although remote sensing products can be used to completely and properly capture the dynamic evolution of large extent floodplains, which can provide important insights into floodplain environments and their assessment (Alsdorf et al., 2010; Karim et al., 2015; Tan et al., 2019), the use of static products for complex floodplains may not be adequate to test hypotheses and to analyze various scenarios that can affect floodplain settings (Li et al., 2015b). Hydrodynamic modeling of floodplain systems is cumbersome, but models have become a more widespread approach and are used as an alternative tool for assessing many critical aspects of floodplains, such as bathymetry effects (Trigg et al., 2012; Yamazaki et al., 2012; Yao et al., 2018), surface connectivity dynamics (Karim et al., 2015; Beck et al., 2019), and water quality responses (Li et al., 2019a). Therefore, it is important to use hydrodynamic models to obtain an improved understanding of the complex functioning of seasonal lakes in floodplains, and quantitative and qualitative information should be provided to support their conservation.

Poyang Lake, which is the largest freshwater lake in China, creates extensive floodplains that adjoin the main lake (Feng et al., 2012; Li et al., 2019b). The lake and its floodplains are influenced by seasonal dynamic interactions with the surrounding rivers, including strong catchment inflows and the Yangtze River's effects (Hu et al., 2007; Li et al., 2014; Zhang et al., 2014). The most notable feature of the lake-floodplain system is that the floodplain behavior varies between that of a long river and a large lake on a seasonal scale (Zhang and Werner, 2015). In recent years, there has been renewed interest in the floodplain hydrology and associated wetland ecosystem of Poyang Lake. This is mostly because of disturbed fluctuations of the lake water levels (Zhang et al., 2012; Mei et al., 2016), dynamic lake-floodplain interactions (Li et al., 2019a), and increasing human activities (Yang et al., 2016), which in combination have greater effects on the floodplain than the main lake. In addition, the extensive floodplains of Poyang Lake are more prone to changes in the external environment in a rapid manner, due partly to their shallow and wide characteristics (Li et al., 2018b; Yao et al., 2019).

The behavior of the Poyang Lake system is distinct from that of other floodplains in that it has a particularly complex topography and hydrological regime that creates ~102 seasonal lakes of varying depth and area (Ji, 2017; Li et al., 2019a). The water quality of the seasonal lakes and their ecological functions for the wetlands are thought to be largely dependent on the hydrological dynamics and the associated lake-floodplain exchanges (Xia et al., 2016; Li et al., 2019a; Tan et al., 2019). For example, the highly variable hydrological connectivity has recently been recognized as essential to protecting the ecology of the seasonal lakes and their floodplains using field observation data (Xia et al., 2016). In addition, field sampling data and hydrodynamic simulations have shown that lateral lake-floodplain interactions may contribute to water quality trends of seasonal lakes (Li et al., 2019a). There are still, however, information gaps. First, although seasonal lake responses in floodplain regions have previously been examined, the characteristics and possible influences of seasonal lakes remain unclear from a hydrological perspective. Second, available data are not sufficient to evaluate the effects of seasonal lakes in the lake's floodplains, lacking of the knowledge regarding the lake's floodplains response to the current and future floodplain settings, in which climate and human interventions are likely to be more frequent and intensive (Li et al., 2016a; Yao et al., 2018; Ye et al., 2019). An improved understanding of the role of these seasonal lakes is essential for water resource management and lake-floodplain planning, as well as for understanding how seasonal lakes affect the hydrological processes and subsequent ecological conservation of the lake.

Given the hydrological and ecological importance of small, shallow, seasonal lakes in the Poyang Lake floodplains and similar floodplain regions elsewhere, the objectives of this study were to: (1) use a two-dimensional hydrodynamic model to examine hydrological responses of the Poyang Lake-floodplain system for a historical dry and wet year; and (2) use modeling in combination with a bathymetry adjustment approach to assess the coupling effects of a seasonal lake group on major hydrological behaviors in the floodplain system. The key innovation of this study was the insight into a seasonal lake group on large scale floodplains and the integration of a modeling and hypothetical approach to overcome the limitations of current studies exploring floodplain hydrology in a data-limited environment.

In the next section, we provide a detailed description of the study area including climate, hydrology, and floodplain settings. This is followed by details regarding the methods used to simulate the hydrodynamics of the lake-floodplains under natural and hypothetical conditions. Sections 4 and 5 provide the results and discussion, respectively. Major conclusions from this study are summarized in Section 6.

2. Study area

2.1. Poyang lake

Poyang Lake is one of the few large lakes in middle reaches of the Yangtze River that remains naturally connected to surrounding rivers (Fig. 1a). The lake has high-flow channels, gently undulating floodplains, and bays and islands characterized by irregular shorelines, an incised lake morphology, and contrasting bathymetric features (Li et al., 2017a). It is a topographically and geometrically complex lake that varies from the lake's floodplain regions at elevations of 28.2 m to the flow channels at elevations of about −8 m (Fig. 1a). Generally, 85% of the water depth within Poyang Lake is < 6 m during flood seasons, while the maximum depth can reach 30 m in the downstream portion of the lake's main flow channels (Li et al., 2017a). The flow velocities range from < 0.1 m/s in the floodplains to > 1.0 m/s in the lake's flow channels (Li et al., 2016b). In addition, the residence times of the lake vary from < 20 days in the flow channels to > 300 days in some bays, suggesting a heterogeneous spatial distribution of the hydrodynamic conditions (Li et al., 2015b).

Poyang Lake experiences a subtropical monsoon climate. The lake receives upstream surface runoffs from the Ganjiang, Fuhe, Xinjiang, Raohe, and Xiushui rivers in the catchment, and subsequently interacts with the Yangtze River through the narrow outlet of the lake (Fig. 1a). The hydrological variations in both the surface rivers and the Yangtze River play a combined role in controlling lake water-level changes of 8

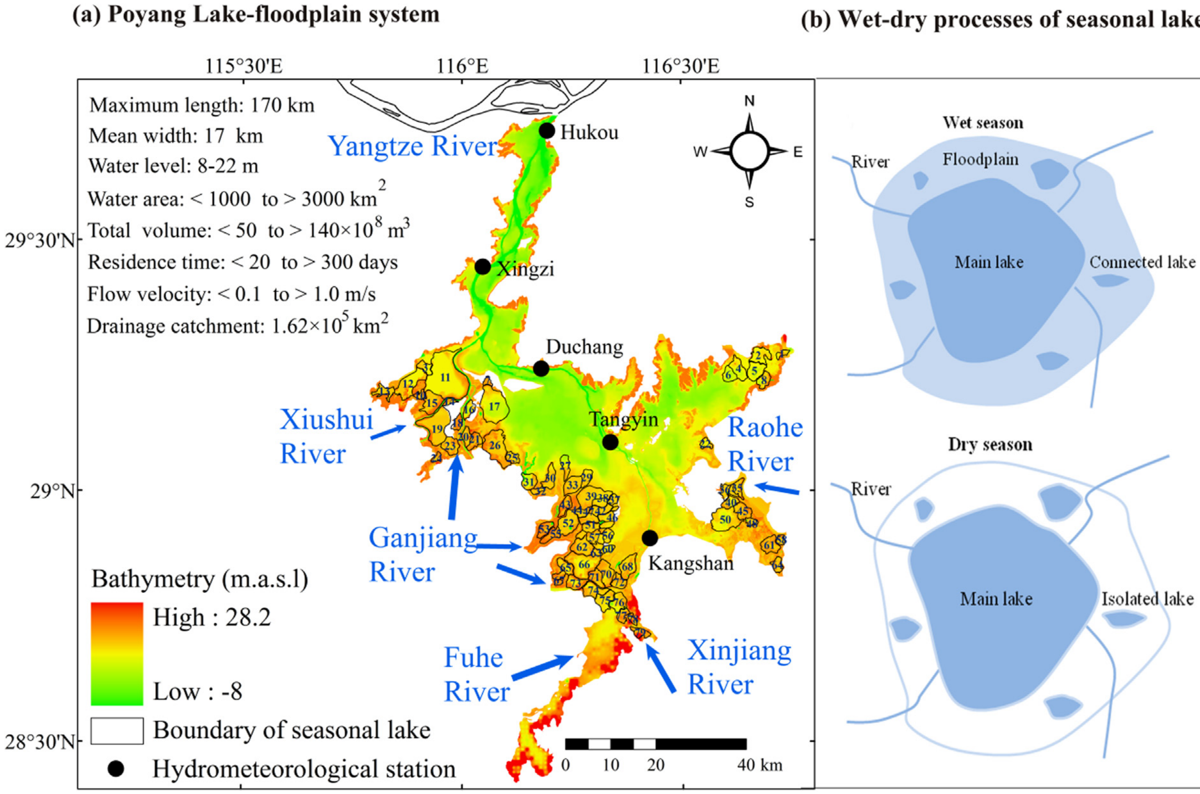

Fig. 1. Map of Poyang Lake and its floodplain system: (a) main lake and floodplain topography, major surrounding rivers, hydrometeorological stations and 77 seasonal lakes; and (b) schematic diagram for dynamic dry and wet conditions of the seasonal lakes within the floodplains (modified from Li et al. 2019a). Main lake represents the permanently inundated area with deep flow channels, and floodplains represent the shallow areas adjoining the main lake.

to 22 m/yr (Li et al., 2014). The lake and surrounding rivers not only provide industrial and urban water, but also serve agricultural and environmental functions for Jiangxi Province (Zhen et al., 2011). Poyang Lake is a prominent system of a highly dynamic lake water that contracts and expands annually from < 1000 to > 3000 km^2 (Feng et al., 2012), creating extensive floodplain areas adjoining the main lake (Fig. 1b). The shallow floodplains play a critical role in flood regulation and protection of ecosystem services and biodiversity conservation (Huang et al., 2018; Li et al., 2019b). Vegetation in the floodplains mainly includes floating vegetation, submerged vegetation, emergent aquatic vegetation, and mesophytic vegetation (Tan et al., 2016).

2.2. Seasonal lakes

A notable feature of Poyang Lake is that it experiences complex floodplain settings that consist of numerous and interconnected seasonal lakes (Hu et al., 2015), with a total area of approximately 800 km^2 (Ji, 2017). The ecosystems of the seasonal lakes are thought to be largely dependent on the hydrological regime and associated lake-floodplain exchanges (Xia et al., 2016). In addition, water quality dynamics in the seasonal lakes and responses to lake-floodplain hydrology play critical roles in the ecological and environmental functions (Li et al., 2019a). Generally, the floodplains and their seasonal lakes are partly or fully coupled to the main lake during the wet summer months (e.g., June-October), but become isolated during the dry winter months (December-February) (Fig. 2a), creating hydrological differences within Poyang Lake between wet and dry seasons (Fig. 1b). The main source for the seasonal lakes is floodwater of the main lake during the wet summer season (Hu et al., 2015; Wu and Liu, 2017). The seasonal lakes hold significantly lower volumes of water (~ < 8.0 × 10^8 m^3) than the main lake (~110 × 10^8 m^3); therefore, the hydrology and ecology are expected to be more sensitive to variations in the complex floodplain environment (Ji, 2017; Li et al., 2019a). Geographically speaking, the bottom elevations for most of the seasonal lakes vary between 12 m and 13 m (Fig. 1a), and these levels are almost higher than those of the main lake and its flow channels (Fig. 2b). These seasonal lakes are located at various distances to the main flow channels of the lake. Additionally, the area of these seasonal lakes varies considerably from < 1 to > 80 km^2 across the floodplains (Fig. 2c). Fig. 1a shows the distribution and boundary of the 77 seasonal lakes (hereafter referred to as the "seasonal lake group") within the floodplains that were chosen for modeling and analysis.

