Impacts of the emergency operation of the South-to-North Water Diversion Project's eastern route on flooding and drainage in the water-receiving area: An empirical case from China

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Abstract. The water levels of lakes along the eastern route of the South-to-North Water Diversion Project (ER-SNWDP) are expected to rise significantly and subsequently affect the process of flood control and drainage in those lake basins. However, few studies have focused on the impacts of interbasin water diversion on the flood control and drainage of water-receiving areas at the lake basin scale. Using MIKE software, this paper builds a coupled hydrodynamic model to address the existing literature gap on the impacts of interbasin water diversion on the process of flood control and drainage in a water-receiving lake basin, and it considers the many types of hydraulic structures in the model. First, a flood ~~and waterlogging ~~simulation model was constructed to simulate the complex ~~interactions~~movement ~~between~~among ~~ ~~of the transferred water, waterlogging water ~~of~~in the lakeside area ~~surrounding ~~around Nansi Lake (NL)~~,~~ and the water in NL and its tributaries. The ER-SNWDP was also considered in the model. Second, the model was calibrated and verified with measured data, and the results showed that the model is efficient and presents a Nash-Sutcliffe efficiency coefficient (NSE) between 0.65 and 0.99. Third, the process of flood and drainage in the lakeside area of NL was simulated under different water diversion and precipitation values. Finally, the impacts of emergency operations of the ER-SNWDP on flood control and waterlogging drainage in the lakeside area of NL were ~~analyzed~~analysed based on the results from the proposed model, and some implications are presented for the integrated management of the interbasin water diversion and the affected lakes.

1 Introduction

Interbasin water diversion is a useful approach to solving the spatial unevenness of water resources, ~~but at the same time it~~however, it makes the water cycle of the water-receiving area more complicated and brings a great challenge to integrated water management of the water-receiving area and the water diversion project (Matete and Hassan, 2006; Webber et al., 2017). The key to the long-term healthy operation of interbasin water transfer project is to clarify the influence of interbasin water transfer on the water-receiving area. In the last decades, several authors have revealed and discussed the impacts of the interbasin water transfer on water-receiving area from many perspectives, mainly including water quality, water resources and water ecosystem, and some ~~implications~~suggestions of scientific management of the water-receiving area and water diversion project were proposed (Cole et al., 2011; Emanuel et al., 2015; Zhuang, 2016). A large quantity of transferred water will not only ~~In addition to changing~~change the water quality, the water environment and other hydrological characteristics of the water-receiving areas~~, a large quantity of transferred water will~~ but ~~also ~~have an impact on flood control and waterlogging drainage in some water-receiving areas (Gupta and Zaag, 2008; Liang et al., 2012). Flood~~s~~ and waterlogging are one of the main natural disasters in terms of losses of human life and economic damages, and~~,~~ flood control and drainage are the top priorities of watershed management(Arrighi et al., 2013; He et al., 2018; He et al., 2018b). However, to the best knowledge of the authors, there are very few studies on the impacts ~~that~~of interbasin water transfer on the flood control and drainage in water-receiving area from watershed perspective.

The eastern route of the South-to-North Water Diversion Project (ER-SNWDP) links Gaoyou Lake, Hongze Lake, Luoma Lake, Nansi Lake and Dongping Lake with 13 pump stations that transfer water from the downstream Yangtze River to the Huang-Huai-Hai Plain and Shandong Peninsula (Fig.1a and b). According to the comprehensive plan of the SNWDP, (1) the first phase planning –(before 2030) of the eastern route is designed to transfer 8.9 billion m^3 water annually, and approximately 7 billion m^3 is expected to be consumed in the above five lake basins and the route; (2) the water diversion period covers the non-flood season (October to next May), and the water diversion will be stopped in the rest of the time (Bureau of South to North Water Transfer of Planning, Designing and Management, Ministry of Water Resources, 2003). As the water-receiving areas and the transmitting channels of the ER-SNWDP, the five lakes are used to store and regulate water resources, and the water level of the five lakes are significantly raised when the project is operating. ~~Encountering rainstorm, t~~The raised lake level will impede the flood control and waterlogging drainage during a rainstorm, and especially during the flood in the low-lying lake basin.

Otherwise, the Shandong Peninsula has suffered from severe drought and the water supply cannot meet the water demand even in the flood season~~conditions~~ (June to October) for four consecutive years since the eastern route operated in 2013. Emergency water diversion, that is, the water ~~from Yangtze River to northern China~~ transfer through the water diversion project in flood seasons to alleviate water shortages in the water-receiving areas, has been performed many times to supply water for Shandong Peninsula~~this area during the flood season~~. Furthermore, considering the rigid demand for water resources caused by the rapid socioeconomic development ~~development of economic and social development~~, more frequent water transfers are expected in the flood season (Guo et al., 2018). Meanwhile, extreme ~~hydrological~~ rainfall events caused by ~~environment~~ climate changes have increased in eastern China~~along the ER-SNWDP~~ (Liu et al., 2015). Thus, the probability of rainstorms during water diversion period in these lake basins will increase. In order to strengthen the scientific scheduling of flood control projects in water-receiving areas and water diversion projects, it is necessary to clarify the influence law of water diversion on flood control and drainage in these lake basins.

Based on data availability and regional distribution, the Nansi Lake Basin (NLB), a flood prone area, is chosen as the research area in this study (Fig.2). The reason why we choose the NLB is ~~because this lake~~that the NL~~ basin~~ is an important storage node of the ER-SNWDP for NL is the largest freshwater lake in northern China and has the largest water storage capacity among the lakes along the ER-SNWDP (Zhang, 2009). Otherwise~~,~~ the NLB has a history of frequent flooding and waterlogging disasters due to the low ~~lake is shallow and the~~ drainage capacity~~ is low~~ in the geomorphic low-lying area around NL (lakeside area)~~ flood drainage efficiency in the lakeside area has a sensitive response to the lake level, the NLB has a history of frequent flooding and waterlogging disasters~~. NL is a storage pond of the ER-SNWDP~~eastrn route of the south to north water diversion project~~, and the flow of water transferred into Nansi Lake is 200 m^3/s and the outflow is 100 m^3/s. A large quantity of water assumed in the Nansi Lake Basin, so it is a water receiving area. According to the overall plan of the SNWDP, the water level of the upper lake is expected to rise by 50 cm and the lower lake is expected to rise by 70 cm during the project operation period. The lake level raised by the ER-SNWDP will decrease the drainage efficiency of pump stations and hinders flood discharge of rivers in lakeside area, and then influence the flood control and waterlogging drainage of NLB.

Therefore, this paper proposes a model that integrates MIKE 11, MIKE 21 and MIKE FLOOD to simulate the flood and waterlogging process in NLB~~akeside areas~~ under the condition of emergency water diversion by the ER-SNWDP. And then,~~and~~ simulate the flood and waterlogging under different rainstorm and water diversion condition. Finally, according the simulation results to quantify~~analyses of~~ the impacts of ~~emergency water diversions~~the interbain water transfer on the flood control and waterlogging drainage in NLB. ~~drainage characteristics and the scheduling of flood control and drainage projects must be performed to strengthen the scientific scheduling of water diversion projects and flood control projects in water-receiving regions. This situation represents a major scientific problem that must be resolved. However, to the best of the authors' knowledge, few studies have focused on the impacts of interbasin water transfer on flooding and drainage in~~

~~lake basins along the water diversion route. Therefore, an important gap exists in the literature, Apart from a few papers, the effects of water-level increases caused by water diversion on the flooding and drainage process and inundated areas in lake basins have not been estimated via relevant models. the existing literature and address the gap mentioned above.~~

This paper attempts to address three issues:

(1) Establish~~Identify a method of building~~ a flood and waterlogging simulation model for a water-receiving region affected by ~~with multiple hydraulic structures under~~ interbasin water diversion;

(2) Determine how emergency water diversion affects the flooding and drainage process in the NLB and analyze the waterlogging situation in the lakeside area of NL;

(3) Evaluate how to balance the risk of water shortage and flooding caused by interbasin water diversion in the water-receiving regions.

