Water Research 195 (2021) 117005

Contents lists available at ScienceDirect

Water Research

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

Refining the concept of hydrological connectivity for large floodplain systems: Framework and implications for eco-environmental assessments

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ARTICLE INFO

Article history:
Received 7 July 2020
Revised 20 February 2021
Accepted 2 March 2021
Available online 3 March 2021

Keywords:
Hydrological connectivity
Threshold effect
Hydrodynamic model
Floodplain lake
Connectivity assessment
Ecological and environmental goals

ABSTRACT

Recent years, the hydrological connectivity has gained popularity in various research fields, however, its definition and threshold effects at a system scale have not received adequate attention. The current research proposes a promising framework to refine the concept of surface hydrological connectivity by combining hydrodynamic modeling experiments, threshold effects and geostatistical connectivity analysis, exemplified by the flood-pulse-influenced Poyang Lake floodplain system (China). To enhance the inherent linkage between hydrological connectivity and eco-environments, total connectivity (TC), general connectivity (GC), and effective connectivity (EC) were proposed to refine the metrics of hydrological connectivity. The results show that substantial differences between the three connectivity metrics are observed for all target directions, demonstrating that the joint role of water depth and flow velocity may produce more dynamic and complex influences on EC than the other two metrics of TC and GC. Topographically, the connectivity objects/areas within the flood pulse system reveal that the floodplain is a more sensitive area than the lake's main flow channels under different connectivity conditions. The modelling experimental studies show that variations in water depth thresholds are more likely to have a strong effect on connectivity for the dry, rising, and falling limbs, rather than the flooding period, while the flow velocity may exert an opposite threshold effect. The lake-floodplain system is characterized by a dynamic threshold behavior, with seasonally varying water depth and velocity thresholds. This study highlights the importance of redefined connectivity concept for facilitating scientific communication by combining hydrodynamic thresholds and offering recommendations for future connectivity assessments using our proposed metrics of TC, GC, and EC.

Introduction

In recent years, floodplain systems have gained considerable attention in fields like hydrology, ecology, and environment (Funk et al., 2019; Karpack et al., 2020). They are regarded as the most important natural regions and frequently function as significantly valuable and productive hotspots on earth (Bonnet et al., 2008; de Resende et al., 2019). Floodplain connectivity has been a renewed interest for interpreting transport mechanisms of the constituent materials (Li et al., 2019a; Park, 2020). Building upon ecological theory, hydrological connectivity refers to the water and water-mediated exchanges (e.g., sediment, energy, and organisms) between rivers or lakes and their floodplains, as well as between heterogeneous regions within floodplains (Bracken et al., 2013; Saco et al., 2020). Therefore, the hydrologically dynamic and complex floodplains, and hence their processes and functions, can be understood and evaluated using hydrological connectivity (Yang and Chu, 2013; Singh and Sinha, 2019; Tan et al., 2019).

While the concept of hydrological connectivity has been developed and widely used in many investigations, there is little agreement on its definition and metric method (Antoine et al., 2009; Rinderer et al., 2018). During the past few years, two relevant and complementary concepts, structural and functional connectivity, have been adopted to represent the degree and dynamics of hydrological connectivity in spatiotemporal scales

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https://doi.org/10.1016/j.watres.2021.117005
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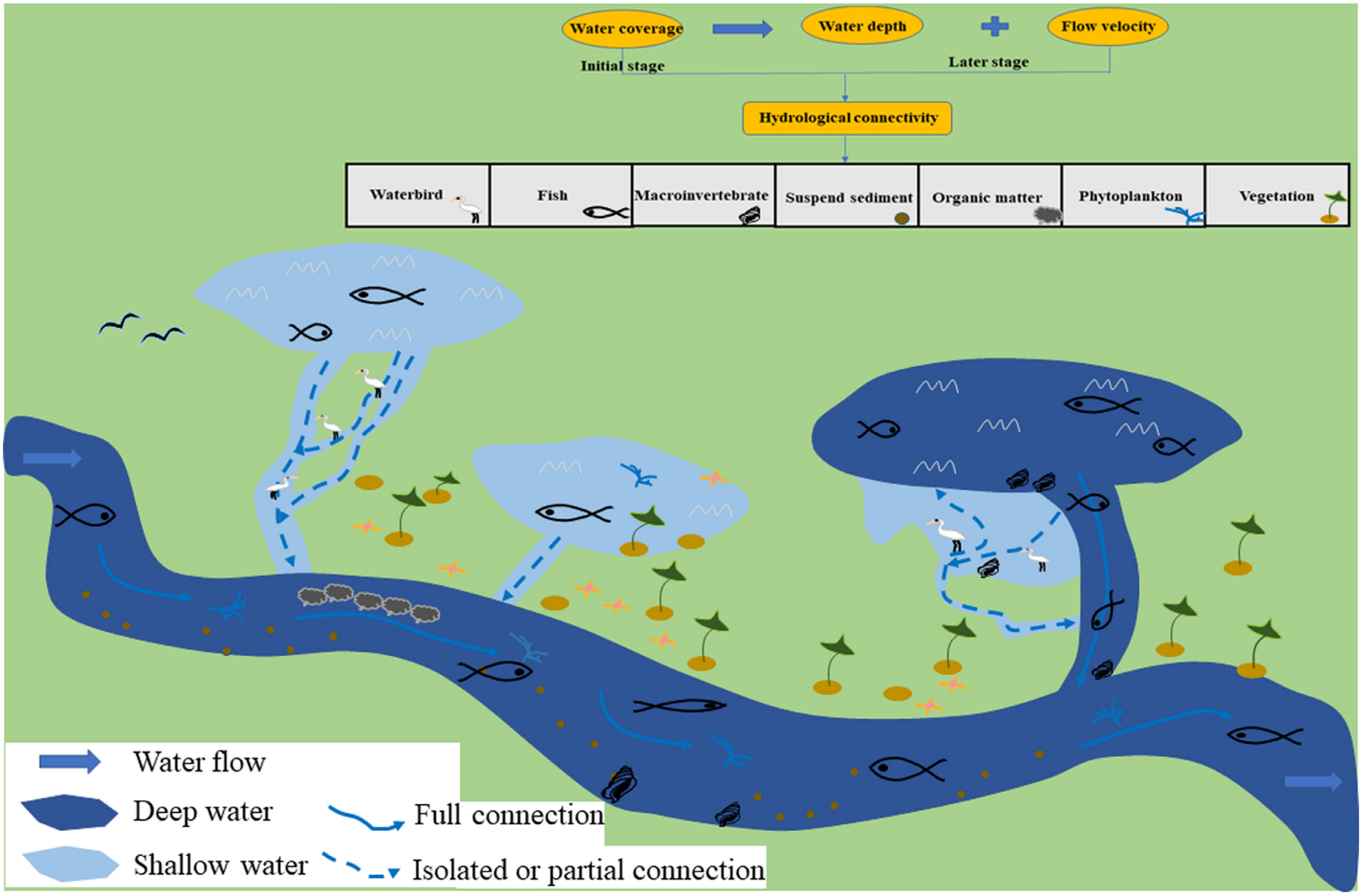

Fig. 1. Schematic diagram illustrating influences of the water depth and water flow on the hydrological connectivity and ecological indicators.

(Saco et al., 2020). The combined role of physical topography (e.g., channel bed and bank elevation) and hydrological pulses determines water exchanges and spatial pathways within the floodplain (Trigg et al., 2013; Liu et al., 2020). Additionally, the flood pulse concept shows that the floodplain heterogeneity is mainly attributable to the shifting water sources and dynamic flow pathways (Junk et al., 1989; Trigg et al., 2013). Given the above background, hydrological connectivity in recent work has been assessed using graph theory, percolation theory, pattern analysis, and spatial statistics (e.g., Yang and Chu, 2013; Deng et al., 2018; Shao et al., 2020) based on the results of field measurements or numerical models (Kupfer et al., 2015; Yeo et al., 2019), waterbody extent from remote sensing products (Tan et al., 2019; Liu et al., 2020; Park, 2020), and physical or chemical transport (Casanova et al., 2009; Fazi et al., 2018; Granados et al., 2020).

Although many approaches such as field measurements and remote sensing techniques provide directly information (e.g., water level, water coverage) for identifying connectivity conditions between different waterbodies, they have difficulty providing sufficient data about the spatiotemporal distributions of water depth and flow velocity. Water depth and flow velocity are generally viewed as the two most important factors in floodplain connectivity, particularly for various kinds of ecological indicators (USEPA, 2015). Generally, the irregularity and remoteness of the majority of floodplains lead to independent localized hydrological units such as surface depressions, river channels, and topographic barriers (Khaki and Awange, 2019; Liu et al., 2020), creating heterogeneous water depth and flow velocity distributions that directly affect hydrological connectivity. In general, dynamics in water depth may exert a significant role in influencing fishes, mollusc communities, and waterbirds (Reckendorfer et al., 2006; Bennion and Manny, 2014; Liu et al., 2020), flow velocity is prone to affect sediment transport, organic matter, and water quality trends (Jager et al., 2012; Giblin et al., 2014), while the joint role of the two is expected to control the most ecological goals. Although previous studies have highlighted the importance and implications of connectivity for the analysis of floodplain settings and as a potential tool for planning and management strategies, they do not provide sufficient knowledge regarding the individual or joint influence of water depth and flow velocity on hydrological connectivity from a systemic perspective. A conceptual schematic diagram of the hydrological connectivity and the associated relationships between the water depth, flow velocity and ecological indicators is provided in Fig. 1. To the best of our knowledge, hydrological connectivity has a more significant implication for ecology and environment fields by considering the water depth and flow velocity (referred to as the “later stage”) than the pure hydrology that focuses on the water extent information (referred to as the “initial stage”). Consequently, the concept of hydrological connectivity should be refined or redefined to improve its usefulness for ecological and environmental studies.

Hydrological connectivity is an emerging property of systems that is changing in both its prevalent structural features and its short-response functional elements (Saco et al., 2020). The response of systems and the detection of threshold behavior are paramount in floodplains and wetlands where the transitions to degraded conditions are tightly related to changes in hydrological connectivity (Turnbull et al., 2008; Moreno-delas Heras et al., 2012). More importantly, early detection of threshold signals may prevent a transition to more rapid degradation (Saco et al., 2018).

