Study on the Evolution of Runoff in Middle and Lower Reaches of Yangtze River Under Low Water Conditions

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Abstract. In recent years, due to factors such as extreme climate and human activities, droughts have occurred frequently in middle and lower reaches of Yangtze River, causing certain adverse effects. In order to understand the runoff evolution law in middle and lower reaches of Yangtze River under dry conditions, and provide scientific reference for the water replenishment scheduling of the Three Gorges Project during dry water period. This study analyzed the measured data of various stations along middle and lower reaches of Yangtze River before and after the construction of the Three Gorges Project, to obtain changes in runoff propagation characteristics in various sections of the Yichang to Datong River section. Based on MIKE11, a hydraulic model of middle and lower reaches of Yangtze River was constructed, to study the dry water propagation characteristics of middle and lower reaches of Yangtze River under different scheduling methods of the Three Gorges. The research results have certain significance for the rational replenishment and scheduling of the Three Gorges Reservoir during dry water period, ensuring the production, living, and ecological water use in the middle and lower reaches, and further meeting the needs of navigation, irrigation, urban water supply, and resistance to salt tide invasion during the dry season.

Keywords: Middle and lower reaches of Yangtze River; Dry water; Runoff evolution law; MIKE11

1 Introduction

With rich water resources, there are numerous rivers and lakes in the middle and lower reaches of the Yangtze River. However, due to several factors like extreme climate and human activity, droughts occur frequently [1], which make varying degrees of impact on agriculture, person and animal drinking, ecological environment, so

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cio-economy, etc [2]. Serving as a key project in the management, development and preservation of the Yangtze River basin, the Three Gorges Reservoir yields comprehensive benefits including flood control, water supply, power generation and shipping. With socio-economic development of the river basin, the water demand for production, daily life and ecological needs is rising continuously in the middle and lower reaches of the Yangtze River. Therefore, it’s crucially important to maximize advantages of the controlled reservoir with Three Gorges as its core, like the drought-resistance and water-replenishment, to guarantee the security of the water supply in the middle and lower reaches of the Yangtze River [3].

In recent years, many experts and scholars have conducted research on the water level and discharge during the dry season in the Yangtze River Basin, as well as the water replenishment scheduling of the Three Gorges Project in extremely dry years. Dai Lingquan et al. [4] studied the spatial distribution pattern of water replenishment effects in Dongting Lake under different drawdown methods, based on a constructed integrated river-lake coupled hydrodynamic model, and assessed the impact of different schemes on power generation. Wu Qiong et al. [5], utilizing the measured data of the mainstream in the middle and lower reaches of the Yangtze River after the operation of the Three Gorges Reservoir, analyzed the changes in the cross-sectional profiles at each station along the way, the trend of the water level and flow relationship in low dry water, and the changes in riverbed erosion and deposition. Their findings revealed that after the operation of the Three Gorges Reservoir, water levels during periods of low and dry flow at representative stations along the middle and lower reaches decreased to varying degrees at the same flow rate, among which the decrease of Shashi Station is the most significant, and the erosion intensity in the river channel from Yichang to Chenglingji is the strongest. Yang Chenggang et al. [6] investigated the trends and causes of low water levels in the middle and lower reaches of the Yangtze River, since the Three Gorges Reservoir began storing water and operating. It was indicated that there was a cumulative decline in low water levels in the middle reaches of the Yangtze River, particularly in the Jingjiang River section. Considering the existing studies.

Based on the existing research results on the characteristics of water level and discharge changes during the dry season in Yangtze River Basin, as well as the Three Gorges water replenishment scheduling, this study analyzes the changes in runoff propagation characteristics, between stations along the Yichang-Datong section of the Yangtze River before and after the construction of the Three Gorges Reservoir. By constructing a hydrodynamic model of the middle and lower reaches of the Yangtze River using MIKE11, the study further analyzes the propagation characteristics of the dry water of the mainstream in these reaches, under different operational modes of the Three Gorges Reservoir. Corresponding to the characteristics of flood propagation, it fills the gap in research on the characteristics of low water propagation in the middle and lower reaches of the Yangtze River. At the same time, in the context of increasingly prominent extreme climates such as drought, this research plays a significant role in rational water replenishment and operation of the Three Gorges Reservoir during the dry season, ensuring water supply for "production, living, and ecological" needs in the middle and lower reaches, and further meeting the demands of shipping, irrigation, urban water supply, and defense against saltwater intrusion during the dry season.

