Hydrological changes along the Jing River and its causal analysis

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Abstract. The hydrological response of rivers to upstream reservoir regulation is one of the increasingly important research issues of watershed management. In this study, a hydrodynamic coupling model was used to simulate water level and flow processes of the Jing river and diversion flow of three outlets before and after the operation of TGP (Three Gorges Projects). The results indicated that water level and flow of three diversion channels both decreased in flood and dry seasons: the compensation regulation of the TGP was significant to maintain the water level and flow of three diversion outlets in the Jing river, but it also increased zero-flow days in the diversion channels of the Yangtze River. The riverbed erosion of channels in the upper reaches as well as lower reaches caused hydraulic gradient varying so much that it can’t be ignored in the water exchange process between the Yangtze and Jing river. This mechanism cooperates with the operation of TGP to change the natural process of the Yangtze-Jing river’s hydrologic process. This work provides essential information for future water resources and environmental management of the river-lake system and facilitates the effective flow regulation of dams, which has significant implications not only for the Dongting river-lake system but also the similar lakes and rivers elsewhere.

1. Introduction
Hydraulic river-lake relation, referring to interactions between naturally connected rivers and lakes, has been frontiers in some aspects of water sciences. To release universal and particular laws of the hydrological cycle involving many aspects, further analysis of hydraulic river-lake relations can predict the trend of the relationship in the river-lake system then raise effective measures to control. Under the impact of the Three Gorges Project (TGP), research on the main-stream of the Yangtze and hydrographic features of Dongting lake shows that their water exchange mechanism is basically in balance, and even make up a supplement of the runoff of the estuary of Dongting lake by 5% [1]. Back to 2000, there is no obvious change of runoff in the Jing river reach of the Yangtze River, which is a random chance. However, the regulation and storage of TGP will cause the runoff into the Jing river course to be greatly adjusted in the middle and low water periods, in return, these changes will affect the scouring and water level changes of the Jing river and so on [2].

And results show that the water surface slope of Jianli-Chenglingji and Chenglingji-Luoshan increased after the water storage of TGP [3]. It can be divided into three stages as 1991-2002, 2003-2007 and 2008-2017, the occurrence time of monthly minimum water surface gradient in Jianli Chenglingji reach has been delayed, the corresponding Chenglingji water level has increased, the concentration ratio has decreased, and the lake's jacking effect on the river has been weakened [4]. The reason for the decrease of the jacking dissipation ratio in three periods is the weakening of the jacking
effect rather than the strengthening of the dissipation effect [5-8]. Whether TGP is under operation or not, the natural inflow is the primary factor to reduce partial discharge. Since the operation of the Three Gorges reservoir, the average runoff of Zhicheng station in 2003-2008 and 2009-2015 is 406.4 billion m$^3$ and 412.8 billion m$^3$ respectively, which is far lower than that before the operation of TGP, and more than 60% of the reduction of the partial flow is caused by the partial dry of natural inflow [9-10]. After the optimal operation of TGP, with the impoundment time in advance and the rise of the impoundment water level, the partial discharge of the three outlets is further reduced [11]. From 2003 to 2008, the contribution rates of natural inflow, reservoir operation, and riverbed scouring in the process of runoff reduction are 76.19%, 10.32%, and 13.49% respectively, while from 2009 to 2015, the contribution rates of the three are 66.05%, 19.75% and 14.20% respectively [12-13].

According to statistics, since 1980, the annual runoff of the Jing River at three months has shown a clear downward trend, the number decreased from 69,605 million m$^3$ in 1980~2002 to 47,960 million m$^3$ in 2003~2015, nearly a reduction of 31.1% [14-15]; the diversion ratio of the Jing River's three mouths to the mainstream of the Yangtze River also showed a similar trend, the number decreased from 15.74% in 1980~2002 to 11.95% in 2003~2015. Excluding the dry year and abundant year, the downward trend in runoff changes and diversion ratios will be more pronounced [16-17].

However, current studies of river and lake diversions do not consider the coupling of mainstem flows with three mouths and Dongting lakes, nor do they include and separate the topographic adjustments and TGP’s operation on its hydrological characteristics. In this paper, it simulated the hydrodynamic processes of the Jing River mainstem and the three-gate diversion before and after the water storage of TGP. The changes in the hydrological situation of the Jing River mainstem and three mouth due to different dispatch periods of TGP and channel topography adjustments. This study provides new strategies for the future operation of TGP, ecological environment planning, and protection of Dongting Lake, as well as new strategies for the hydraulic power exchange of other lakes and rivers.