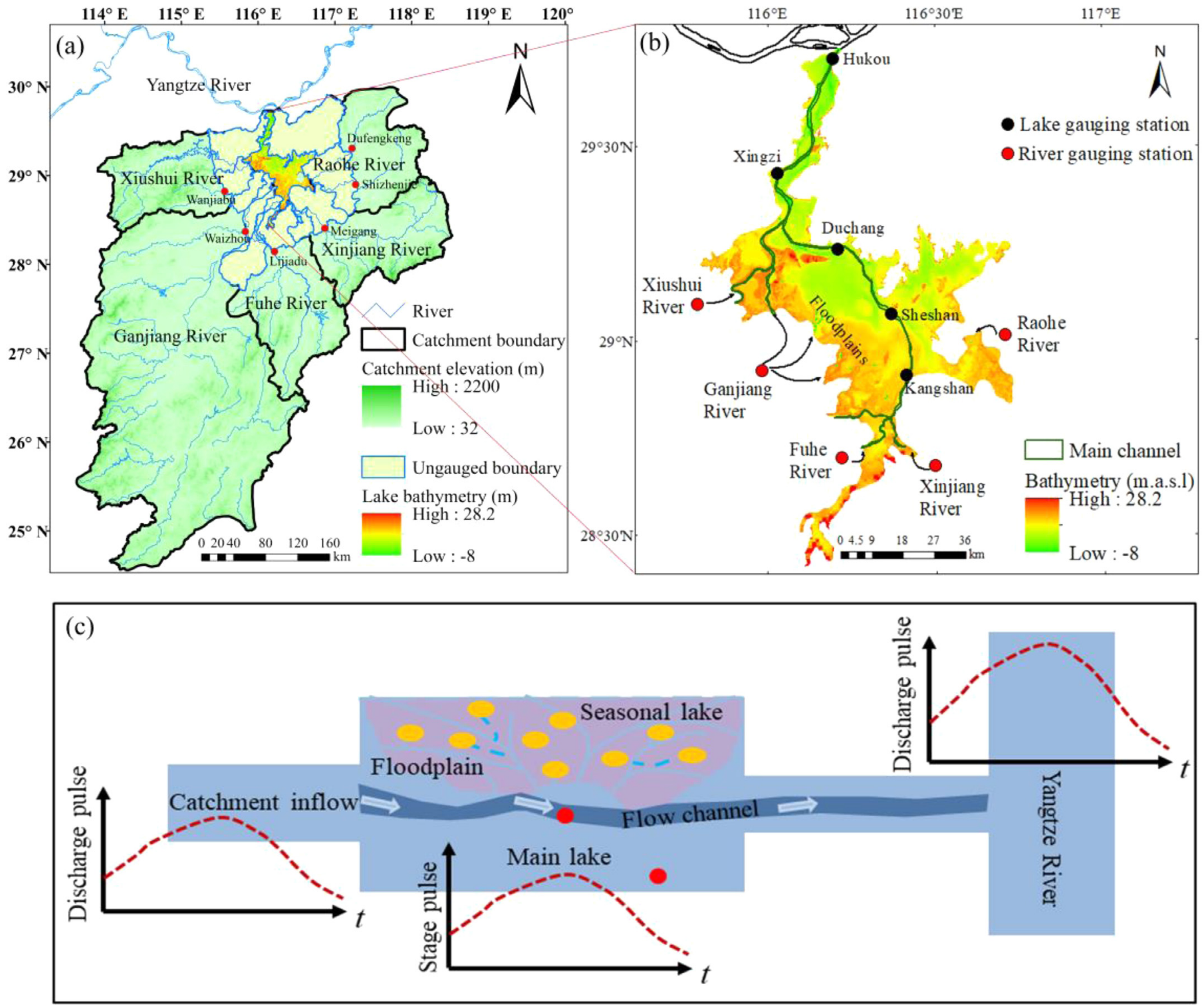

Fig. 2. (a) Topographic map, major inflow rivers, and gauging stations in the Poyang Lake catchment; (b) a close-up of the lake's floodplain feature; and (c) conceptual diagram illustrating the lake-floodplains response to different hydrological pulses.

However, threshold behaviors of floodplain systems have not been frequently identified as an important factor in analyzing the nature of hydrological connectivity (Phillips et al., 2011; Liu et al., 2020). Additionally, there is no widely accepted definition of surface hydrological connectivity regarding the connection and disconnection thresholds (Restrepo A et al., 2020). Consequently, investigating the system thresholds and the corresponding threshold dynamics has practical implications for healthy floodplain functions.

Due to considerable concern for various water resource, ecological, and environmental goals in floodplains (Karpack et al., 2020), it is vital to improve the understanding regarding threshold effects of water depth and flow velocity on hydrological connectivity in flood pulse systems, as this area has not received the same degree of attention as hydrodynamic processes. Different from previous work, this study also intends to refine the concept of hydrological connectivity and seeks to bridge the gaps between connectivity and the related ecological and environmental processes. The specific objectives of this paper are to: (1) improve the understanding of spatiotemporal variations in floodplain hydrodynamics and hydrological connectivity by combining a 2D hydrodynamic model and geostatistical analysis; (2) combine water depth and flow velocity thresholds to propose new metrics of hydrological connectivity by considering ecological and environmental goals; and (3) assess the influences of threshold changes on floodplain hydrological connectivity and the associated eco-environmental indicators using a series of modeling experiments.

2. Study area

Poyang Lake-floodplain system is located at the southern bank of the middle reaches of the Yangtze River in northern Jiangxi Province. Poyang Lake has a typical subtropical monsoon climate (Hu et al., 2007). In the Yangtze River catchment, Poyang Lake is considered a distinctive flood-pulse-influenced system that sustains free connection with its inflow rivers (Zhang et al., 2014; Li et al., 2020a). The lake receives five major river inflows from a catchment area of 1.62 $\times$ 10^5 km^2 and subsequently discharges to the downstream Yangtze River (Fig. 2). Lake water balance shows that about 91.2% of yearly inflows are from river discharges from the catchment, lake discharges to the Yangtze River occupies

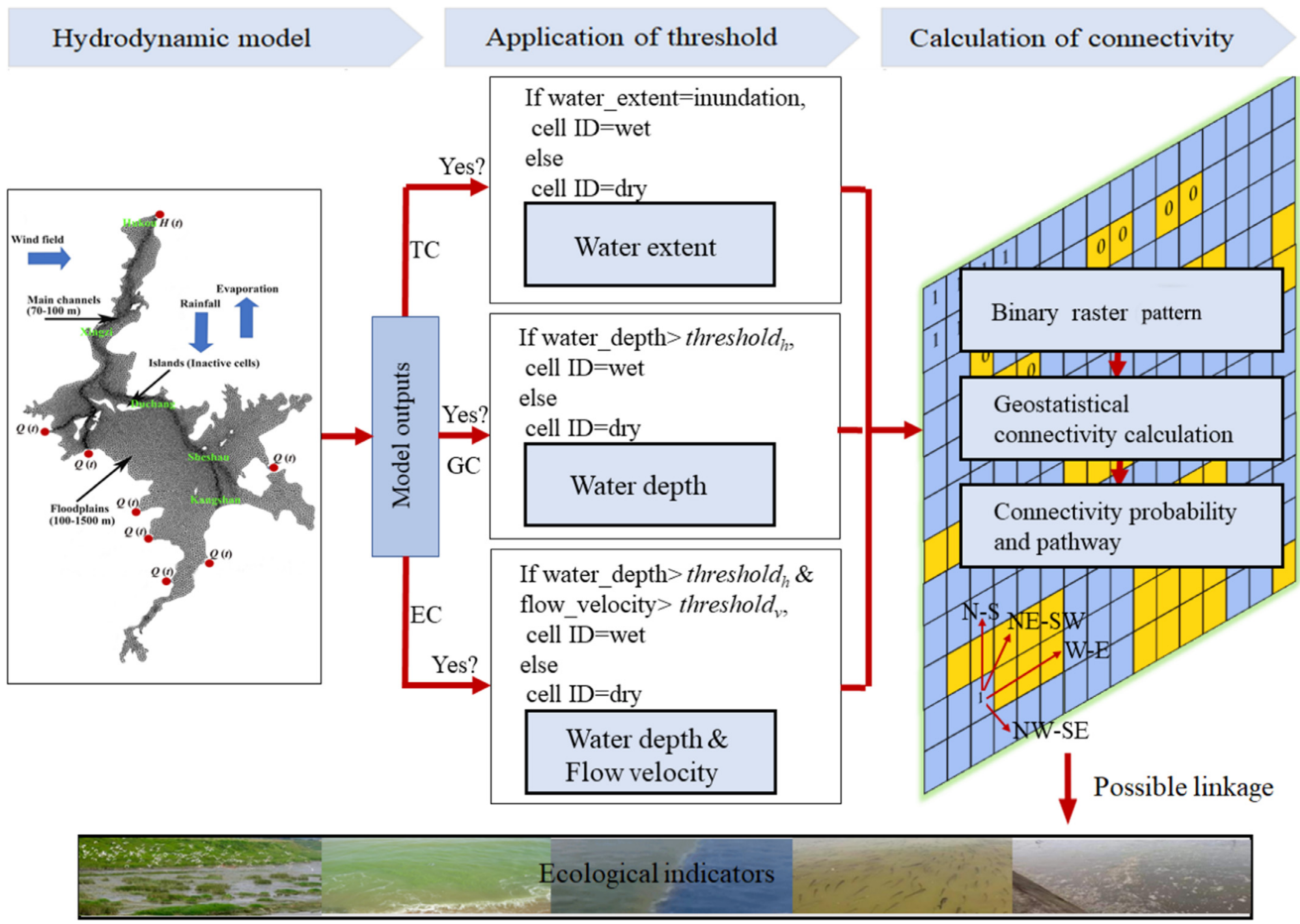

Fig. 3. Major methodology and procedure used in this study. $Q(t)$-time-varying discharges, $H(t)$-time-varying water levels, TC-total connectivity, GC-general connectivity, EC-effective connectivity, $threshold_h$-water depth threshold, $threshold_v$-flow velocity threshold, wet=1, and dry=0. N-S (north-south), W-E (west-east), NE-SW, and NW-SE represent different directions for connectivity analysis.

around 86.9% of the total outflow (Li et al., 2020a). The floodplain areas of ~2000 km^2 are almost fully connected to the main lake during the flooding season, but become isolated or partly connection during the dry season (Li et al., 2019b; Tan et al., 2019), due to the flood pulses from both the catchment rivers and the lake inundation (Wei et al., 2020). Generally, the water depth exhibits an increasing trend from the floodplains to the flow channels varied from <6 m to ~30 m, and the water velocities vary from <0.1 to >1.0 m/s (Li et al., 2017). The flushing ability of the lake-floodplain system is characterized by spatial varying residence times in the range of ~20-300 days (Li et al., 2016).

3. Materials and methods

This work used a two-dimensional (2D) hydrodynamic model to represent the hydrodynamic behaviors of the flood-pulse influenced Poyang Lake (see Section 3.2). The validated model and its simulation results in combination with the threshold definition were used to identify the water spatiotemporal pattern. The geostatistical analysis was subsequently applied to the binary raster data to investigate the responses of surface hydrological connectivity (see Section 3.3) and allowed to further explore the threshold effects on connectivity conditions (see Section 3.4). The major methodology in this study regarding the hydrodynamic modeling, threshold definition, and connectivity calculation is presented in Fig. 3.

3.1. Data collection and purpose

3.1.1. Hydrological and meteorological data

The daily hydrological and meteorological data were collected for the purpose of driving and validating the floodplain hydrodynamic model of Poyang Lake during 2018. Daily discharges at the four main river gauging stations and two tributary stations were adopted to reflect the five major rivers from the lake's catchment (Fig. 2a). Lake water levels and outflow hydrographs at the five gauging stations were used to represent the spatial responses of the lake during 2018 (Fig. 2b). The bathymetry map surveyed in 2010 (1:10,000) was used to depict the physical topography of the lake-floodplain system (Fig. 2b). Spatial flow velocities were used to reproduce the flow field of Poyang Lake, based on Acoustic Doppler Current Profile (ADCP) measurements in August, 2018 (see Section 4.1). Meteorological parameters (time-series precipitation, evaporation, wind speed, and wind direction) obtained from the lake gauging stations were selected to represent the atmospheric conditions of the floodplain system.

3.1.2. Water quality data, waterbird population and fish distributions

In order to explore the importance and implications of the proposed connectivity metrics, this study used water quality parameters, waterbird and fish as proxy indicators of the eco-environments in the Poyang Lake floodplain system. A total of 144 vertically integrated water samples were collected within consecutive days during 10-15 July 2019. The locations of sampling sites differ in space to cover different lake regions (see Section 4.5). For a comprehensive analysis, the popular trophic state index (TSI; Carlson, 1977) was calculated and used to present the condition of the lake ecosystem, based on the total dissolved nitrogen (TN), total dissolved phosphorous (TP), Chlorophyll *a* (Chl-*a*), chemical oxygen demand (COD_{Mn}) concentrations, and Secchi disk depth. The analysis method of these parameters is same to Li et al., 2019a. Waterbird population distributions were obtained from Huang et al. (2018), and fish distribution map was derived from the Atlas of Poyang Lake (1993). In order to analyze and explain the implications of different connectivity metrics proposed by this study, these data obtained in 2019 were presumed to represent the conditions in 2018.