2 Study Area, Data and Methodology

2.1 Study Area

The study area is concentrated in the mainstream of the middle and lower reaches of the Yangtze River, specifically the section from Yichang to Datong in the downstream of the Three Gorges Dam. The stations involved in the analysis and calculations include Yichang Station, Zhicheng Station, Shashi Station, Jianli Station, Luoshan Station, Hankou Station, Huangshigang Station, Matouzhen Station, Jiujiang Station, Balijiang Station, Anqing Station, and Datong Station. The middle and lower reaches of the Yangtze River are studied in segments based on these stations along the way.

2.2 Data Resources

In the factual analysis section of this study, we utilized the flow and water level data of each station mentioned in section 1.1 during the dry seasons from 1990 to 2023. For the model construction section, we employed the following data and materials: water level and flow process data corresponding to the Three Gorges regulation process during the dry season at major control stations, along the mainstream and tributaries of the Yangtze River, water level-flow relationship data from key stations, rainfall data from various rainfall stations for different time periods, results of daily evaporation analysis for the middle and lower reaches of the basin, and cross-sectional measurement data collected in 2022 from the survey along the Yichang to Datong section of the river, as well as from the survey on various tributaries, the "Four Waters" and lake areas of Dongting Lake, and the "Five Rivers" and lake area of Poyang Lake.

2.3 Methodology of Analysis

(1) Employing peak-valley feature recognition method for the analysis of runoff propagation time and the response time for rise based on actual conditions. The basic principle of this method is to deduct the influence of interval flow and restore the corresponding runoff process of downstream control stations. Based on the time difference between peak/valley occurrence in the runoff process of upstream and downstream stations, the runoff propagation time between two control stations is calculated [7].

(2) Applying the correlation chart method in the analysis of smoothing features based on actual conditions and calculating rise difference coefficient. The basic principle of the correlation diagram method is to draw a correlation diagram of the maximum discharge or highest water level of upstream and downstream stations, to reflect

the correlation between the maximum discharge or highest water level of upstream and downstream stations. The basic principle of the calculation method for the coefficient of variation, is to calculate the ratio between the increase in downstream station runoff process and the increase in upstream station runoff process, and analyze the runoff flattening situation, by combining the discharge/water level correlation chart of upstream and downstream stations and the coefficient of variation [7].

(3) The study on the propagation characteristics of runoff in the middle and lower reaches of the Yangtze River under different dispatching modes in the Three Gorges, relies on the hydrodynamic module and rainfall runoff module in MIKE11 for calculation and analysis. The basic principle of the MIKE11 model is to use the Saint Venant equation system as the basic equation to simulate one-dimensional hydrodynamic flow in the river channel. This study uses the RR and HD modules in MIKE11 for model construction and parameter setting, and constructs a hydraulic production convergence coupling model for the Yichang Datong section for research and analysis [8-11].

3 Study Findings

3.1 Analysis of Changes in Runoff Propagation Characteristics in the Mainstream of the Middle and Lower Reaches of the Yangtze River Based on Actual Conditions

3.1.1 Analysis of Propagation Time.

Multiple samples from different sections along the Yichang to Datong reach before and after the construction of the Three Gorges Reservoir was selected, to analyze the runoff propagation time between upstream station and downstream station in each section. The results are showed in Table 1. From Table 1, it can be found that after the construction of the Three Gorges Reservoir, the runoff propagation times have all decreased by varying degrees in the river section from Yichang to Zhicheng, Zhicheng to Shashi, Shashi to Jianli, with propagation times decreasing by 5 hours, 4 hours and 4 hours respectively. The propagation times virtually remained no change in the river section from Jianli to Luoshan, Luoshan to Hankou, Hankou to Huangshigang, Huangshigang to Matouzhen, Matouzhen to Jiujiang, Jiujiang to Balijiang, Balijiang to Anqing, Anqing to Datong.

