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ORIGINAL ARTICLE

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Simulation of Poyang Lake water levels and outflow under historical extreme hydrological scenarios

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Abstract

Due to an intensification of anthropogenic activities and climate change in recent decades, the hydrological connections and relationships between rivers and lakes have been significantly modified globally. Poyang Lake is one of the largest freshwater lakes globally and is one of the few that remain naturally connected to the Yangtze River. To investigate the full hydrological conditions (extreme high and low discharge) of Poyang Lake outflow under current bathymetric conditions, a large-scale 1D- and 2D-coupled high-resolution hydrodynamic model of the Poyang Lake basin–Yangtze River system was developed. We simulated the outflow and water levels of Poyang Lake under nine different extreme hydrological scenarios with high precision and computational efficiency. We propose (1) a novel partition calibration method to characterize the roughness coefficient of large water bodies in complicated geographical terrain both for wet and dry seasons; (2) a new method for setting initial conditions for hydrodynamic simulation of large water bodies subject to strong hydrological regulation. Results indicated that (1) maximum outflow and water levels will reach 37,200 m^3/s and 22.28 m when Poyang Lake basin floodwater coincides with flooding on the Yangtze River; (2) precipitation over the lake has increased outflow but this has had very limited influence on its changing hydrological pattern; (3) the effect of hydrological conditions within the system differs for both the lake outflow and water level. The research provides important reference conditions for the application of the InfoWorks ICM model in future applications and studies of large river–lake systems.

KEYWORDS

flood and drought, hydrodynamic model, outflow, Poyang Lake, rainfall, Yangtze River

1 | INTRODUCTION

Modeling water levels and outflows of large lakes represents an important component of lake hydrology (Croley II, 1983; Kebede et al., 2006; MacKay & Seglenieks, 2013), particularly for online lakes that are influenced by multiple inflows, large outflows and complex hydrodynamic conditions. This is especially important to consider for systems where large rivers and lakes potentially interact (Chen et al., 2004; Cotte & Vennemann, 2020; Kennedy, 1984) and discharge may be dynamic, exchanging between both the river and lake (Hu et al., 2007; Yuan et al., 2015); resulting in discharge moving in both directions within the channel depending on antecedent boundary conditions (Zhang et al., 2011; Zhang et al., 2012; Zhang et al., 2014). Poyang Lake is the largest freshwater lake in China and is also one of the few lakes that remains naturally connected to the Yangtze River. The Lake receives water from five major tributaries comprising the rivers Ganjiang, Fuhe, Xinjiang, Raohe, Xiushui (simplified as "five-rivers"), and discharges to the Yangtze River. The dynamic lake–river interactions determine the lake level, the expansion and contraction of the lake surface area, and the occurrence of droughts and floods within the wider lake basin. Given the considerable public interest in flooding and drought, complex lake–river interactions represent a challenge to research and water resource management. The probability of concurrent hydrological droughts in the Poyang Lake-catchment-river system has been examined in detail (Zhang et al., 2017), while Li et al. (2018) explored the spatiotemporal variations and causal factors of thermal stability in Poyang Lake. It has been shown that backflow from the Yangtze River is the primary factor controlling lake discharge from July to October, rather than catchment inflows to the lake (Li et al., 2017). Lai et al. (2016) simulated the potential impacts of the planned Poyang Lake dam on lake hydrodynamics and suggested that it would effectively raise the average depth of water across the lake by 11 m during the normal low-flow period and resulting in longer and lower water levels during the dry period in the Yangtze River. It is widely recognized that the Yangtze River plays a crucial role in controlling lake water levels (Dai et al., 2015; Guo et al., 2012; Li et al., 2015; Zhang et al., 2014), while Hu et al. (2007) indicated that the five-rivers inflowing to the lake are usually the most significant control on water levels. However, limited research to date has directly integrated lake rainfall, one of the main inputs to the lake, into hydrodynamic simulations of Poyang Lake. It should be noted that the controlling catchment area of the five-rivers inflowing is about ~85% of the Poyang Lake Basin, while the runoff generated by the rainfall from the region between the hydrological gauge stations of the five-rivers and the lake outlet was not controlled by gauge stations; therefore, lake rainfall should be used as the model boundary condition in future studies. With the intensification of anthropogenic activities (i.e., land reclamation, levee construction, and lake sedimentation) and climate change in recent decades, the hydrological interactions between the inflowing rivers and Poyang Lake have been modified (Li & Li, 2020), leading to more frequent and severe hydrological extreme events (Li et al., 2016; Li et al., 2017; Shankman et al., 2006; Shankman et al., 2009; Shankman & Keim, 2016; Wang et al., 2019; Zhang et al., 2011; Zhang et al., 2015; Zhang et al., 2017; Zhou et al., 2020). This has resulted in severe water supply, irrigation, and environmental flow requirement challenges (Chen et al., 2019; Wang et al., 2019). It is also predicted that a reduction of water availability during the dry season, and an increase in flood magnitude and frequency, and an increase in water availability will occur during the wet season in the future (Dong et al., 2019). Therefore, it is of critical importance to investigate lake outflow under extreme hydrological conditions (Zhang et al., 2017). Although a large volume of research has been undertaken on the Poyang Lake basin-Yangtze River system, the behavior of the lake outflow under extreme hydrological conditions, in combination with future scenarios of Yangtze River condition and the five-rivers inflowing to the lake has not been considered thus far. This situation can be partially attributed to the lack of appropriate data and high computational requirements. However, it is now possible to address this issue using updated long-term hydrological and meteorological data series, river cross-section data and high-resolution lake terrain data. This study uses this newly available data to investigate the outflow of Poyang Lake under combined scenarios of extreme hydrological conditions for the Yangtze River discharge, precipitation data over the lake area and inflows from the five-rivers.

It is a common practice to investigate the hydrodynamic behavior of rivers and lakes by well-developed hydrodynamic model/software (Yin, Yu, Yin, et al., 2013; Yin, Yu, Yin, Wang, & Xu, 2013) Li et al., 2015). Until now, MIKE 21 (Li et al., 2015), artificial neural networks (Li et al., 2015), MIKE 3 (Li et al., 2018), and EFDC (Chen et al., 2019) have been used to investigate the hydrodynamic behavior of Poyang Lake outflow. Due to greater computational ability and more flexible settings in 1D- and 2D-model coupling of the InfoWorks ICM, this study developed a 1D- and 2D-coupled hydrodynamic model of a reach of the Yangtze River, Poyang Lake, and the five-rivers flowing into the lake, utilizing the most up to date high-resolution geospatial data, meteorological, hydrological, and hydraulic data available. This was used to investigate (1) the outflow and water level envelop of Poyang Lake in the context of current bathymetric/terrain conditions under extreme hydrological condition scenarios from the five-rivers inflowing to the lake, Yangtze River discharge, and rainfall over the lake surface; (2) the influence that lake rainfall has on the pattern of lake outflow and water level; and (3) re-examine the contributions of the Yangtze River, the five-rivers inflowing, and lake rainfall to the outflow and water level under changing environmental conditions. There are four key advantages of the coupled flooding simulation approach used within the current study: (1) It considered the impact of lake rainfall on the outflow regime by setting the rainfall boundary conditions in the model; (2) It developed a novel calibration method of the roughness coefficient for large lakes or rivers with complicated bathymetric terrain during both wet and dry seasons; (3) It identifies a new way of setting initial conditions for hydrodynamic simulation for different scenarios for large water bodies subject to strong hydrological regulation; (4) High-resolution modeling of river channel and lake conditions were carried out using high-precision model simulations with high computational efficiency.

2 | POYANG LAKE STUDY SITE AND DATA PROCESSING

2.1 | Poyang Lake study site

Poyang Lake, located between 115°49′E and 116°46′E, 28°24′N and 29°46′N, is situated on the southern bank of the middle reaches of the Yangtze River, with a drainage area of 162,225 km^2. The lake receives inflow from five-rivers and then drains north into the Yangtze River at Hukou (Figure 1). Located in the warm, humid subtropical zone, the region is subject to seasonal monsoons, resulting in a mean annual temperature of 16.5–17.8°C and precipitation of 1400–1700 mm. The complex inflows from the five-rivers, the outflow from the lake and backflow from the Yangtze River (discharge from the Yangtze being forced into Poyang Lake) frequently leads to dynamic seasonal water-level fluctuations, such that the historical water surface area of the lake ranges from about 4553 km^2 to 244 km^2 (Tan et al., 2013). Between 2019 and 2020, however, water levels varied from being almost completely dry to the highest on record (Figure 2).