3.2. Floodplain hydrodynamic model

The present study used a two-dimensional (2D) MIKE 21 model to investigate the floodplain hydrological and hydrodynamic behaviors of Poyang Lake. The modelling work of Poyang Lake involved several major aspects. The model domain is about 3,124 km^2 and the element sizes varied from 70 m to 1,500 m to capture the lake-floodplain inundation dynamics (Fig. 2). Therefore, a total of 20,450 triangular elements were generated to perform the floodplain hydrodynamic simulation (Fig. 3). The time-varying catchment inflows (five large rivers) were used as the lake upstream boundary conditions ($Q(t)$; Fig. 2), the Hukou water level observations (lake outlet) were used as the lower boundary condition ($H(t)$; Fig. 3). The model also used precipitation, evaporation, and wind fields to reflect the influences of meteorological conditions on the lake hydrodynamics (Fig. 3). The Smagorinsky factor of eddy viscosity (C_s=0.28) and Manning numbers (M=10-59 $m^{1/3}/s$) were used to represent heterogeneous bed roughness for the lake flow channels and the floodplains (e.g., vegetation area, mudflat, and permanent waterbody) of the flood pulse system (Li et al., 2020b). The model adopted the depth rule h_{drying} (0.005 m) < $h_{flooding}$ (0.05 m) < $h_{wetting}$ (0.1 m) to capture the wetting and drying cycle in the floodplain system (DHI, 2014; Li et al., 2014). To maintain the target Courant-Friedrich-Levy number of 1.0, the minimum and the maximum time step were set to 0.1 s and 3600 s, respectively.

Extensive validation and applications in many previous studies have been conducted for the hydrodynamic model of the Poyang Lake-floodplain system (e.g., Li et al., 2014; Li et al., 2017, 2019a,b, 2020a,b). Therefore, a brief description regarding the theoretical basis and other model aspects of the MIKE 21 is given in this section. In this study, the floodplain hydrodynamic model of the lake was further validated using water level and flow velocity observations during 2018. The determination coefficient (R^2), root-mean-square error (*RMSE*), and Nash-Sutcliffe coefficient (E_{ns}) were used to quantify the goodness of fit and to assess the model's performance.

3.3. Geostatistical connectivity analysis

We used geostatistical connectivity metrics to quantify and characterize the surface hydrological connectivity of the Poyang Lake-floodplains. The geostatistical method is effective for investigating the transport pathway, connection, or isolation between different surface water elements (Trigg et al., 2013). Generally, connectivity analysis adopts binary data to analyze the surface water connectivity and the associated spatial patterns of connected components (Fig. 3). This method has the capacity to describe spatiotemporal patterns and quantify thresholds and transitions in large systems by identifying the subtle differences in the data fields (Michaelides and Chappell, 2009). The geostatistical approach is multi-point connectivity statistics that quantify the probability of any connected cells and corresponding connected magnitude for binary state patterns of hydrological systems (Pardo-Iguzquiza and Dowd, 2003).

The basic mathematical expression of connectivity function (CF) in different directions, including north-south (N-S), west-east (W-E), NW-SE, and NE-SW, is expressed by (Journel et al., 2000):

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

$$\mathrm{If} Z\left(u_j\right) > z_c, I\left(u_j; z_c\right) = 1.0 \tag{2}$$

$$\mathrm{If} Z\left(u_j\right) \le z_c, I\left(u_j; z_c\right) = 0 \tag{3}$$

where n represents the total number of points; Π represents the product operator; u_j represents the location; z_c is the threshold value; $I(u_j; z_c)$ represents a connectivity indicator; Pr is the calculated probability. Here, the connectivity statistic is a probability-distance function CF that was produced to express the probability Pr.

3.4. Connectivity definition and threshold scenario

The individual or combined threshold effects of spatiotemporal water inundation, water depth, and flow velocity distributions obtained from the hydrodynamic model were used to define different connectivity types, corresponding gridded patterns/wet-dry were used as input for geostatistical connectivity analysis (Fig. 3). Three connectivity definitions, namely 'Total Connectivity', 'General Connectivity', and 'Effective Connectivity', are discussed in Table 1. Since this study aimed to provide insights into the effects of proposed connectivity metrics, the general idea was to show the differences between the connectivity conditions under the three definitions based on a representative year of the floodplain system. To represent the significant importance of threshold effect, the recommended values of water depth threshold ($threshold_h$=20 cm) and flow velocity threshold ($threshold_v$=0.1 m/s) were based on literature values from Poyang Lake and other similar areas (Jager et al., 2012; Bennion and Manny, 2014; Giblin et al., 2014; Liu et al., 2020). That is, 20 cm-depth or 0.1 m/s-velocity environments are more likely to create a better connectivity condition that has significant implications for most ecological and environmental goals (e.g., sediment, organic matter, fish, phytoplankton; see Table 1).

In order to investigate the influence of variations in different thresholds (water depth and flow velocity) on hydrological connectivity, this study uses a series of experimental scenarios by setting specified threshold values for water depth and flow velocity (Δh=10 cm, Δv=0.05 m/s). Consequently, the resulting wet-dry binary data were used to calculate the surface hydrological connectivity in N-S, W-E, NW-SE, and NE-SW directions. Since the general idea was to identify the differences between the connectivity conditions under different Δh and Δv threshold values, the authors limit the modeling experiments within the threshold range of water depth (0-90 cm) and velocity (0-0.3 m/s), given the difficulties in conducting detailed analyses of threshold effect for every small offset value.

4. Results

4.1. Validation of hydrodynamic model

Observed water levels and flow velocities distributed in the floodplain system were used to reproduce the dynamic changes in the hydrological behaviors (Fig. 4). The observed and modelled water levels at the Xingzi, Duchang, and Kangshan gauging stations

Table 1
Definition of hydrological connectivity considering the individual or combined role of water extent, water depth and flow velocity.

Name	Definition	Threshold	Explanation
Total Connectivity (TC)	The connectivity analysis is based on water extent information, including water coverage and no water.	No threshold. The water extent is similar to the inundation data obtained from remote sensing products (land and water), i.e., neglected water depth (h) and flow velocity (v).	The concept of TC is widely used in previous studies, but can be regarded as a rough and total indicator for connectivity analysis. It does not have significant implications for most ecological goals.
General Connectivity (GC)	The connectivity analysis considers the effects of water depth or flow velocity.	The water depth threshold ($threshold_h$) is used to separate the input pattern into 'wet' and 'dry' (equivalent to $threshold_v$), i.e., eligible and not eligible for connection.	The concept of GC reflects the influence of water depth on connectivity conditions. In general, it has significant implications for most ecological goals.
Effective Connectivity (EC)	The connectivity analysis considers the effects of both water depth and flow velocity.	The water depth threshold ($threshold_h$) and flow velocity threshold ($threshold_v$) are combined to separate the input pattern into 'wet' and 'dry', i.e., eligible and not eligible for connection.	The concept of EC reflects the combined influence of water depth and flow velocity on connectivity conditions. It is the most effective interpretation of connectivity analysis for most ecological goals.

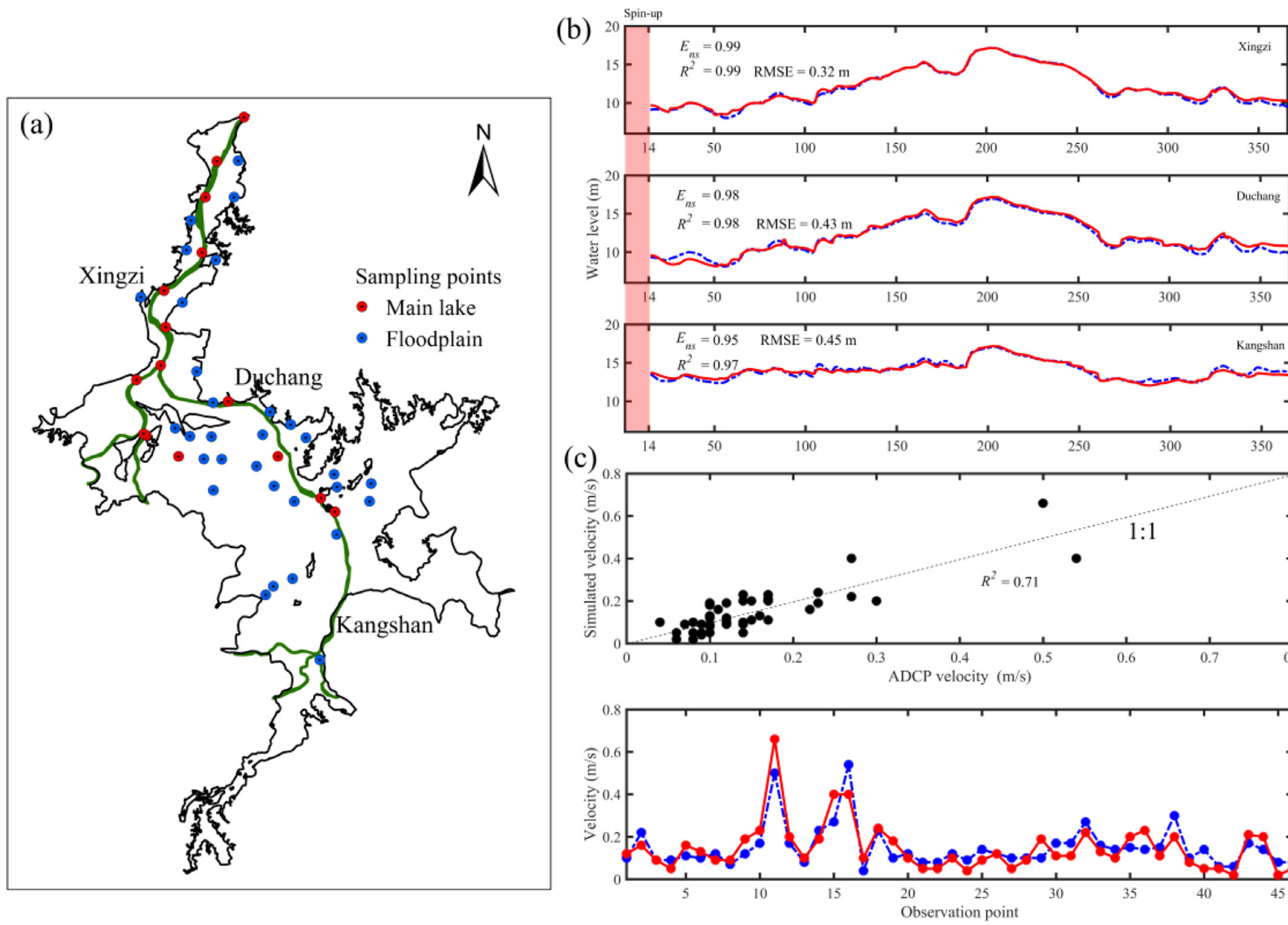

Fig. 4. (a) Spatial location of velocity measurements within Poyang Lake (in red dot) and the lake's floodplains (in blue dot); (b) comparisons between the observed (in blue line) and simulated (in red line) water levels at the three lake gauging stations; and (c) scatter plot of the observed and modelled velocity and corresponding linear comparison for all the sampling points.

matched well during the validation procedure (Fig. 4b). The statistics showed that the E_{ns} varied from 0.95 to 0.99, and R^2 ranged from 0.97 to 0.99, the values of $RMSE$ were lower than 0.45 m. Although the impact of the complex topography (e.g., the flow channel, shallow floodplains) and model conceptualization (e.g., mesh size, boundary condition) on generated patterns of hydrodynamics can almost be neglected during the flooding water phase, slight discrepancies between the simulation and the observation are found during low lake level seasons (Fig. 4b). For the spatial flow velocity simulations (Fig. 4a), the statistics also revealed a close agreement between the modelled and observed points (R^2 =0.71; Fig. 4c). The validation presented in Fig. 4 demonstrates the floodplain hydrodynamic model has an overall capability in capturing the rising, high, falling, and low water phases in the flood-pulse-influenced Poyang Lake, building confidence in the applicability of the modeling experimental studies and scenarios analysis.