3. Materials and methods

A hydrodynamic model was used to investigate the hydrodynamics of the Poyang Lake-floodplain system (see Section 3.2). The model was validated and used to reproduce the hydrodynamics of the dry and wet years (see Section 3.3). The delineation and conceptualization of the seasonal lake group were applied to the lake's hydrodynamic model using a bathymetry adjustment method (see Section 3.4). Comparative analyses and corresponding statistical approaches (see Section 3.5) were subsequently used to explore the coupling effects of seasonal lake groups on the hydrological behavior of Poyang Lake. The modeling methodology used in this study is presented in Fig. 3.

3.1. Data availability

Wind speed, wind direction, precipitation and evaporation were observed at gauging stations (i.e., Hukou, Xingzi, Duchang, Tangyin, and Kangshan stations; Fig. 1a) and used to represent the meteorological conditions of the dry (2006) and wet years (2010), which were applied to force the hydrodynamic model of Poyang Lake. Daily river discharges from the five major rivers in the catchment (Fig. 1a) were adopted when setting inflows within the model. To represent the lake's

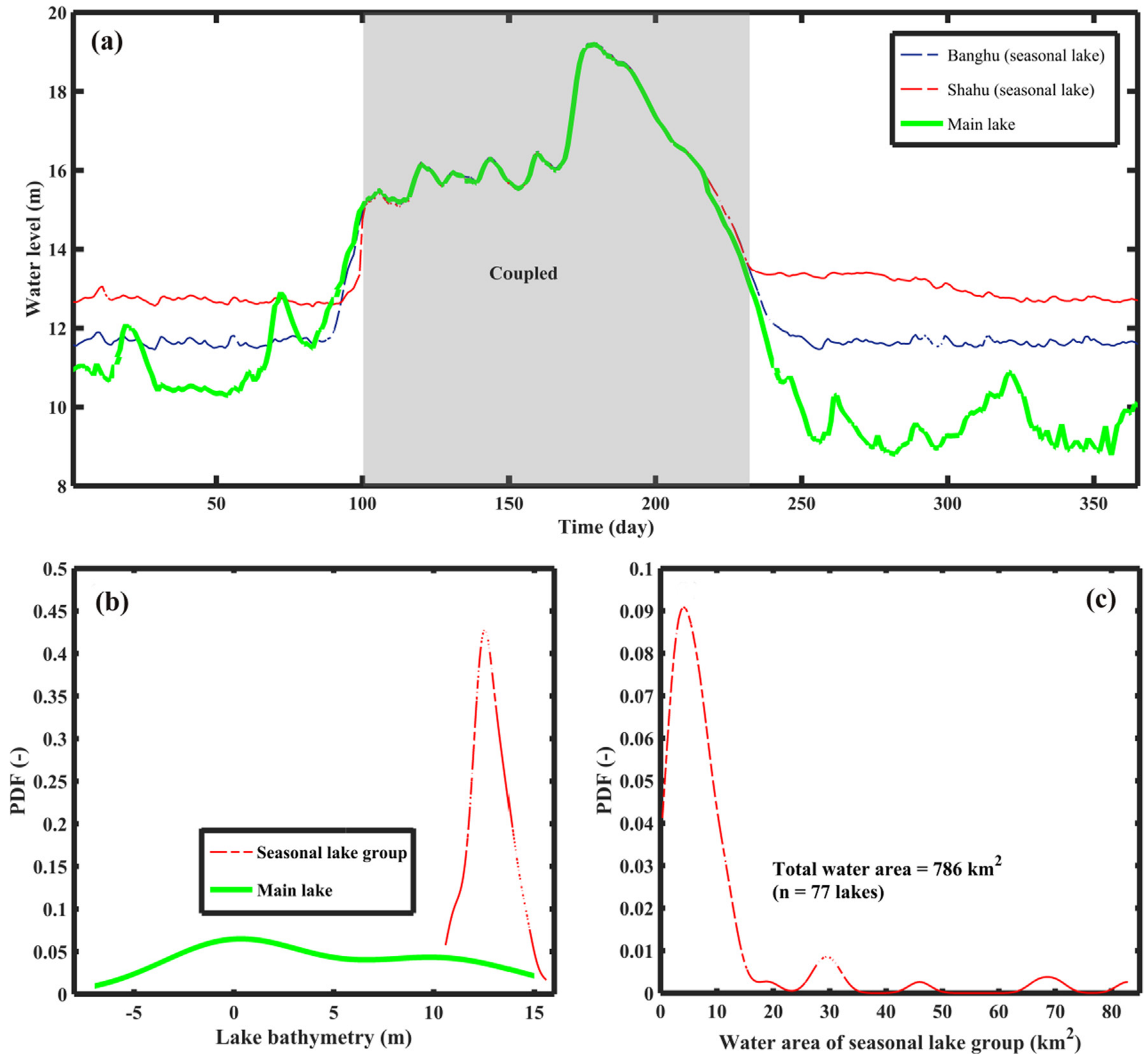

Fig. 2. (a) Observed water levels for the two seasonal lakes (11 and 15 in Fig. 1a) and the main Poyang Lake during 2016. (b) Probability distribution functions (PDFs) of bathymetry for Poyang Lake and the associated seasonal lakes. (c) PDF of water area for the seasonal lakes. The bathymetry and water area data for the seasonal lake group are available from Ji (2017).

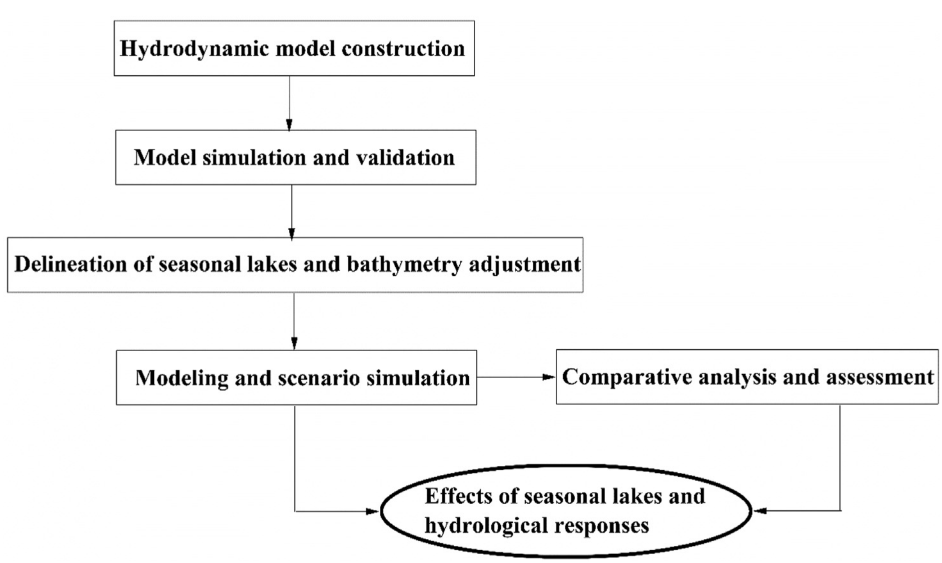

Fig. 3. Modeling methodology used in this study.

hydrodynamic responses, lake water levels and outflow discharges obtained from Hukou, Xingzi, Duchang, Tangyin, and Kangshan gauging stations (Fig. 1a) were used to build and validate the model. Additionally, the bathymetry of Poyang Lake from a 1:10,000 map surveyed in 2010 (30 m × 30 m) was used to describe the topographical features of both the main lake and floodplain areas. All of the hydrological and meteorological data for the hydrodynamic model were derived from the routine observations of the Hydrological Bureau of Jiangxi Province.

For Poyang Lake, a total of 17 cloud-free Landsat8 images (30 m × 30 m) were extracted and used to represent the lake water surface areas for the hydrological years 2006 and 2010. In brief, the radiometric calibration coefficients from the metadata file (https://glovis.usgs.gov/app) were employed to convert the Landsat8 images to top-of-atmosphere (TOA) radiance. Surface reflectance (SR) was produced using atmospherically corrected radiance. In this study, the Modified Normalised Difference Water Index (MNDWI) was adopted to delineate the lake water surface area (Li et al., 2019a). All processing and analysis of the lake water surface area were implemented in ArcGIS software.

3.2. Hydrodynamic model construction

MIKE 21 solves two-dimensional, free surface equations using the incompressible Reynolds-averaged Navier-Stokes equations invoking the assumptions of hydrostatic pressure and the Boussinesq (DHI, 2014). The MIKE 21 model has the ability to simulate the hydrodynamic conditions of estuaries, coastal areas, bays, and floodplain lakes in response to a variety of forcing functions. The MIKE 21 model has proven to be useful in reproducing the flow features of the Poyang Lake-floodplain system and has been widely applied in various studies, including hydrodynamic analysis (Li et al., 2014, 2017a; Zhang et al., 2014), thermal regime investigation (Li et al., 2017b, 2018b), hysteretic simulation (Zhang and Werner, 2015), and hydrological connectivity estimation (Li et al., 2019a). Therefore, a previously developed MIKE 21 model by Li et al. (2014) was revised and expected to investigate the hydrodynamic behaviors of the Poyang Lake-floodplains.

In this study, the hydrodynamic simulations in 2006 and 2010 were selected to reproduce the representative conditions in Poyang Lake, where the hydrometeorological forcings followed a typical dry and wet behavior (Yao et al., 2018). The upstream boundaries of the lake model were specified as time-varying river discharges from the five rivers, and the lower boundary condition of the model was specified as the water levels at the Hukou gauging station. Spatially uniform, time-varying meteorological parameters including precipitation, evaporation, wind speed, and wind direction were used as atmospheric conditions of the hydrodynamic model. To capture the topographical features of the lake-floodplain system, the simulated domain of the model covers the maximum flood inundation area of ~3124 km^2 (Li et al., 2014). The trial and error method was used to adjust and determine the element sizes, leading to variable sizes of 70 to 1500 m across the computational domain, with a total of 20,450 triangular elements (Li et al., 2014). The numerical option of wetting and drying, h_{dry} (0.005 m) < h_{flood} (0.05 m) < h_{wet} (0.1 m), was employed in the model to better represent the floodplain dynamics. The minimum time step was restricted to 0.1 s to maintain the target Courant-Friedrich-Levy number at < 1.0. The Manning number of the lake bed (i.e., 30–50 m$^{1/3}$/s) and the Smagorinsky factor of eddy viscosity (i.e., 0.28) obtained by Li et al. (2014) were used to perform the hydrodynamic simulations. The observations from the five lake gauging stations (Fig. 1a) were used as the initial water surface elevation, while the initial water velocities were set to zero throughout the model domain. A spin-up time of 14 days was used to achieve representative initial conditions of the lake.