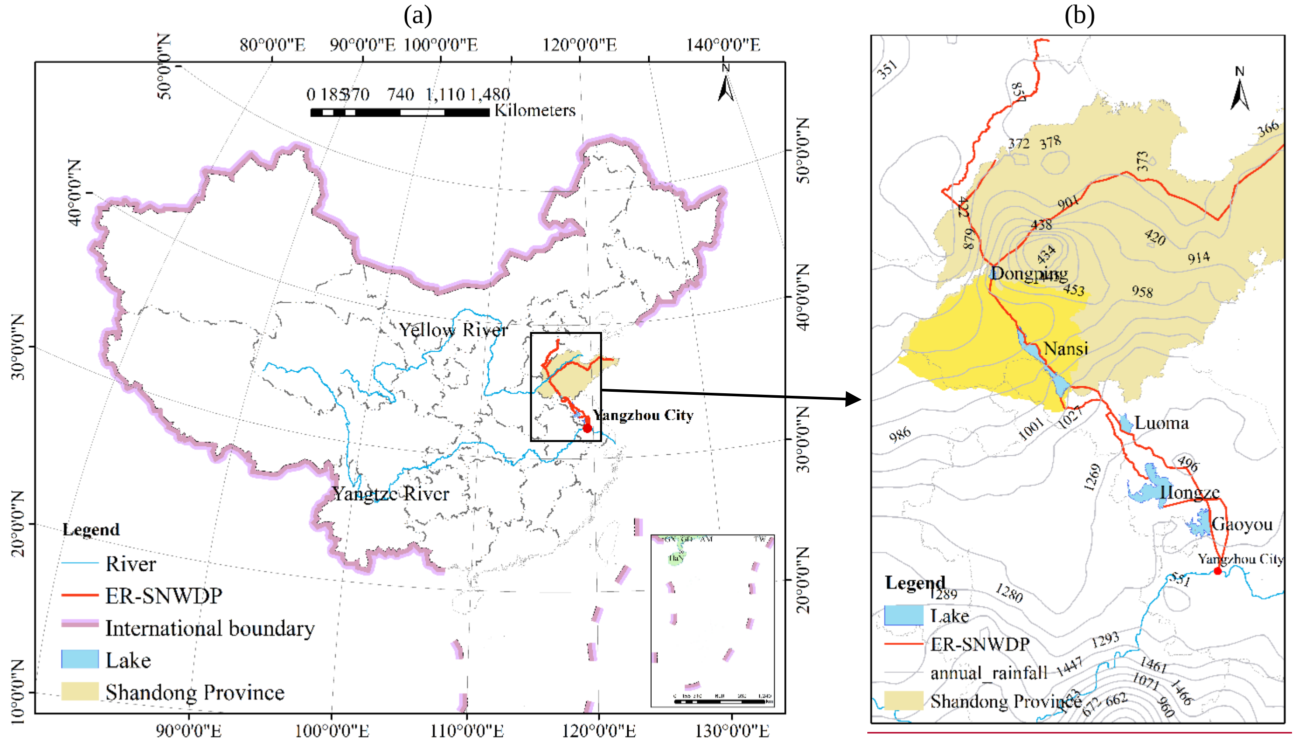


Figure 1: Sketch map of the eastern route of the South-North Water Transfer Project (a). Annual rainfall contour and lakes along the route (b).

2 Literature review

2.1 Impacts of interbasin water diversion on the water-receiving regions

Due to the uneven spatial distribution of water resources and regional socio-economic development, the demand for water in certain regions far exceeds the available water amount, thereby resulting in an increasingly serious imbalance between water demand and supply (Cai and Ringler, 2007; Hu et al., 2010;~~ Matete and Hassan, 2006; Webber et al., 2017~~). As the most effective and direct method of resolving the problem of water resource shortages, interbasin water diversion projects have been widely applied in water-deficient areas around the world (de Andrade et al., 2011; Wang et al., 2014; Zhang et al., 2015). According to data released by ICID (2005), the total annual amount of water transferred by water diversion projects around the world is 540 billion m^3, which accounts for approximately 14% of the world's annual water withdrawals. By 2025, the annual water diversion is expected to reach 940 billion m^3. In the water supply and receiving area, interbasin water transfer projects significantly affect hydrological elements, such as the water quantity, water quality, water environment and flood disasters. A full understanding of these impacts is key to the scientific management and long-term operation of interbasin water diversion and represents the most popular global topic in water resource planning and management research (Aron et al., 1977; Davies et al., 1992; Khan et al., 1999; Liu and Zheng, 2002). Zhang et al. (2015) summarized relevant studies on interbasin water transfer from 1991 to 2014 and noted that the effects on the hydrological environment caused by China's SNWDP and the corresponding long-term monitoring and protection policy for this project represent the most important current issues.

Current research on the hydrological effects caused by interbasin water transfer mainly focuses on the following aspects. (1) For groundwater, Kundell (1988) argues that a large amount of imported water significantly increases the available water and directly participates in the water cycle of the water-receiving regions, which has a positive effect on the water environment, groundwater exploitation and wetland restoration. Relevant studies indicate that a large amount of imported water can effectively alleviate the problem of decreased groundwater levels and ground subsidence caused by the perennial over-extraction of groundwater in selected areas (Larson et al., 2001; Liu and Zheng, 2002; Wang et al., 2014). Based on a large distributed hydrological model, Ye et al. (2014) evaluated the effect of the middle route of the SNWDP on the groundwater level of Haihe basin. The results showed that although the imported water cannot change the decreasing trend of the groundwater level in the water-receiving area, it can significantly reduce the rate of decrease. (2) Water quality is one of the most important factors underlying the success of interbasin water transfer projects. Scholars have simulated and evaluated the effects of interbasin water transfer projects on water quality in water supply and receiving areas. The imported water dilutes the concentration of nutrients, improves the ratio of runoff and pollution in the receiving area and subsequently improves the water quality. However, interbasin water transfer projects might also transfer pollutants from the water supply area or the river basin along the water diversion line into the water-receiving regions, thus worsening the water quality (Hu et al., 2008; Karamouz et al., 2010; Tang et al., 2014; Welch et al., 1992; Zhai et al., 2010). The Chicago interbasin water diversion project, which uses the Lake Michigan basin as its source, has come under criticism due to its chronic exposure risk of organic pollutants (Rasmussen et al., 2014). (3) Interbasin water transfer brings water from the water-supplying area to the water-receiving area through the water transmission channel, which is not conducive to flood control in the water-receiving area and the water transmission channel. Wang et al. (2013) studied the influence of an inter-basin water transfer project on hydraulic parameters during the flood season in a water-supplying area. Based on a two-dimensional mathematic model, Sun et al. (2008) took the Anyang River Basin, which is crossed by the middle route of the SNWTP as an example to study the influence of ~~the middle line of the SNWTP~~ the water diversion project on flooding~~ disasters~~ in the river basin~~ that through which~~ the project passes through. As the storage node of the water diversion project, the large amount of water transferred to the lake significantly changes the interaction law between the water body of the lake basin and the water in the lake tributaries and subsequently affects the flood control and drainage of the lake basin. However, few quantitative research studies have focused on this issue.

2.2 Simulation of flooding and waterlogging disasters in a basin

Simulating the flood and waterlogging process based on a mathematical model is an important method for analyzing flood and waterlogging characteristics and assessing the flood and waterlogging disaster risk of a basin, and it is also an effective tool for planning the layout of flood and waterlogging control engineering (Dutta et al., 2015; Liu et al., 2015; Wang et al., 2018). The early flood and waterlogging simulations of a basin are mainly based on hydrological models, including SWMM (Lee and Heaney, 2003), MUSIC (Dotto et al., 2011; Hamel and Fletcher, 2014), SWAT (Dixon and Earls, 2012), and MIKE SHE (Vrebos et al., 2014), among others. However, hydrological models only simulate the flood-routing process according to the water balance equation and are unable to display the spatial distribution of flood movement. In addition, these models cannot accurately simulate the drainage process of the sluice, dam, pumping station and pipeline hydraulic structures. A hydrodynamic model simulates the water routing by solving the Saint-Venant equations, which can accurately reflect the movement of water in the plane and various hydraulic structures. With improvements in computer processing speed and the development of spatial digital elevation information, hydrodynamic models have gradually become an important tool for flood simulations (Moel et al., 2015). Hsu et al. (2000) built a waterlogging simulation model by coupling the SWMM model and a two-dimensional hydrodynamic model and simulated the rainstorm waterlogging of Taipei City. Bisht et al. (2016) combined SWMM with the MIKE URBAN and MIKE 21 models to simulate waterlogging in West Bengal, India. Li et al. (2016) established a 1-D and 2-D ~~coupling~~ coupled hydrodynamic model of Taining county in China based on MIKEFLOOD model, and simulated and analyzed the flood and waterlogging risk in the region. The MIKE 11 and MIKE 21 hydrodynamic models can simulate the influence of a variety of hydraulic structures on the water flow movement process, and the one-dimensional model and two-dimensional model can describe the coupling in different ways. Therefore, this model has been applied to simulate flow movement of a variety of water bodies, including rivers, lakes, flood water on the ground~~land~~ and estuaries (Karim et al., 2016; Quan, 2014; Zolghadr et al., 2010).

3 Research area and data sources

3.1 Research area

NL (34°27'N–35°20'N, 116°34'E–117°21'E) is composed of four consecutive lakes, namely, Nanyang Lake, Dushan Lake, Zhaoyang Lake and Weishan Lake (Fig. ~~1~~2), and it is a typical large and shallow lake with an area of 1266 km^2 and an average depth of only 1.5 m (An and Li, 2009). To manage flooding in this basin, a pivotal project composed of a dam and sluices (Erji dam) was constructed at the middle of NL, and it divides the lake into an upper lake and lower lake. The sluices of the Erji dam control the flood discharge of the upper lake, and the Hanzhuang sluice and Linjia sluice control the flood discharge of the lower lake. The NLB is located in Yi-Shu-Si river system of the Huaihe River Basin with an area of 31700 km^2. The lakeside area~~,~~ refers to the area with a ground elevation (above sea level) ~~of~~ below 36.79 m ~~or less~~ around the lake, ~~is approximately 3969 km^2~~ and ~~has~~ the ground~~a~~ slope in this area ~~slope~~ is between ~~1/5000~~0.0029 ° and ~~1/20000~~0.0057 ° (Tian et al., 2013; Wang et al., 2010). A total of 53 rivers flow into NL, and 11 of them have a drainage area greater than 1000 km^2. Due to the low height and gentle slope of the riverbed, the rivers in the lakeside area have strong interactions with NL. Flood control embankments have been built on both sides of the main inflow channels and around NL to prevent flooding from entering the lakeside area. Due to the low-lying terrain and the construction of flood control embankments, waterlogging in lakeside areas cannot ~~longer directly~~ drain itself into rivers and ~~lakes~~NL. The waterlogging water in the lakeside area ~~is primarily carried~~ mainly pumped into rivers and NL ~~by~~ through pumping stations ~~in the lakeside area~~. However, the existing pumping stations in this region cannot resist the rainstorm waterlogging occurred every five years, some pumping stations even cannot resist rainstorm waterlogging occurred every three years. When ~~E~~encountering heavy rainstorm, the water cannot be discharged in time, therefore the NLB is a flood prone area in the history~~belongs to the historical frequent flooding area~~.