2.2 | Data processing

Based on the long-term historical daily discharge series from the five-rivers inflowing to the lake and the Yangtze River discharge series from 1949 to 2018 from the Hydrology Bureau of Jiangxi Province and the Changjiang Water Resources Commission, China, their typical monthly maximum/minimum inflow characteristics for the wet season and dry season are presented in Table 1. Based on 105 rainfall gauging stations around Poyang Lake, the monthly precipitation of Poyang Lake for the 1956–2018 period was

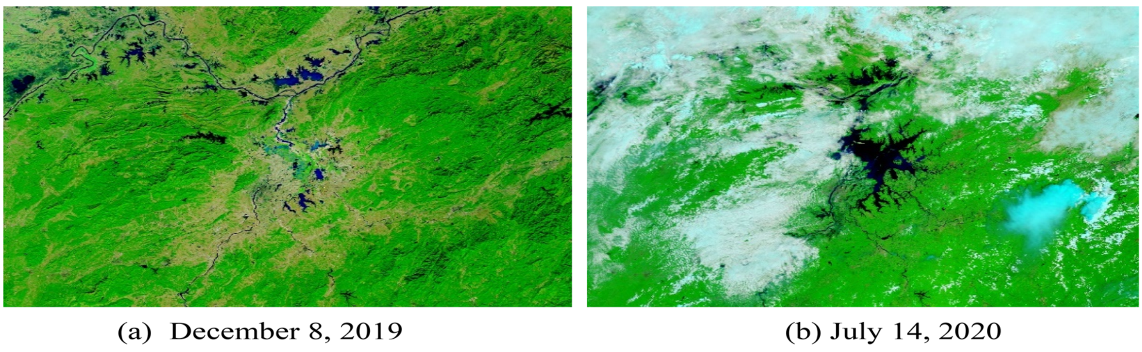

FIGURE 1 Water levels of Poyang Lake varied from being almost (a) completely dry to (b) the highest on record (https://earthobservatory.nasa.gov/images/146987/poyang-lake-extremes)

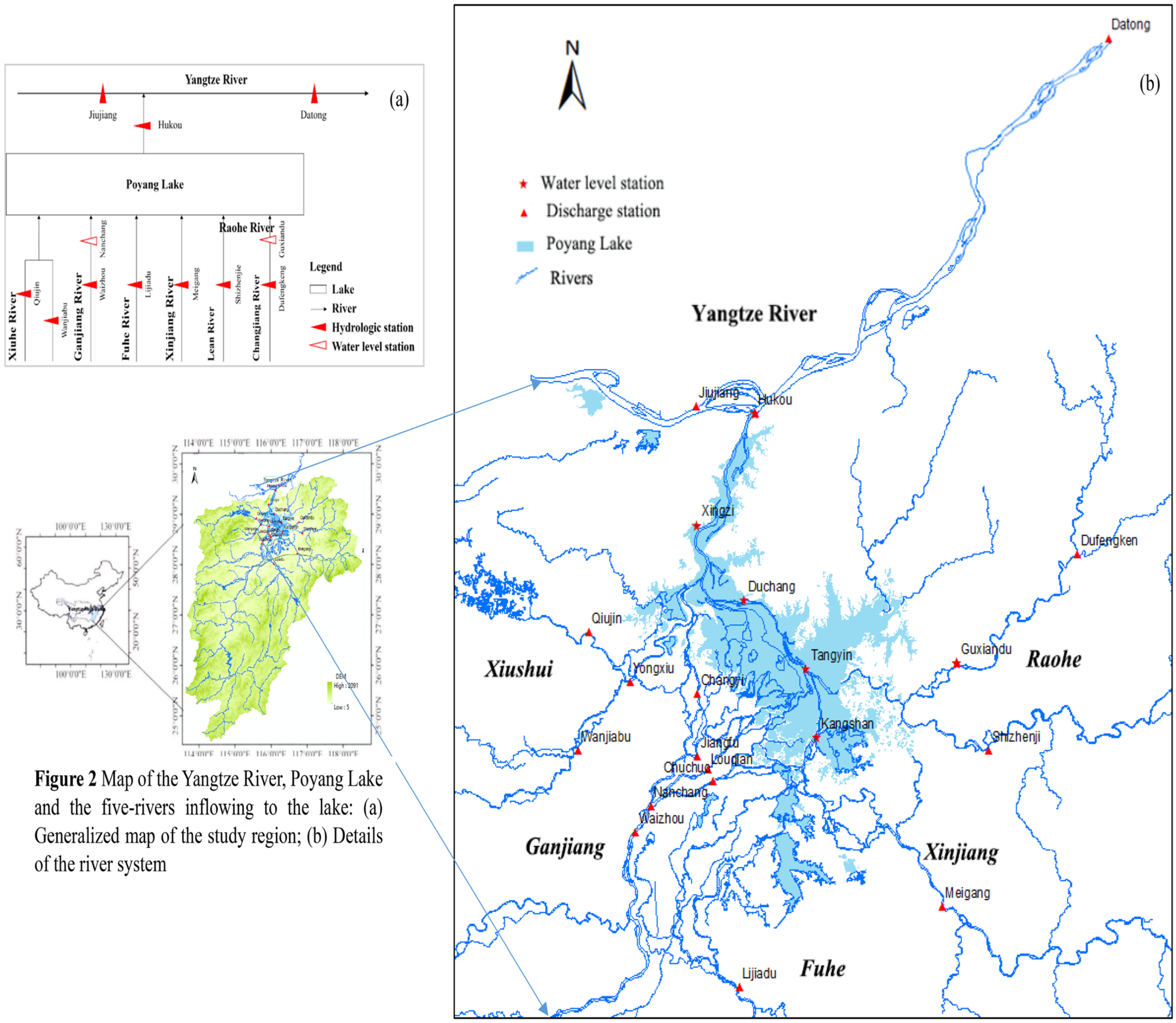

FIGURE 2 Map of the Yangtze River, Poyang Lake, and the five-rivers inflowing to the lake: (a) generalized map of the study region; (b) details of the river system

calculated following the Thiessen Polygons method. Based on these results, the maximum and minimum total monthly rainfall for Poyang Lake was recorded in June 1995 (635.5 mm) and in December 1987 (0 mm), respectively. Therefore, the daily rainfall values for the lake in June 1995 and December 1987 were selected as the lake rainfall input (Figure 2). The monthly discharge and precipitation conditions were selected from the month where the average (accumulated) monthly flow and precipitation were the highest or lowest, respectively. We chose the daily discharge and rainfall during the whole month because of the large volume of floodwater and the long flood duration of the Yangtze River. The monthly discharge and precipitation selected were for the historical extreme hydrological scenario setting. The resulting Poyang Lake DEM with a resolution of 10 m × 10 m for the dry season of 2012 is presented in Figure 3 (provided by the Water Resources Department of Jiangxi Province). Data from 545 river cross-sections along the five-rivers and 177 cross-sections on the Yangtze River (from Jiujiang to Datong) were used based on data from the Changjiang Water Resources Commission, China. It is worth noting that all the water level data used in this research are based on the Yellow Sea Elevation. The river cross-section data and the lake DEM data were provided for the 1D river model and 2D lake model construction.

3 | INTEGRATED HYDRODYNAMIC MODEL DEVELOPMENT

The InfoWorks ICM 6.0.7 was used to develop the Integrated hydrodynamic model in the study (Figure 4).

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TABLE 1 Typical wet season and dry season maximum and minimum discharge conditions (average monthly flow) for the five main rivers inflowing to Poyang Lake and discharge for the Yangtze River over the 1949–2018 period

		Wet season				Dry season	
River	**Station**	**Max.**	**AMF**	**Min.**	**AMF**	**Min.**	**AMF**
Five-river							
Gan River	Waizhou	Jun-62	8537	Sep-56	340	Dec-56	254
Fu River	Lijiadu	Jun-98	2926	Sep-63	27	Jan-65	39
Xin River	Meigang	Jun-98	5161	Sep-67	49	Dec-78	30
Rao River	Shizhenjie	Jun-95	2573	Jul-58	5	Oct-67	11
	Dufengkeng	Jul-98	1000	Sep-78	3	Jan-65	5
Xiu River	Qiujin	Jun-95	1624	Sep-66	27	Nov-68	54
	Wanjiabu	Jun-98	653	Sep-66	9	Jan-65	11
Yangtze River	Jiujiang	Aug-98	69,448	7-Apr	12,140	Mar-99	6261

Note: AMF represents the Averaged Monthly Flow, m^3/s.

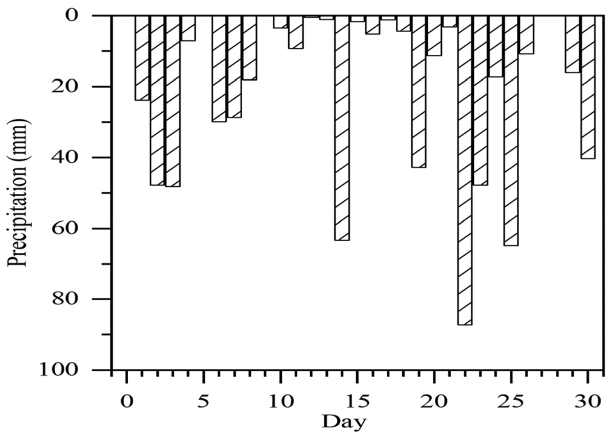

FIGURE 3 Typical monthly rainfall (June 1995, mm) pattern for Poyang Lake

There are four advantages of using the coupled model: (1) It allows fine resolution model construction and simulation due to the excellent computation performance of InfoWorks ICM and abundant river cross-section data and terrain data; (2) A newly developed partition calibration method for the lake roughness coefficient is proposed; (3) It identifies a new way of setting initial conditions for hydrodynamic simulation for different scenarios for large water bodies subject to strong hydrological regulation (Figure 5); (4) Lake rainfall is directly accounted for in the coupled 1D and 2D model.