Table 1. Statistical Table of Runoff Propagation Time in Different Sections from Yichang to Datong along the Yangtze River Before and After the Construction of the Three Gorges Reservoir

Section	Before				After			
	Number of Samples	Min(h)	Max(h)	Avg.(h)	Number of Samples	Min(h)	Max(h)	Avg.(h)
Yichang ~ Zhicheng	29	2.5	12	6.9	44	1	4.3	2.1
Zhicheng ~ Shashi	39	6	15	9.9	39	3	10	6
Shashi ~ Jianli	31	8.5	20	13.3	24	6	13	9.3
Jianli ~ Luoshan	20	12	26	18.5	30	12	24	18.2
Luoshan ~ Hankou	31	7	20.6	13.4	25	9	20	13.2

Hankou ~ Huangshigang	31	6	21.6	13.6	39	6	24	14.2
Huangshigang ~ Matouzhen	21	6	18	11.4	32	7	19	11
Matouzhen ~ Jiujiang	24	1.6	12	7.7	37	4	11	7.2
Jiujiang ~ Balijiang	10	4.4	6	5.8	34	3	9	5.8
Balijiang ~ Anqing	10	12	24	16.8	32	12	22	16.9
Anqing ~ Datong	20	0	12	6.9	30	0	10	7

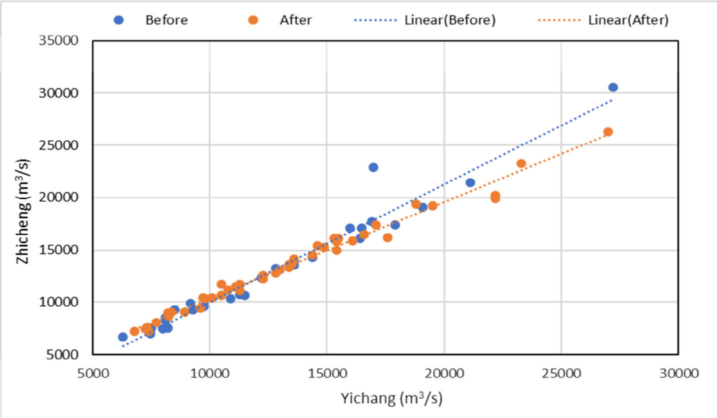
The obtained runoff propagation times were compared and analyzed with the previously studied flood propagation times in the middle reaches of the Yangtze River. The results are presented in Table 2. It can be found that before and after the construction of the Three Gorges Reservoir, the propagation times of low water are generally longer than that of flood water in each section from Yichang to Luoshan along the middle reaches of the Yangtze River.

Table 2. Statistical Table of Propagation Time for Low Water and Flood in Different Sections from Yichang to Luoshan along the Yangtze River Before and After the Construction of the Three Gorges

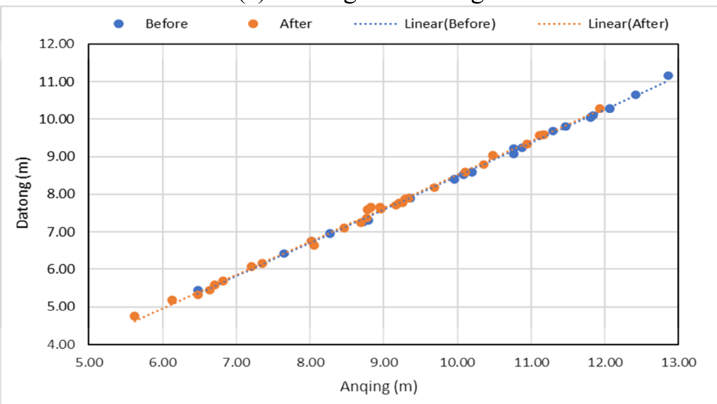
River Section	Before			After		
	Propagation Time(Low Water)(h)	Propagation Time(Flood)(h)	Propagation Time Difference (h)	Propagation Time(Low Water)(h)	Propagation Time(Flood) (h)	Propagation Time Difference (h)
Yichang ~ Zhicheng	6.9	4.6	2.3	2.1	1.7	0.4
Zhicheng ~ Shashi	9.9	9.9	0	6.0	4.6	1.4
Shashi ~ Jianli	13.3	13	0.3	9.3	9	0.3
Jianli ~ Luoshan	18.5	18.1	1	18.2	18.1	0.1