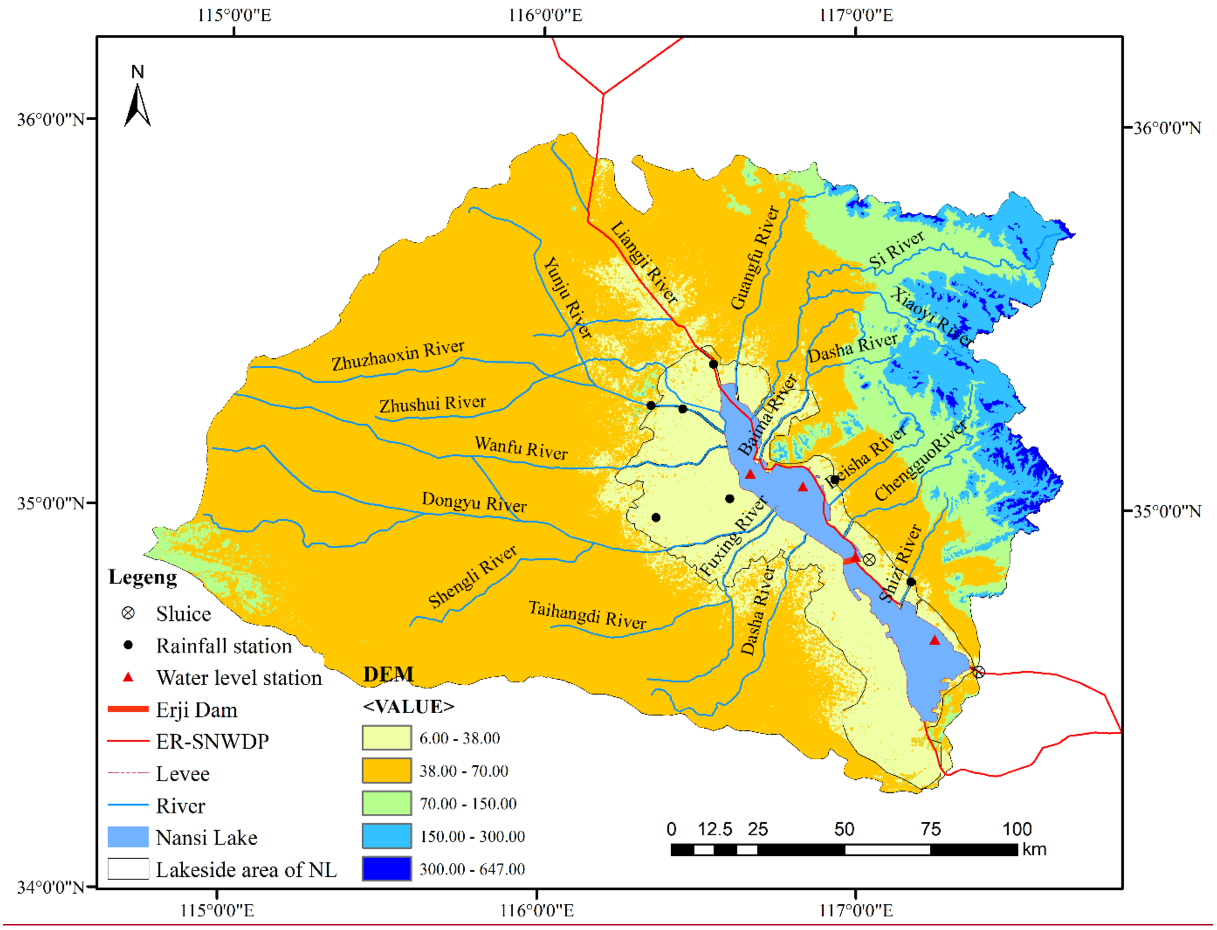


Figure ~~1~~2: Location of the study area, with the positions of rainfall and water level gauges, rivers and hydraulic projects considered in the study River system and topographic map of Nansi Lake Basin ~~Sketch map of the eastern route of the South-North Water Transfer Project and Nansi Lake BasinThe logo of Copernicus Publications.~~

The ER-SNWDP transfers water from Yangzhou City to NL and is divided into two sections in the NLB: water entering the lower lake at the Hanzhuang sluice and~~ water entering~~ the Linjia dam sluice. A pumping station has been built at the secondary dam to lift water from the lower lake to the upper lake~~,~~. ~~and t~~The Changgou pumping station is built at 24m south of Liangji River Estuary in the upper lake,~~ will be built at the higher lake 24.6 km the Liangji River mouth~~ to ~~send~~ transfer water to the Shandong Peninsula. According to the first phase planing of the ER-~~-~~SNWDP, the discharge that enters the lower lake ~~occurs at~~is 200 m^3/s, and 5/8 of this amount will be pumped into the upper lake. When the water diversion project is running~~During project operation~~, the water level (in respect to mean sea level) of the lower lake will reach 32.8 m, which is 0.70 m higher than the mean annual water level. The project ~~also~~ transfers water from the upper lake to the north at the flow rate of 100 m^3/s. The water level of the upper lake maintains a normal storage level of 34 m, which is 0.48 m higher than the mean annual water level.

3.2 Data sources

The data sources for this study include terrain, hydrology, meteorology and hydraulic engineering data from the NLB and engineering layout and operation data of the eastern route of the SNWDP. (1) The digital elevation model (DEM) and river channel bathymetry were supplied by the Planning and Design Institute of the Huaihe Basin Hydraulic Management Bureau in Shandong Province, China. The lakeside area of NL is also provided by this Planning and Design Institute. The DEM of the lakeside and NL in 2013 was derived from 1:7000 topographic maps, and the river channel bathymetry of all rivers simulated ~~used~~ in the 1-D model was reflected by 550 cross-sections separated by distances between 500 and 1000 m. (2) The hydrological data originated from the Shandong Provincial Hydrology Bureau. These data mainly include the discharge processes of typical floods in the upper boundaries of the rivers and the daily rainfall records at ~~seven~~ six rainfall stations:

Huayu(HY), Liangshanzha(LSZ), Wanglu(WL), Wanggudui(WGD), Wangzhong(WZ) and Xuecheng (XC). Each station has daily precipitation records covering approximately 30 to 50 years. The daily water level records of four stations, Nanyang, Makou, Erji Lake, and Weishan (shown in Fig. ~~1~~2), were also supplied. (3) The meteorological data were downloaded from the National Meteorological Scientific Data Sharing Service Platform (http://data.cma.cn/), and the data include daily records of numerous meteorological parameters, including the wind field and evapotranspiration information. (4) The hydraulic engineering data, includes the technique parameters of sluices, pumping stations and levees in NLB, were supplied by the Planning and Design Institute of the Huaihe Basin Hydraulic Management Bureau in Shandong Province, China. These data include the location and drainage capabilities of the pump stations, the locations and sizes of flood control embankments, and the hydraulic parameters of sluices. (5) The engineering data of the ER-SNWDP were supplied by the Planning and Design Institute of the Huaihe Basin Hydraulic Management Bureau in Shandong Province, China.

4 Methodology

4.1 Research framework

To quantitatively study the impact of the water diversion project on flood control and drainage in the NLB, a hydrodynamic model of waterlogging in lakeside areas of NL was constructed based on MIKE software with consideration of the ER-SNWDP. This model includes a one-dimensional model to simulate flood routing in the river that flows into NL (MIKE 11) and a two-dimensional model to simulate the evolution of plane flow in the lakeside area of NL (MIKE 21). Different hydraulic structures are set up in the model to simulate the flood control and drainage process of sluices, dams, pumps and other hydraulic structures in the research area and the water lifting process of the ER-SNWDP pumping station. Coupling of the one-dimensional and two-dimensional models is supplied by reasonable links to reflect the interaction of water in the NL, tributary rivers and lakeside area. The established model is used to simulate the waterlogging process in the lakeside area under different scenarios. According to the results of the calculation, the influence law of the SNWDP on waterlogging in the lakeside area of NL is analyzed. Finally, related suggestions for balancing the water diversion and waterlogging risk are proposed. Fig. ~~2~~ 3 illustrates the research framework of this paper.