4.2. Spatiotemporal changes in hydrodynamics and connectivity conditions

Spatial and temporal dynamics in the hydrodynamic characteristics of the Poyang Lake-floodplains are inextricably linked to surface water connectivity. For both water depth and flow velocity, the temporal trends show that, in general, the two hydrodynamic forcings exhibit a distinct negative relationship throughout the year (Fig. 5a), mainly due to the influence of dynamic hydraulic gradient on velocity. On average, low hydrological connectivity can be observed during the dry water phase (e.g., February; mean CF= 0.3), intermediate connectivity tends to occur during the rising and falling limbs (e.g., May and October; mean CF= 0.4-0.5), while high connectivity is found during flood phase (e.g., August; mean CF= 0.7).

Spatial variations of the Poyang Lake hydrodynamic and connectivity conditions in the dry, rising, flooding, and receding hydrological phases are illustrated in Figs. 5b-c. The water depth and flow velocity show high spatial heterogeneity and varies quite distinctly within the lake. However, the hydrodynamic behaviors in the lake-floodplains exhibit similar characteristics in terms of their spatial pattern. That is, the lake's main flow channels and the associated extensive floodplains can be recognized across the flood pulse system. Geographically, the water depth in the main lake flow channels can exceed around 10 m, but the depth within the shallow floodplain areas is generally less than 2 m (Fig. 5b). Spatially, the flow velocities vary from <0.1 m/s in the lake's floodplains to >0.9 m/s in the main flow channels (Fig. 5c). The result presented in Fig. 5d reveals the changes in connectivity objects/areas between the main flow channels and the lake's floodplains, as well as between heterogeneous areas within the floodplain, indicating relatively complex connections (in different colors) throughout the lake-floodplain system. This is the expected outcome given that the spatially varying topographic features may exert substantial influences on the connectivity condition, particularly for the dry, rising, and receding phases of the flood-pulse system (Fig. 5d). That is, water depth in the lake flow channels is much deeper than that of the surrounding floodplains during different hydrological water phases, and filling-spilling process generally extends from lower-lying channels to upper-lying floodplains.

4.3. Comparison of different connectivity metrics

Connectivity analysis of the Poyang Lake-floodplains generated a series of monthly N-S, W-E, NW-SE, and NE-SW CF changes under TC, GC, and EC conditions (Fig. 6). For all three connectivity scenarios, the temporal trends show that the CF plots exhibit highly dynamic changes along the distance scale (*x*-axis) for the four directions. However, the results reveal that, in general, low connectivity is observed during the dry seasons, intermediate connectivity tends to occur during the rising and receding periods, while high connectivity is found during the flood period (Figs. 6a-d). Under different connectivity types, the CF results indicate that the connectivity conditions of TC are distinctly higher than those of GC and EC during most times of the year. As expected, the effects of water depth and flow velocity thresholds on hydrological connectivity (GC and EC) may produce large differences relative to the baseline scenario (TC). The results presented in Fig. 6 indicate that the combined effect of water depth and velocity may generate a more complex role on connectivity (EC) than that of the water depth alone (GC). On average, it seems that the CF curve is more likely to generate abrupt changes under the EC scenario than the other two connectivity scenarios (Fig. 7). Additionally, it should be noted that the CF curves decreased to zero in a more rapid manner along the distance scale, especially for the EC scenario (Figs. 6-7).

In order to explore the influence of TC, GC, and EC scenarios on hydrological connectivity, four typical water phases of the Poyang Lake-floodplains were selected to reflect the connected areas and corresponding connected objects/areas (Fig. 8a). It is expected that the connected areas under GC and EC scenarios are lower than in the TC scenario, mainly due to the limitation of water depth and flow velocity. Correspondingly, the spatial variations of connected objects/areas show a similar trend to that of the connected areas for the three connectivity scenarios, as illustrated in Fig. 8b. It can be found that the most notable changes mainly occur in the floodplain areas and in some high elevation areas. In addition, the effective connectivity objects/areas (EC) are mainly distributed in the lake's flow channels across the lake's length (from south to north). In a word, the results presented in Fig. 8b demonstrate that the individual or joint effects of water depth and flow velocity are mostly likely to play a dominant role in controlling flow pathways and associated spatial patterns of connectivity objects/areas.

4.4. Threshold effect of hydrological connectivity

When the CF curves exhibit subtle changes over time implies that the system can be characterized by a steady state condition, or that a threshold behavior may affect the hydrological system. In order to further investigate the threshold effects on surface hydrological connectivity, a series of daily mean CF plots are obtained from the designed modeling experiments, as shown in Fig. 9. The results demonstrate that the variations in water depth thresholds appear to have a large effect on CF during the dry, rising, and falling limbs, opposed to the flooding limb (see the dotted line in Fig. 9a), whereas the flow velocity tends to have an opposite threshold effect (see the dotted line in Fig. 9b). The reason can be attributed to the negative relationship between the water depth and flow velocity (see Fig. 5a). These previous results imply that the combined effect of water depth and flow velocity thresholds on connectivity may be dynamic and complex (e.g., EC; see Figs. 6-7).

Although there is difficulty in quantifying the threshold values of water depth and flow velocity, the results tend to show that the threshold effects are more likely to exhibit a temporal evolution in terms of the line shape of threshold (Fig. 9). That is, the influence of depth and velocity thresholds on connectivity will change along the dry ($threshold_h$= 10-20 cm, $threshold_v$= 20-25 cm/s), rising ($threshold_h$= 50-60 cm, $threshold_v$= 25 cm/s), flooding ($threshold_h >$ 80 cm, $threshold_v$= 5-10 cm/s), and receding ($threshold_h$= 50-60 cm, $threshold_v$= 20 cm/s) water phases (see the dotted lines in Fig. 9). Additionally, the calculated CFs presented in Fig. 10 demonstrate that, on average, the lake-floodplain system seems to exhibit an abrupt change the water depth and velocity thresholds are around 20 cm and 5 cm/s, respectively (see the yellow shadow areas). Additionally, different connectivity conditions are observed for N-S, W-E, NW-SE, and NE-SW directions, which can be explained by the joint influence of spatial varying topographic features (e.g., flow channels and depressions) and different hydrological pulses (e.g., river inflows and lake inundation).

4.5. Implications of the refined connectivity concept and assessment applications

This study attempts to use water coverage, water depth, and flow velocity to describe the hydrological connectivity and its implications for eco-environmental research. The distributions of water quality parameters, waterbirds and fishes in Poyang Lake were selected and used to validate the connectivity metrics of TC, GC, and EC, as illustrated in Fig. 11a. Although these indicators exhibit distinctly heterogeneous distribution, the spatial pattern is highly consistent with the connectivity condition of GC and EC, demonstrating that the threshold range of water depth and flow veloc-

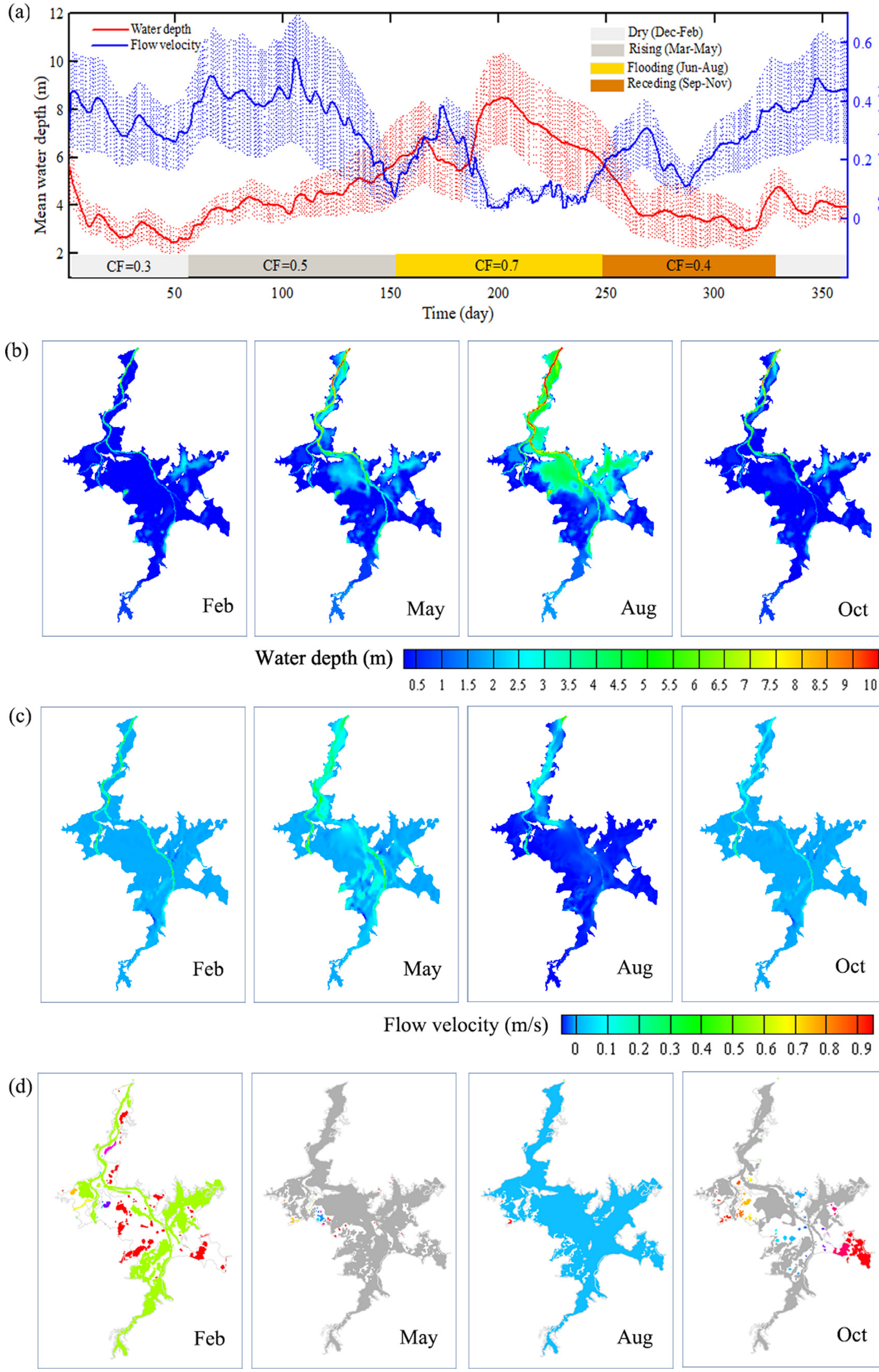

Fig. 5. (a) Changes in water depth and flow velocity averaged over Xingzi, Duchang, Tangyin, and Kangshan gauging stations with corresponding ±standard errors (in scatter plots); and spatial distributions of (b) water depth, (c) flow velocity, and (d) connected object/area during the dry, rising, flooding, and receding water phases. The mean connectivity functions (CFs) in (a) were calculated and the different connected objects in (d) were plot with different colors for the four water phases based on the total connectivity (TC). Note that the light green color and the blue color in (d) represent the largest connected object/area for the dry and flooding water phases, respectively, and the gray color represents the largest connected object/area for both the rising and receding water phases. Other colors (e.g., red, yellow) represent the remaining individual objects/areas.