3.1.2 Analysis of Hydraulic Smoothing Feature.

Based on the sample analysis in the previous section, we established the corresponding relationships of low water runoff in each section, along the main stream of the middle and lower reaches of the Yangtze River before and after the construction of the Three Gorges Reservoir, specifically for the sections from Yichang to Zhicheng, Zhicheng to Shashi, Shashi to Jianli, Jianli to Luoshan, Luoshan to Hankou, Hankou to Huangshigang, Huangshigang to Matouzhen, Matouzhen to Jiujiang, Jiujiang to Balijiang, Balijiang to Anqing, Anqing to Datong. Taking the Yichang-Zhicheng and Anqing-Datong sections as examples of the flow correlation and water level correlation (Figure 1). We analyzed the smoothing effect of low-water runoff in each section of the middle and lower reaches of the Yangtze River before and after the construction of the Three Gorges Reservoir. The correlation of low-water runoff in each section before and after the reservoir construction was found to be good.



(a)Yichang～Zhicheng



(b)Anqing～Datong

Fig. 1. Comparison of Flow/Water Level Relationships Among Different River Sections Before and After the Construction of the Three Gorges Reservoir

Multiple samples from different sections along the Yichang to Datong reach before and after the construction of the Three Gorges Reservoir was selected, to analyze the rise difference coefficient between upstream station and downstream station in each section. The results are showed in Table 3. From Table 3, it can be found that after the construction of the Three Gorges Reservoir, the degree of smoothing has been enhanced to varying degrees in the river sections from Yichang to Zhicheng, Zhicheng to Shashi, Shashi to Jianli. The degree of smoothing virtually remained no change in the river section from Jianli to Luoshan, Luoshan to Hankou, Hankou to Huangshigang, Huangshigang to Matouzhen, Matouzhen to Jiujiang, Jiujiang to Balijiang, Balijiang to Anqing, Anqing to Datong.

Table 3. Statistical Table of Rise Difference Coefficients during Low-Water Periods for the Yichang-Datong Section of the Main Stream in the Middle and Lower Reaches of the Yangtze River Before and After the Construction of the Three Gorges Reservoir

River Segment	Before				After			
	Number of Samples	Min	Max	Avg.	Number of Samples	Min	Max	Avg.
Yichang ~ Zhicheng	20	0.63	0.98	0.85	25	0.65	0.99	0.82
Zhicheng ~ Shashi	30	0.49	0.96	0.77	31	0.41	0.74	0.63
Shashi ~ Jianli	21	0.19	0.96	0.76	22	0.45	0.95	0.71
Jianli ~ Luoshan	21	0.53	2.12	1.11	30	0.89	2.23	1.14
Luoshan ~ Hankou	27	0.81	1.08	0.91	25	0.58	1.14	0.94
Hankou ~ Huangshigang	31	0.75	1.13	0.97	39	0.74	1.33	0.93
Huangshigang ~ Matouzhen	17	0.66	0.96	0.90	31	0.54	1.03	0.90
Matouzhen ~ Jiujiang	21	0.64	1.21	0.96	36	0.78	1.05	0.95
Jiujiang ~ Balijiang	10	0.82	1.14	1.00	33	0.91	1.13	1.02
Balijiang ~ Anqing	10	0.80	0.93	0.86	31	0.72	1.09	0.86
Anqing ~ Datong	20	0.84	1.08	0.92	29	0.79	1.23	0.94

3.1.3 Analysis of the Response Time for Rise.

Selecting eight runoff processes during water replenishment scheduling by the Three Gorges Project under low-flow conditions, the response times of flow and water level rises at each station from Yichang to Datong reach were analyzed statistically. Through the analysis, the response times for flow and water level rises at each station were obtained. (Table 4,5) From the results, it can be found that the response times for flow and water level rises at different stations were basically consistent with each other, and it was consistent with the research of Xu Yinshan et al. [12] on the propagation time of water releasing from the Three Gorges Reservoir to main downstream stations under low-flow conditions.