2. Study area
Yangtze River is the third-longest river in the world, which originated from the Tibetan plateau and ends at the sea area northeast of Dong Bei. Based on the geographical environment and hydrographic features, the Yangtze River has been cut into three parts, and the Jing River locates at the middle reaches. Jing River is composed of the reaches from Zhijiang to Chenglingji, crossing Hubei and Hunan. Due to its zigzag channel and harsh surface slope, its whole length can be about 347.2km and abundant in waterpower resources. Furthermore, the Jing River is divided into the upper reach of the Jing River and the lower reach of the Jing River by Ouchikou. There are significant differences in each reach. The river network shape of the upper reach presents as typical netted shape, aits develop well in it. But the lower reach changes frequently during the past decades. Since the 20’s century, affected by human activities, its shape mainly shows as the convex bank deposits and pushes forward, while the concave bank collapses and retreats.
3. Methodology
This study collected the speed and flow quantity of hydrological stations alongside the mainstream of the Jing river as well as the diversion flow of 3 diversion outlets of the Jingjiang River. Then it constructed a 1D and 2D hydrodynamic model powered by DHI to restore the runoff before the operation of TGP to find out the relationships and differences between the two situations.

MIKE11 dynamic river network hydrodynamic simulation is a one-dimensional comprehensive treatment software that is widely used in river and wetland ecological and water quality evaluation, flood area erosion analysis, comprehensive analysis of groundwater and surface water, drainage, and irrigation research, real-time flood prediction, etc. HD hydrodynamic module is the basis of other modules in MIKE 11. By simulating the unsteady flow in the open channel and river network, the time series of water level flow is obtained, to carry out the mathematical simulation calculation of rainfall-runoff, sediment transport, pollution load, convection-diffusion, and water quality.

The core of MIKE11 is to solve the completely nonlinear Saint Venant equations of open channel flow.

\[
\begin{aligned}
\frac{\delta Q}{\delta x} + \frac{\delta A}{\delta t} &= q \\
\frac{\delta Q}{\delta t} + \delta \left( \frac{\alpha O^2}{A} \right) + gA \frac{\delta h}{\delta x} + \frac{gO|Q|}{C^2AR} &= 0
\end{aligned}
\] (1)

The equations are discretized by the Abbott Ionescu six-point implicit finite difference method. The river network is discretized into alternating grids, and the linear equations are solved by the catch-up method. At the same time, the equations are suitable for tree or ring river network, achieving the purpose of stability and high calculation accuracy.
Fig.2 The calculation grid of each section

Continuous equation
\[ \frac{\partial Q}{\partial x} + b_j \frac{\partial h}{\partial t} = q \] (2)

Momentum equation
\[ \frac{\partial Q}{\partial x} \approx \frac{Q_j^{n+1} - Q_j^n}{\Delta t} \] (3)

By simplifying the flow continuity equation and the motion equation
\[ \alpha_j Q_{j+1}^{n+1} + \beta_j h_{j+1}^{n+1} + \gamma_j Q_{j+1}^{n+1} = \delta_j \] (4)
\[ \alpha_j h_{j+1}^{n+1} + \beta_j Q_{j+1}^{n+1} + \gamma_j h_{j+1}^{n+1} = \delta_j \] (5)

Nodal control volume equation
\[ \frac{H_{j+1}^{n+1} - H_j^n}{\Delta t} A_{ji} = \frac{1}{2} (Q_{a,n-j}^n + Q_{b,n-j}^n - Q_{c,j}^n) \]
\[ + \frac{1}{2} (Q_{a,n-j}^{n+1} + Q_{b,n-j}^{n+1} - Q_{c,j}^{n+1}) \] (6)

External boundary control volume condition
\[ \frac{H_{j+1}^{n+1} - H_j^n}{\Delta t} A_{ji} = \frac{1}{2} (Q_j^n - Q_j^{n+1}) + \frac{1}{2} (Q_j^n - Q_j^0) \] (7)

The accuracy of the mathematical simulation depends on the accuracy of the boundary conditions. Therefore, the boundary conditions must be limited to avoid the discontinuity or objective contradiction in the continuous calculation of parameter adjustment. In the typical flood simulation, the major flood makes the dam break. To limit the depth of water, the dry wet boundary is divided into three types: dry, semi-dry, and wet, every time step calculated by the model will check the water depth of all cell grids, and determine the boundary type according to the screening conditions set by the user.

4. Results and discussion
The Three Gorges Reservoir officially entered the 175 m experimental water storage period in 2008, so the four-year series from 2008 to 2011 was selected as the typical hydrological process, and the five representative stations of the Jing River section dry flow (i.e. Zhicheng Station, Sha City Station, Xinchang Station, Jianli Station, and Luoshan Station) and the Chenglingji Water Level Station at the outlet of Dongting Lake from 2008 to 2011 (1 January to 31 December) were used, and the pre-storage water level flow data of the Three Gorges Project was reduced by the 1D/2D water environment coupling model. Quantitative comparative analysis of the water level along the mainstream of the Jing River before and after the Three Gorges Project, the ratio of the three diversions into the lake, and the changes in the water level and flow process at the Chenglingji outlet of the lake, and on this basis,
further explore the impact of the Three Gorges water storage on the water environment characteristics of Dongting Lake.