3.3. Model validation and assessment

The revised hydrodynamic model was validated and expected to reproduce the hydrodynamic conditions of the dry and wet years. Model validation was performed using routine observations (from 2006 and 2010) of lake water levels (i.e., at Xingzi, Duchang, Tangyin and Kangshan gauging stations) and outflow discharge (i.e., at Hukou gauging station). Lake water area obtained from remote sensing images was also used to validate the model. To evaluate the model's performance, quantification of goodness-of-fit was assessed using the root-mean-square error (*RMSE*), determination coefficient (R^2), and Nash-Sutcliffe coefficient (E_{ns}) (Li et al., 2015a).

3.4. Conceptualization and bathymetry adjustment

The seasonal lakes within the Poyang Lake's floodplains are highly susceptible to modification due to increasing human activities, and they have suffered obvious bottom deposition and differed between lakes (Yao et al., 2018). Hydrological and hydrodynamic processes in the floodplain system are strongly dependent on the bathymetry changes. Although the seasonal lakes are somewhat interconnected, their spatial distribution is still decentralized near the lake's shoreline (see Fig. 1a). Since the water area and water volume of these seasonal lakes are smaller than those of the main lake, research regarding the coupled effects of the seasonal lakes is more important than that of the individual seasonal lakes.

Given these considerations, this study conceptualized the functioning of the seasonal lake group based on the lake bathymetry (i.e., elevation) and GIS-supported geospatial data model (Arc Hydro). Arc Hydro is a hydrologic data modeling tool for the application of water resources that was developed to build hydrologic information systems to synthesize geospatial and temporal data supporting modeling and analysis (Maidment, 2002; Merwade, 2012). In this study, the seasonal lake groups across the Poyang Lake floodplain are regarded as depressional elements below the surrounding terrain (Fig. 1a). That is, the water is considered to be trapped in the seasonal lakes and cannot flow during the low lake level period. The Fill Sinks function in Arc Hydro is commonly used to modify the elevation data to eliminate these problems (Maidment, 2002). Therefore, the bathymetry adjustment method is expected to represent changes in the floodplain settings without the seasonal lake group, based on the Fill Sinks function. In brief, the elevation map of the lake's floodplains were used and converted to a grid-based format (250 m × 250 m). Fill Sinks process fills the sink in the grid if cell is in the lower than elevation of neighbor cell. This tool used the grid input to modify the elevation values of the 77 seasonal lakes fully or partially by keeping a small slope gradient (< 0.001) between the depressions and their adjacent elevations. That is, all the seasonal lakes (or sinks) were filled to the spill elevation which created almost flat areas at local floodplains. Details regarding the basic algorithm of the bathymetry adjustment are described in above references (Maidment, 2002; Merwade, 2012). Pre-processing and adjustment of the bathymetry data were conducted using the ArcGIS software. It is beyond the scope of this study to assess the accuracy of bathymetry adjustment for the seasonal lakes, but we aimed to explore a simple and effective method for representing floodplain bathymetry changes in relation to the seasonal lake group.

The original and adjusted bathymetry of the Poyang Lake floodplain are intended to represent conditions with (i.e., natural conditions) and without (i.e., hypothetical conditions) the seasonal lake groups, respectively (Fig. 4a-b). To examine the role of bathymetry on the hydrodynamic results for our example seasonal lakes, the adjusted bathymetry and the associated mesh information were subsequently used as input for the lake's hydrodynamic simulations (Fig. 4c). The general idea was to show the differences between the lake hydrodynamics under the two bathymetry scenarios to provide insight into the influences of bathymetry changes on lake hydrological behaviors

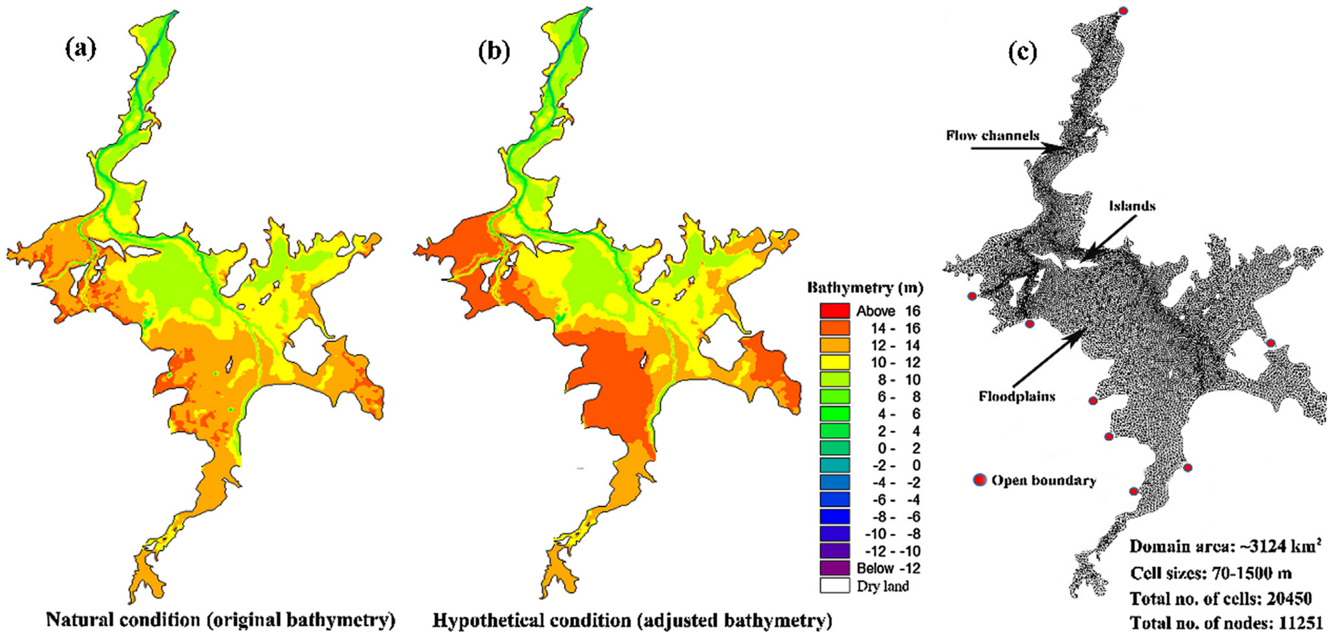

Fig. 4. (a) Original bathymetry, (b) adjusted bathymetry and (c) mesh information of the hydrodynamic model.

based on a dry year (2006) and a wet year (2010).

3.5. Statistical and geostatistical methods

The Richards-Baker Flashiness Index (i.e., R-B index) was developed to assess the degree of streamflow and water level variations (Baker et al., 2004; Ovando et al., 2018). In this study, the R-B index was used to explore the influence of seasonal lakes on the hydrological variability of the lake. The index was calculated using the following equation:

$$R - B\ index = \frac{\sum_{i=1}^{n} |h_i - h_{i-1}|}{\sum_{i=1}^{n} h_i} \tag{1}$$

where R-B index represents the R-B index for the flood signature in the floodplain system, and h_i represents the water level at time step i. R-B index is a dimensionless measure in range of 0–2 (Holko et al., 2011). Zero denotes an absolutely constant hydrological regime, and increased index values represent increased flashiness and fluctuations of hydrological regime (Ulén et al., 2016).

To describe the dry-wet hydrological shift in the floodplain system, the shift frequency between dry and wet conditions (*DWF*) was defined as follows:

$$DWF\,(\%) = \frac{NDW}{T} \times 100 \tag{2}$$

where *NDW* represents the number of dry to wet (i.e., $h_{i} < h_{dry}$ and $h_{i+1} > h_{\mathrm{wet}}$) and wet to dry (i.e., $h_{i} > h_{\mathrm{wet}}$ and $h_{i+1} < h_{dry}$) shifts within a time series, and T is the total number of records.

A geostatistical connectivity function (CF) was used to analyze the surface hydrological connectivity of floodplain areas (Pardo-Iguzquiza and Dowd, 2003). The geostatistical method uses the binary state data to calculate and estimate surface water pathways and linkages on the basis of a multi-point statistic (Trigg et al., 2013; Li et al., 2019a). A probability-distance function (i.e., CF) was produced to express the probability (Pr) that n points along a specified direction are all valued above the threshold value (Journel et al., 2000).

$$\mathrm{CF}(n; z_c) = \mathrm{Pr}\left\{\prod_{j=1}^{n} I(u_j; z_c) = 1\right\} \tag{3}$$

where Π is the product operator. $I(u_j; z_c)$ represents an indicator of the variable $Z(u_j)$ at location u_j that exceeds the threshold value z_c, which is defined as: $I(u_j; z_c) = 1$ if $Z(u_j) > z_c$, and $I(u_j; z_c) = 0$ otherwise. The underlying principles of the geostatistical method are described in detail in Trigg et al. (2013). In this study, the CF of surface hydrological connectivity in north–south (N-S) and west-east (W-E) directions was investigated across the Poyang Lake-floodplain system, which represents an average condition of the whole lake-floodplain system (Li et al., 2019a). The N-S and W-E are approximately parallel and perpendicular to the lake's main flow direction (i.e., from south to north), respectively. All of the above statistical analyses were conducted using the MATLAB software.

4. Results

4.1. Hydrodynamic model validation

The modelled and observed water levels and outflow discharges at the five lake gauging stations matched well during the validation years of 2006 and 2010 based on a time-series visual inspection and statistical evaluation (i.e., E_{ns}, R^2, and *RMSE*) (Fig. 5). The goodness-of-fit statistics showed that the *RMSE* values of the water levels were < 0.43 m, the E_{ns} varied from 0.94 to 0.97, and R^2 ranged from 0.96 to 0.99 for the dry and wet years. The lake outflow discharges at the Hukou gauging station also showed satisfactory agreement between the simulated and observed series. The associated values of E_{ns} and R^2 varied from 0.90 to 0.91 and 0.92 to 0.94, respectively, suggesting a reasonable simulation for the lake hydrodynamic field. However, the model results were somewhat overestimated during the lake dry seasons (i.e., December–February), as illustrated in Fig. 5a–e. The impact of the complex topography on model-generated patterns of hydrodynamic behaviors can almost be ignored during the flood periods (i.e., June–August), and amplified during the low-level dry periods.