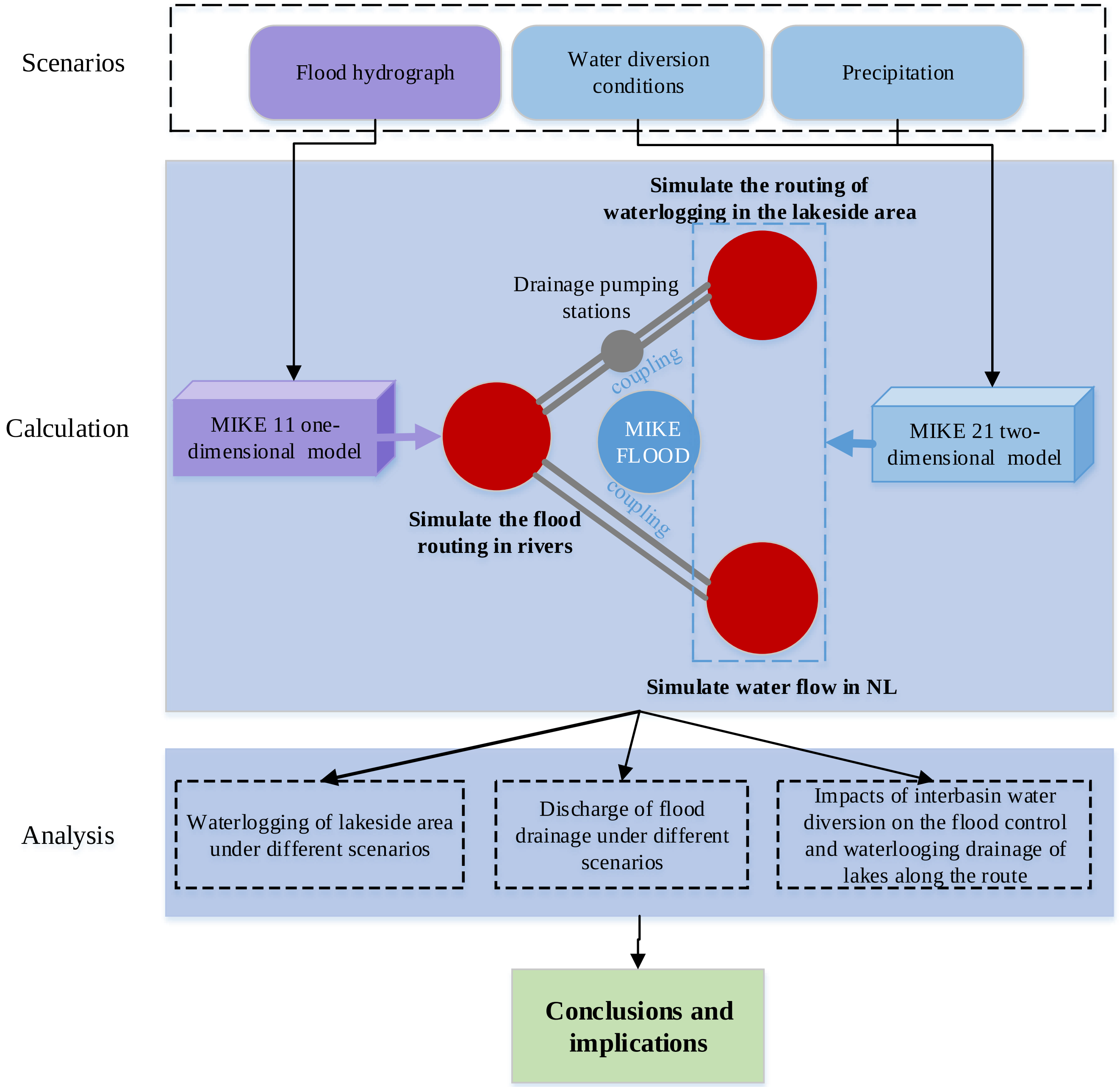


Figure ~~2~~3: Research framework of the interbasin water diversion influence on flood control and waterlogging drainage of lakes along the route.

4.2 One-dimensional hydrodynamic model of river net

A total of 53 tributary rivers are located around NL, and they represent the key to studying the influence of water diversion on waterlogging in the lakeside area for accurately simulating the flood evolution and the interaction between flood evolution and the high water level of NL. Therefore, a 1-D mathematical model (MIKE 11) was used to simulate the flood routing. The control equation of the model is the Saint-Venant equations (Abbott et al., 1979), which are composed of the continuity equation and momentum equation ~~(DHI,2007)~~:

continuity equation:

$$B = \frac{\partial Z}{\partial T} + \frac{\partial Q}{\partial x} = q \ , \tag{1}$$

momentum equation:

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial X}\left(\frac{\alpha Q^2}{A}\right) + gA\frac{\partial z}{\partial x} + \frac{gQ|Q|}{C^2AR} = 0, \tag{2}$$

where x and t denote the spatial and temporal coordinates, respectively; A is the cross-sectional area; Q and z denote the discharge and water level of cross-section, respectively; q is the lateral inflow; R is the hydraulic radius; C is the Chezy coefficient; a is the momentum correction factor; and g denotes the gravitational acceleration. The Abbott-Ionescu 6 implicit difference method is used to solve the equation.

First, we generalized the river net based on a consideration of the data and computational efficiency. This river net primarily contains 11 rivers with drainage areas greater than 1000 km^2. A total of 550 cross sections were input into the river network model to reflect the changes of river topography with adjacent sections spaced approximately 1000 m apart. We generalized the drainage pump stations in the lakeside area of NL. A total of 1000 draining pump stations are used to drainage waterlogging water from ~~present in the~~ lakeside area to ~~of~~ rivers and NL, and the model generalized the pump station according to each pump station distribution on both sides of the rivers. The basic principle is to ensure that the total drainage discharge remains the same, with the generalized pumping stations along the river on both sides evenly distributed for a total of generalized 41 pumping stations. Finally, the boundary conditions of the model were set. The upper boundary of the model inputs the discharge hydrograph of the upstream hydrological station of each river. As the lower boundary, the water level of the estuary is based on NL, which is simulated by the two-dimensional model.

4.3 Two-dimensional hydrodynamic model of NL and the lakeside area

The MIKE 21 hydrodynamic model was used to simulate the water movement in NL and the waterlogging evolution in the lakeside area. ~~The model covers the area below the 36.79 m contour line around NL and the lake surface.~~ The model area include NL and the lakeside area around the lake (Fig.2). Because the one-dimensional model is adopted to simulate the rivers around the lake, the area of the rivers is removed from the two-dimensional model. The two-dimensional model is based on the Reynolds average stress equation of a three-dimensional incompressible fluid, which is subject to the Boussinesq hypothesis and the hydrostatic pressure hypothesis (J V Boussinesq, 1872), and the control equations used in this model are given as follows ~~(DHI, 2007)~~:

continuity equation:

$$\frac{\partial h}{\partial t}+\frac{\partial h\bar{u}}{\partial x}+\frac{\partial h\bar{v}}{\partial y}=hS\ , \tag{3}$$

momentum equation of x direction:

$$\frac{\partial h\bar{u}}{\partial t}+\frac{\partial h\bar{u}^2}{\partial x}+\frac{\partial h\bar{v}\bar{u}}{\partial y}=f\bar{v}h-gh\frac{\partial \eta}{\partial x}-\frac{h}{\rho_0}\frac{\partial p_a}{\partial x}-\frac{gh^2}{2\rho_0}\frac{\partial \rho}{\partial x}+\frac{\tau_{sx}}{\rho_0}-\frac{\tau_{bx}}{\rho_0}-\frac{1}{\rho}\left(\frac{\partial s_{xx}}{\partial x}+\frac{\partial s_{xy}}{\partial x}\right)+\frac{\partial}{\partial x}(hT_{xx})+\frac{\partial}{\partial x}(hT_{xy})+hu_sS, \tag{4}$$

momentum equation of y direction:

$$\frac{\partial h\bar{v}}{\partial t}+\frac{\partial h\bar{v}^2}{\partial y}+\frac{\partial h\bar{u}\bar{v}}{\partial x}=f\bar{u}h-gh\frac{\partial \eta}{\partial y}-\frac{h}{\rho_0}\frac{\partial p_a}{\partial y}-\frac{gh^2}{2\rho_0}\frac{\partial \rho}{\partial y}+\frac{\tau_{sy}}{\rho_0}-\frac{\tau_{by}}{\rho_0}-\frac{1}{\rho_0}\left(\frac{\partial s_{yx}}{\partial y}+\frac{\partial s_{yy}}{\partial x}\right)+\frac{\partial}{\partial x}(hT_{xy})+\frac{\partial}{\partial y}(hT_{yy})+hv_sS, \tag{5}$$

where x, y and z are Cartesian coordinates; t denotes temporal coordinates; η is the bottom elevation of the river; d is the depth of the water, $h=d+\eta$ is the total head of the water; u, v and w are the velocity components in the x, y and z directions, respectively; p_a is the local atmospheric pressure; ρ is the density of water; ρ_0 is the reference water density; $f=2\Omega sin\phi$ is a Coriolis parameter; $f\bar{v}$ and $f\bar{u}$ are the acceleration caused by the earth's rotation; S_{xx}, S_{xy}, S_{yx} and S_{yy} are the components of the radiation stress tensor; T_{xx}, T_{xy}, T_{yx} and T_{yy} are the horizontal viscous stresses; S is the magnitude of the discharge due to point sources; and (u_s,v_s) is the velocity by which the water is discharged into the ambient water.

The total area of the 2-D model is approximately 4750 km^2, including NL (1266km^2), the lakeside area (3696km^2) shown in Fig.2 and deducts the area of the rivers that simulated by 1-D model, with both sides of the river embankment and the 36.79 m contour line as the outer boundaries of the model. Dikes were set up on both sides of river around NL and at the Erji dam to simulate the flood control effect of levees. Sources were added to simulate the water transfer process of the ER-SNWDP. When the model is running, the rainfall process of the HY, LSZ, WL, WGD, XC, and WZ~~XueCheng (XC)~~, ~~ZhongXingJi (ZXJ), WangZhong (WZ), JuYe (JY), and HouYing (HY)~~ rainfall stations in the research area are input.

4.4 Waterlogging simulation model of NL and lakeside area with consideration of the SNWDP

The MIKE FLOOD model is used to couple the 1-D and 2-D model, and the specific process is described as follows: (1) A lateral link is applied to connect the lakeside area ~~into-lake rivers~~ and ~~lakeside area~~ tributaries of NL to simulate the flood exchange between the lakeside area and tributaries ~~overtopping of dikes~~; and (2) a standard link is applied to connect the into-lake rivers and NL to reflect the influence of the height of the lake level in blocking the drainage of the into-lake rivers. A total of 22 lateral connections and 52 standard connections are present in the coupling model.