Table 4. Statistical Table of Flow Rise Response Times at Various Stations in the Section from Yichang to Datong

Station		Time							
The Time for Increasing the Discharge from the Three Gorges Reservoir		2011/9/19 2:00	2013/9/16 2:00	2014/10/27 2:00	2018/1/22 6:00	2019/5/14 6:00	2021/1/5 8:00	2022/10/1 9:00	2023/12/6 7:00
Yichang	Time to Rise	2011/9/19 5:00	2013/9/16 6:00	2014/10/27 7:00	2018/1/22 7:00	2019/5/14 7:00	2021/1/5 8:00	2022/10/1 10:00	2023/12/6 8:00
Zhicheng	Time to Rise	2011/9/19 7:00	2013/9/16 8:00	2014/10/27 9:00	2018/1/22 9:00	2019/5/14 8:00	2021/1/5 10:00	2022/10/1 12:00	2023/12/6 9:00
	Rise Response Time(h)	2	2	2	2	1	2	2	1

Shashi	Time to Rise	2011/9/19 14:00	2013/9/16 13:00	2014/10/27 18:00	2018/1/22 16:00	2019/5/14 12:00	2021/1/5 15:00	2022/10/1 20:00	2023/12/6 21:00
	Rise Response Time(h)	9	7	11	9	5	7	10	13
JIanli	Time to Rise	2011/9/19 18:00	2013/9/17 1:00	2014/10/28 2:00	2018/1/23 3:00	2019/5/14 23:00	2021/1/5 22:00	2022/10/2 4:00	2023/12/7 1:00
	Rise Response Time(h)	13	19	19	20	16	14	18	17
Luoshan	Time to Rise		2013/9/18 1:00	2014/10/28 10:00	2018/1/23 18:00		2021/1/6 15:00	2022/10/3 1:00	2023/12/7 20:00
	Rise Response Time(h)		43	27	35		31	39	36
Hankou	Time to Rise		2013/9/18 13:00	2014/10/29 7:00	2018/1/24 9:00		2021/1/7 16:00	2022/10/3 16:00	2023/12/8 8:00
	Rise Response Time(h)		55	48	50		56	54	48
Jiujiang	Time to Rise		2013/9/20 20:00	2014/10/30 23:00	2018/1/26 0:00		2021/1/9 3:00	2022/10/4 18:00	2023/12/9 15:00
	Rise Response Time(h)		110	88	89		91	80	79
Datong	Time to Rise		2013/9/21 0:00	2014/10/31 20:00	2018/1/26 22:00		2021/1/10 0:00	2022/10/6 0:00	2023/12/10 21:00
	Rise Response Time(h)		114	109	111		112	110	109

Table 5. Statistical Table of Water Level Rise Response Times at Various Stations in the Section from Yichang to Datong

Station		Time							
The Time for Increasing the Discharge from the Three Gorges Reservoir		2011/9/19 2:00	2013/9/16 2:00	2014/10/27 2:00	2018/1/22 6:00	2019/5/14 6:00	2021/1/5 8:00	2022/10/1 9:00	2023/12/6 7:00
Yichang	Time to Rise	2011/9/19 5:00	2013/9/16 6:00	2014/10/27 7:00	2018/1/22 7:00	2019/5/14 7:00	2021/1/5 8:00	2022/10/1 10:00	2023/12/6 8:00
Zhicheng	Time to Rise	2011/9/19 7:00	2013/9/16 8:00	2014/10/27 9:00	2018/1/22 9:00	2019/5/14 8:00	2021/1/5 10:00	2022/10/1 12:00	2023/12/6 9:00
	Rise Response Time(h)	2	2	2	2	1	2	2	1
Shashi	Time to Rise	2011/9/19 14:00	2013/9/16 15:00	2014/10/27 18:00	2018/1/22 16:00	2019/5/14 12:00	2021/1/5 15:00	2022/10/1 22:00	2023/12/6 21:00
	Rise Response Time(h)	9	9	11	9	5	7	12	13
JIanli	Time to Rise	2011/9/19 18:00	2013/9/17 0:00	2014/10/28 4:00	2018/1/23 3:00	2019/5/14 21:00	2021/1/5 22:00	2022/10/2 6:00	2023/12/7 8:00
	Rise Response Time(h)	13	18	21	20	14	14	20	24
Luoshan	Time to Rise		2013/9/17	2014/10/28 10:00	2018/1/23		2021/1/6 20:00	2022/10/3 0:00	2023/12/7 19:00