Fig. 6 shows that the hydrodynamic model is generally capable of simulating daily water surface areas for the lake-floodplain system, producing R^2 in range of 0.93–0.95 for both the hydrological years. It is noteworthy that the slight discrepancies between the simulation and the remote sensing can be partly attributable to the difference between the model's mesh sizes (i.e., 70–1500 m) and the remote sensing resolution (30 m × 30 m). Overall, the results presented in Figs. 5 and 6 suggest both the phase and magnitude of temporal dynamics have

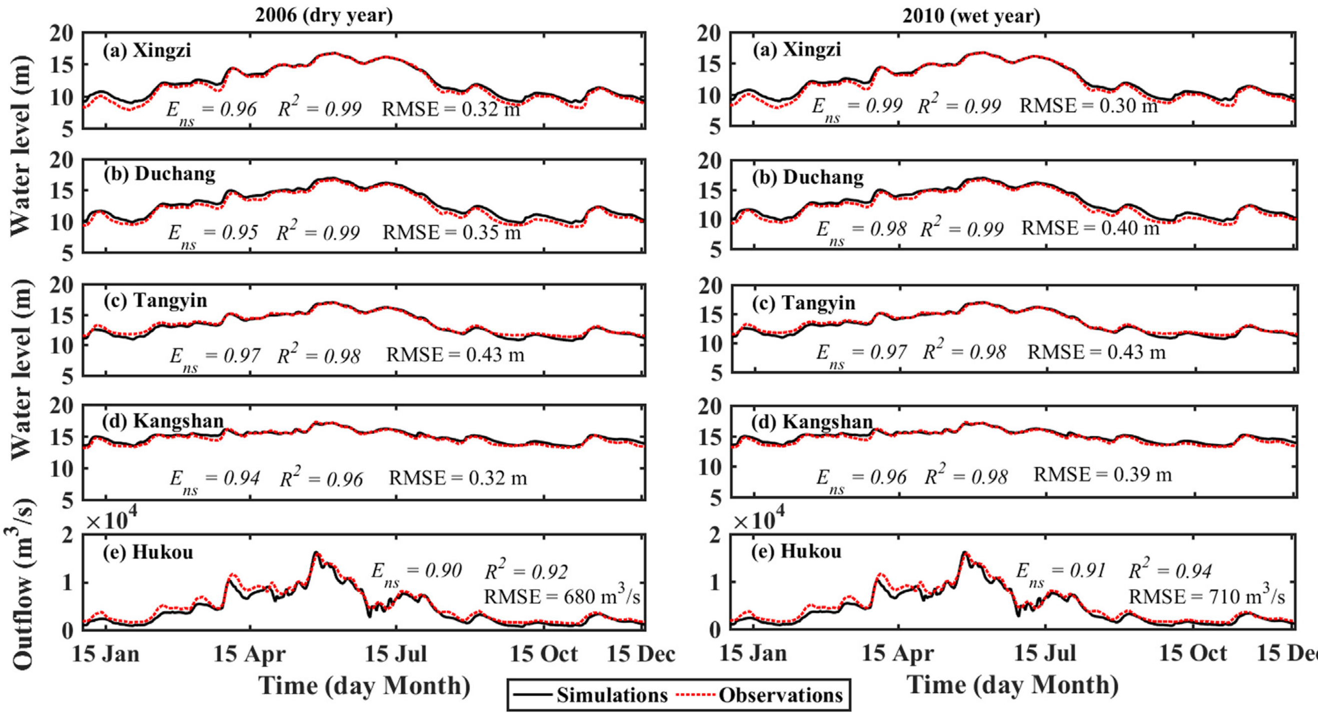

Fig. 5. Time series comparison of modelled and observed lake water levels at: (a) Xingzi, (b) Duchang, (c) Tangyin, (d) Kangshan gauging stations; and (e) lake outflow discharge hydrograph at Hukou gauging station for the validation years 2006 and 2010.

similar precisions during dry and wet years, which demonstrates that the current MIKE 21 model has the capability to reproduce major hydrological behaviors in the floodplain system of Poyang Lake.

4.2. Effects of seasonal lake group

4.2.1. Lake water level changes

The effects of the seasonal lake group within the Poyang Lake's floodplains, in terms of the water level difference between the natural condition and hypothetical condition, are illustrated in Figs. 7 and 8. For both the main lake and the floodplain regions, the simulation results show that the coupling effects of the seasonal lake group on the water levels during the flood months (e.g., June–August) were distinctly weaker than during the dry winter months (e.g., December–February) of 2006 and 2010. That is, the hypothetical condition results in a more likely high water level than the natural condition during the dry seasons, as reflected in an increased water level of the main lake by up to 0.6 m and 0.4 m for the dry year (2006) and the wet year (2010), respectively (Figs. 7 and 8). In addition, the corresponding water level increases of the floodplain regions reached 0.9 m for both

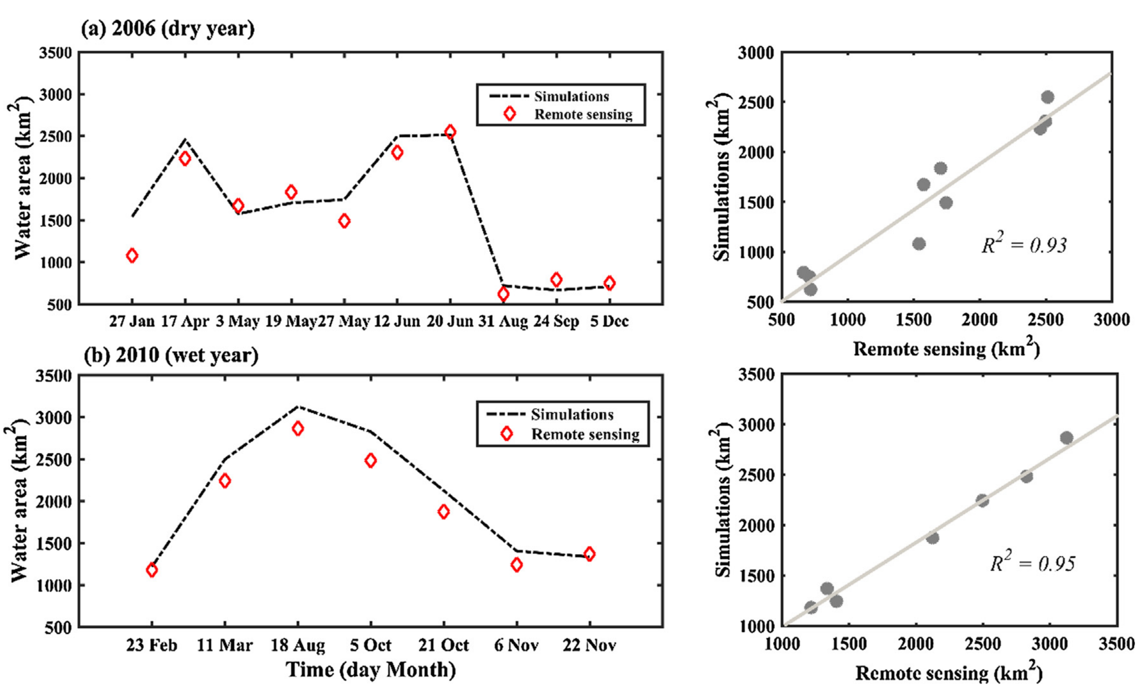

Fig. 6. Comparison of lake water areas simulated by model and derived from remote sensing images for the validation years (a) 2006 and (b) 2010.

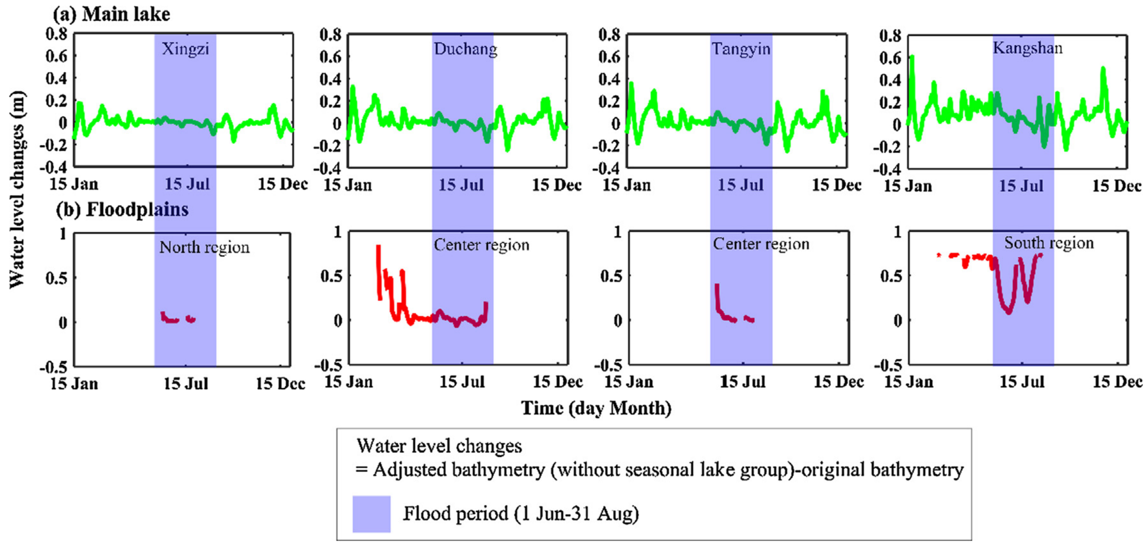

Fig. 7. Influence of the seasonal lake group on hydrological behaviors within the lake-floodplains in the dry year (2006): (a) water level changes in the main lake; and (b) water level changes in the floodplains (four arbitrary points from north to south). Positive values indicate that the water level under the hypothetical condition is higher than under the natural conditions. The missing data in sub-figure (b) represents the shift between dry land and wet land in the current time period.

the dry year and the wet year. The seasonal lake group tended to have a limited effect on water level changes for both the main lake and the floodplains (< 0.2 m) during the flood seasons, especially for the typical wet year (2010; ~0 m). In general, the influences of the seasonal lake groups on water levels were stronger during the dry year (2006) than the wet year (2010), and more significant during the drier dry seasons than the wetter wet seasons. It is likely that the impact of bathymetry adjustment on water level behaviors is more significant during the dry seasons than the flood seasons.

Fig. 9 shows the changes in the spatial pattern of the water level during the flood and dry period of 2006 and 2010, respectively. The results revealed that, in general, the lake-wide pattern during the flood periods (Fig. 9a and Fig. 9b) exhibited a similar spatial distribution to that during the dry periods (Fig. 9c and d). However, the spatial water levels in the dry periods presented more significant changes (i.e., up to 1.6 m) than in the flood periods (i.e., up to 0.6 m), as expected. Although water level reductions were observed in some floodplain regions, the water level increases were found across the majority of the lake-floodplains (Fig. 9). Additionally, the water level variations in the floodplains (~ > 0.6 m) were distinctly higher than those of the main lake (~ < 0.2 m) for both hydrological years. This is an expected outcome given that the local bathymetry changes and the associated flow structure may substantially influence water level behaviors throughout the lake-floodplains. The results presented here indicate that the contribution of the seasonal lake group to the lake-floodplain behaviors has experienced a significantly spatial change.