4.1. Streamflow variations

The water level flow process calculated by the one-dimensional and two-dimensional coupled model is in good agreement with the actual data, and the water level simulation data of the Jing River before the Three Gorges Project reservoir and the actual measured water level data of the hydrological station after the Three Gorges Project reservoir are used to study the changes in the hydrological process of Dongting Lake before and after the reservoir.

As it shows in Fig.3, it concludes that before and after every regulation in TGP, the mainstream of Jing river displays the same trend: pre-rainy season sees the water level of TGP is decreasing while the mainstream is increasing for the sake of emptying its storage capacity. When it turns into the flood season, the two consequences do not differ that much. During the dry season, the water level decreased sharply but it’s obvious that after the impoundment line is higher than before impoundment which proves the operation of TGP supplied a lot of runoff to Jing river.

4.2. Water level changes along the channels

Take channels’ changing into consideration and contrast the following two figures, the statistics pictures that when under the same flow, water level descends apparently. Dividing Zhicheng’s flow into three ranks as low flow(0~10000m³/s), medium flow(20000~30000m³/s) and high
flow (40000~50000 m$^3$/s). The low flow decreased by 1.61%, the medium flow decreased by 1.25% when the high flow decreased by 0.89%. Same as Zhicheng, there are three ranks in Shashi, low flow (0~10000 m$^3$/s), medium flow (15000~25000 m$^3$/s), and high flow (40000~50000 m$^3$/s). The low flow decreased by 5.18%, the medium flow decreased by 2.34% when the high flow decreased by 2.59%.

The adjustments in two stations are diverse but it uncovered the fact that the low flow has been affected intensively and shown the most declining. Furthermore, the division into Songzikou, Taipingkou, and Ouchikou is decreasing, weakening the supply offered by TGP to the Jing River.

![Fig.4 Water level flow relationship](image)

4.3. Variation in flow diversion ratio
As shown in the figure, in the dry season, Taipingkou and Ouchikou were nearly cut off without any branch afflux therefore Songzikou got all the diversion flow. In the rainy season, Songzikou shares 60% to 70% of diversion flow, Taipingkou and Songzikou split equally the left flow. Under the impact of TGP, before and after impoundment, Taipingkou’s diversion flow grows mildly and the prospect of three diversion stays the same. The most significant difference lies in 10~11 month, before impoundment, the decline speed of diversion ration has a short-time slow down; after impoundment, the trend of diversion ratio presents up first and then down. The phenomenon is caused by water storage, lowering runoff, and exacerbating low flow then increasing overall percentage.
In fig.7, it made a systemic and comprehensive analysis to detect transformation in terrain. It’s obvious that the flow of Songzikou had increased, within which Xinjiangkou’s maximum increment is 7.76%, the average increment is 3.35%. Shadaoguan’s maximum increment is 14.04%, the average increment is 6.31%, the higher the flow is, the more the diversion flow is after adjustment. Taipingkou’s diversion had decreased, Mituosi’s maximum reduction is 26.38%, the average reduction is 14.17%. Ouchikou’s flow reduction was more notable, the maximum reduction is 74.14%, the average reduction is 61.61%, unlike Songzikou, low flow in Taipingkou and Ouchikou varied more significant and had reduced more.

Above all, the change of water surface slope caused by terrain made diversion flow of Songzikou increased but the others decreased. Although in Yangtze-Jing river’s interaction, the impoundment takes a dominant position, this terrain change weakened its compensation and also make up an important trigger.
5. Conclusions
This study thoroughly uses the hydrodynamic coupling model to simulate water level and flow of Jing river and diversion flow of three before and after operation of TGP. We found that after operation of TGP, water level and flow of three diversions both decreased in flood season; in the dry season, TGP’s effect of water Replenishment is significant, making up compensation regulation of water level and flow of three diversions in Jing river, but it also adds zero-flow days in the diversion of three. The change of channels in upper reaches as well as lower reaches riverbed entrenchment, causing hydraulic gradient to vary so much that it can’t be ignored in the water exchange process between the Yangtze and Jing river. This mechanism cooperates with the operation of TGP to change the natural process of the Yangtze-Jing river’s hydrologic process.

Acknowledgments
This research was supported by The National Key Research and Development Program of China (Grant No.2016YFC0400901).

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