3.1 | Coupled 1D and 2D hydrodynamic model

The Saint Venant Equations were adopted to build the 1D hydrodynamic model for the Yangtze River (from Jiujiang to Datong) and the five-rivers inflowing (Figure 6). A total of 349 river cross-sections on the Gaijiang, 37 on the Fuhe, 59 on the Xinjiang, 79 on the Raohe, 21 on the Xiushui, and 177 Yangtze River reaches were used. The total river length considered was approximately 650 km. The governing equations were as follows:

$$B\frac{\partial Z}{\partial t}+\frac{\partial Q}{\partial x}=q \quad (1)$$

$$\frac{\partial Q}{\partial t}+\frac{\partial}{\partial x}\left(\alpha\frac{Q^2}{A}\right)+gA\frac{\partial Z}{\partial x}+g\frac{|Q|Q}{c^2AR}=qV_x \quad (2)$$

$$c=\frac{1}{n}R^{1/6} \quad (3)$$

where x is space coordinate, m ; t is time, s ; Q is discharge, m^3/s ; Z is stage above datum, m ; A is flow area, m^2 ; R is hydraulic or resistance radius, m ; q is lateral inflow, $m^3/s/m$; c is the chezy resistance coefficient ; n is roughness coefficient; g is gravitational acceleration, m^2/s ; α is the momentum distribution coefficient. It should be noted that there is no source used in the model of the study, that is, q equals 0.

An unstructured triangular mesh was selected to build the 2D hydrodynamic model of Poyang Lake, with an area of approximately 4250 km^2. To better reflect the real lake terrain conditions, variable resolution was adopted for the mesh construction, particularly for the confluence region between rivers and the Lake (Figure 7). In total, 181,099 cells were produced for Poyang Lake, with the grid size ranging from 205 m^2 to 10^5 m^2. The Conservative shallow water wave equations were used as the governing equations for two-

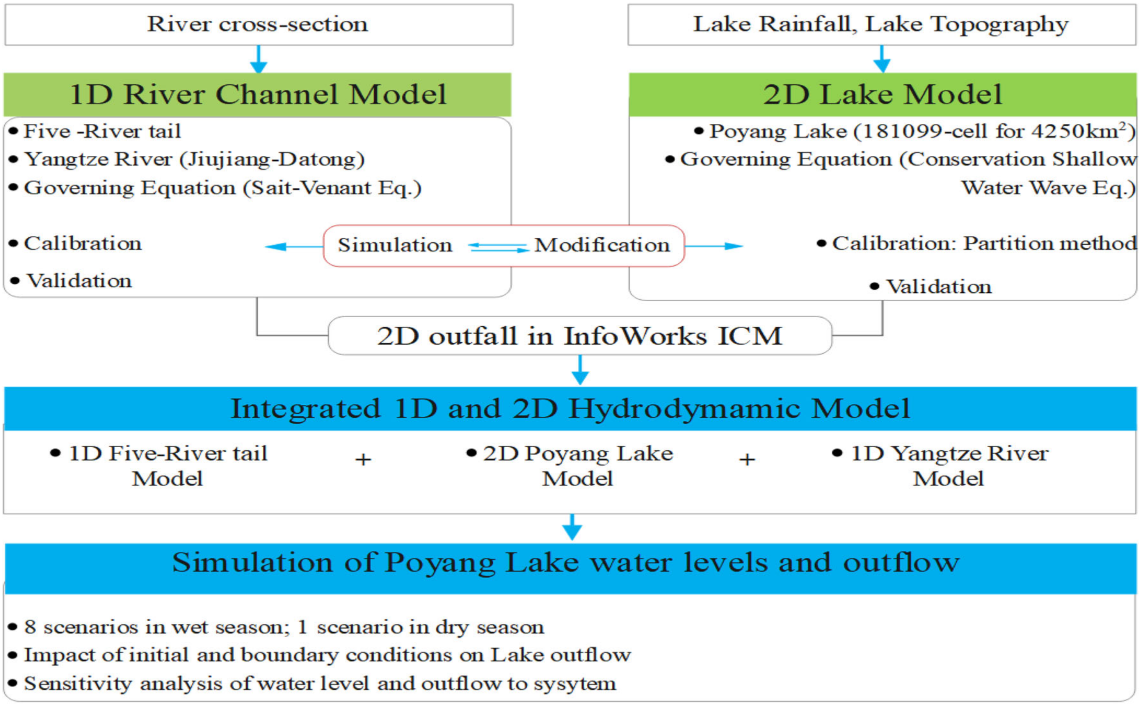

FIGURE 4 Flow chart of the methodology

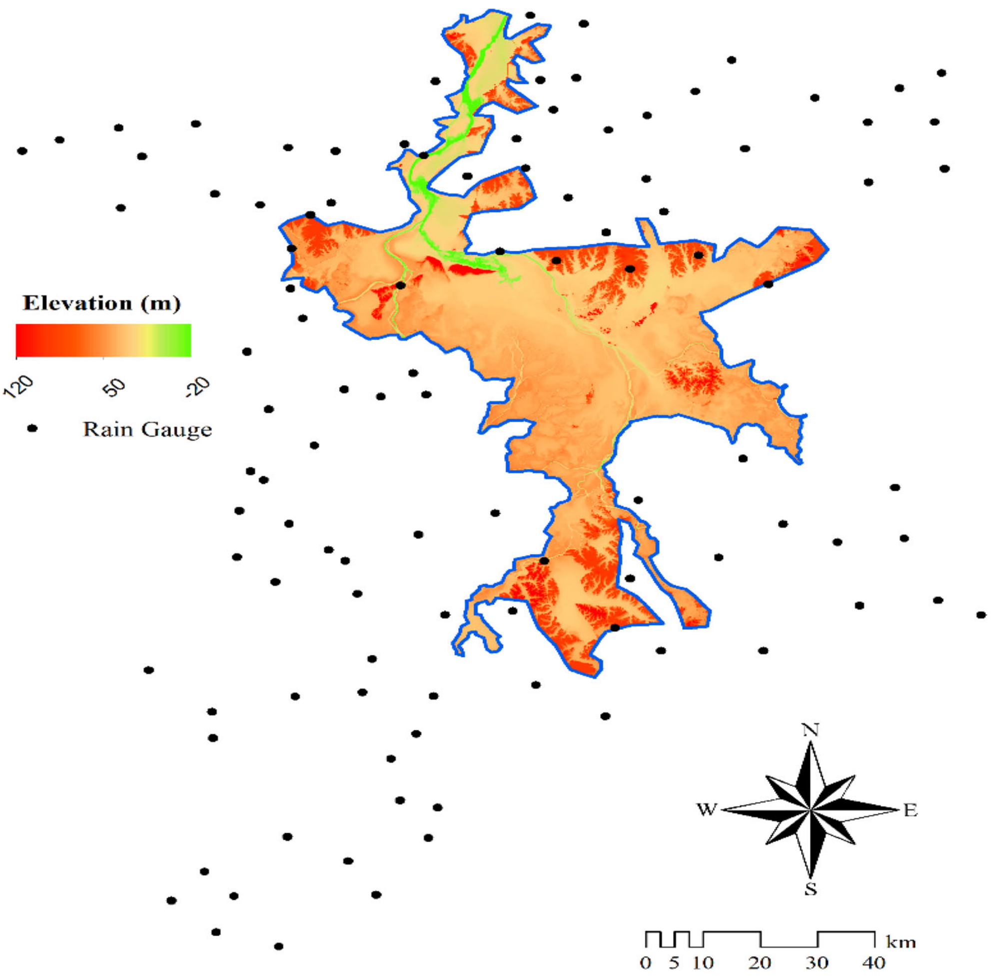

FIGURE 5 Digital elevation model (DEM) of Poyang Lake for dry season conditions during 2012—all elevations are presented in meters)

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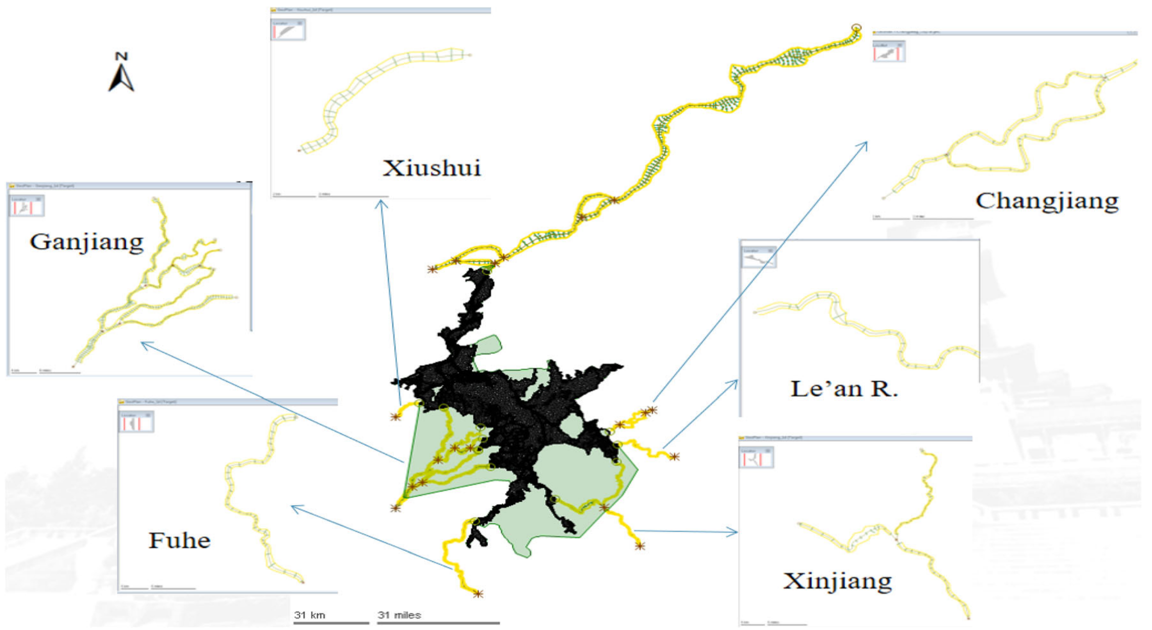