			23:00		15:00				
	Rise Response Time(h)		41	27	32		36	38	35
Hankou	Time to Rise		2013/9/18 8:00	2014/10/29 2:00	2018/1/24 9:00		2021/1/7 11:00	2022/10/3 16:00	2023/12/8 10:00
	Rise Response Time(h)		50	43	50		51	54	50
Huangshigang	Time to Rise		2013/9/19 11:00	2014/10/29 17:00	2018/1/24 15:00		2021/1/7 21:00	2022/10/4 5:00	2023/12/8 20:00
	Rise Response Time(h)		77	58	56		61	67	60
Matouzhen	Time to Rise		2013/9/19 13:00	2014/10/30 0:00	2018/1/25 9:00		2021/1/8 10:00	2022/10/4 9:00	2023/12/9 11:00
	Rise Response Time(h)		79	65	74		74	71	75
Jiujiang	Time to Rise		2013/9/20 4:00	2014/10/30 15:00	2018/1/25 21:00		2021/1/8 22:00	2022/10/5 2:00	2023/12/9 15:00
	Rise Response Time(h)		94	80	86		86	88	79
Balijiang	Time to Rise		2013/9/20 13:00	2014/10/30 15:00	2018/1/26 2:00		2021/1/9 4:00	2022/10/5 9:00	2023/12/10 4:00
	Rise Response Time(h)		103	80	91		92	95	92
Anqing	Time to Rise		2013/9/20 14:00	2014/10/31 6:00	2018/1/26 21:00		2021/1/9 23:00	2022/10/5 21:00	2023/12/10 12:00
	Rise Response Time(h)		104	95	110		111	107	100
Datong	Time to Rise			2014/11/1 5:00			2021/1/9 23:00	2022/10/6 8:00	2023/12/10 20:00
	Rise Response Time(h)			118			111	118	108

3.2 Analysis of Changes in Runoff Propagation Characteristics in the Mainstream of the Middle and Lower Reaches of the Yangtze River Based on MIKE11

3.2.1 Construction of Hydraulics Model.

Building the hydraulics model of the middle and lower reaches of the Yangtze River based on MIKE11, the water replenishment process of the Three Gorges project under low-flow conditions was selected for model parameter calibration, utilizing the low-flow process from September 24 to October 24, 2022, to calibrate the parameters. The results were shown in Table 6, and the fitting of the water level hydrograph was based on the example of Zhicheng Station (Figure 2). From the results, it can be found that the simulated water level process fits well with the measured process. Overall, the constructed hydraulic model for the Yichang-Datong section showed reliable simulation accuracy.

Table 6. Evaluation Table for Water Level Errors During the Calibration Period

Station	Measured Value		Simulated value		Water Level Error (m)	Peak Timing Error (h)	Process Determinacy Coefficient
	Highest Water Level(m)	Corresponding Time	Highest Water Level(m)	Corresponding Time			
Zhicheng	39.92	10-10 22:00	39.75	10-10 22:00	-0.17	1	0.991
Shashi	33.00	10-11 5:00	33.09	10-11 4:00	0.09	-1	0.986
Jianli	26.47	10-11 14:00	26.89	10-11 14:00	0.42	0	0.992
Luoshan	20.46	10-12 3:00	20.84	10-12 3:00	0.38	0	0.996
Hankou	15.04	10-13 7:00	14.73	10-13 9:00	-0.31	2	0.978
Huangshigang	11.73	10-14 1:00	11.79	10-14 1:00	0.06	6	0.987
Matouzhen	10.29	10-14 9:00	10.29	10-14 7:00	0	8	0.963
Jiujiang	9.25	10-14 17:00	8.98	10-15 4:00	0.27	11	0.909
Anqing	6.38	10-15 8:00	6.08	10-15 9:00	-0.30	1	0.895
Datong	5.49	10-15 5:00	5.33	10-15 5:00	-0.16	0	0.926