4.2.2. Lake flood flashiness

Changes in the water level behavior of the main Poyang Lake are inextricably linked to the flood signature. Fig. 10 shows the calculated R-B flashiness index for the dry year (2006) and the wet year (2010) between the natural and hypothetical conditions. The results show that the R-B index in the lake's downstream area was significantly higher than that of the upstream area under both conditions, indicating

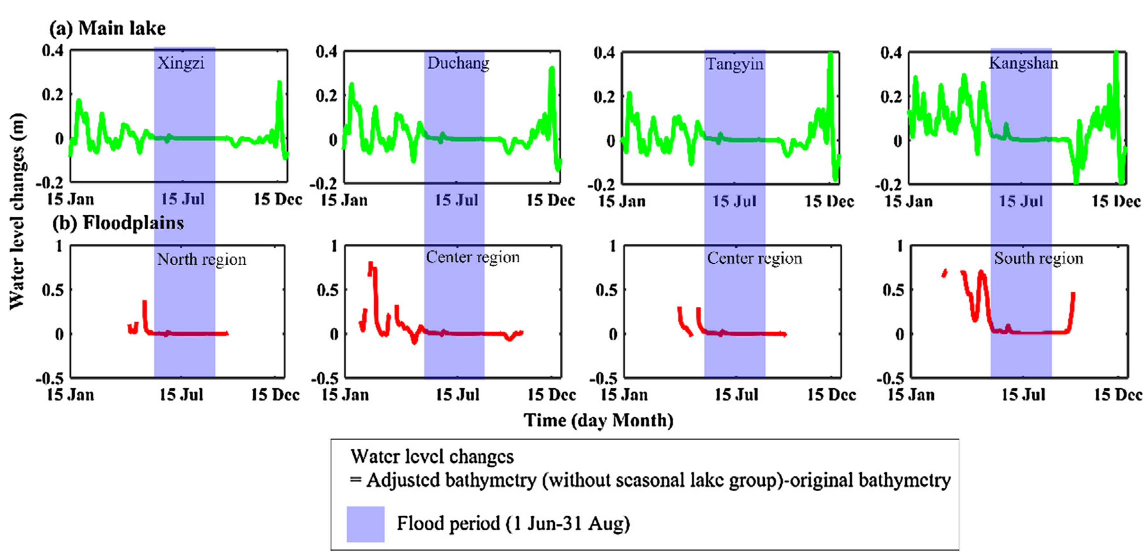

Fig. 8. Influence of the seasonal lake group on hydrological behaviors within the lake-floodplains in the wet year (2010): (a) water level changes in the main lake; and (b) water level changes in the floodplains (four arbitrary points from north to south). Positive values indicate that the water level under the hypothetical conditions is higher than under the natural conditions. The missing data in sub-figure (b) represents the shift between dry land and wet land in the current time period.

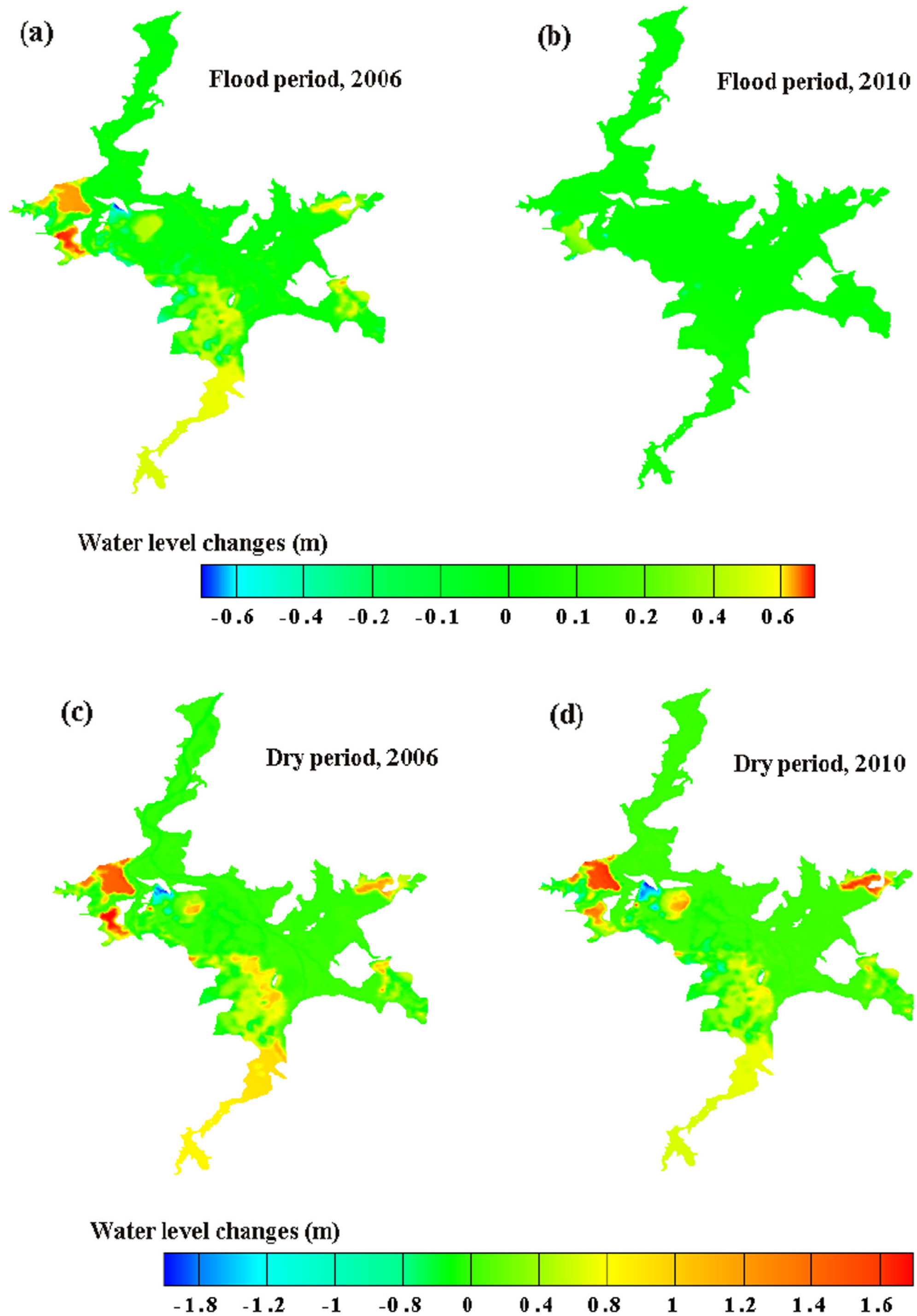

Fig. 9. Spatial distribution of water level changes between the hypothetical and natural conditions averaged over the (a–b) flood and (c–d) dry period in 2006 and 2010, respectively. Positive values indicate that the water level under the hypothetical condition is higher than the natural condition. Flood = June–September, and Dry = December–February.

different responses of the flood flashiness across the lake's length (i.e., from Xingzi gauging station to Kangshan gauging station). In addition, the values of the R-B flashiness index under hypothetical condition were obviously higher than those of the natural condition for both the dry year and the wet year, although small R-B index values were observed at the four gauging stations (i.e., ~7.7–9.0 × 10^{-3}; Fig. 10). These results indicate that the hypothetical conditions are more likely to result in a flashier flood regime in dry years than wet years, suggesting a possible impact of the seasonal lake group. This is a logical outcome of the bathymetry changes for the floodplains to increase water level dynamics and hydrological variability, particularly in the lake dry conditions.

4.2.3. Lake discharge changes

The outflow of Poyang Lake (i.e., at Hukou gauging station) is an important indicator of the lake-Yangtze River interactions. The effects of the seasonal lake group on the outflow discharge are shown in Fig. 11, taking 2006 and 2010 as examples. The simulations revealed that the outflow discharge may exhibit a complex response (i.e., positive and negative differences) to the condition of without the seasonal

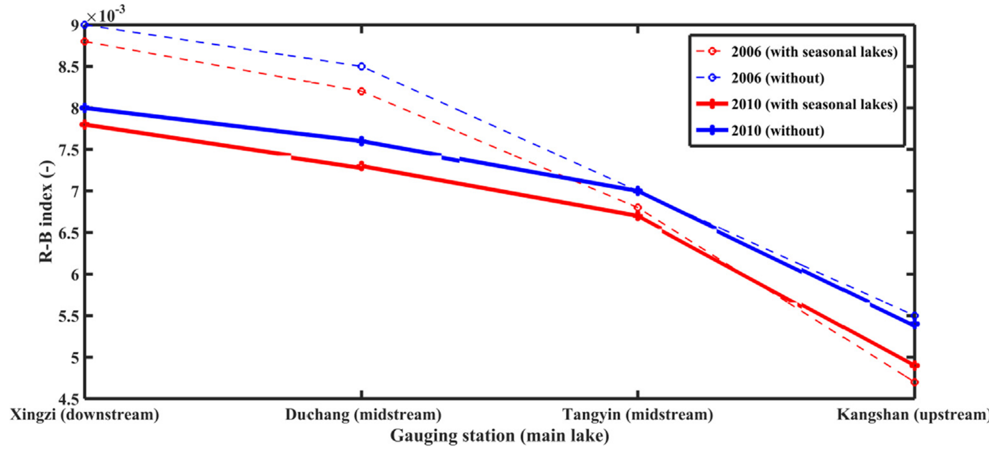

Fig. 10. R-B flashiness index derived from continuous water level time series for the dry year (2006) and the wet year (2010). Higher R-B values correspond to higher flood flashiness.

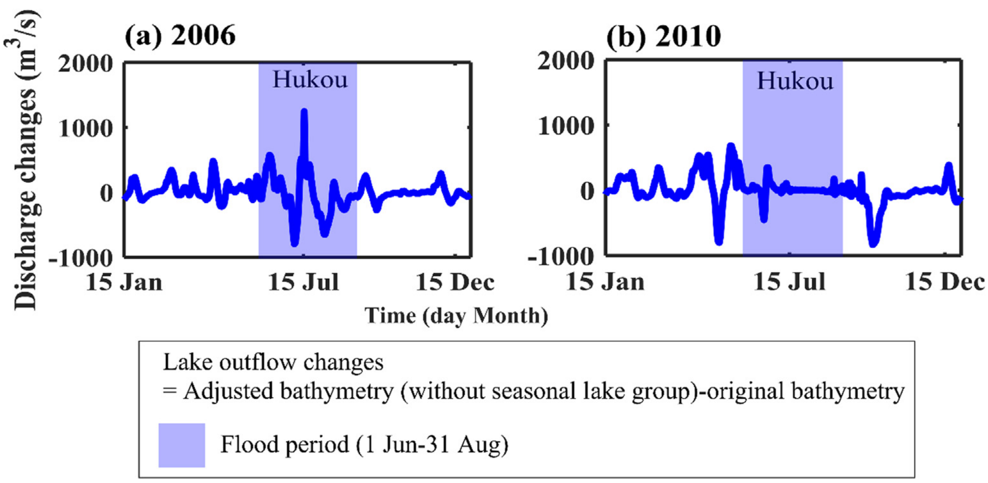

Fig. 11. Influence of seasonal lake group on lake outflow discharges in (a) a dry year (2006) and (b) a wet year (2010). Positive values indicate that the water level under the hypothetical condition is higher than under the natural condition.