FIGURE 6 Integrated 1D and 2D hydrodynamic model in the study and distribution of the river cross-sections

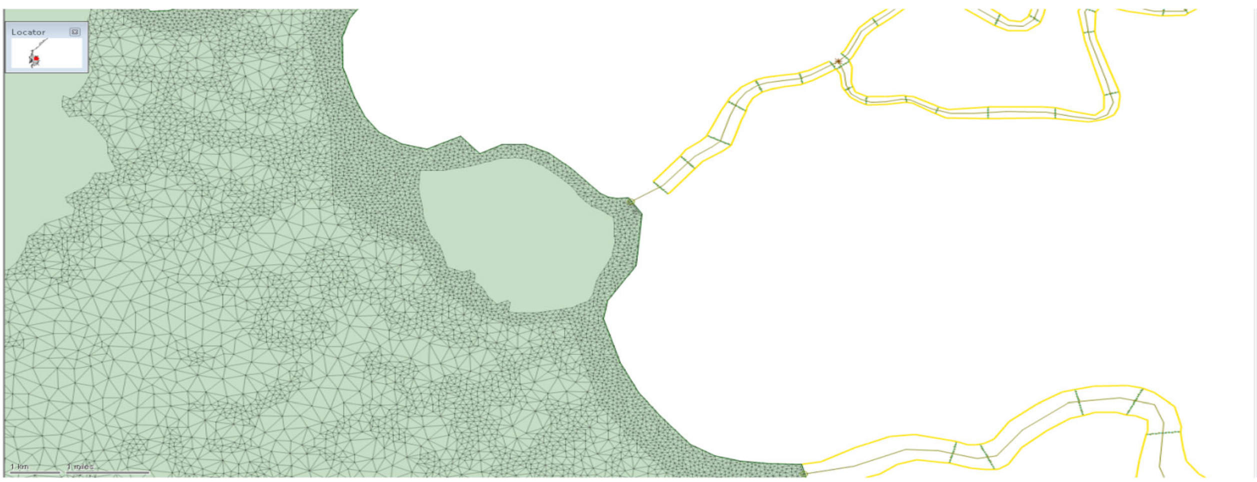

FIGURE 7 Mesh splitting effect of Poyang Lake: Construction of irregularities near the Lake shore

dimensional lake movement. The governing equations are as follows (Alcrudo and Mulet-Marti (2005)):

$$\frac{\partial h}{\partial t}+\frac{\partial (hu)}{\partial x}+\frac{\partial (hv)}{\partial y}=\sum_{i=1}^{m} q_i \tag{4}$$

$$\frac{\partial (hu)}{\partial t}+\frac{\partial}{\partial x}\left(hu^2+\frac{gh^2}{2}\right)+\frac{\partial (huv)}{\partial y}-\frac{\partial}{\partial x}\left(\varepsilon h\frac{\partial u}{\partial x}\right)-\frac{\partial}{\partial y}\left(\varepsilon h\frac{\partial u}{\partial y}\right)=gh\left(S_{0,x}-S_{f,x}\right)+\sum_{i=1}^{m} q_i u_i \tag{5}$$

$$\frac{\partial (hv)}{\partial t}+\frac{\partial}{\partial y}\left(hv^2+\frac{gh^2}{2}\right)+\frac{\partial (huv)}{\partial x}-\frac{\partial}{\partial x}\left(\varepsilon h\frac{\partial v}{\partial x}\right)-\frac{\partial}{\partial y}\left(\varepsilon h\frac{\partial v}{\partial y}\right)=gh\left(S_{0,y}-S_{f,y}\right)+\sum_{i=1}^{m} q_i v_i \tag{6}$$

where h is the water depth (m), u and v are the velocities (m/s) in the x and y directions, respectively, q_i is the i^{th} net source discharge per area (m/s), u_i and v_i are the velocities (m/s) in the x and y directions of the i^{th} net source discharge, respectively; g is gravity acceleration (m^2/s); ε is eddy viscosity (m^2/s), $S_{0,x}$ and $S_{0,y}$ are the bed slopes in the x and y directions, respectively; $S_{f,x}$ and $S_{f,y}$ are the friction slopes in the x and y directions, respectively; m is the number of source discharges. It should be noted that there is no source used in the model of the study, that is, q_i eqauls 0.

The integrated 1D and 2D hydrodynamic model of the five-rivers–Poyang Lake–Yangtze River was developed by coupling the 1D river model of the five rivers inflow, the 2D lake model of Poyang Lake, and the 1D river model of the Yangtze River. The connection between the 1D and 2D models is achieved using a 2D Outfall, a type of node defined in InfoWorks ICM. During simulation, the 2D Outfall node would be viewed as a series of break node, vortex control with nominal head-discharge relationship and outfall node to exchange the flow between a 1D river and a 2D zone. It should be noted that to guarantee the flow capacity, the 2D element to be connected should have a similar length to the last section of the river, since the 2D outfall discharges to the 2D-mesh element where it resides; therefore, a multipolygon element was developed to assure the successful model coupling (Figure 8). The obtained water level-discharge process for the 2D outfall is regarded as the inflow boundary condition for the 2D mesh. There was a total of 13 locations for the integrated model coupling processing. The amplification of the1D and 2D hydrodynamic model connection between the western tributary of the Ganjiang and the lake is shown in Figure 8.

3.2 | Model calibration and validation

3.2.1 | 1D hydrodynamic model

The roughness coefficient was the most critical and sensitive parameter for the 1D hydrodynamic model. Model calibration and validation was carried out for the Ganjiang River and the Yangtze River (from Jiujiang to Datong) since they have observed data within the study reaches. The initial roughness coefficient was set according to the detailed description information for every river section. Parameters for rivers without observed data were obtained from the hydrodynamic calculation manual (Li, 2006).

Model calibration

The observed water levels at Changyi, Louqian, and Chuchuo stations between June 17, 2010 and August 31, 2010 were selected for the 1D river channel model calibration of the Ganjiang River tail, while the observed water level at Hukou in 2012 was selected for the 1D river model calibration of the Jiujiang-Datong reach of the Yangtze River. The model simulation–modification process was repeated until the simulated water level process was very close to the observed data. It showed that the simulated water level process at the Changyi, Louqian, Chuchuo, and Hukou stations were highly consistent with the observed data, including for the value and timing of the highest flood water level. Therefore, the river roughness coefficient of the Ganjiang River tail was finally set within 0.018–0.05, with the average being

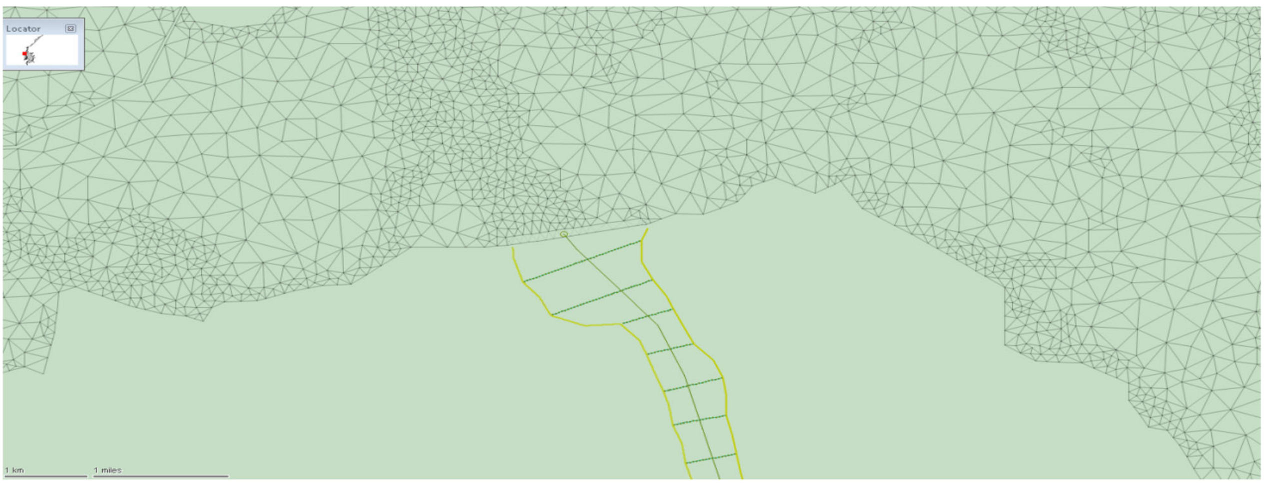

FIGURE 8 Detailed close up of the connection between the 1D and 2D hydrodynamic model: Western tributary of the Ganjiang River and Poyang Lake

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of 0.032, while that of the Jiujiang-Datong reach was set within 0.012–0.03, with the average of 0.021.

Model validation

The observed water levels at Changyi, Louqian and, Chuchuo stations between June 22, 1998 and August 31, 1998 were selected for the 1D river channel model validation of the Ganjiang River tail, while the observed water level at Hukou in 2013 was selected for the 1D river model validation of the Jiujiang-Datong reach of the Yangtze River. It can be seen that the calculated water level process at Changyi, Louqian, Chuchuo, and Hukou stations was highly consistent with the observed data including the value and timing of the highest flood water level (Figure 9a for the validation at Hukou), with the maximum absolute error (MAE) of water level being 0.085, 0.198, 0.172, and 0.120 m, respectively. This demonstrates that the 1D hydrodynamic river model developed performed well in capturing the flood process, extreme values and its timing, the output of which could be used as the input to the 2D Poyang Lake model.