4.5 Calibration and validation of the coupling model

The model is calibrated and validated using two actual floods that occurred in July 2007 and July 2008 in the NL basin. Fig. ~~3~~ 4shows the simulated and measured water levels of four stations: Nanyang (NY), Makou (MK), Erji Dam (ED) and WeiShan (WS) in NL. Overall, the measured water level process shows good agreement with the simulated water level process, and the arrival of the simulated flood peak is consistent with the measured data. The Nash-Sutcliffe efficiency coefficient (NSE), which was proposed by Nash and Sutcliffe (1970), is used to evaluate the coupling model. The NSE for the daily flow varied from 0.67 (Erji Lake) to 0.82 (Weishan) during calibration and from 0.65 (Nanyang) to 0.99 (Weishan) during verification (Table 1), thus showing good agreement between the observed and simulated water levels. As a result, the calibrated roughness coefficients n were 0.055 for agricultural fields, 0.08 for residential areas in the lakeside area, and 0.028 for NL.

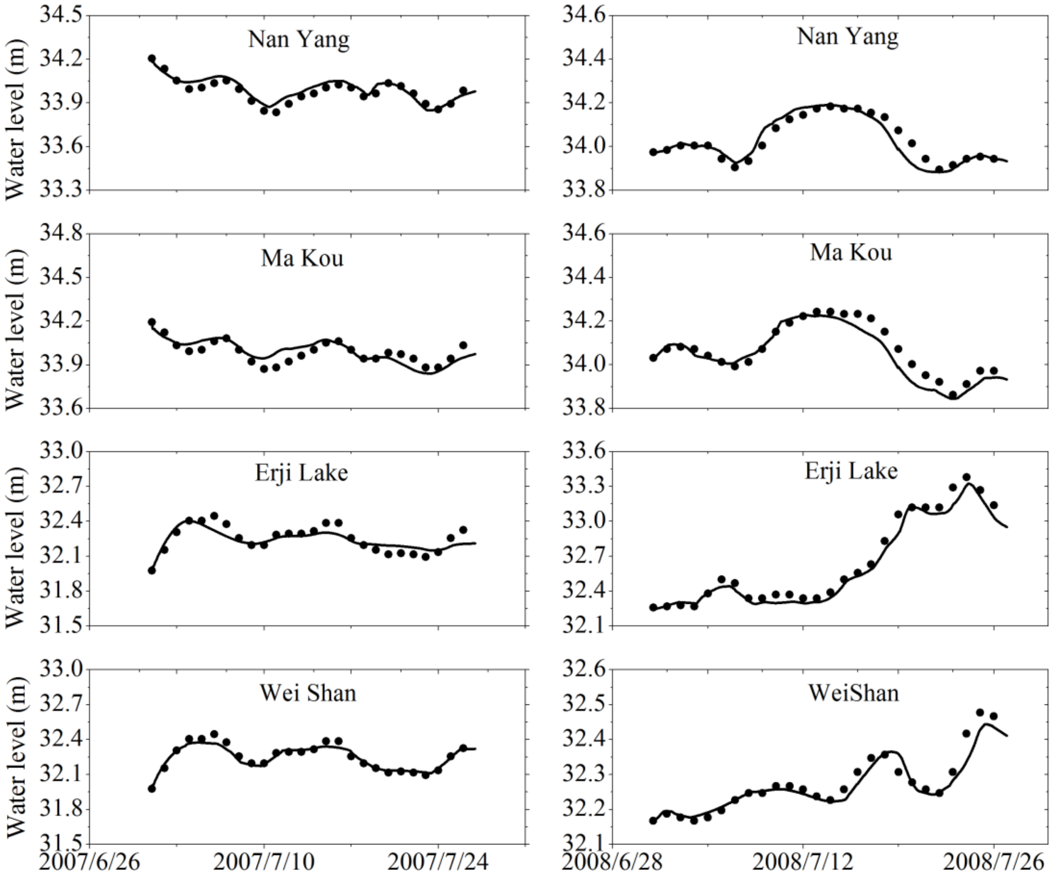


Figure ~~3~~4: Comparison of the observed and simulated water levels at selected locations for 2007 flood events under calibration conditions (left) and 2008 events under validation conditions (right). Black dots represent observed data, and black lines represent model simulation results.

5 Results and discussion

5.1 Scenario design

NL is located in the China's north-south climate transition zone, and the time distribution of rainfall is severely uneven, with rainfall in the flood season accounting for 72% of the annual precipitation. This basin is located in the north-south climate transition zone of China, and the phenomenon of drought−flood abrupt alternation (DFAA) frequently occurs. DFAA refers to a rainstorm after a long period of drought and can result in severe flood damage. ~~The phenomenon of abrupt drought-flood alternations frequently occurs, with this region experiencing drought disasters prior to the arrival of the flood season and waterlogging disasters during the flood season.~~ Fig. ~~4~~5 shows the process of rainfall at Wanglu station and the water level~~s~~ of upper and lower lake at Nanyang and Weishan station in 2003. Since there was no precipitation in the first half of the year, NL dried up from April to June 2003, which caused a devastating impaction to the ecosystem of Nansi Lake. In the future, if NLB encounters another drought like 2003, emergency water diversion by the ER-SNWDP will be the first choose to provide ecological water for NL.~~For example, in 2003, the rainfall of this basin was nearly 0 mm in the first half year, and the upper lake of NL even had a dry period from April to June.~~ However, heavy rains occurred after August 22 and caused a steep increase in the water level in NL, and 2003 represented a typical year of DFAA~~abrupt drought-flood alternations~~. The statistical data show that the waterlogged area of the NLB is 2360 km^2, and waterlogging disasters resulted in ~~notably large losses~~a great economic loss in the lakeside area.~~ Fig. 4 shows the process of rainfall at Wanglu station and the upper and lower lake levels at Nanyang and Weishan station in 2003~~. So we take 2003 as an example to research the impacts of the emergency ecological water diversion by the ER-SNWDP on the waterlogging of the NLB.

~~After the ER-SNWDP was completed in 2013, it became the first choice for alleviating local drought via this project.~~ In recent years, the situation of water resource shortages has become increasingly tense in Shandong Peninsula, China. Even in the flood season, local water resources still encounter difficulty in meeting the demand; thus, the supply of water to the region that relies on the ER-SNWDP is expected to be more frequent.

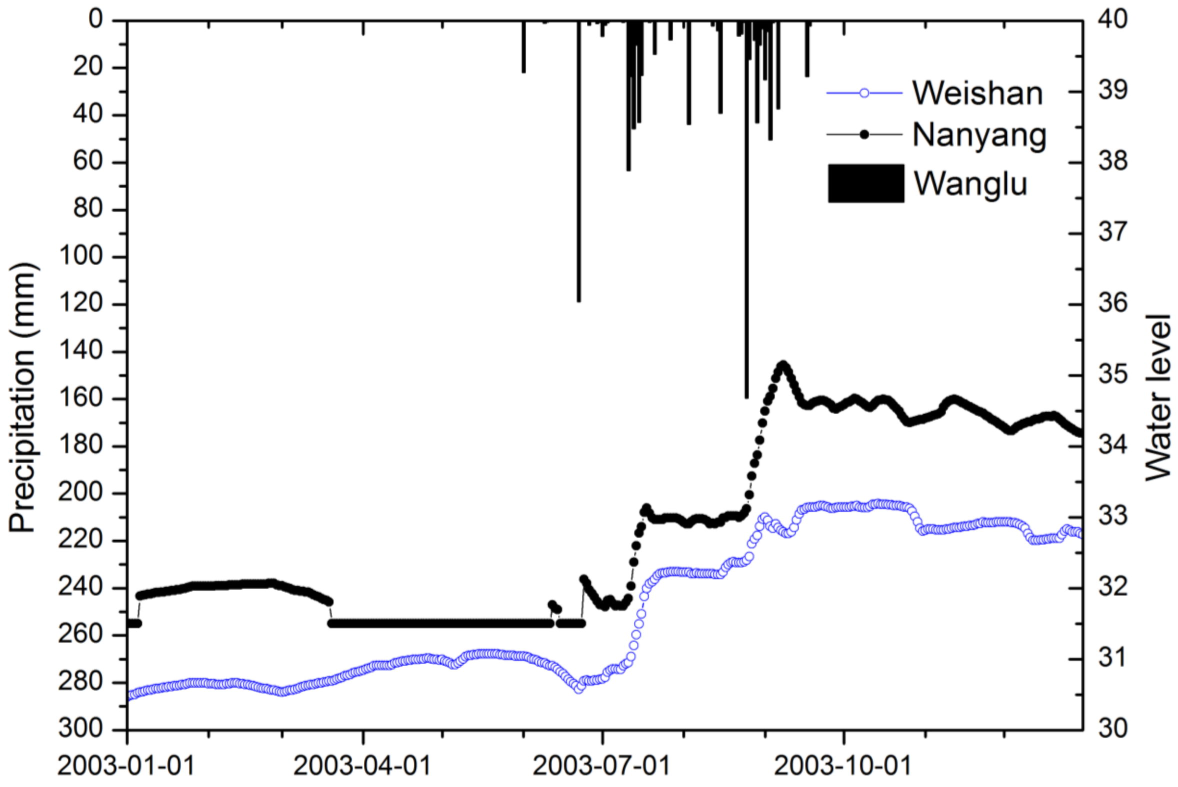


Figure ~~4~~5: Rainfall at Wanglu station in NLB and water level variations of the upper lake and lower lake in 2003. The upper lake is dry when the water level of Nanyang is 31.5 m. Before July 2003, the Nansi Lake Basin suffered severe drought, but heavy rains in August caused serious floods.

To analyze the influence of water diversion on waterlogging disasters in the lake basin along the ER-SNWDP, this paper set two conditions in which the ER-SNWDP supplies an emergency transfer of ecological water to NL and an emergency transfer of water to Shandong Peninsula. The ecological water refers to the transferred water to maintain the normal development and relative stability of all kinds of ecological systems in NL during drought period~~,~~ and to prevent the recurrence of the dry lake situation ~~that~~ occurred in 2003.