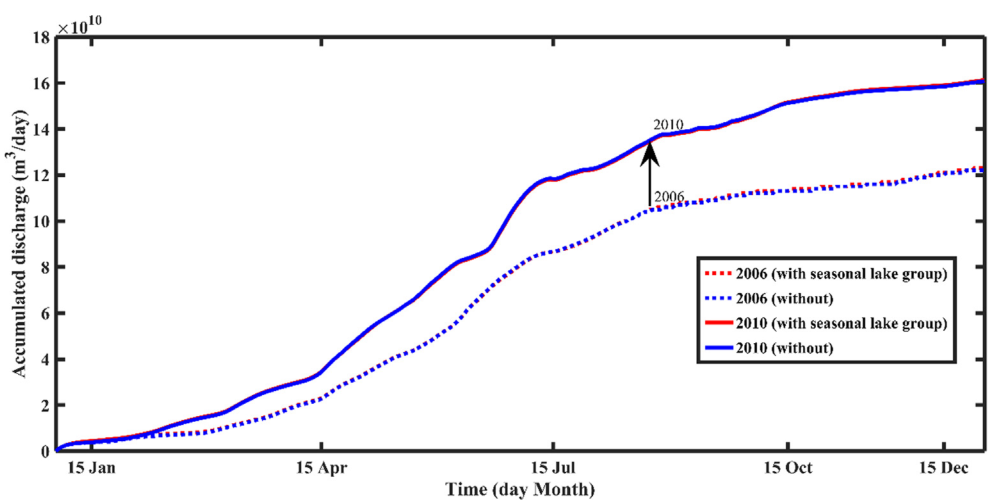

Fig. 12. Comparison of accumulated lake discharges at Hukou gauging station for the hypothetical conditions (blue lines) and natural conditions (red lines) in a dry year (2006) and a wet year (2010).

lake group. Furthermore, more pronounced outflow changes were visible during the dry year (2006) and the dry seasons in 2010 (Fig. 11). It follows that the blocking role of the Yangtze River may be a key process affecting the lake outflow condition, as discussed by Li et al. (2017a). Generally, the seasonal lake group is likely to play a minor role in affecting the lake discharge regime, mainly because the accumulated lake discharges appear to be unchanged between the hypothetical and the natural conditions (Fig. 12).

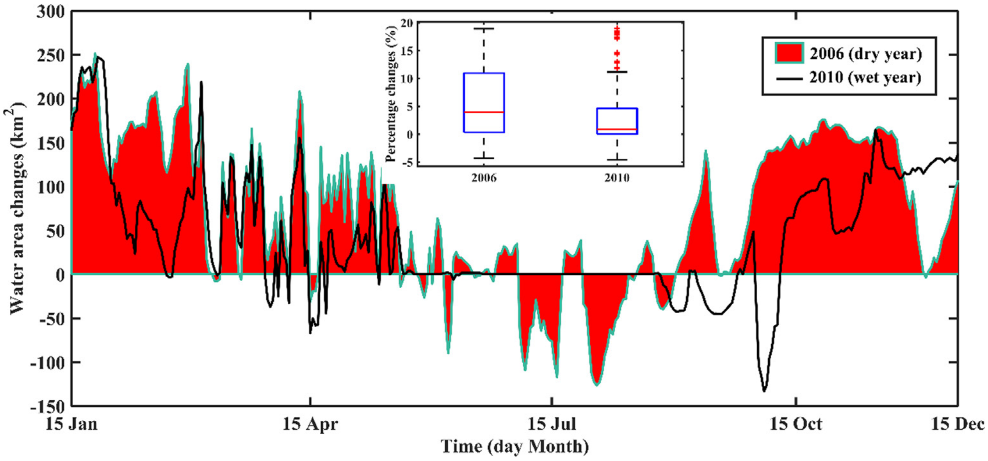

Fig. 13. Changes in lake water area between hypothetical and natural conditions in the dry year (2006) and the wet year (2010). Positive values indicate that the water level is higher under hypothetical than natural conditions. Box plots represent the comparison of percentage changes between the two conditions. The line in the box represents the median, and the top and bottom of each box represent the 25th and 75th percentile values, respectively, and outliers are plotted individually.

4.2.4. Lake water area changes

Fig. 13 shows the lake water area changes between the hypothetical and natural conditions. Similar to the water level variations, the effects of the seasonal lake group on water area changes tended to be more significant during dry months than flood months based on a comparison of 2006 and 2010. Although the seasonal lake group may lead to a small effect on changes in water area ($< 50\,km^2$) during the flood months, a significant increase in water area ($\sim 120\,km^2$) was observed during the other months of the year (averaged over 2006 and 2010). Overall, it seems that the seasonal lake group is most likely to exert a significant impact on the entire lake water area during the relatively dry seasons (i.e., approximately 10%-18%; see Fig. 13), indicating a possible effect of the floodplain bathymetry changes on inundation dynamics.

4.2.5. Dry-wet hydrological shift and dynamics

It is essential to assess dry-wet hydrological shifts in floodplains that characterize transitional processes induced by hydrological behavior. Fig. 14 shows the effects of seasonal lake groups on dry-wet hydrological shifts in the floodplain system of Poyang Lake, as determined from hydrodynamic simulation of the hypothetical and natural conditions. The simulations revealed that slight changes in hydrological shift *DWF* (i.e., ~2–8%) were found in the main lake regions, while obvious changes in *DWF* (i.e., by up to 30%) were observed in the floodplain regions for both the dry and wet years. However, the decreased *DWF* could also be found in the southern floodplains of the lake (Fig. 14). These previous results indicate that the hypothetical condition is more likely to promote a dry-wet hydrological shift across the floodplain system relative to variations in the natural condition. Additionally, the changes in the dry-wet shift in the dry year (2006) were slightly stronger than in the wet year (2010). Furthermore, the hypothetical condition in combination with the bathymetry changes is expected to enhance the floodplain connectivity (see the next section), potentially contributing to the dry-wet shift.

4.2.6. Hydrological connectivity and changes

Changes in the hydrological behavior of the lake-floodplain system are inextricably linked to the dynamic surface hydrological connectivity, which largely depends on changes in bathymetry changes. Fig. 15 shows the spatial patterns of surface hydrological connectivity in the Poyang Lake floodplain under hypothetical and natural conditions as determined from the hydrodynamic field and the associated streamline trajectory. For clarity, this is illustrated for four major periods during the water level hydrograph, dry, rising, flood, and recession. For both years, the N-S connectivity exhibited a more continuous

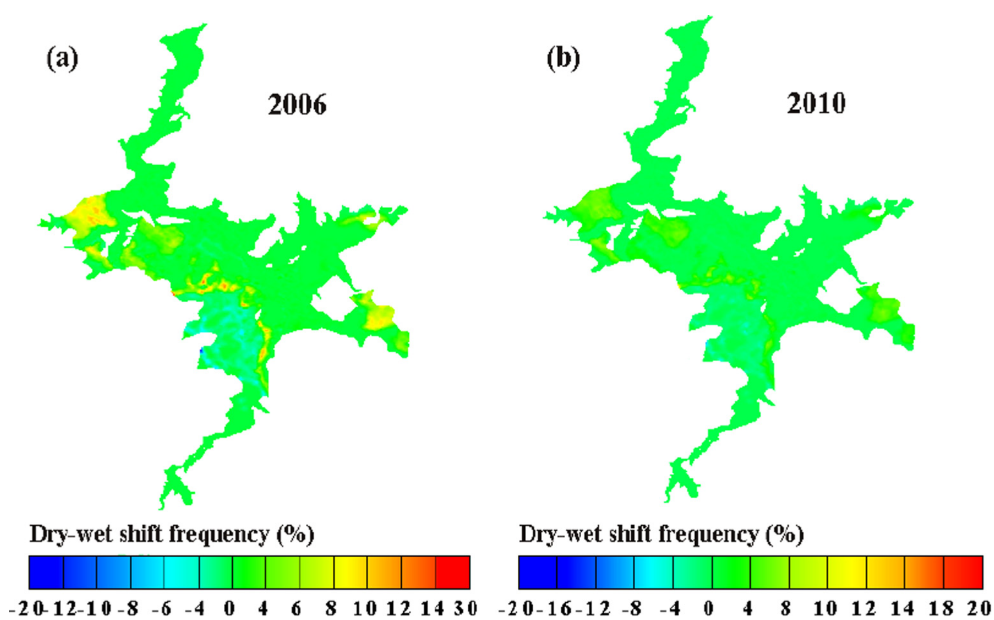

Fig. 14. Percentage change of dry–wet hydrological shift (*DWF*) between hypothetical and natural conditions in the dry year (2006) and the wet year (2010). Positive values indicate that the shift frequency is higher under the hypothetical condition than the natural condition.

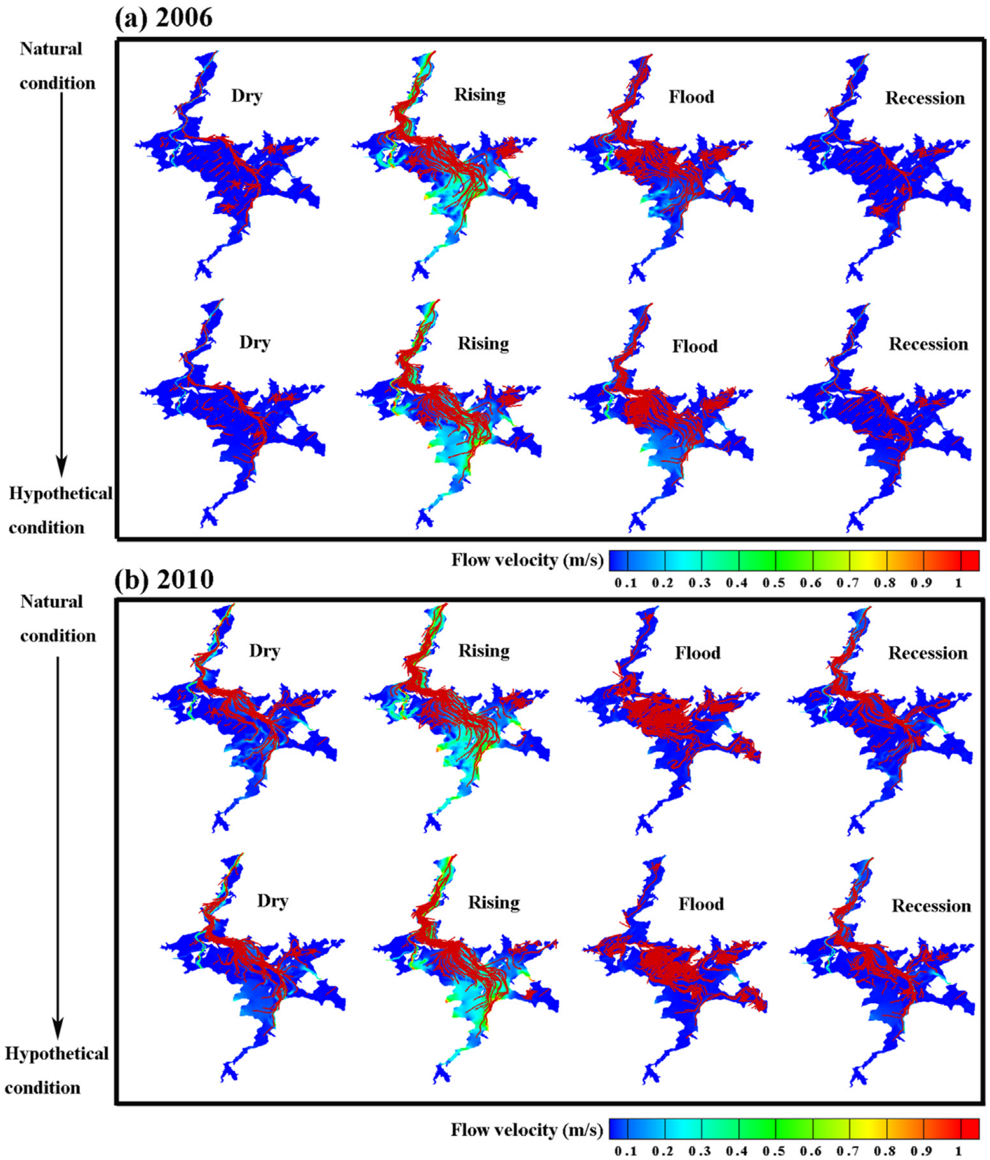

Fig. 15. Comparison of hydrological connectivity between hypothetical and natural conditions using the hydrodynamic field and the associated Lagrangian trajectory (in dark red streamlines): (a) dry year (2006); (b) wet year (2010). Dry = December–February, Rising = March–May, Flood = June–September, and Recession = October–November.

pathway than the W-E connectivity during all four periods because of the North-South orientation of the water flow of the main lake (Fig. 15). In addition, the W-E connectivity increases rapidly from the dry to flood period, then decreases during the recession period, as expected. In general, visual comparison revealed that the hypothetical condition tends to enhance the hydrological connectivity in the center regions of the lake's floodplains. This is a logical outcome of the bathymetry adjustment for the seasonal lake group relative to the natural condition to ensure flow connectivity.