3.2.2 | 2D hydrodynamic model

The roughness coefficient of the Poyang Lake area was the most important parameter for the 2D hydrodynamic model. Based on the changing pattern of bathymetry, the whole Poyang Lake area was divided into 136 roughness zones to reflect the complicated change in the lake underwater/bathymetric terrain friction, and different roughness coefficients were determined for each zone.

Model calibration

The observed water levels at Xingzi, Duchang, Tangyin, and Kangshan stations during May 10, 2012 to October 5, 2012 were selected for the 2D Lake model calibration. The model simulation-modification process was repeated until the simulated water level process was very close to the observed data. It showed that the simulated water level at Xingzi, Duchang, Tangyin, and Kangshan stations were highly consistent with the observed data including the value and timing of the highest flood water level. Therefore, the river roughness coefficient of the 2D Lake hydrodynamic model was set within 0.01–0.02, with the average being of 0.015.

Model validation

The observed water level at Hukou in 2013 was selected for the 1D river model validation of the 2D Lake model. It can be observed that the calculated water level process at Xingzi, Duchang, Tangyin, and Kangshan stations were consistent with the observed data as well as the value and timing of the highest flood water level (see Figure 9b–d for the validation at Xingzi, Duchang Tangyin and Kangshan), with a MAE of water level being 0.03, 0.05, 0.12, and 0.32 m, respectively. With the

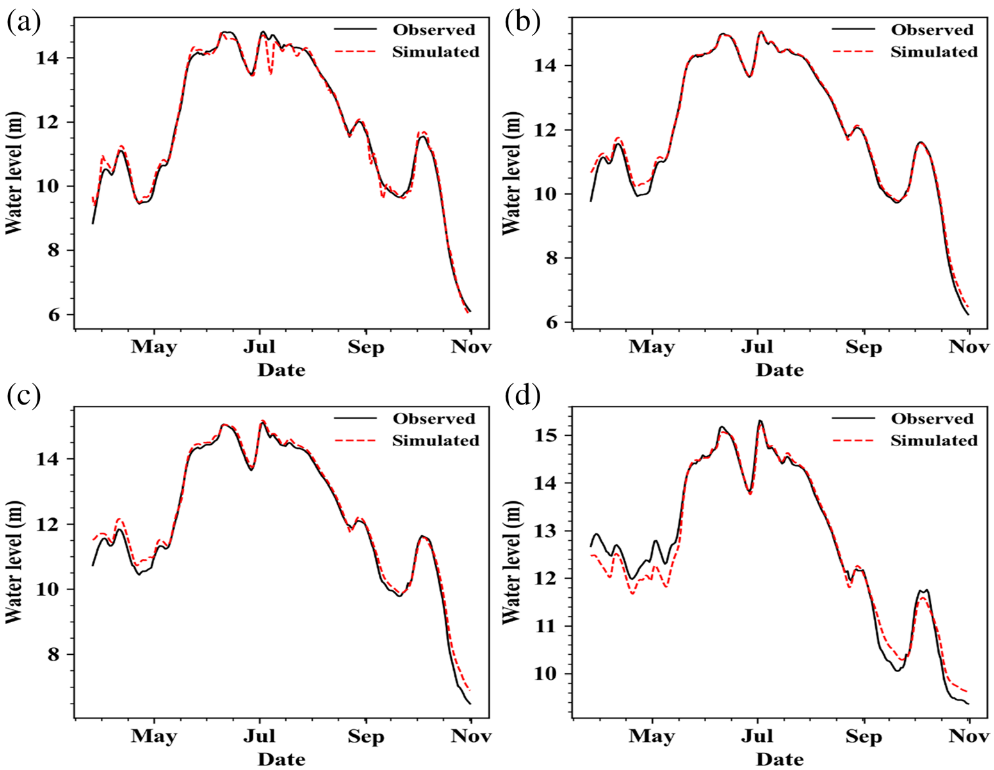

FIGURE 9 Comparison of simulated water level and observed water level (m): (a) Hukou, (b) Xingzi, (c) Duchang, and (d) Tangyin

exception of Kangshan, the MAE of water level was less than 0.2 m.

The coupled 1D and 2D hydrodynamic model was able to capture the hydrological variability of the Yangtze River, the five-rivers, and water levels of Poyang Lake satisfactorily and were in general agreement with the observed data; thus, it is suitable for use in further hydrodynamic scenario simulations.

3.3 | Scenario settings, boundary conditions, and initial condition

3.3.1 | Combination scenario settings

The outflow process of Poyang Lake was affected by the five-river inflows, lake rainfall, and the Yangtze River discharge simultaneously. With the aim of characterizing the upper and the lower hydrological envelop of the Poyang Lake outflow under current bathymetric terrain conditions, the typical historical hydrological conditions of the five-rivers inflows, Poyang lake, and the Yangtze River (including the maximum and the minimum flood and rainfall during wet season, and the minimum flood in dry season) were selected to construct different extreme combination scenarios. It should be noted that the daily discharge and rainfall during the whole month was selected because of the large volume of floodwater and the long flood duration of the Yangtze River, particularly during the wet season. Therefore, nine scenario combinations were considered in total, that is, one maximum and one minimum hydrological process for each subject (the Yangtze River discharge, the five-rivers inflow, and the lake rainfall), respectively ($2 \times 2 \times 2 = 8$ in wet season; 1 in dry season) were set for the outflow simulations of Poyang Lake (Table 2).

The scenarios were selected to capture the variability between the wet season (scenarios 1–8) and the dry season (scenario 9); maximum discharge of the five-rivers inflowing into Poyang Lake under wet/flood conditions (scenarios 1–4); minimum discharge of the five-rivers inflowing into Poyang Lake under wet/flood conditions (scenarios 5–8); maximum precipitation over the lake surface under wet/flood conditions (scenarios 3, 4, 7, and 8); no precipitation over the lake surface under wet/flood conditions (scenarios 1, 2, 5, and 6); maximum discharge from the Yangtze River under wet/flood conditions (scenarios 1, 3, 5, and 7); minimum discharge from the Yangtze River under wet/flood conditions (scenarios 2, 4, 6, and 8), and dry season minimum discharge of the five-rivers inflowing in to Poyang Lake, no precipitation over the lake and minimum discharge from the Yangtze River (scenario 9) Table 2 for further details. Outflow and water levels modeled in scenarios 1–5 provide essential reference conditions for flood control and flood water resource management, while those modeled in scenarios 6–9 will provide vital baseline information to inform drought management, drought mitigation, and water resources allocation under drought conditions for the Poyang Lake basin.

Up to now, research has focused on the floods experienced by the Yangtze River and Poyang Lake Basin (Bing et al., 2018; Li et al., 2014; Wu et al., 2019). This research has demonstrated that the floods within the Yangtze

TABLE 2 Different boundary conditions used for the nine different scenarios considered in this study

Scenario	Seasons	Inflow of the five-river (m^3/s)	Lake rainfall (mm)	Yangtze River discharge (flow from the lake to river) (m^3/s)
S1	Wet season	$Q^{wet}_{5r,max}$	/	$Q^{wet}_{y,max}$
S2		$Q^{wet}_{5r,max}$	/	$Q^{wet}_{y,min}$
S3		$Q^{wet}_{5r,max}$	P_{max}	$Q^{wet}_{y,max}$
S4		$Q^{wet}_{5r,max}$	P_{max}	$Q^{wet}_{y,min}$
S5		$Q^{wet}_{5r,min}$	/	$Q^{wet}_{y,max}$
S6		$Q^{wet}_{5r,min}$	/	$Q^{wet}_{y,min}$
S7		$Q^{wet}_{5r,min}$	P_{max}	$Q^{wet}_{y,max}$
S8		$Q^{wet}_{5r,min}$	P_{max}	$Q^{wet}_{y,min}$
S9	Dry season	$Q^{dry}_{5r,min}$	/	$Q^{dry}_{y,min}$

Note: $Q^{wet}_{5r,max}$, $Q^{wet}_{5r,min}$ are maximum and minimum observed discharge of the five inflowing rivers, respectively; P_{max} is for the maximum observed rainfall over the Poyang Lake area; / indicated no rain; $Q^{wet}_{y,max}$, $Q^{wet}_{y,min}$ are maximum and minimum observed discharge processes for the Yangtze River at Jiujiang station; $Q^{dry}_{5r,min}$, $Q^{dry}_{y,min}$ are for the minimum observed discharge of the five major inflowing rivers and the Yangtze River during the dry season, respectively.

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River basin are to some degree independent of those of Poyang Lake Basin. This reflects the fact that the main flood season of Poyang Lake basin is May–August while the dominant flood season on the middle Yangtze River is June–September. Previous published studies have focused on the probability of maximum floods from these two regions separately and considering smaller/minimum flood events (or the variability minimum to minimum/maximum). Therefore, it is hard to compare the probability of occurrence of the different historical extreme hydrological scenarios considered in this study because of the absence of a systematic investigation into the floods that consider both basins together. In addition, due to the size of the basins, Poyang Lake basin and the middle Yangtze River Basin can be regarded as two independent climatic regions. Thus, the different extreme scenarios used in the study should be considered as a simulation of the upper and the lower hydrological envelop of Poyang Lake outflow.

3.3.2 | Boundary conditions and initial condition

Upstream boundary

The upper river gauging station represent the river flow/discharge process boundaries, that is, the discharge at Jiujiang station on the Yangtze River, flow at Waizhou on the Ganjiang, Lijiadu on the Fuhe, Meigang on the Xinjiang, Shizhenjie on the Lean, Dufengkeng on the Cangjiang, and Qiujin and Wanjiabu on the Xiuhe (Figure 10a–c).