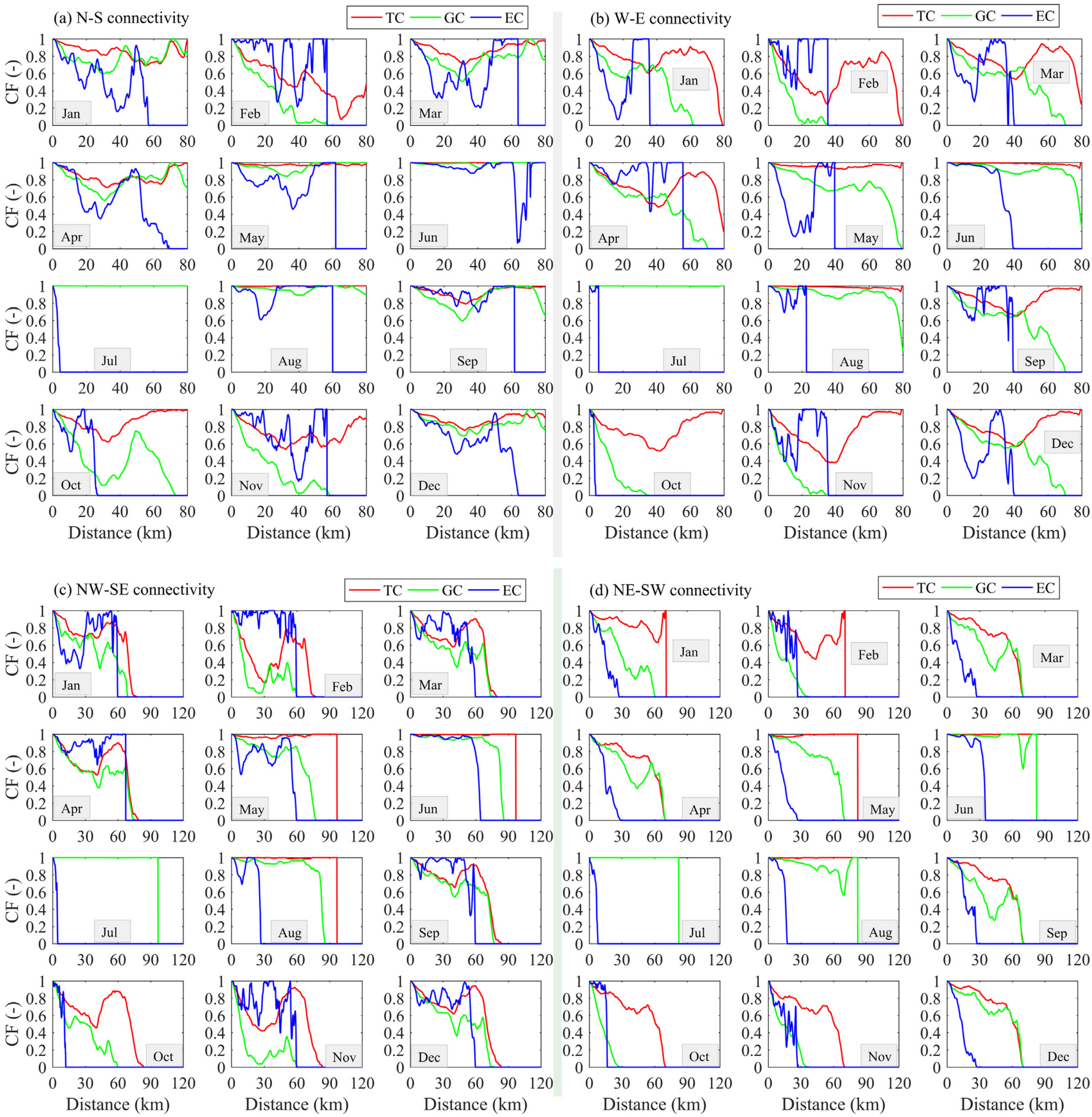

Fig. 6. (a)-(d) North-South (N-S), West-East (W-E), NW-SE, and NE-SW connectivity function (CF) plots from January to December under the three connectivity types.

ity is critical for connectivity assessment in the system. For example, the connectivity objects/areas of EC is most likely to control the TSI of the lake, especially for the main flow channels (see ② in Fig. 11a). The spatial coincidence of connectivity objects/areas with waterbird, and fish distributions are well reproduced by the changed water depth threshold of GC. Statistical analysis reveals that the refined hydrological connectivity of GC and EC has a close relationship with the eco-environmental indicators, as reflected in R^2 values of 0.92 and 0.69 for the TSI and the waterbird population, respectively ($p<0.05$; Fig. 11a). The results present here highlight the effectiveness and implications of the refined connectivity metrics.

From the perspective of hydrodynamics, the spatial distributions of TN, TP, Chl-*a* concentrations, and the TSI can be directly explained by the complex depth-velocity relationships (see ①②③ in Fig. 11b). For most rivers, lakes and wetlands, water depth and flow velocity generally exhibit positive relationships that play a cumulative or equivalent role on connectivity condition, GC can be selected to evaluate the connectivity effects on ecosystems, while EC is an appropriate metric to investigate regions with negative re-

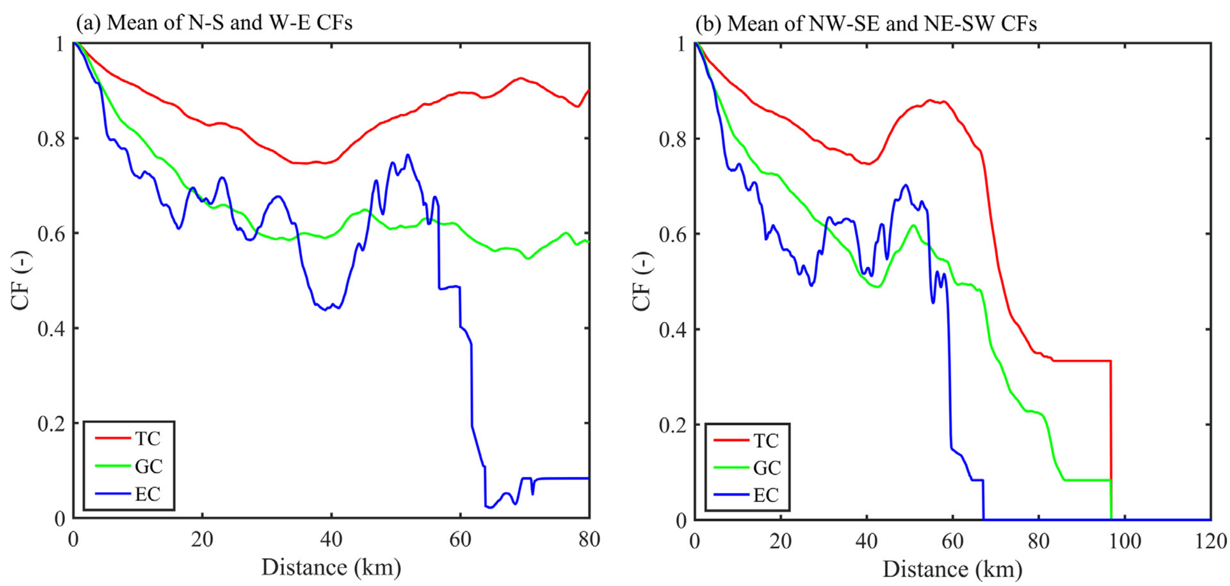

Fig. 7. Mean connectivity function (CF) plots for (a) N-S and W-E, and (b) NW-SE and NE-SW directions under the three connectivity types.

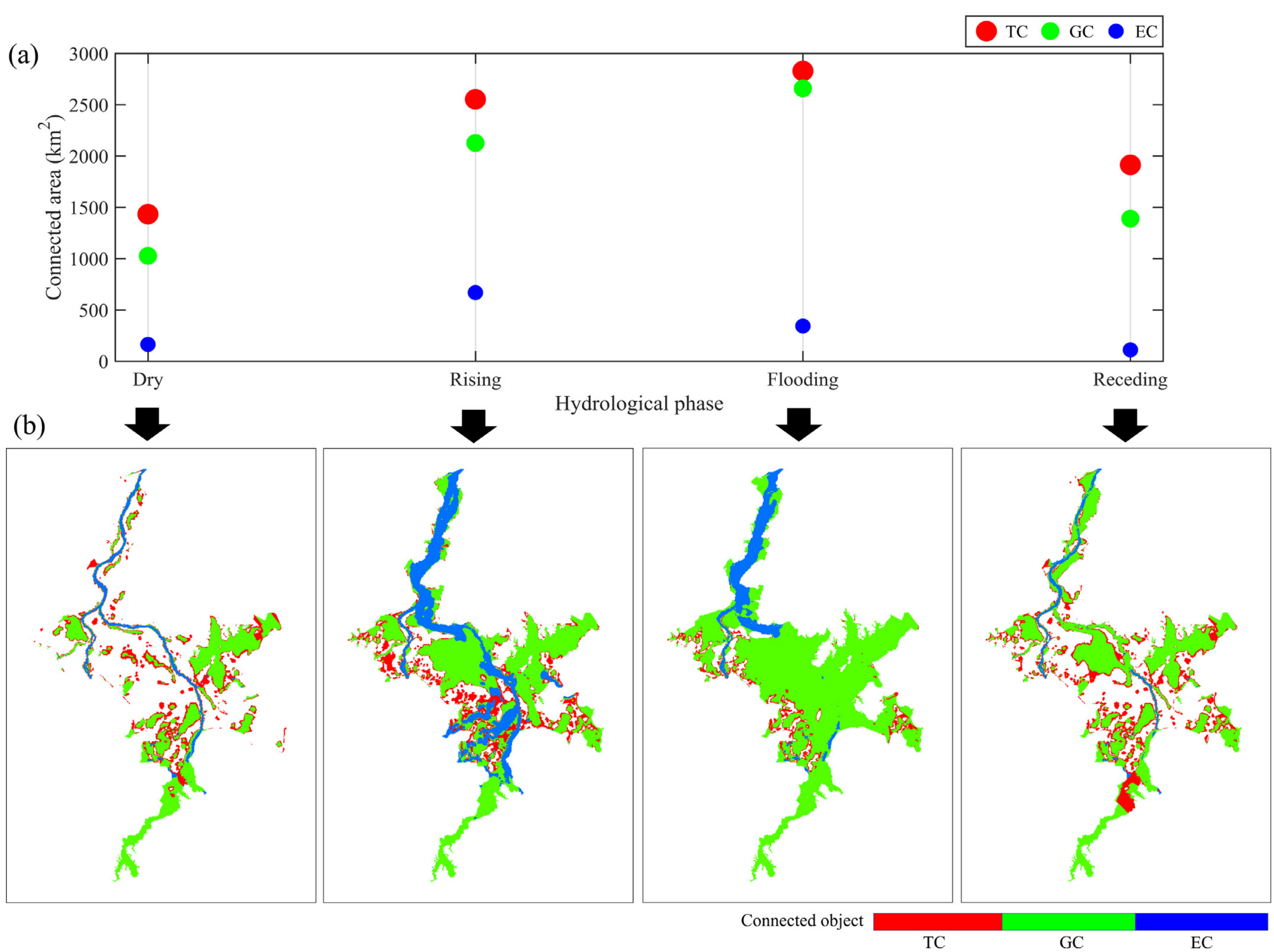

Fig. 8. Influence of TC, GC, and EC scenarios on (a) connected areas and (b) corresponding connected objects for the four water phases of the Poyang Lake-floodplains.