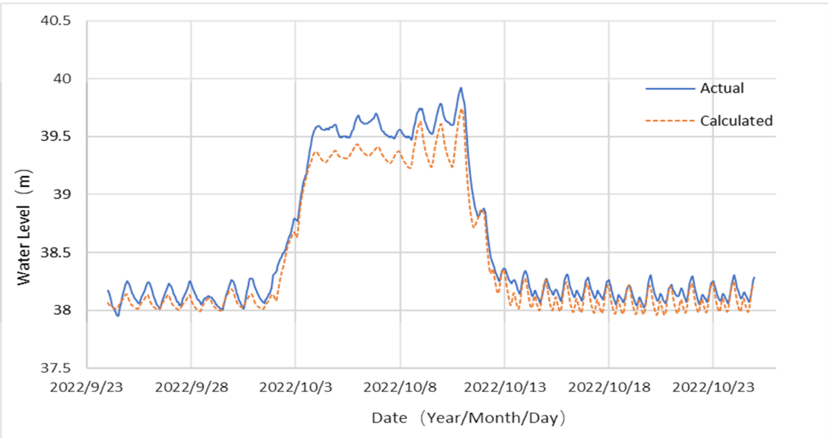


Fig. 2. The Simulated Water Level Hydrograph for Zhicheng Station from September 24th to October 24th, 2022.

3.2.2 Analysis of Different Dispatching Methods for the Three Gorges Dam.

Based on the measured data, the maximum flow at the downstream Yichang Station has not exceeded 20,000 m^2/s, in the water replenishment dispatch process during low-flow period since the formation of the Three Gorges Reservoir. Given the differences in inflow from tributaries of the middle reaches of the Qingjiang River, Dongting Lake, and Poyang Lake water systems, the actual condition in October 2022 was selected as a typical sample for tributaries, and the discharge flows of the Three Gorges with different dispatching methods (with different flow levels and durations), were set as the inflow from the upstream mainstems, combining them to form different inflow scenarios. We utilized the constructed hydrodynamics model as a tool, to simulate conditions at different stations along the middle and lower reaches of the mainstream, like Zhicheng Station, Shashi Station, Jiali Station, Luoshan Station, Hankou Station, Huangshigang Station, Matouzhen Station, Jiujiang Station, Anqing Station and Datong Station, analyzing and comparing the propagation characteristics of low-flow under different scenarios.

(1) Dispatch Methods for Increasing Outflow at Various Flow Levels from the Three Gorges Reservoir

To simplify the analysis, the outflow point of the Three Gorges Dam is moved downstream to Yichang. Considering different inflow conditions from downstream tributaries and the backwater effect based on the selected typical sample, a starting flow rate of 6,000 m^2/s at Yichang was chosen after comprehensive consideration. The constructed Yichang-Datong hydraulic model was then used for simulation analysis. The different outflow increments from the Three Gorges Reservoir were set at 2,000 m^2/s, 4,000 m^2/s, 6,000 m^2/s, 8,000 m^2/s, 10,000 m^2/s, 12,000 m^2/s, and 14,000 m^2/s respectively, with the flow rate increasing equably over 6 hours, and maintaining the maximum flow for a certain period before decreasing back to 6,000 m^2/s. Taking the scenario where the maximum flow is maintained for 7 days as an example, seven sets of generalized wave processes are generated (Figure 3). The simulated water level processes at each station along the middle and lower reaches of the main stream took Zhicheng Station as an example (Figure 4).