Geostatistical analysis of the hydrodynamic results of the lake-floodplain produced a series of connectivity function curves (CF) for the two typical years, as shown in Figs. 16 and 17, respectively. The CF plots showed that the hydrological connectivity in both N-S and W-E was much stronger during the spring and summer seasons (i.e., CF values were close to 1.0) than during the autumn and winter seasons (i.e., CF values could decrease to 0) (Figs. 16 and 17), as expected. The CF results also revealed that the linkage of the surface water pathway in the N-S direction is greater (~130 km; see the *x*-axis in Figs. 16 and 17) than that of the W-E direction (~80 km) because of the N-S orientation of the main flow across the lake's length. In addition, daily plots of CF (Figs. 16 and 17) indicate that the connectivity behaviors in the W-E direction tend to be more dynamic than those in the N-S, suggesting a dominant role of W-E connectivity is influencing the lake-floodplain interactions. These findings coincide with the fact that the topographical slope of the lake-floodplain interactions is greater in the W-E direction than the N-S direction.

Although it was beyond the scope of this study to quantify the degree of hydrological connectivity in an accurate manner, the results suggested that high hydrological connectivity (i.e., CF values close to 1.0) occurs during summer season (June–August), while low connectivity (i.e., CF values can drop to 0) occurs during winter season (December–February), whereas intermediate connectivity arises during other months of the year (Figs. 16 and 17). For both the dry year (2006) and the wet year (2010), the hypothetical condition may play an important role in enhancing the N-S connectivity throughout the year relative to the natural condition, especially for the winter months, along with low connectivity. Notably, the results presented in Figs. 16 and 17 indicate that W-E connectivity may have exerted positive and/or negative responses to the hypothetical condition along the water pathway, except during the summer flood period in the wet year (2010;

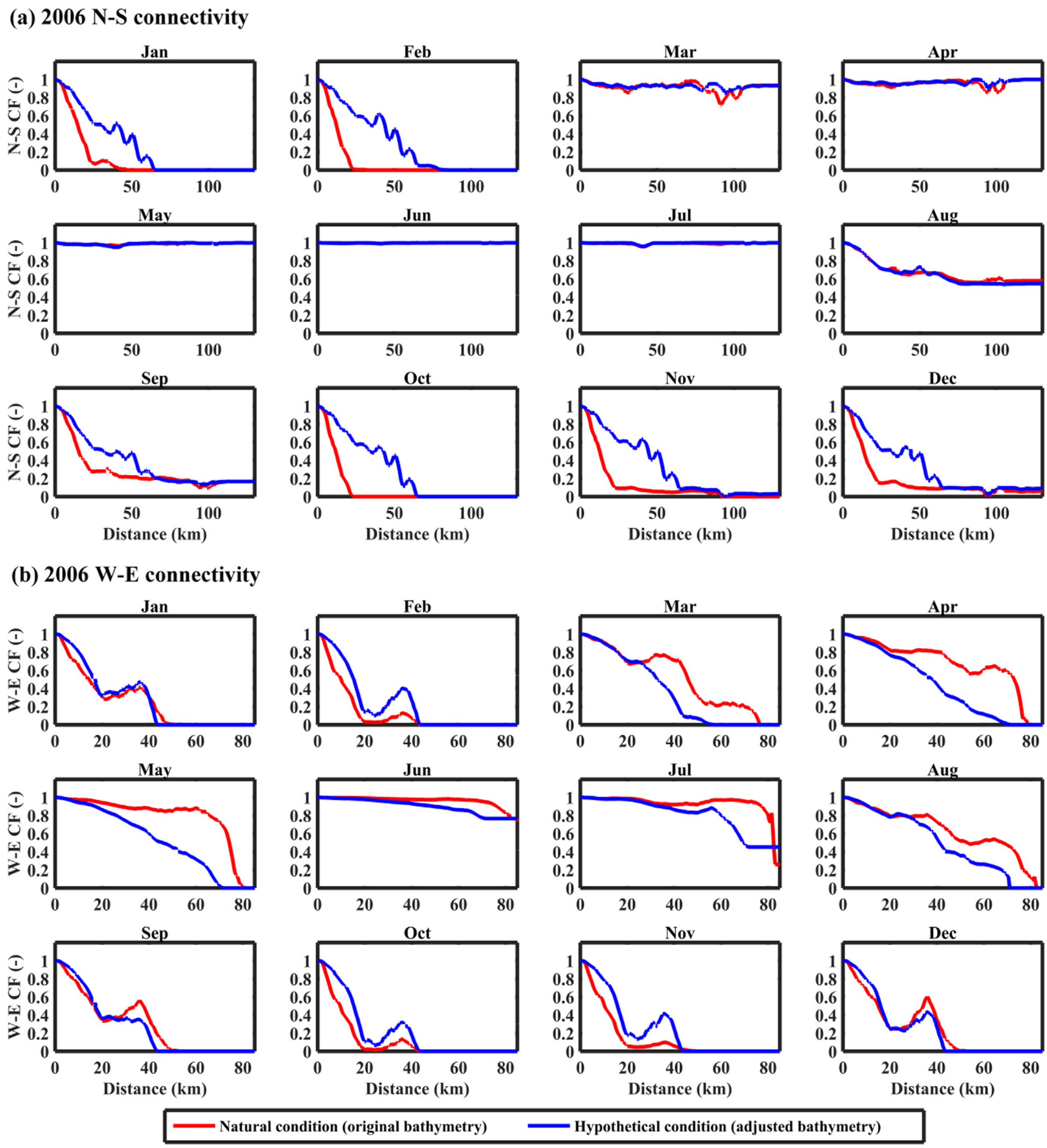

Fig. 16. Influence of the seasonal lake group on monthly hydrological connectivity within the lake-floodplains in the dry year (2006): (a) N-S hydrological connectivity; and (b) W-E hydrological connectivity.

Fig. 17b). The results presented herein further indicate that the seasonal lake group may have significant effects on hydrological connectivity in the lake's floodplains during the drier dry seasons. Overall, the results indicate that hydrological connectivity is at least partially responsible for the inundation dynamics (e.g., Fig. 13) and the associated dry-wet hydrological shift (Fig. 14) within the floodplain of Poyang Lake.

5. Discussion

5.1. Comparison with other relevant work

River- and lake-floodplains are most often geomorphologically dynamic systems characterized by highly complex surface processes and exchanges (Thomas et al., 2015). However, few studies of the hydrological behaviors of floodplain systems have been conducted to date, due, at least in part, to difficulty collecting the fundamental data (Karim et al., 2015; Khaki and Awange, 2019). Among these floodplains, the Poyang Lake system is unique in that it has a large number of seasonal

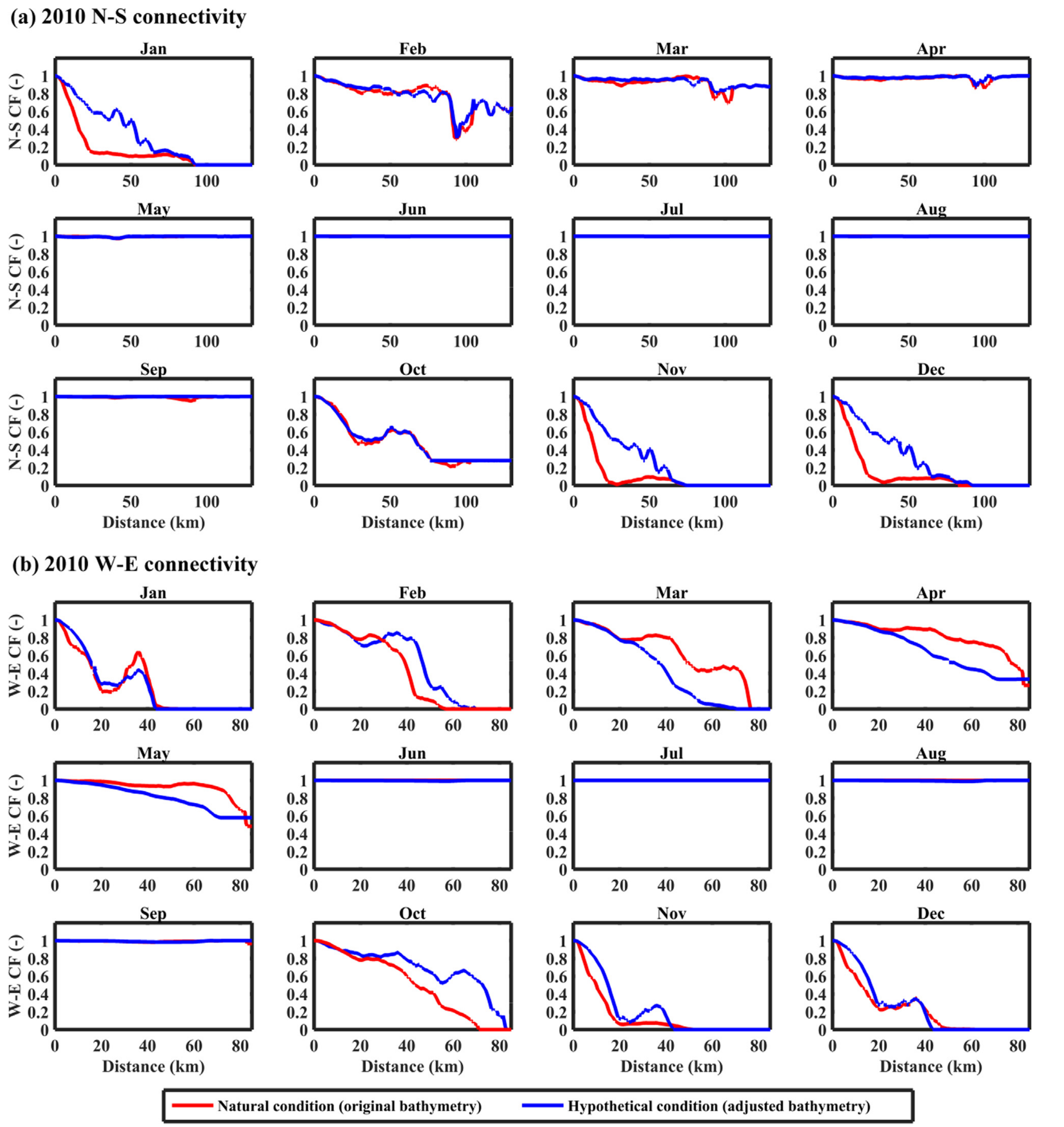

Fig. 17. Influence of the seasonal lake group on monthly hydrological connectivity within the lake-floodplains in the wet year (2010): (a) N-S hydrological connectivity; and (b) W-E hydrological connectivity.