(1) An ER-SNWDP emergency requires a supply of ecological water for NL.

Take a waterlogging occurred in NLB after August 22, 2003 as example, the impact of water diversion on the waterlogging process in NLB was studied. Considering flood control safety of NLB, ~~W~~we assume that the emergency water transfer ~~ended~~ stopped ~~on August 22, 2003 when~~ ~~rainfall began~~at the beginning of rain, on August 22, 2003 (Fig.5). Because the water diversion project is no longer operational during the rainfall, the effect of water diversion on the flood process of NL is mainly to lift the water level of NL. ~~which means that water diversion only affected the initial water level of NL under this condition.~~ Therefore, two scenarios of waterlogging of NLB in August 2003 were simulated: The waterlogging process of NLB under the influence of the emergency water transfer in August 2003 is recorded as scenario ② , and the waterlogging process without water diversion is recorded as scenario ① , see table 2 for scenario Settings. The difference between scenario ① and scenario ② is the initial water level of the NL. In scenario ① , the water level of the upper lake and lower lake are 33.01 m and 32.20 m, which measured on August 22, 2003. In scenario ② , the water level of the upper lake and lower lake have been raised to 34 m and 32.3 m by the emergency water diversion. The rainfall process of the two scenarios was measured from August 22, 2003 to September 2, 2003. ~~During the water diversion period, the water level of NL maintained a normal storage level, with water levels in the upper lake and lower lake of 34 m and 32.8 m, respectively. However, we consider that emergency water diversion occurs during the flood season.~~ ~~The initial water levels of the upper lake and lower lake are 34 m and 32.3 m when rainfall begins in the 2-D model, respectively. This situationis recorded as scenario ②, and the situation in which the waterlogging process occurs without water diversion is recorded as scenario ① (Table 2).~~

(2) An ER-SNWDP emergency requires a supply of water for Shandong Peninsula, China.

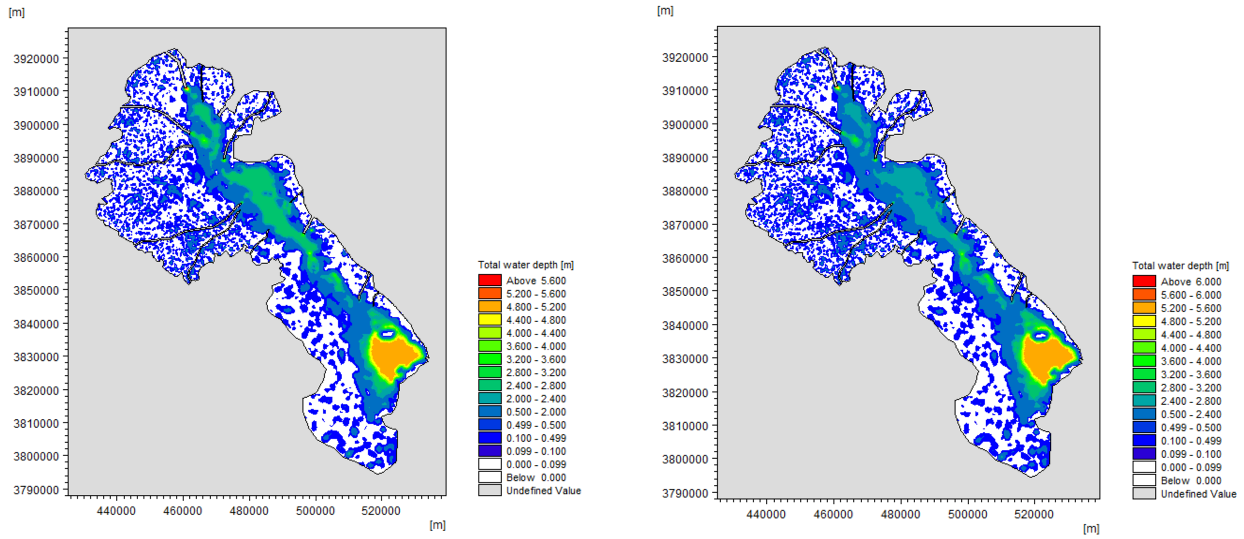
In this condition, the influence of water diversion on waterlogging disasters in the lakeside area of NL under different rainstorm intensities is analyzed. The processes of a 3-day designed rainfall with return periods of 5 years, 10 years and 20 years at six precipitation stations were calculated. Affected by the emergency water diversion, the initial water level of the upper lake and lower lake are 34.00 m and 32.30 m in scenario ⑥, ⑦ and ⑧. Because the water was transferred to alleviate the water shortage of Shandong Peninsula, China, the ER-SNWDP continued to operate during the rainfall. As a contrast, the initial water level of the upper lake and lower lake are 33.01 m and 32.20 m, which measured on August 22, 2003, in scenario ③, ④ and ⑤.In summary, a total of 8 simulation scenarios were set up as shown in Table 2.

5.2 Impacts of the emergency water diversion by the ER-SNWDP ~~emergency supply of ecological water for NL~~ on the waterlogging of the NLB.

Rice, cotton, corn and soybean are the main crops in, and the waterlogging tolerance depths of them are 0.5m, 0.1m, 01m and 0.1m, respectively (Wang, 2015). Therefore, the area with inundated deep above 0.1m and 0.5 is counted in the simulation results. In the calculation results of scenario ① and scenario ②, the areas with a submerged depth larger than 0.1 m and 0.5 m were counted respectively. Table 3 shows that the rainfall from August 22 to September 2, 2003 under the condition of no water diversion caused the inundated area in the lakeside area to reach 1126.59 km^2 and the area with a submerged depth over 0.5 m reached 383.68 km^2. Statistical data show that the total waterlogging area under the 36.79 m contour line was 1284.21 km^2 in 2003. The simulation result is slightly smaller than the survey result because the simulation did not cover the entire year and rain remained in the basin after September 2, 2003. In general, the simulation results can be considered reasonable.

Table 4 shows the increase in the waterlogging area in the lakeside area of NL under the condition of water diversion in the ER-SNWDP compared with that without water diversion. When the phenomenon of DFAA~~abrupt drought-flood alternation~~ occurs, the lake level increase via emergency operation of the ER-SNWDP during the flood season increases the waterlogging intensity in the lakeside area of NL. Compared with the situation without water diversion, the area with a submerged depth over 10 cm increased by 34.26 km^2. Emergency water diversion resulted in a relative increase of 0.99% in submerged area. ~~In the study area, the region with a submerged depth above 10 cm increased by 34.26 km^2, which represented an increase of 0.99% compared with that without water diversion.~~ The heavy disaster area with a water depth of more than 50 cm increased by 51.09 km^2, which was 13.32% higher than that without water diversion.

Fig. ~~5~~ 6 shows the waterlogging distribution in the lakeside area of NL under two scenarios. The comparison in Fig. ~~5~~6~~(~~a~~)~~ and ~~(~~b~~)~~ shows that the water diversion primarily increased the waterlogging area between the Dongyu River and Wanfu River in the western region of NL and had a relatively small impact on the eastern area of NL. Comparing with the eastern NL, due to the lower and flat terrain in the western NL, the raised water level of NL has a greater impediment to the drainage in the western NL. ~~Because of the lower and flat terrain in the western part of NL, the high water level of NL has a greater impediment to the drainage in the western part of the lakeThe primary reason for this observation is that the western portion of NL is mountainous, whereas the western portion of NL is a low-lying plain. The interaction between NL and the western rivers is stronger than that between NL and the eastern rivers.~~ Therefore, water-receiving lake-basins with plain areas should consider the effects of interbasin water diversion on the waterlogging disaster~~ in~~. Fig. ~~6~~ 7 presents the stage hydrograph for the Makou hydrographic station and the flood discharge of Erji dam for two scenarios. Fig. ~~6~~ 7 indicates that emergency water diversion has an obvious influence on the water level of NL during the initial period of rain and the regulation of the Erji dam junction leads to a decrease in the water level difference between the two scenarios. Emergency water diversion increases the initial water level of NL at the beginning of the rainfall event, and the water level of the upper lake in scenario ② first reaches the water level at which the Erji dam begins flood drainage. With the increase in the water level, the discharge of the Erji dam also increases, which satisfactorily adjusts the water level of the upper lake. Affected by the higher initial water level ~~of the lake in the early stage of~~ raised by the water diversion, the flood discharge start time~~time at which~~ of the Erji dam junction ~~begins to drain the flood water~~ in scenario ② ~~occurs~~ is 4 days earlier than that in scenario ①~~, ~~. Furthermore, ~~and~~ the total amount of flood discharge in scenario ② increased by approximately 249 million m^3 compared to scenario ① (Fig.7).



a) Calculation result of scenario 1

b) Calculation result of scenario 2

Figure ~~5~~6: Distribution of waterlogging in the lakeside area of NL.