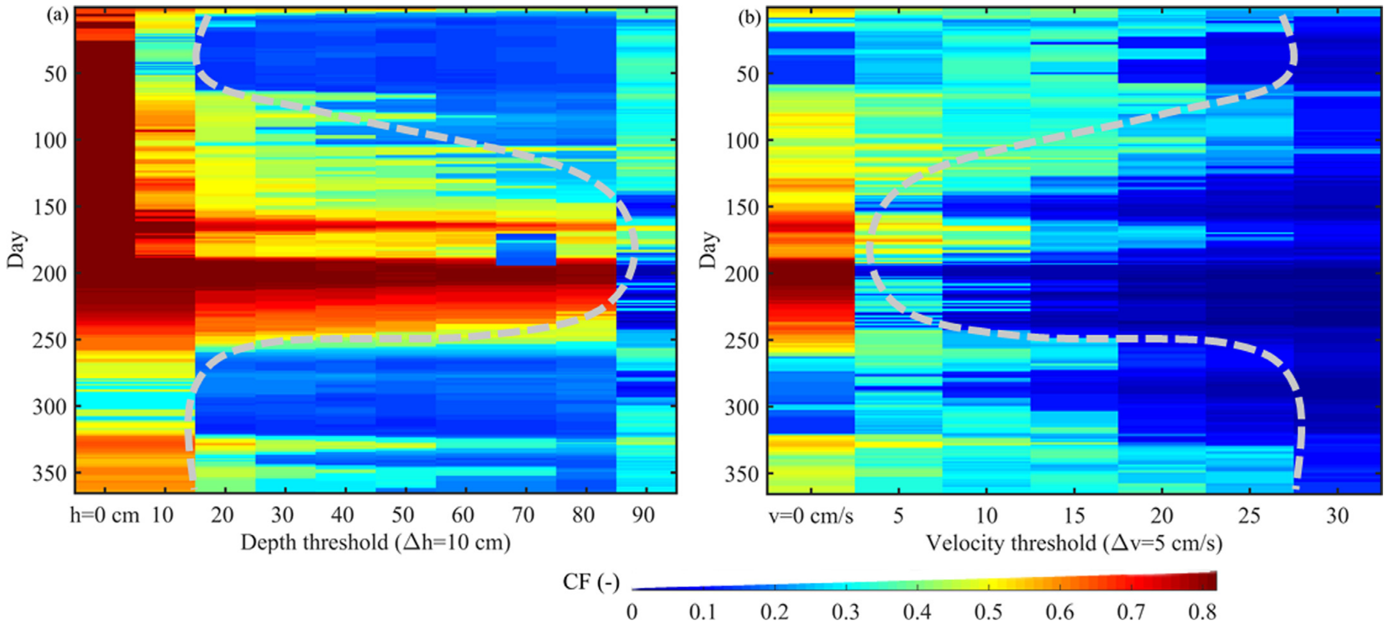

Fig. 9. Hydrological connectivity function (CF) in response to different threshold values of (a) water depth and (b) flow velocity. The CF in this figure represents the average connectivity for N-S, W-E, NW-SE, and NE-SW directions. The dotted line represents the threshold line and the associated temporal distribution.

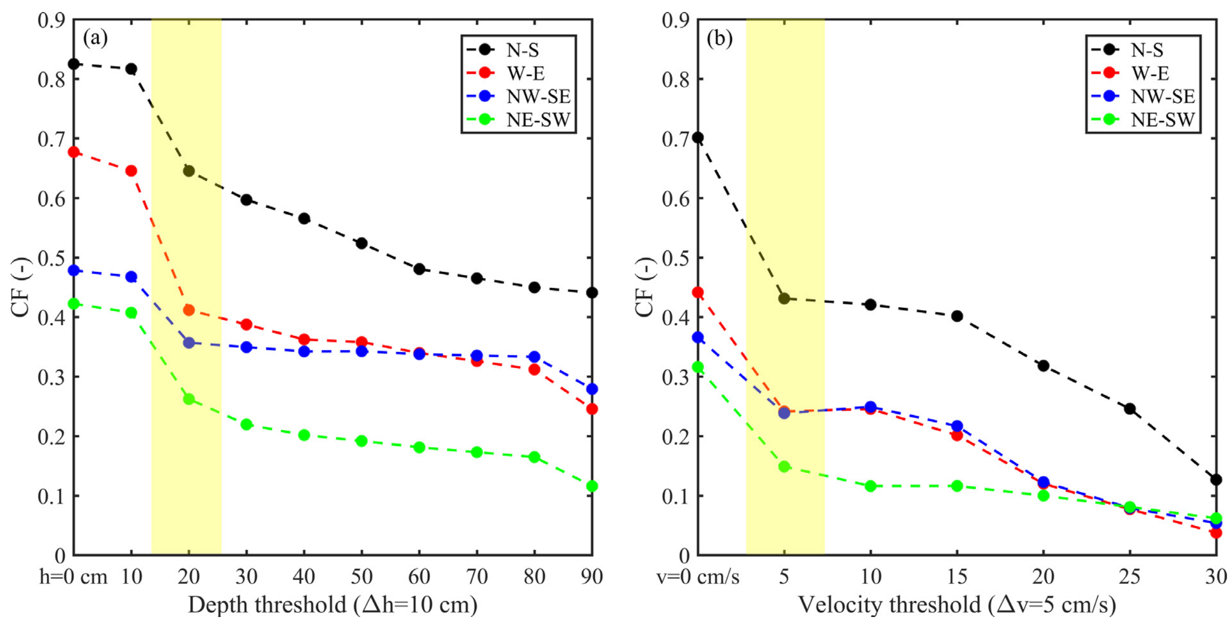

Fig. 10. Mean hydrological connectivity function (CF) in response to different threshold values of (a) water depth and (b) flow velocity. The CF in this figure represents the average connectivity during 2018. The yellow shadow area represents an abrupt change in CF curves and the corresponding threshold value.

lationships between water depth and flow velocity (compensatory role; Fig. 11b). The researchers should take caution that the threshold value of EC may produce significant influences on the connectivity and the associated assessment applications, particularly for shallow water flow areas (e.g., floodplains).

5. Discussion

For this study, we provided new insight into the threshold effects of key hydrodynamic variables on surface water connectivity for the Poyang Lake-floodplains and other similar floodplains around the world. Although the current work improves our understanding of hydrological connectivity and its causal factors in large flood pulse-influenced systems, connectivity dynamics are also affected by complex hydro-geomorphologic properties, including channelized water flowpaths, overbank processes, and local recharge (Stevaux et al., 2013; Restrepo A et al., 2020). In large floodplains, the surface topography and hydrological pulses are dominant in different parts of the system, the threshold behaviors from this work may have somewhat different outcomes if other floodplain areas are investigated. Therefore, specific studies should be conducted to identify individual thresholds for different geomorphic units.

Knowledge regarding the temporal evolution and the spatial continuity, as well as the complexity of heterogenous topographic features, is a necessity for any restoration effort (Singh and Sinha, 2019). The current hydrodynamic model and spatial analysis provide a combination approach to consider past and present con-

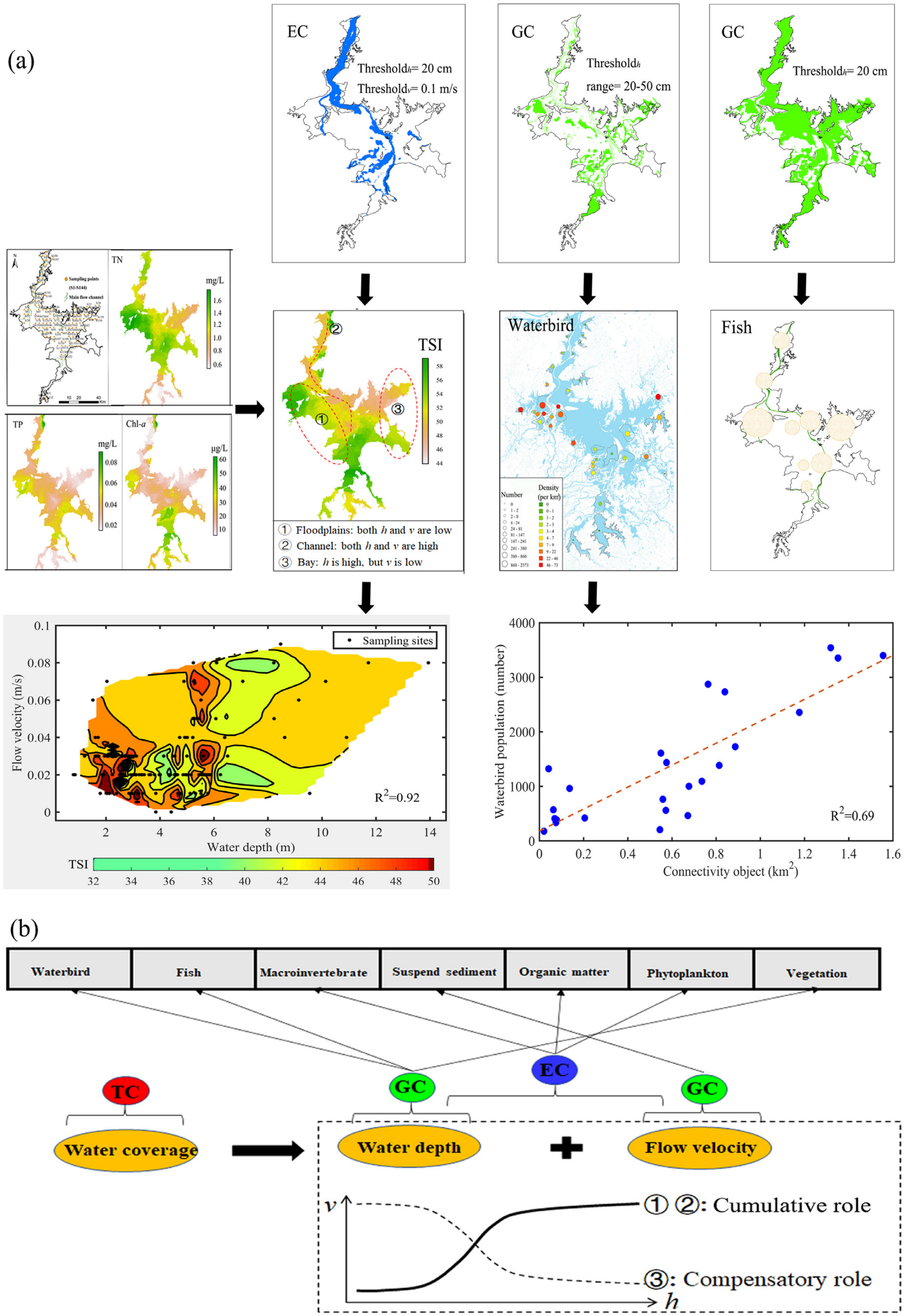

Fig. 11. (a) Linkage between distributions of TSI, waterbird, and fish and the refined hydrological connectivity based on visual inspection, contour plot and linear-fitting approaches with a determination coefficient R^2; (b) schematic diagram showing assessment applications of the refined connectivity metrics.