Downstream boundary

The 90% and 10% water level during the wet season at Datong were selected as the lower boundaries for the coupled model for the wet season scenarios. Similarly, the 10% water level during the dry season at Datong was selected for the lower boundary scenario. It should be noted that these three water levels corresponded to those at Jiujiang since the effects of the hydrological conditions at Jiujiang exert a stronger effect on Datong than that of Poyang Lake (Figure 10d).

Rainfall boundary

The rainfall boundary conditions of the lake comprised the maximum total monthly rainfall and no rainfall for both the wet and dry season. The maximum rainfall conditions during the wet season are presented in Figure 2.

Initial condition

The discharge and water level conditions of the Yangtze River, the five rivers inflow, and the Poyang Lake water level on May 10, 2012 were used as the initial conditions

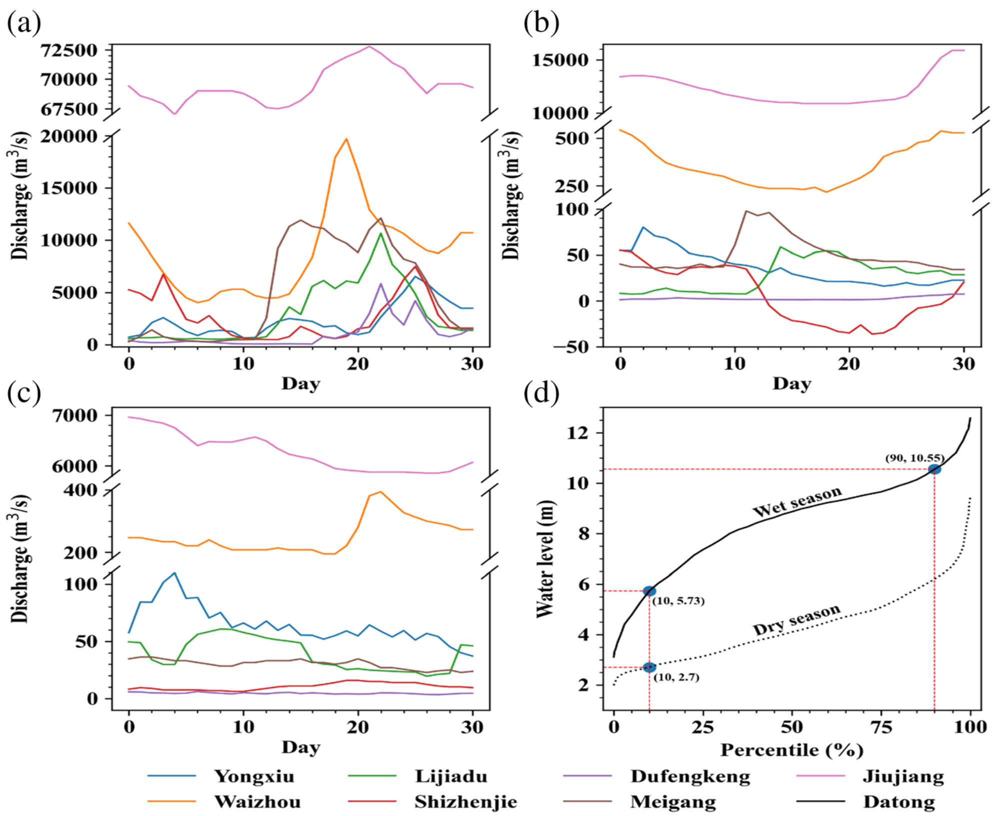

FIGURE 10 Boundary conditions of the 1D- and 2D-coupled hydrodynamic model: (a) maximum flow process in wet season (m^3/s), (b) minimum flow process in wet season (m^3/s), (c) minimum flow process in dry season (m^3/s), and (d) lower boundary condition at Datong (m)

for the integrated model. This hydrological condition corresponded to the 50% discharge and water level conditions of Poyang Lake. The hydrodynamic status after 5 days of adaptive simulation of the model was selected as the "real" initial conditions for the different scenarios.

4 | RESULTS

The outflow discharge and water level conditions of Poyang Lake under the nine scenarios considered are presented in Figures 11 and 12.

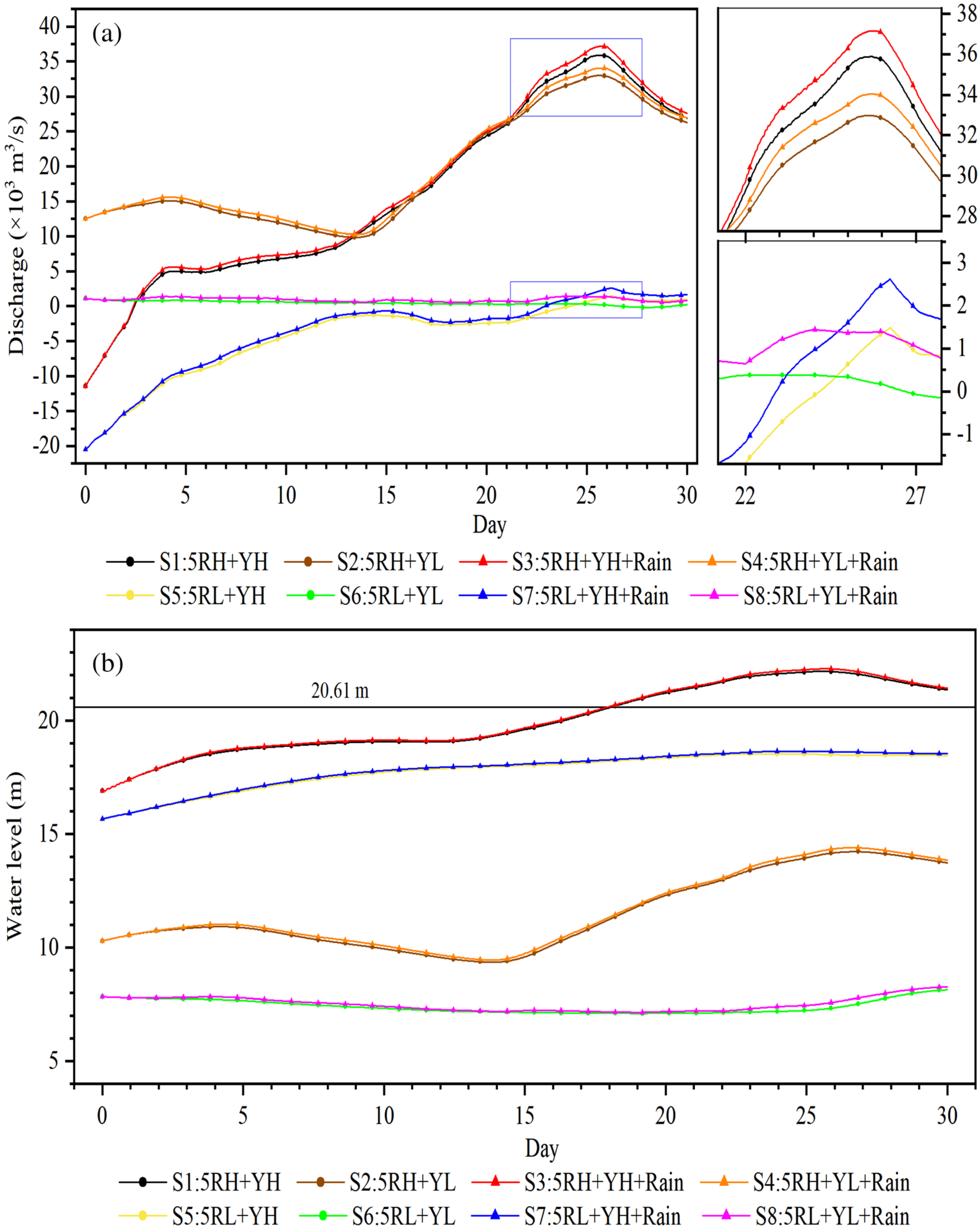

FIGURE 11 Outflow conditions of the Lake under different scenarios during wet season: (a) flow discharge (10^3 m^3/s), (b) water level. 5RH and 5RL are for the maximum and minimum discharge conditions of the fiver major inflowing rivers, respectively; YH and YL represent the maximum and minimum discharge conditions of the Yangtze River, respectively; precipitation represents the maximum areal rainfall for the Lake catchment

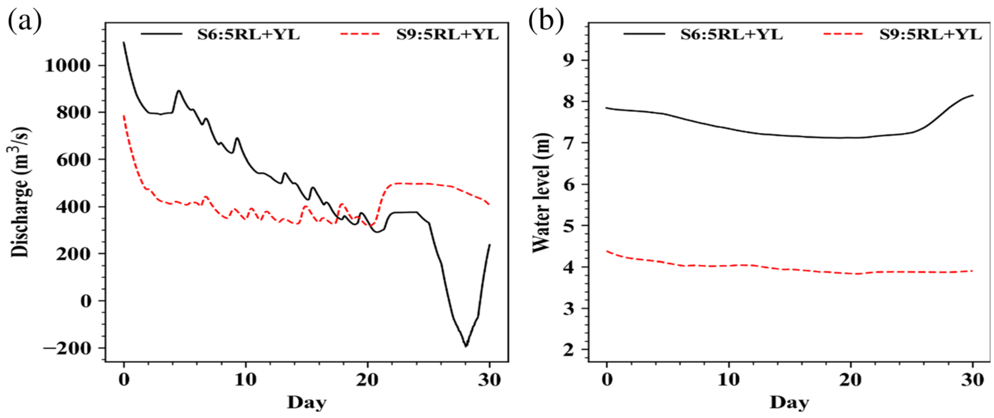

FIGURE 12 Comparison of conditions for the driest scenarios for the wet season and dry season: (a) discharge (m^3/s), (b) water level (m)

4.1 | Outflow discharge

Examination of S1 versus S2 and S3 versus S4 indicated that the outflow from Poyang Lake for S1 and S3 was significantly lower than that of S2 and S4 before the 14th day. This is because of the rising discharge of the Yangtze River held back and blocked the lake outflow during S1 and S3 simulations. Due to the initial holding back of water in the lake from the increasing inflow from tributaries upstream and the effect of the Yangtze River, the outflow increased quickly. The discharge hydrographs for S1 and S3 were obviously higher than those of S2 and S4 from day 22 onwards, with the maximum peak flow recorded for S3. Water from the lake can discharge freely when the discharge of the Yangtze is relatively low. However, lake outflow is inhibited or is forced to flow back into lake when the water level is high in the Yangtze River. The results indicated that the blocking effect of the Yangtze River intensifies when discharge in both the five-rivers inflowing and the Yangtze River are high (flood levels). The level of the Yangtze River significantly influences the pattern of lake outflow, and the effect diminishes when lake levels are elevated due to the discharge of water from the inflowing rivers within the catchment of the lake (Hu et al., 2007).