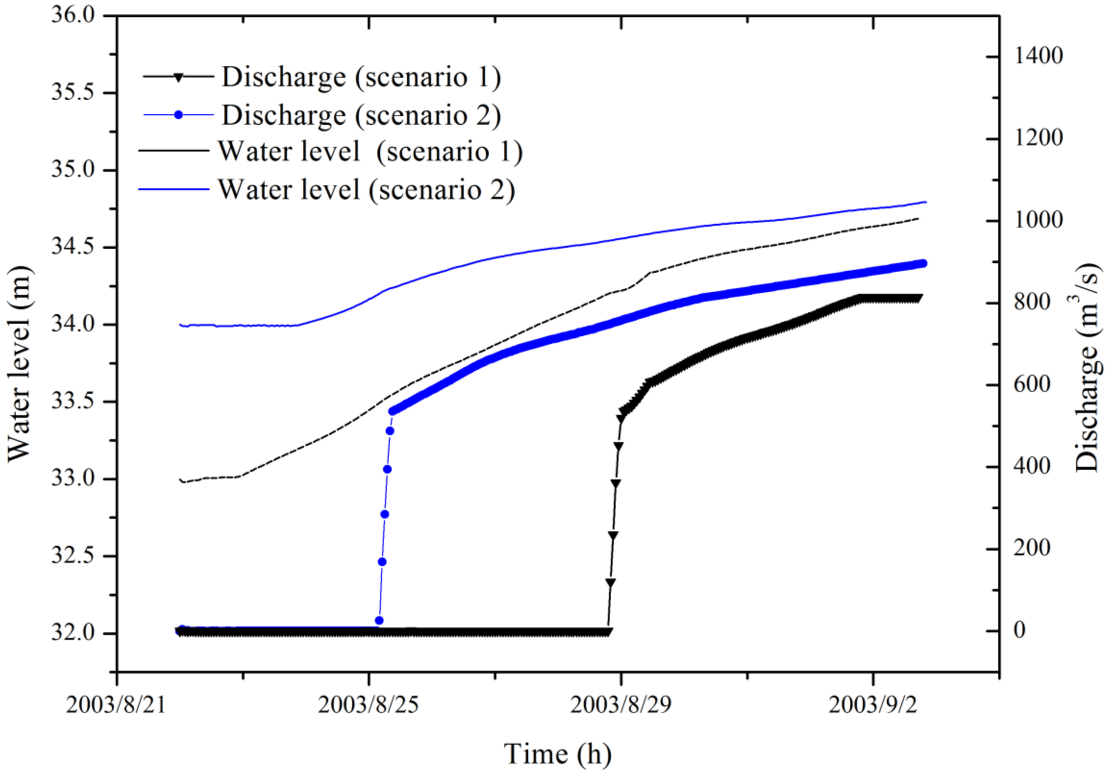


Figure ~~6~~7: Water level of Makou station in the upper lake and discharge of flood drainage of the Erji dam from August 22 to September 2, 2003 under scenario 1 (without water diversion) and scenario 2 (with water diversion).

5.3 Impacts caused by ER-SNWDP emergency water diversion for Shandong Peninsula during waterlogging of NLB.

Table 5 shows the simulation results of waterlogging in the lakeside area in the case of water diversion and non-diversion by the ER-SNWDP to the Shandong Peninsula when a designed rainfall with 5- year, 10- year and 20-year return periods occurs in the basin. Emergency water diversion has certain effects on the waterlogged area in the lakeside area of NL. According to the comparison of scenario ③ and scenario ⑥, when the NLB encounters rainfall with a 5-year return period, the areas with a submerged depth over 0.1 m and 0.5 m increase by 22.27 km^2 and 26.14 km^2, respectively, under the condition of emergency water diversion.

Fig. ~~7~~ 8 illustrates the relative increase in the waterlogging area and its change trend in the lakeside area of NL under three designed rainfall conditions with water diversion and non-water diversion. Graph (a) shows the contrast of the waterlogged area with an inundated water depth above 0.1 m under different rainfalls, and graph (b) shows the waterlogged area with an inundated water depth above 0.5 m. The black line in graph (a) and (b) both show a downward trend, which indicate that ~~T~~the influence of emergency water diversion on waterlogging in the lakeside area decreases with increasing rainfall. Affected by the emergency water diversion, the relative increase in the waterlogging area with an inundated water depth above 0.1 m is between 1.5% and 2.8% (Fig. ~~7~~8~~(~~a~~)~~), ~~whereas~~ and the relative increase in the waterlogging area with an inundated water depth above 0.5 m is between 8.4% and 43.1% (Fig. ~~7~~8~~(~~b~~)~~) when a storm with 5-year, 10-year and 20-year return periods occurs in the NLB. Under the same rainfall condition, such as the rainstorm with 5-year return periods, the area change of submerged water depth greater 0.5 m (43.1%) in the lakeside area is obviously larger than that of submerged water depth greater than 0.1m (2.8%). The calculated results indicate that emergency water diversion has more obvious effects on the waterlogging area with deeper submerged water.

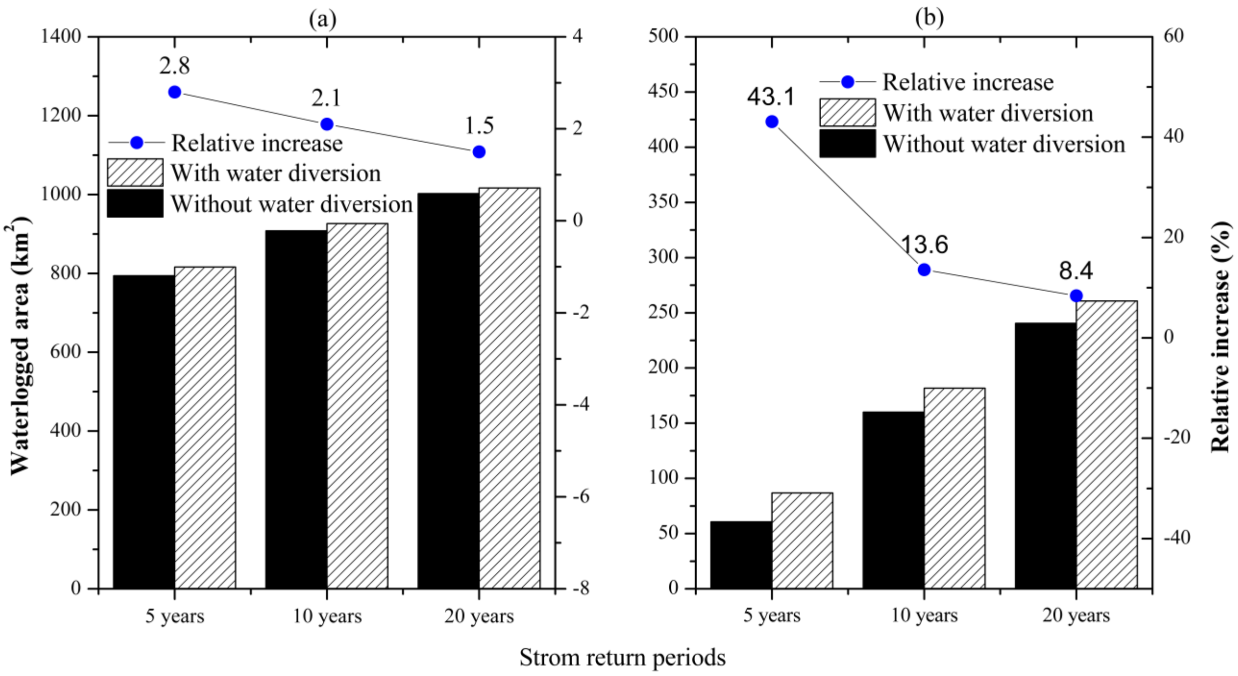


Figure ~~7~~8: Changes ~~in the area~~ of waterlogging area in the lakeside area ~~affected~~ under the influence ~~by~~ of water diversion (shadow bar), and not affected by water diversion (black bar). The black line represents the trend of the relative increase of waterlogged area caused by water diversion.

The emergency water diversion of the SNWDP alleviated the drought situation in Shandong Peninsula area and also increased the degree of waterlogging in the NLB under the situation of DFAA~~abrupt drought-flood alternations~~. The sluices of the Erji dam are the only flood-discharge channels of the upper lake, and the increased water in the upper lake due to water diversion also enlarged the task of flood discharge in those sluices. Fig. ~~8~~ 9 shows the flood discharge process of the Erji dam project under different design rainfalls~~ levels~~. When the NLB encountered a storm with 5-year return periods, the upper lake level did not reach the flood discharge conditions~~water level necessary to begin drainage~~ without the influence of water diversion (Fig.8 a). ~~In the case of~~ Affected by water diversion, the sluices began to drain the flood after ~~36~~ 30 hours of rain, with a total discharge volume of 85 million m^3 (Fig. ~~8~~9~~(~~a~~)~~). When the NLB encountered a rainstorm with a 10-year return period, under the condition of water diversion, ~~the time at which~~ the sluices began to drain the flood ~~was the 30th~~after 28 hour of rain, which was ~~e~~36 hours ahead of the situation of no water diversion (at the 66th hour).~~,~~ ~~and the~~ The total flood volume that discharge ~~volume~~ by the Erji dam project was 104 million m^3 higher than that with~~ no~~out the affected of water diversion (Fig. ~~8~~9~~(~~b~~)~~). When the NLB encountered a storm with a 20-year return period, under the condition of water diversion, the time ~~at which~~ that the Erji dam project began to discharge the flood was ~~the~~ 26~~th~~ hours after the rain, which was 32 hours ahead of the situation with no water diversion (at the 58th hour).~~,~~ Comparing with the scenario without water diversion, ~~and~~ the total discharge volume ~~was~~ has increased 129 million m^3 ~~higher than that of no water diversion~~ (Fig. ~~8~~9~~(b~~c~~)~~).