lakes within its floodplains. Hydrological and hydrodynamic processes within shallow floodplains are strongly dependent on the bathymetry changes, and many previous studies have attempted to investigate the influences of bathymetry changes in rivers or lakes on the surrounding floodplain hydrology using remote sensing techniques and physically based models (Trigg et al., 2012; Park and Latrubesse, 2017; Yao et al., 2018; Reisenbüchler et al., 2019). For floodplains of Poyang Lake, Lai et al. (2014) used remote sensing and field survey data to investigate the influence of sand mining on the water level variations during the dry season of Poyang Lake. They found that the decline in lake levels is closely related to extensive sand mining and the associated bathymetry changes in the outflow channels. Similarly, Jiang et al. (2015) used hydrological, remote sensing, and bathymetry data to analyze the sand mining and associated hydrological responses during 2001–2010. They found that a wider and deeper outflow channel in the northern lake resulted in rapid lake discharge and subsequently lower water levels during the dry seasons. More recently, Yao et al. (2018) quantified the contribution of changes in bathymetry to the low water levels in different hydrological years based on a combination of bathymetry data and hydrodynamic models. They concluded that the bottom erosion of the northern outflow channel exerts a more significant role in decreasing the low water levels and enhancing the drought during the dry seasons. These previous studies of floodplain hydrology have mainly focused on bathymetry changes in the related river or lake flow channels and the associated effects, potentially leading to insufficient references for the assessment of bathymetry changes in the complex floodplain areas of Poyang Lake.

The results of the present study further extend the findings of previous work (Lai et al., 2014; Jiang et al., 2015; Yao et al., 2018) by providing new insight into the possible contribution of changes in bathymetry in floodplains to hydrological behaviors using a two-dimensional hydrodynamic model. Comparison with previous studies of Poyang Lake indicates that bathymetry changes in both the main channels and the floodplains of the lake may have significant effects on the hydrological behaviors during the dry seasons, while making limited contributions during flood seasons. However, the effects of bathymetry changes in the main flow channel are likely to be more pronounced (i.e., several meters; Yao et al., 2018) than those of the lake's floodplains (i.e., $\sim < 1$ m; this study) because of the different magnitudes of water level variations. Overall, the results of this study improve our understanding of the bathymetry effects of the floodplain Poyang Lake and other similar floodplain regions worldwide.

5.2. Floodplain bathymetry and management implications

The combination of natural and anthropogenic processes results in spatiotemporal variations in floodplain bathymetry (van der Most and Hudson, 2018; Yao et al., 2018). The location of suitable ecological indicators (e.g., aquatic habitat and vegetation type) across the floodplains is dependent on floodplain geomorphology and hydrology (e.g., Junk et al., 1989; van der Most and Hudson, 2018). Changes in bathymetry in floodplains may lead to changes in hydrological and hydrodynamic processes, affecting inundation extent and timing, which play significant roles in dominating biogeochemical cycles occurring in floodplains (Marks et al., 2000; Malhadas et al., 2009). For Poyang Lake, the erosion of the lake's main flow channels and the deposition of the floodplains occurred from the 1990s to 2010s. This could be attributed to the afforestation and reservoir construction program in the lake's catchment and the natural state of slight deposition and sand mining within the lake (Wu et al., 2015). Notably, sand mining has extended from the northern lake to the southern lake and the bathymetry has been experienced a dynamic changing environment (Jiang et al., 2015; Yao et al., 2018).

The results of this study have important implications regarding the management and planning of floodplains in Poyang Lake. The erosion and deposition of the floodplain lake may directly influence the hydrological regime and the associated floodplain connectivity. More importantly, dynamic connectivity between seasonal lakes and surrounding floodplain regions potentially play important roles in downstream channels of the lake through temporary inputs of materials and energy (Li et al., 2019a). Several studies have concluded that the seasonal hydrological connectivity in Poyang Lake plays an important role in the water quality and ecosystem of the floodplain system (Xia et al., 2016; Li et al., 2019a). Considering the outcomes of this study, the seasonal lake group may play a limited role in regulating the lake's flood event during summer, which is different from previous conclusions (e.g., Hu et al., 2015). However, stored water during the recession period is highly valued for its ecosystem protection services and biodiversity conservation (Hu et al., 2015; Ji, 2017). Although the floodplains are usually large and remote, increasing human interventions are directly influencing the seasonal lakes and the associated floodplain settings (Wu and Liu, 2017). Notably, a large number of seasonal lakes high on the floodplains will also infrequently obtain flood water from the main lake. From a hydrodynamic perspective, the whole lake-floodplain system is inundated during the flood months, leading to a high connectivity between the main lake and the seasonal lakes. However, the water flow velocities throughout the system are small and the associated hydrodynamic field is stable during this high lake level period (Li et al., 2014). Accordingly, the lake-floodplain system is mainly controlled by the flow regime of the Yangtze River (Zhang et al., 2014), rather than changes in bathymetry in both the floodplains (e.g., the seasonal lake group) and the main lake (e.g., sand mining). During the other seasons (e.g., rising, falling and dry), the floodplain inundation of Poyang Lake is more sensitive to the water level changes than that of the flood season. In other words, changes in floodplain bathymetry may alter the water flow pathway and the associated surface hydrological connectivity, and hence lead to a highly dynamic and complex hydrodynamic field (Li et al., 2014).

Lake and wetland managers should pay more attention to the local bathymetry changes and associated flow connectivity during the dry seasons, which can be simple and in many cases practical. From a conservation perspective, floodplain engineering (e.g., levee construction and sluice gates) should be avoided in the natural floodplains of Poyang Lake because the floodplain hydrology and ecological processes are sensitive to any changes in the region.

5.3. Limitations and uncertainties

It should be noted that there are limitations and uncertainties associated with applying hypothetical conditions in a hydrodynamic model to bathymetry adjustment, floodplain structure, and model mesh size. Exact quantification of these uncertainties would significantly increase the scope of our study. Although the Arc Hydro tool was adopted to set up the hypothetical scenario, modification of the elevations for the seasonal lake group using the bathymetry adjustment method is only close to the surrounding terrains. Although influences of the seasonal lake group on hydrological behaviors in the Poyang Lake floodplain were investigated in this study, the outcomes from the hypothetical conditions may have had somewhat different outcomes if other bathymetry adjustment techniques had been used. However, the hydrodynamic model along with a bathymetry adjustment approach may be the best manner to distinguish the effects of numerous seasonal lakes, which can be applicable to other similar floodplain systems. Our future work will certainly consider new and novelty methods of investigation that build on our current research.

The current hydrodynamic model exhibits its ability to provide continuous and dynamic datasets, but the cell resolution remains a significant issue when capturing complex floodplain structure and environment (Li et al., 2019a,b; Tan et al. 2019). Within the floodplains of Poyang Lake, there are numerous long, narrow, shallow channel networks with complex interactions. Considering the extensive data and computational requirements of the hydrodynamic model, it is important to note that the model necessitated some simplifications to the channel networks, which may lead to errors in the hydrodynamic simulations and the associated floodplain assessments. For example, simplification of the channel networks in the hydrodynamic modeling may strongly influence flow connectivity and inundation dynamics of floodplains (Tan et al., 2019). Despite these limitations, the present model is considered to be adequate as an important attempt at physical simulation of the complex Poyang Lake floodplain system. This is because a comparative analysis between hypothetical and natural conditions allows us to eliminate the effects of uncertainty factors on the current results. The model also has high potential to be applied to various floodplain settings in which hydrological observations are sparse, missing, or inconsistent.

5.4. Future research

Further studies are required to obtain remote sensing data that have been widely used to describe complex floodplain environments and validate hydrodynamic models. The combination of hydrodynamic models and remote sensing data will provide valuable new insights into the dynamic natural system and evolution of floodplains. Notably, the Chinese government has launched a key research program "Beautiful China" (Zhao, 2019) to perform a joint assessment of the hydrodynamics, water quality, and ecology of the floodplain Poyang Lake for the purpose of management and protection. Additionally, floodplain groundwater is an important topic in the study of floodplain lakes because of the close relationships between the floodplains and the lake (Li et al., 2018a, 2019b). Therefore, future studies of floodplain systems should be paid more attention to the water quality, wetland ecosystem, and lake health using dynamic surface–groundwater modeling coupled with relevant ecological processes. Future study into the effects of bathymetry changes in the floodplain of Poyang Lake should develop sediment transport models for a comprehensive investigation of the effects of bathymetric variability on floodplain behaviors.

6. Conclusions

Seasonal, shallow, small lakes are distinctive hydrological units in floodplains that have significant implications for various functions of many floodplain systems. Despite the hydrological and ecological importance of seasonal lakes in the extensive floodplains of Poyang Lake, the present study is the first to investigate the coupled effects of seasonal lakes on hydrological behaviors within a large floodplain lake system using a physically based hydrodynamic model along with a bathymetry adjustment method. We expect to overcome the limitations of current studies exploring seasonal lakes in the data-limited environment of the Poyang Lake floodplain.

The hydrodynamic model reproduced the lake-floodplain hydrodynamics reasonably well during the dry year (2006) and the wet year (2010). The simulated results reveal that, in general, the temporal influences of the seasonal lake group on water levels, lake outflow discharges, and associated inundation dynamics were stronger during the dry year than the wet year, and this difference was greater during the drier dry seasons (2006) than the wetter wet seasons (2010). The results show that, on average, the role of the seasonal lake group during the dry seasons is around several times stronger than during the flood seasons in terms of the magnitudes of different hydrological responses (e.g., water level, outflow and inundation area). The spatial effects of the seasonal lake group on the hydrological behaviors of the lake's floodplains were more significant than those of the main lake for both hydrological years, indicating a sensitive response of the floodplain settings. In addition, the seasonal lake group is more likely to play an important role in the surface hydrological connectivity across the lake-floodplains, potentially influencing the dry-wet hydrological shift, indicating an important role of the floodplain bathymetry changes. The outcomes from this study can be extended to other similar floodplain regions by providing improved understanding of the bathymetry changes and the associated lake-floodplain management.

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.

Acknowledgements

This work was jointly supported by the Strategic Priority Research Program of the Chinese Academy of Sciences (XDA23040202), the National Natural Science Foundation of China (41771037), the Youth Innovation Promotion Association of the CAS, the Science Foundation of Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences (NIGLAS2018GH06), and the Key Research Program of the Chinese Academy of Sciences (KFZD-SW-318-2). We are grateful to the editor and anonymous reviewers for the constructive suggestions given during the review process.

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