Comparing S1 versus S5 and S3 versus S7 – discharge from the Yangtze River into Poyang Lake occurred up to the second day in all scenarios. Subsequently, it became positive (flowing from Poyang Lake into the five rivers) and increased to maximum peak discharge in S1 and S3. In contrast, during S5 and S7 discharge remained negative, with water moving from the Yangtze River into Poyang Lake most of the time. The results demonstrate that when the discharge of the Yangtze River is high, the discharge from the five-rivers is also typically high, this potentially exacerbates the flood risk in the region.

Comparing S5 versus S6 and S7 versus S8—the outflow during S5 and S7 was generally negative while during S6 and S8 it was typically positive but characterized by low discharge. The results demonstrate that when low inflow from the five-rivers meets floodwaters from the Yangtze River, the lake acts like a detention pond and is characterize by discharge from the Yangtze back into Poyang Lake.

The patterns of outflow during S1 and S3 were generally similar. The outflow from Poyang Lake during S1, S2, S5, and S6 was generally lower than that during S3, S4, S7, and S8, respectively. The results indicated that rainfall within the lake catchment had a limited effect on the pattern of outflow, even though it does increase the outflow over time.

4.2 | Lake water level

Poyang Lake water level during S1, S3, S5, and S7 was markedly higher than that during S2, S4, S6, and S8, respectively. The results demonstrate that when the Poyang watershed is under stable water level conditions, the larger the discharge from the Yangtze River, the higher the water level at Hukou on the outflow from the lake. Similarly, comparisons, between S1 and S5; S2 and S6; S3 and S7; S4 and S8, indicate that when the Poyang Lake catchment and the Yangtze River experience similar hydrological conditions, the greater the inflow from the five-rivers, the higher the water level at Hukou station.

By directly comparing the water levels modeled during S1 and S3; S2 and S4; S5 and S7; S6 and S8, it can be observed that water level in each pair of scenarios displayed similar patterns, with the water levels during S1, S2, S5, and S6 being slightly lower than those during S3, S4, S7, and S8, respectively. This demonstrates that precipitation within the lake catchment area elevated water levels at Hukou but had a limited effect on the overall trend.

The water level during S1 and S3 exceeded the flood control level of 20.16 m from day 19 onward, reaching a peak level of 22.17 m and 22.28 m, respectively. The simulated maximum outflow peak occurred during S3 with a discharge of 37,200 m^3/s, significantly higher than the maximum observed peak flow of 31,900 m^3/s. This suggests that when the floodwaters from the Yangtze River encounter the floodwaters from Poyang Lake, extremely high water levels will be recorded at Hukou station. This significantly intensifies the flood control situation within the Poyang Lake region and demonstrates that increasing the hydrological stage of the Yangtze River is one of primary causes for the increasing severe flood frequency recorded (Shankman et al., 2009).

Since early June 2020, floods have severely impacted large tracts of southern China due to heavy rains during the regional rainy season (https://www.globaltimes.cn/content/1201803.shtml). In particular, flooding on the Yangtze River and its tributaries have been described as the worst since at least 1998 (Zhu et al., 2003; Zong & Chen, 2000). The Changjiang Water Resources Commission issued a red alert for floods in the Poyang Lake area on July 10, 2020, and a day later Jiangxi Province raised its flood-control response from level II to level I, the highest level of China's four-tier emergency response for floods. The water level and discharge at Hukou rose to 20.57 m (only 0.1 m lower than that of the 1998 flood) and 26,100 m^3/s, respectively (http://slt.jiangxi.gov.cn/col/col28224/index.html). The observed values were significantly lower than the simulated values of 22.28 m and 37,200 m^3/s in the current research. The recent flooding experienced clearly illustrates the rationale for the scenario simulations undertaken and emphasize the importance of modeling the Poyang Lake water levels and outflows over a range of different extreme hydrological conditions.

4.3 | Lake outflow regime contrasts between the wet and the dry season

S6 and S9 represent the driest scenarios during the wet and dry season, respectively. In general, the outflow discharge during these two scenarios were small, except for a few days of reversed flow from the Yangtze River during S6. The outflow for the driest scenarios for both the wet and dry season were very similar. However, a substantial blocking effect from the Yangtze River occurred during the wet season driest scenario (scenario 6). In contrast, no obvious effects of the Yangtze River were recorded for the driest scenario during the dry season. Similar conclusions and patterns were found for water level models. The water level during S6 was surprisingly higher than that recorded during S9. These results indicate that the water levels during the wet season were significantly elevated by the Yangtze River while this effect was not as pronounced during the dry season.

5 | DISCUSSION

5.1 | Hydrodynamic model simulation of high precision and computational efficiency

How well a hydrodynamic model reflects the real river channel or lake terrain which it simulates has a major control on the final model performance (Twigt et al., 2009). To achieve the best model performance and simulation accuracy, a large volume of the most up to date river cross-section data were used in the 1D river channel model development (i.e., 21 river reaches for 409 km river length were created for the five-rivers inflowing by using 545 river cross-sections, and 177 river cross-section for the Jiujiang-Datong reach with the length of 105 km). In addition, based the high-resolution bathymetric data for Poyang Lake, 181,099 fine meshes were established for the 2D lake model by controlling the elevation difference between two neighboring meshes, compared to a previous study where only 1000–20,000 were used for the whole Poyang Lake (Li et al., 2017). Fine mesh setting for the Poyang Lake is necessary because: (1) its characteristics change dramatically from more "lake" like in the wet season to more "river" like in the dry season; (2) it captured the lake surface water slope precisely during the wet season; (3) it improved the simulation accuracy of the "river" phase for Poyang Lake during the dry seasons. It verified the feasibility of the InfoWorks ICM for high-resolution simulation of large-scale 1D- and 2D-coupled hydrodynamic modeling, which could be applied to other systems with complex hydrological and hydrodynamic conditions.

5.2 | A novel partition calibration method of roughness coefficient for all seasons

Sensitive parameter setting was of great importance for the model performance during hydrodynamic simulation (Jahandideh-Tehrani et al., 2020). How to calibrate the roughness coefficient for water bodies that change dramatically from lakes during the wet seasons to rivers during the dry seasons is challenging. The Poyang Lake area often has the characteristics of a "lake" during the wet season and "river" or even "canal" during the dry season. The roughness coefficient of the Poyang Lake area was the most important parameter for the 2D hydrodynamic model. Due to the large lake area and its complex bathymetric conditions, determining a reliable roughness coefficient for the lake terrain was challenging. We proposed and developed a partition calibration method to derive the roughness coefficient by dividing the lake area into 136 roughness zones based on the change of the lake terrain friction. This distributed partition method for deriving the roughness coefficient overcame the error caused by dramatic changes in water body characteristics during the wet and dry seasons and significantly improved the hydrodynamic simulation performance. This method could also be applied to areas where flood diversions or where floodwater storage areas exists, especially where there is a transition from flowing (riverine) to lentic (lake) at different points in time. The novel partition calibration method for the roughness coefficient can be easily understood and is simple to apply, which means it could be easily applied to other large lakes with complex bathymetry, or water bodies with transitions between riverine and lake conditions.

5.3 | Initial condition setting of designed scenarios for large highly regulated water bodies

The study proposed a new method for initial condition setting for scenarios for large-scale water bodies. The 50% and 90% water levels of Poyang Lake during the wet season were selected to simulate and compare the impact of the initial conditions on lake outflow processes (Figure 13). It can be clearly seen that during in the initial period (up to 5 days), this resulted in significant differences in discharge and water levels. However, over time, the discharge and water level curves overlapped. These results strongly suggest that the initial conditions exerted a strong influence on the Poyang Lake outflow processes at the beginning of the simulation period. However, it had almost no effect on the pattern of discharge variability and the peak flow recorded at the outflow, suggesting there are strong regulation influences of the Poyang Lake. In this study, the water condition on the fifth day of the simulation was selected as the initial conditions for different scenarios for Poyang Lake. Therefore, the outputs from the nine scenarios can be considered the most reliable and comprehensive developed thus far. The analysis undertaken also clearly indicated the necessity to consider the effect of initial conditions on lake outflow processes, particularly for highly regulated large water bodies.