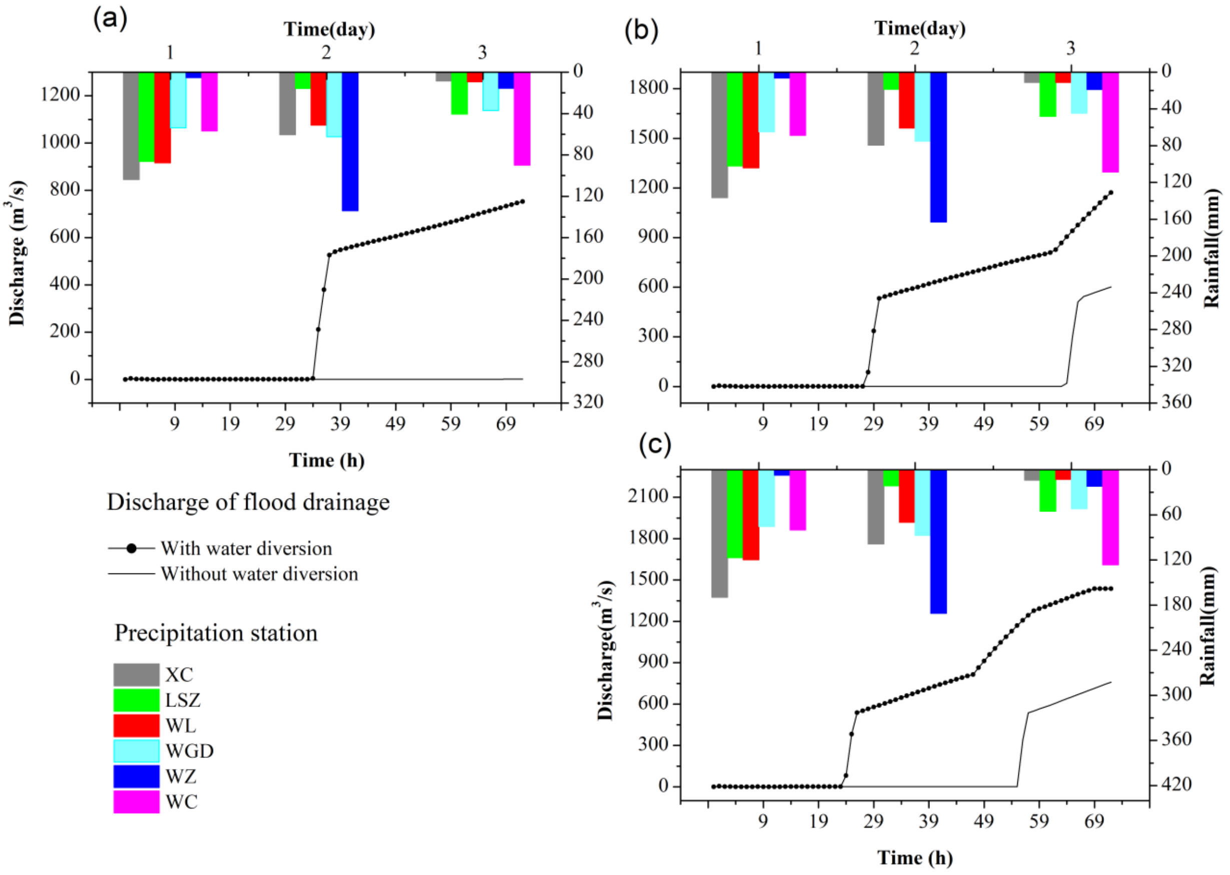


Figure ~~8~~9: Changes in the flood discharge of the Erji dam under water diversion with different storm levels. Flood discharge under rainfalls for different return periods: 5 year (a), 10 year (b), 20 year (c). The bar chart with different colors show the three-day rainfall process at each rainfall station. Black lines show the flood discharge process of the Erji dam with and without the effect of water diversion.

6 Conclusions and policy implications

The following selected conclusions are presented.

(1) In order to clarify the impacts that interbasin water transfer on the water-receiving area, this study using MIKE model to simulate the flood and waterlogging in NLB. One- and two-dimensional coupled floods and a waterlogging simulation model of the NLB were established to simulate the water diversion of the ER-SNWDP. The MIKE 11 model was applied to simulate the flow movement of water in the water diversion channel and the tributaries of NL, and the MIKE 21 model was applied to simulate the waterlogging in the lakeside area and the water flow in NL. The verification results show that the presented method can effectively simulate the flood and waterlogging process in NLB under the effect of the ER-SNWDP.

(2) The ER-SNWDP emergency water transfer to NL increases the risk of waterlogging damage in the lakeside area if it occurs simultaneously with DFAA~~abrupt drought-flood alternations~~. The increased water level caused by water diversion decreases the efficiency of waterlogging drainage, and as a result, the waterlogged area with an inundated water depth above 0.1 m increased by 0.99% and an inundated water depth above 0.5 m increased by 13.32%. The flood-discharge time of the Erji dam increased by 4 days, and the total discharge volume increased by 249 million m^3 during the simulation.

(3) The ER-SNWDP emergency water transfer to Shandong Peninsula raised the water level of NL, which acted as a regulation and storage lake. Compared with the no water transfer situation, the waterlogging areas in the lakeside area increased when NL encountered a storm with 5-year, 10-year and 20-year return periods under water diversion. The calculation results show that water diversion has a more obvious effect on the waterlogging area with an inundated water depth above 0.5 m, with the area increasing by 8.4-43.1%. The total volume of flooding discharged by the Erji dam also

increased. In addition, we found that with the increase in rainfall intensity, the influence of water diversion on the lakeside area in the NL inundated area gradually decreased and the water transfer had more serious effects in a rainstorm with a lower return period.

Certain implications for the management of interbasin water diversion and the lake basin along the route of water diversion project are presented below.

(1) For a complicated flood control and drainage system that contains a number of hydraulic structures, such as pumping stations, sluices, and embankments, flood movement behavior regulations must be implemented and flood disaster losses must be reduced by establishing a one- and two-dimensional coupled hydrodynamic model to accurately simulate the flow process and a clear movement direction of flooding.

(2) For a long-distance interbasin water transfer project, due to the large difference between high and low precipitation in the water-supply and water-receiving areas combined with global climate change and hydrological uncertainty, strengthening the analysis of emergency water diversion influence on flood control and drainage is not only necessary for scientific management of the inter-basin water transfer project but also conducive to realizing the expected benefits and reducing the negative effects of the project.

(3) To reduce the interbasin water transfer project effect on waterlogging in the water receiving area, we can take steps based on the following factors. First, additional emphasis should be placed on planning projects, increasing the waterlogging drainage pumping stations and enlarging the capacity of the flood discharge buildings in the water-receiving basin. Second, the hydrological forecasting and early warning ability should be improved and the accuracy and forecast period of the rainfall event should be increased and so to stop the water diversion or lower the water level of the lake before the rainstorm.

With respect to the directions for future research, we can expand on the following several aspects: (1) considering the vulnerability of hazard-affected bodies, populations as well as GDP and other information should be considered to more accurately reflect waterlogging disasters in the research area; and (2) a case study analysis of the balance between water transfer risk and water resource benefits should be conducted~~.~~; (3) in the future, adding the spatial distribution of roughness in NL to improve the accuracy of flood simulation in NL.

Data availability. All data except for the DEM of the lakeside and Nansihu Lake in 2013 were acquired by the authors. Data except for the DEM can be requested by email from the author wangzz77@163.com.

Competting interests. The authors declare that they have no conflict of interest.

Author contribution. Kun Wang prepared the manuscript with contributions from all co-authors. Kun Wang and Zongzhi Wang developed the model and Zongzhi Wang designed the scenario. Kelin Liu, Liang Cheng and Lihui Wang guided and participated in the modelling, Kelin Liu and Liang Cheng dealt with the boundary conditions of the model. Ailing Ye made the electric artworks and words processing.

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Appendix

Table 1 Statistical evaluation of model performance for water level simulations at selected gauging stations for 2007 and 2008 flood events.

Gauging station	NSE	
	2007	2008
Nanyang	0.72	0.65
Makou	0.69	0.76
Erji Lake (downstream)	0.67	0.98
Weishan	0.82	0.99

Table 2 Computational scenario setting

Sr. no.	Initial water level of NL	Rainfall	Whether the ER-SNWDP works during the simulation
①	33.01 m in upper lake, 32.20 m in lower lake~~Actual water level on August 22, 2003~~	Actual daily rainfall from August 22 to September 2, 2003	NO
②	34.0 m in upper lake, 32.3 m in lower lake		
③	Actual water level on August 22, 2003	Designed storm with return periods of 5 years	NO
④		10 years	
⑤		20 years	
⑥	34.0 m in upper lake, 32.3 m in lower lake	5 years	YES
⑦		10 years	
⑧		20years	

Table 3 Results of waterlogging in the lakeside area of NL

Sr. no.	Water depth of NL		Area with an inundated depth above 0.1 m		Area with an inundated depth above 0.5 m	
	Average (m)	Max (m)	Total area (km^2)	Area ratio (%)	Total area (km^2)	Area ratio (%)
①	2.47	5.96	1126.59	32.51	383.68	11.07
②	2.80	6.14	1160.85	33.50	434.77	12.55

Table 4 Increment of the waterlogging area in the lakeside area of NL

Contrastive analysis	Area with an inundated depth above 0.1 m			Area with an inundated depth above 0.5 m		
	Increment (km^2)	Relative increase (%)	Area ratio increase	Increment (km^2)	Relative increase (%)	Area ratio increase
Variation	34.26	3.04	0.99	51.09	13.32	1.47

Table 5 Results of waterlogging simulations of the lakeside area under different scenarios.

Sr. no.	Water depth of NL		Area with an inundated depth above 0.1 m		Area with an inundated depth above 0.5 m	
	Average (m)	Max (m)	Total area (km^2)	Area ratio (%)	Total area (km^2)	Area ratio (%)
③	1.86	5.23	793.75	22.91	60.63	1.75
④	2.03	5.87	907.85	26.20	159.98	4.62
⑤	2.41	6.31	1002.05	28.92	240.54	6.94
⑥	2.10	5.87	816.02	23.55	86.77	2.50
⑦	2.26	6.10	926.40	26.73	181.73	5.24
⑧	2.17	6.08	1016.68	29.34	260.76	7.53