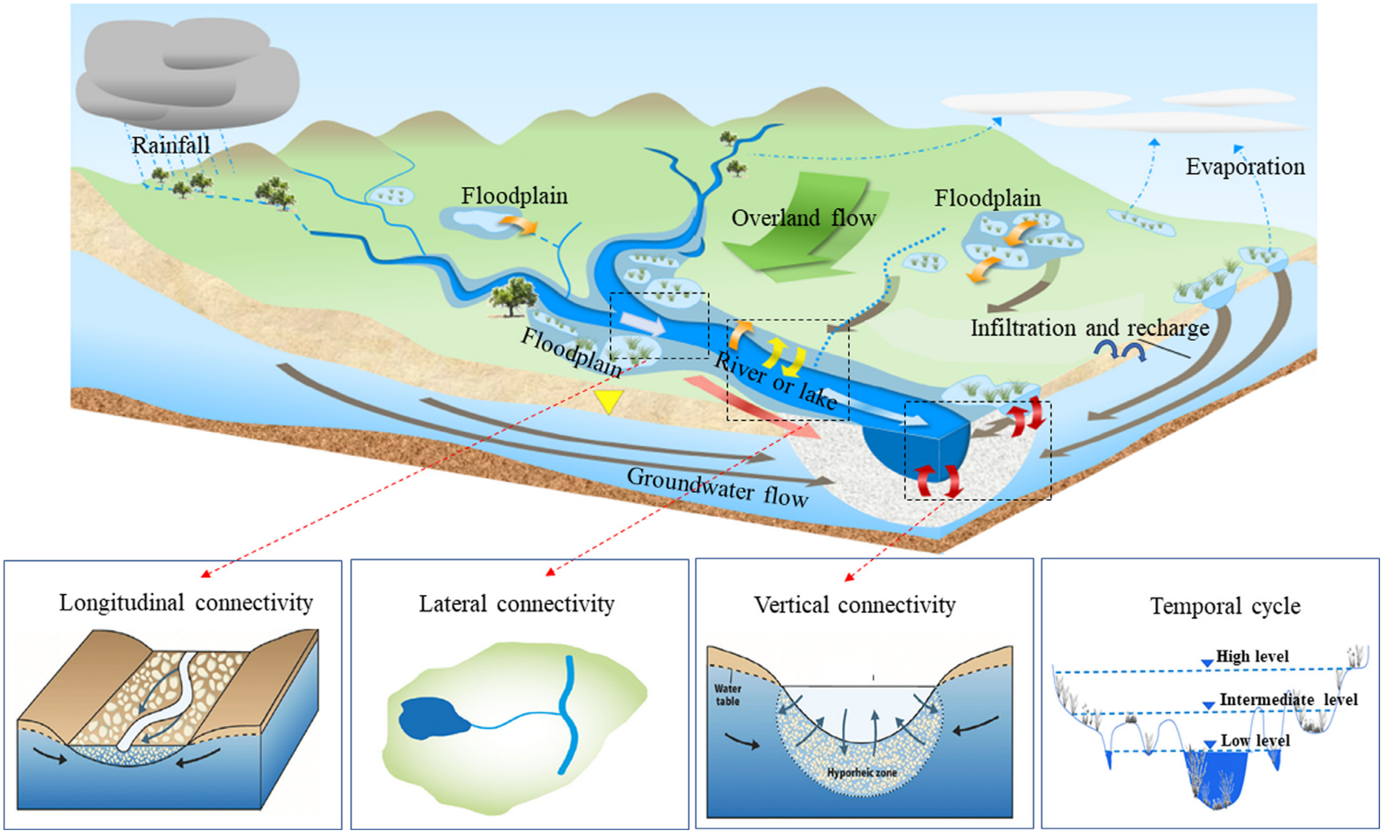

Fig. 12. Generalized diagram illustrating hydrological flowpaths and the associated four dimensions of hydrological connectivity (modified from USEPA, 2015). Arrows are representative of surface water and groundwater flows occurring throughout the whole catchment.

nectivity conditions with intensifying, persistent, and diminishing connectivity potentials. The examination of low and high potential connectivity and spatial connected objects/areas in the current work offers an opportunity to perform effective management and restoration activities. Therefore, this study may contribute to the method and the need for a spatiotemporal framework for connectivity and restoration projects across different landscape elements.

For the flood pulse-influenced Poyang Lake, this study demonstrates that the floodplain and its embedded wetland are sensitive areas that are strongly affected by threshold effects of water depth and flow velocity (see Fig. 8). Therefore, the current assessment of hydrological connectivity should be combined with ecological and environmental processes. Indeed, several previous attempts have been carried out to analyze the relationship between hydrological connectivity and wetland function. For example, field observations have been carried out to explore the effects of hydrological connectivity on wetland waterbirds of Poyang Lake (Xia et al., 2016). A geostatistical calculation was applied in hydrodynamic results and used to examine the influence of connectivity on water quality status of the lake wetland (Li et al., 2019a). More recently, the same geostatistical method as Li et al. (2019a) was adopted to analyze the connectivity dynamics and the associated causal factors for the lake's floodplains based on a series of remote sensing images (Tan et al., 2019; Liu et al., 2020). Although these previous studies highlighted the important role of surface hydrological connectivity on vegetation types, fishes, migratory waterbirds, and water quality status of the Poyang Lake-floodplain system, water depth and flow velocity were not quantitatively combined to explain the effect of hydrological connectivity. The outcomes from the current work increase our knowledge of previous studies by refining the concept of hydrological connectivity and evaluating the influence of water depth and flow velocity on connectivity in the threshold-affected floodplain. In addition, this study also offers recommendations for future work in which researchers should use more comprehensive connectivity data (e.g., habitat suitability data), assessments and measures to facilitate scientific communication and its implication.

According to previous ecological assessments, most lakes surrounding the Yangtze River have lost their natural connections, and as such some lakes have disappeared entirely during recent decades (Zhang et al., 2020). Numerous previous studies have been conducted to investigate the external connectivity between the Yangtze River and their floodplain lakes (river-lake connectivity) such as Dongting Lake and Poyang Lake (e.g., Zhang et al., 2014; Hu et al., 2015; Li et al., 2017). For example, the lowering level in the Yangtze River plays a weakening role in enhancing lake outflows into the river, resulting in a reduced lake water level over the receding water phase (Zhang et al., 2014). Additionally, according to previous hydrological and environmental assessments, the Poyang Lake hydraulic dam linking the lake and the Yangtze River proposed by the Jiangxi Province Government is more likely to increase the low lake water levels and alter the flow fields (Wang et al., 2015). It is noteworthy that the variations in the lake hydrodynamics may exceed the water depth and velocity threshold values, potentially leading to abrupt changes in internal connectivity (lake-floodplain connectivity). However, previous efforts regarding hydrological and ecological conditions and management and policy decisions are often made in the absence of adequate assessments on surface hydrological connectivity. The outcomes from this study play a critical role in guiding future strategies for both Poyang Lake and the Yangtze River, and proposing floodplain behavior management, connectivity dynamics, and associated ecological responses.

In this study, we focus on the surface water connectivity and its threshold effects on the floodplain system. Hydrological connectivity is based on a system-specific concept USEPA, 2015). Indeed, the concept of connectivity develops from its origin in ecology (Goodwin, 2003). During the recent decade, both ecologists and hydrologists have adopted a variety of connectivity definitions (Rinderer et al., 2018). Generally, hydrological connectivity includes longitudinal (e.g., streamflow and downstream transport), lateral (e.g., overbank flow and transport from channels to floodplains), vertical (e.g., surface-subsurface exchange), and temporal dimensions (e.g., seasonal cycles) (see Fig. 12). Since the surface hydrological connectivity analyzed in this study is based on the floodplain hydrodynamic model MIKE 21, we could not provide information regarding subsurface connectivity (e.g., recharge rate, soil water, and groundwater). Previous work in the Poyang Lake floodplains concluded that lake-floodplain groundwater exhibits a significant seasonal exchange and has a strong impact on soil gleyization (Li et al., 2019c; Yang et al., 2019). Additionally, it is important to keep in mind that natural waterbodies (e.g., rivers and lakes) usually have rather complex and sensitive flow dynamics, it is beyond the scope of this study to use velocity directions to identify the variable connectivity conditions. Therefore, the current connectivity method represents an average connectivity condition along the N-S, W-E, NE-SW and NW-SE directions, respectively (see equation (1)-((3)). Refining hydrological connectivity through a threshold approach, as done in this study, indubitably affects multiple dimensions of connectivity. For example, the refined hydrological connectivity may lead to the partial or fragmental connectivity condition for most natural rivers, due to the consideration of water depth or velocity threshold. Given the above background, further work to evaluate the connectivity in complex environments will focus on the following: (1) incorporate a 2D hydrodynamic model and groundwater flow model to provide a complete description of the surface flowpaths, soil water movement, and groundwater flow dynamics; (2) modify the current connectivity algorithm or apply novel methods to represent the longitudinal, lateral, and vertical directions rather than N-S, W-E, NW-SE, and NE-SW, based on river networks and associated flow directions; and (3) develop a simplified scheme to provide new insights into the linkage of multiple dimensions/scales of hydrological connectivity and its response to climate change (e.g., abnormal flooding and drying years) and human activities (e.g., dam construction, sedimentation).

6. Conclusions

The current work aimed to improve the understanding of hydrological connectivity and the threshold effects of hydrodynamics on eco-environmental indicators in a large flood-pulse-influenced floodplain system, Poyang Lake (China). The results reveal that low connectivity is observed during the dry water phase, intermediate connectivity tends to occur during the rising and receding phases, and high connectivity is found during the flood phase of Poyang Lake. Spatial changes in connectivity objects/areas indicate that the heterogeneous floodplain is a sensitive area of the flood pulse system. In order to highlight the inherent linkage between hydrological connectivity and eco-environments, the concepts of total connectivity (TC), general connectivity (GC), and effective connectivity (EC) were proposed and defined based on water inundation, water depth, and flow velocity distributions. The substantial differences between the three connectivity types demonstrate that the joint influences of water depth and velocity (EC) may produce more dynamic and complex roles on connectivity than the other two scenarios (TC and GC). The modelling experiments provide new insight into the threshold effects of water depth and flow velocity on floodplain hydrological connectivity. The results reveal that, in general, the variations in water depth thresholds may have a large effect on connectivity during the dry, rising, and receding limbs, rather than the flooding limb, w hile velocity seems to exert an opposite threshold role in affecting the wetting and drying cycle. The influence of depth and velocity thresholds on connectivity will change along different water phases of the hydrological pulses, indicating a temporal dynamic threshold behavior in flood-pulse-influenced systems. Our study highlights the importance of redefined connectivity concept for both management applications and providing recommendations for future ecological and environmental assessments using our proposed metrics of TC, GC, and EC.

Declaration of competing interest

None.

Acknowledgements

This work was jointly supported by the Strategic Priority Research Program of the Chinese Academy of Sciences (XDA23040202), the National Key Research and Development Program (2019YFC0409002), the Youth Innovation Promotion Association of the Chinese Academy of Sciences (Y9CJH01001), the National Natural Science Foundation of China (42071036, 41771037). We thank Dr. Y.J. Cai from Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences for providing the water quality data of the lake. Also, we are grateful to the editor and anonymous reviewers for their valuable suggestions.