For the boundary conditions, the historic extreme maximum and extreme minimum hydrological conditions of the Yangtze River, the five rivers inflowing, and lake catchment rainfall were used to construct different scenarios to simulate the outflow conditions from Poyang Lake. The results reflect the upper and lower hydrological envelop of the outflow as far as possible. However, the current research did not consider the probability of these scenarios occurring in the future or different combinations of the scenarios occurring simultaneously. Future research should consider the potential combined probability of extreme hydrological conditions occurring on the Yangtze River, the five rivers inflowing and precipitation over lake area simultaneously. For the lower boundary conditions, the 90%, 10% water level during the wet season and 10% during the dry season were utilized for the coupled 1D and 2D hydrodynamic model. These lower boundaries appear appropriate given that they reflect the extreme scenarios, although they require more detailed consideration in future research.

5.4 | Sensitivity analysis of the water level and outflow to the five rivers, Yangtze River, and lake rainfall

To investigate the relative importance of the five rivers inflowing to the lake, the Yangtze River, and lake rainfall

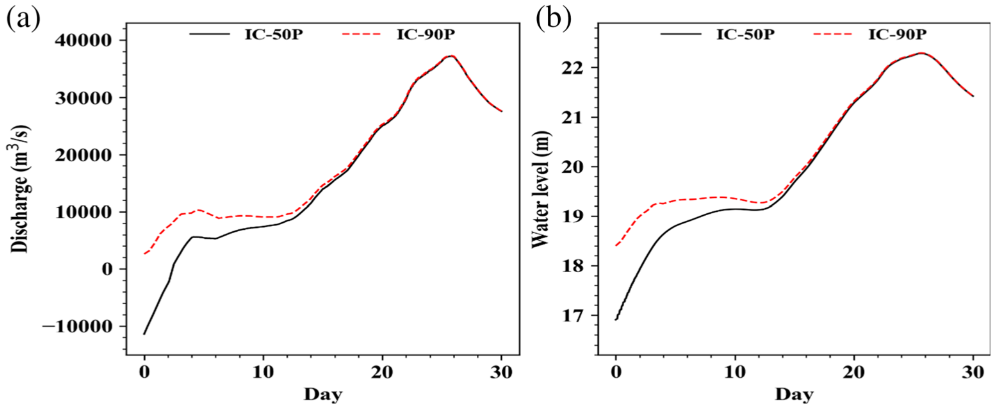

FIGURE 13 Impact of the initial conditions on the Lake outflow discharge: (a) flow discharge (m^3/s), (b) water level (m). IC-50P, IC-90P are for the 50, 90 percentile of the water level at Hukou, respectively

on the outflow regime, a structured, generalized sensitivity analysis of Poyang Lake water level and outflow to the five-rivers, the Yangtze River, and the lake rainfall was undertake using the Delta Moment-Independent Analysis method (Delta; Borgonovo, 2007; Plischke et al., 2013) and Fandom Balance Design-Fourier Amplitude Sensitivity Test (FBD-FAST; Saltelli et al., 1999; Herman & Usher, 2017) simultaneously (Table 3). Generally, the lake outflow discharge is more sensitive to the five-rivers inflowing than the Yangtze River discharge, whereas lake water level is more sensitive to the Yangtze River discharge than the five rivers inflowing; both the outflow discharge and water level display the lowest sensitivity to lake rainfall. This interesting contrast further supported the assumption that the five rivers inflowing play the most significant role in determining the outflow discharge given they represent the maximum input to Poyang Lake, while the Yangtze River discharge is the most important factor for the outflow water level because of the complex River–Lake interactions. The findings for water level are consistent with the study by Guo et al. (2012), Zhang et al. (2014), Dai et al. (2015), Li et al. (2015), but differ from Hu et al. (2007). It has been suggested that the bathymetry of Poyang Lake basin played a primary role influencing the water level and development of severe floods, while the Yangtze River played a complementary role by blocking outflows from the lake. The study by Hu et al. (2007) was undertaken at an annual scale and focused on the wet season with high rainfall and primarily used hydrological data prior to 2003, the year the Three Gorges Reservoir (TGR) commenced operation. It has been demonstrated that the river-bed downstream of the TGR on the Yangtze River has changed significantly since the TGR impoundment came into operation (Li et al., 2011; Yu et al., 2013). The Yangtze River discharge and water level has also been significantly modified by the TGR, and these changes have also affected the River–Poyang Lake interrelations (Guo et al., 2012). In contrast, our study is focused on hydrological events based on historical extremes from 1949 to 2018. This further illustrated the necessity of re-examining the contributions of the Yangtze River, the five-rivers inflowing, and lake rainfall to the outflow and water level under a changing environment as considered in this the study.

6 | SUMMARY AND CONCLUSIONS

This research developed an integrated 1D and 2D hydrodynamic model of the Yangtze River, the five-rivers inflowing, and Poyang Lake. The model developed, simulated, and analyzed the outflow of the Lake under nine different historical extreme scenarios. The results demonstrate:

1. The maximum outflow discharge of Poyang Lake and the highest water level at Hukou occurred when the inflow from the Yangtze River, the five-tributaries, and the lake rainfall reached maximum levels: 37,200 m^3/s and 22.28 m, respectively. The maximum reverse discharge from the Yangtze River (reverse flow from the river into the lake) occurred when the Yangtze River experienced maximum discharge and the inflowing tributaries and lake rainfall were at minimum levels: 20,500 m^3/s; the lowest water level recorded during the wet season occurred when all components were at a minimum level; the lowest water level recorded occurred during the driest scenario: 3.81 m.
2. The upper envelop of outflow was characterized by the two wettest scenarios. The lower envelop was characterized by two scenarios when the inflowing five rivers and lake rainfall were at a minimum level.
3. The extreme high outflow discharge and extreme high-water level occurred when the floodwaters of the Poyang Lake basin coincided with flooding on the Yangtze River.
4. Precipitation over the lake catchment increased the outflow discharge and water level but this had a very limited effect on the patterns of outflow discharge or water level.
5. The lake water level is the outcome of the complex interactions between the hydrology of the Yangtze River, the five-rivers inflowing to the lake, and lake rainfall, with the effects ranked in importance by Yangtze River > five-rivers inflowing >> lake rainfall effects on water level, while for the outflow discharge the ranked importance was the five-rivers inflowing >Yangtze River > lake rainfall.

It should be emphasized that although the results obtained seem relatively simple, it could not be achieved by simple logic reasoning since the outflow and water level of Poyang Lake is affected by hydrological effects both upstream and downstream, lake rainfall, as well at the terrain/bathymetric conditions of the Yangtze River and the lake. The complicated River–Lake interactions should be studied using all available monitoring data, that is, geospatial, meteorological, hydrological, and hydraulic data. Thus, numerical simulation provides an effective way to explore the Yangtze River–Poyang Lake–Five-rivers inflowing relationships.

This research highlights the potential value of InfoWorks ICM for modeling large rivers and large lake

TABLE 3 Sensitivity analysis of the water level and outflow to the five-river, Yangtze River, and lake rainfall

	Outflow discharge						Outflow water level					
	Delta			RBD-FAST			Delta			RBD-FAST		
Scenario	5-river	Yangtze	Rainfall	5-river	Yangtze	Rainfall	5-river	Yangtze	Rainfall	5-river	Yangtze	Rainfall
S1	0.58	0.55	/	0.76	0.61	/	0.59	0.59	/	0.77	0.65	/
S2	0.52	0.10	/	0.62	0.19	/	0.37	0.17	/	0.52	0.28	/
S3	0.58	0.55	0.05	0.76	0.61	0.54	0.58	0.59	0.05	0.77	0.65	0.56
S4	0.51	0.10	0.13	0.62	0.19	0.58	0.36	0.16	0.18	0.52	0.28	0.58
S5	0.17	0.28	/	0.48	0.33	/	0.18	0.42	/	0.43	0.45	/
S6	0.13	0.33	/	0.50	0.57	/	0.78	0.89	/	0.81	0.95	/
S7	0.16	0.28	0.07	0.47	0.33	0.41	0.17	0.41	0.06	0.43	0.45	0.49
S8	0.76	0.66	0.10	0.92	0.75	0.17	0.82	0.92	0.27	0.87	0.99	0.42
S9	0.42	0.44	/	0.44	0.77	/	0.38	0.92	/	0.40	0.99	/
S12569	0.76	0.18	/	0.75	0.18	/	0.30	0.90	/	0.29	0.90	/
S3478	0.76	0.13	0.14	0.76	0.14	0.16	0.12	0.83	0.04	0.11	0.85	0.02

Note: (1) Delta is for Delta Moment-Independent Analysis method; (2) S12569 presents all the data of S1, S2, S5, S6, and S9, without considering the lake rainfall; (3) S3478 presents all the data of S3, S4, S7, and S8, which considered the lake rainfall.

basins with complex hydrological and hydrodynamic conditions. The approach and methods outline in this study could be easily transferred to other large rivers/lakes internationally and also illustrates the advantages of using InfoWorks ICM when undertaking research on large-scale hydrodynamic simulations. Future research will focus on the simulation of Poyang Lake water levels and outflow discharge under further extremes scenarios to inform the future management and guide the development of mitigation measures.

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CONFLICT OF INTEREST

The authors declare no competing interests.

AUTHORS CONTRIBUTIONS

Meixiu Yu and Xiaolong Liu were the main contributors to this work and was responsible for developing and implementing the methods, data generation, and analysis; Paul Wood supervised the writing and revised the paper; Qiongfang Li, Guoqing Wang, Jianyun Zhang, and Li Wei supervised the research.

DATA AVAILABILITY STATEMENT

Research data are not shared.

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SUPPORTING INFORMATION

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