References

Antoine, M., Javaux, M., Bielders, C., 2009. What indicators can capture runoff relevant connectivity properties of the micro-topography at the plot scale? Adv. Water Resour. 32, 1297–1310.
Bennion, D.H., Manny, B.A., 2014. A model to locate potential areas for lake sturgeon spawning habitat construction in the St. Clair-Detroit River System. J. Great Lakes Res. 40, 43–51.
Bonnet, M.P., Barroux, G., Martinez, J.M., Seyler, F., Moreira-Turcq, P., Cochonneau, G., Melack, J.M., Boaventura, G., Maurice-Bourgoin, L., León, J.G., Roux, E., Kosuth, P., Guyot, J.L., Seyler, P., 2008. Floodplain hydrology in an Amazon floodplain lake (Lago Grande de Curuaí). J. Hydrol. 349, 18–30.
Bracken, L.J., Wainwright, J., Ali, G.A., Tetzlaff, D., Smith, M.W., Reaney, S.M., Roy, A.G., 2013. Concepts of hydrological connectivity: research approaches, pathways and future agendas. Earth Sci. Rev. 119, 17–34.
Carlson, R.E., 1977. A trophic state index for lakes. Limnol. Oceanogr. 22, 361–369.
Casanova, S.M.C., Panarelli, E.A., Henry, R., 2009. Rotifer abundance, biomass, and secondary production after the recovery of hydrologic connectivity between a river and two marginal lakes (São Paulo, Brazil).. Limnologica 39, 292–301.
Compliatory Committee, 1993. Atlas of Poyang Lake. Science Press, Shanghai, p. p49.
Danish Hydraulic Institute (DHI), 2014. MIKE 21 flow model: hydrodynamic module user guide. Danish Hydraulic Institute Water and Environment, Hørsholm, Denmark, 132.
de Resende, A.F., Schöngart, J., Streher, A.S., Ferreira- Ferreira, F., Piedade, M.T.F., Silva, T.S., 2019. Massive tree mortality from flood pulse disturbances in Amazonian floodplain forests: The collateral effects of hydropower production. Sci. Tot. Environ. 659, 587–598.
Deng, X., Xu, Y., Han, L., Song, S., Xu, G., Xiang, J., 2018. Spatial-temporal changes in the longitudinal functional connectivity of river systems in the Taihu Plain. China. J. Hydrol. 566, 846–859.
Fazi, S., Butturini, A., Tassi, F., Amalfitano, S., Venturi, S., Vazquez, E., Clokie, M., Wanjala, S.W., Pacini, N., Harper, D.M., 2018. Biogeochemistry and biodiversity in a network of sline-alkaline lakes: Implications of ecohydrological connectivity in the Kentan Rift Valley. Ecohydrol. Hydrobiol. 18, 96–106.
Funk, A., Martínez-López, J., Borgwardt, F., Trauner, D., Bagstad, K.J., Balbi, S., Magrach, A., Villa, F., Hein, T., 2019. Identification of conservation and restoration priority areas in the Danube River based on the multi-functionality of river-floodplain systems. Sci. Total Environ. 654, 763–777.
Giblin, S.M., Houser, J.N., Sullivan, J.F., Langrehr, H.A., Rogala, J.T., Campbell, B.D., 2014. Threshold in the response of free-floating plant abundance to variation in hydraulic connectivity, nutrients, and macrophyte abundance in a large floodplain river. Wetlands 34, 413–425.
Goodwin, B.J., 2003. Is landscape connectivity a dependent or independent variable? Landsc. Ecol. 18, 687–699.
Granados, V., Gutiérrez-Cánovas, C., Arias-Real, R., Obrador, B., Harjung, A., Butturini, A., 2020. The interruption of longitudinal hydrological connectivity causes delayed responses in dissolved organic matter. Sci. Total Environ. 713, 136619.
Hu, C., Fang, C., Cao, W., 2015. Shrinking of Dongting Lake and its weakening connection with the Yangtze River: Analysis of the impact on flooding. Int. J. Sediment Res. 30, 256–262.

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

Huang, Z., Lu, L., Jiao, G., Jiang, J., Ye, Q., 2018. Analysis of the correlations between environmental factors and rare cranes in the Poyang Lake region of China. J. Great Lakes Res. 44, 140–148.

Jager, N.R.D., Thomsen, M., Yin, Y., 2012. Threshold effects of flood duration on the vegetation and soils of the Upper Mississippi River floodplain. USA. Forest Ecol. Manag. 270, 135–146.

Journel, A.G., Kyriakidis, P.C., Mao, S., 2000. Correcting the smoothing effect of estimators: A spectral postprocessor. Math. Geol. 32, 787–813.

Junk, W.J., Bayley, P.B., Sparks, R.E., 1989. The flood pulse concept in river floodplain systems. Can. Spec. Publ. Fish Aquat. Sci. 106, 110–127.

Karpack, M.N., Morrison, R.R., McManamany, R.A., 2020. Quantitative assessment of floodplain functionality using an index of integrity. Ecol. Indic. 111, 106051.

Khaki, M., Awange, J., 2019. Improved remotely sensed satellite products for studying Lake Victoria's water storage changes. Sci. Total Environ. 652, 915–926.

Kupfer, J.A., Meitzen, K.M., Gao, P., 2015. Flooding and surface connectivity of taxodium-nyssa stands in a southern floodplain forest ecosystem. River Res. Appl. 31, 1299–1310.

Li, Y., Yao, J., Zhang, L., 2016. Investigation into mixing in the shallow floodplain Poyang Lake (China) using hydrological, thermal and isotopic evidence. Water Sci. Technol. 74, 2582–2598.

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

Li, Y., Zhang, Q., Liu, X., Yao, J., 2020a. Water balance and flashiness for a large floodplain system: A case study of Poyang Lake, China. Sci. Total Environ. 710, 135499.

Li, Y., Zhang, Q., Lu, J., Yao, J., Tan, Z., 2019c. Assessing surface water-groundwater interactions in a complex river-floodplain wetland-isolated lake system. River Res. Appl. 35, 25–36.

Li, Y., Zhang, Q., Tan, Z., Yao, J., 2020b. On the hydrodynamic bahavior of floodplain vegetation in a flood-pulse-influenced river-lake system (Poyang Lake, China). J. Hydrol. 585, 124852.

Li, Y., Zhang, Q., Werner, A.D., Yao, J., Ye, X., 2017. The influence of river-to-lake backflow on the hydrodynamics of a large floodplain lake system (Poyang Lake, China). Hydrol. Process. 31, 117–132.

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

Liu, X., Zhang, Q., Li, Y., Tan, Z., Werner, A.D., 2020. Satellite image-based investigation of the seasonal variations in the hydrological connectivity of a large floodplain. China). J. Hydrol. 585, 124810.

Michaelides, K., Chappell, A., 2009. Connectivity as a concept for charactersing hydrological behaviour. Hydrol. Process. 23, 517–522.

Moreno-de las Heras, M., Saco, P.M., Willgoose, G.R., Tongway, D., 2012. Variations in hydrological connectivity of Australian semiarid landscapes indicate abrupt changes in rainfall-use efficiency of vegetation. J. Geophys. Res. 117, G03009.

Pardo-Iguzquiza, E., Dowd, P.A., 2003. CONNEC3D: a computer program for connectivity analysis of 3D random set models. Comput. Geosci. 29, 775–785.

Park, E., 2020. Characterizing channel-floodplain connectivity using satellite altimetry: Mechanism, hydrogeomorphic control, and sediment budget. Remote Sen. Environ. 243, 111783.

Phillips, R.W., Spence, C., Pomeroy, J.W., 2011. Connectivity and runoff dynamics in heterogeneous basins. Hydrol. Process. 25, 3061–3075.

Reckendorfer, W., Baranyi, C., Funk, A., Schiemer, F., 2006. Floodplain restoration by reinforcing hydrological connectivity: expected effects on aquatic mollusc communities. J. Appl. Ecol. 43, 474–484.

Restrepo, A.J.D., Kettner, A.J., Brakenridge, R.B., 2020. Monitoring water discharge and floodplain connectivity for the northern Andes utlizing satellite data: A tool for river planning and science-based decision-making. J. Hydrol. 586, 124887.

Rinderer, M., Ali, G., Larsen, L.G., 2018. Assessing structure, functional and effective hydrologic connectivity with brain neuroscience methods: State-of-the-art and research directions. Earth-Sci. Rev. 178, 29–47.

Saco, P.M., Moreno-de las Heras, M., Keesstra, S., Baartman, J., Yetemen, O., Rodriguez, J.F., 2018. Vegetation and soil degradation in drylands: non-linear feedbakcs and early warming signals. Curr. Opin. Environ. Sci. Health 5, 67–72.

Saco, P.M., Rodríguez, J.F., Heras, M.M., Keesstra, S., Azadi, S., Sandi, S., Baartman, J., Rodrigo-Comino, J., Rossi, M.J., 2020. Using hydrological connectivity to detect transitions and degradation thresholds: Applications to dryland systems. Catena 186, 104354.

Shao, X., Fang, Y., Cui, B., 2020. A model to evaluate spatiotemporal variations of hydrological connectivity on a basin-scale complex river network with intensive human activity. Sci. Total Environ. 723, 138051.

Singh, M., Sinha, R., 2019. Evaluating dynamic hydrological connectivity of a floodplain wetland in North Bihar, India using geostatistical methods. Sci. Total Environ. 651, 2473–2488.

Stevaux, J.C., Corradini, F.A., Aquino, S., 2013. Connectivity processes and riparian vegetation of the upper Paraná River. Brazil. J. S. Am. Earth Sci. 46, 113–121.

Tan, Z., Wang, X., Chen, B., Liu, X., Zhang, Q., 2019. Surface water connectivity of seasonal isolated lakes in a dynamic lake-floodplain system. J. Hydrol. 579, 124154.

Trigg, M.A., Michaelides, K., Neal, J.C., Bates, P.D., 2013. Surface water connectivity dynamics of a large scale extreme flood. J. Hydrol. 505, 138–149.

Turnbull, L., Wainwright, J., Brazier, R.E., 2008. A conceptual framework for understanding semi-arid land degradation: Ecohydrological interactions across multiple space and time scales. Ecohydrology 1, 23–34.

USEPA, 2015. Connectivity of streams & wetlands to downstream waters: A review & synthesis of the scientific evidence EPA/600/R-14/475F.

Wang, P., Lai, G., Li, L., 2015. Predicting the hydrological impacts of the Poyang Lake project using an EFDC model. J. Hydrol. Eng. 20, 05015009.

Wei, K., Ouyang, C., Duan, H., Li, Y., Chen, M., Ma, J., An, H., Zhou, S., 2020. Reflections on the catastrophic 2020 Yangtze River basin flooding in southern China. The Innovation 1, 100038.

Xia, S., Liu, Y., Wang, Y., Chen, B., Jia, Y., Liu, G., Yu, X., Wen, L., 2016. Wintering waterbirds in a large river floodplain: Hydrological connectivity is the key for reconciling development and conservation. Sci. Total Environ. 573, 645–660.

Yang, J., Chu, X., 2013. Quantification of the spatio-temporal variations in hydrologic connectivity of samll-scale topographic surfaces under various rainfall conditions. J. Hydrol. 505, 65–77.

Yang, Y., Wang, Z., Xie, Y., Ataie-Ashtiani, B., Simmons, C.T., Luo, Q., Chen, G., Zhang, Q., Wu, J., Wang, J., Wu, J., 2019. Impacts of groundwater depth on regional scale soil gleyization under changing climate in the Poyang Lake Basin. China. J. Hydrol. 568, 501–516.

Yeo, I., Lee, S., Lang, M.W., Yetemen, O., McCarty, G.W., Sadeghi, A.M., Evenson, G., 2019. Mapping landscape-level hydrological connectivity of headwater wetlands to downstream waters: A catchment modeling approach-Part 2. Sci. Total Environ. 653, 1557–1570.

Zhang, L., Pan, B., Jiang, X., Wang, H., Lu, Y., Lu, Y., Li, R., 2020. Responses of the macroinvertebrate taxonomic distinctness indices of lake fauna to human disturbances in the middle and lower reaches of the Yangtze river. Ecol. Indic. 110, 105952.

Zhang, Q., Ye, X.C., Werner, A.D., Li, Y.L., Yao, J., Li, X.H., Xu, C.Y., 2014. An investigation of enhanced recessions in Poyang Lake: Comparison of Yangtze River and local catchment impacts. J. Hydrol. 517, 425–434.