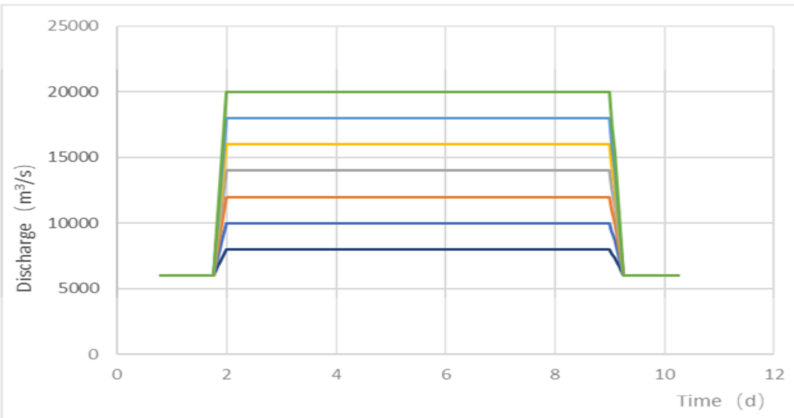


Fig. 3. Generalized Diagram of Water Inflow Process for Yichang

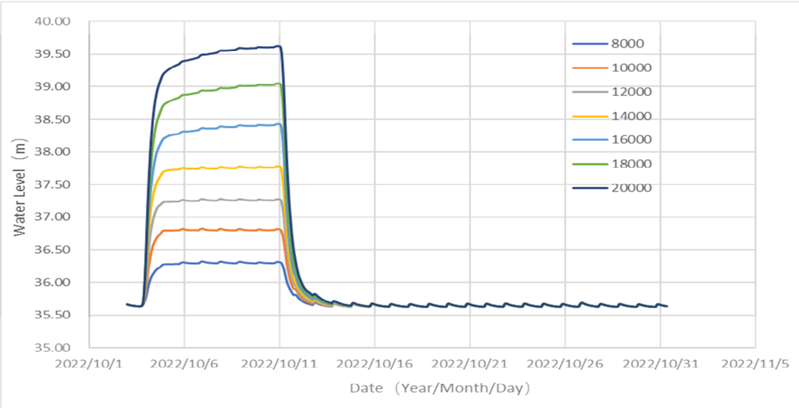


Fig. 4. Simulation Results of Water Levels at Zhicheng Station under Dispatch Methods for Increasing Different Flow Levels from the Three Gorges Dam Outflow

(2) Dispatch Methods for Increasing Outflow from the Three Gorges Dam with Varying Durations

When a reservoir conducts compensatory dispatch for downstream benefits, the volume of the discharge flow and the duration of controlled discharge should taken into consideration. The dispatch method for the Three Gorges Reservoir involved the same discharge waves and different duration in this plan. Using hydrodynamic modeling tools, we analyzed the runoff propagation characteristics along the Yichang to Datong river section under different inflow scenarios. Taking an example where the initial rise flow at Yichang is 6000 m^2/s, the discharge flow (increment) from the Three Gorges Reservoir is 14000 m^2/s, increasing uniformly within 6 hours, with the maximum flow sustained for 3, 5, and 7 days respectively, a total of 3 sets of generalized wave processes are generated (Figure 5). The simulated water level processes at various stations along the mainstream of the middle and lower reaches took Zhicheng Station as an example (Figure 6).

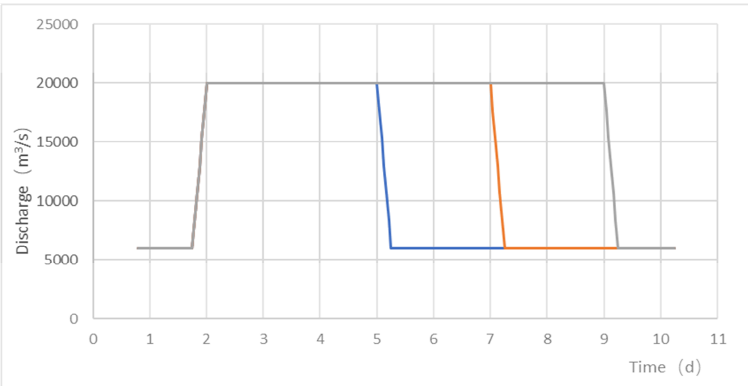


Fig. 5. Water Inflow Process Diagram for Yichang

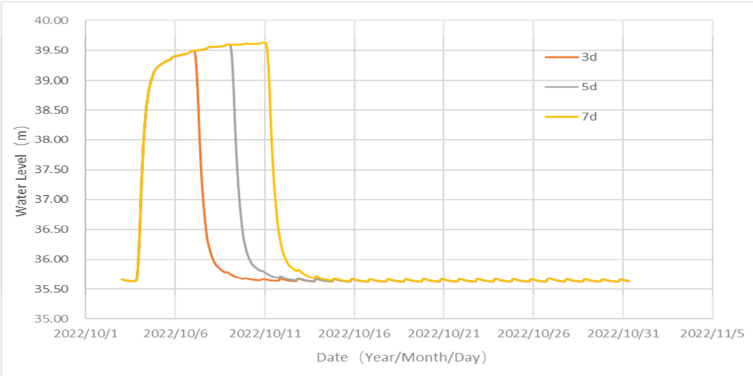


Fig. 6. Simulation Results of Zhicheng Water Levels under Dispatch Methods for Increasing Outflow from the Three Gorges Dam with Varying Durations

3.2.3 Analysis of Propagation Characteristics under Different Dispatch Methods.

The statistical results for the highest water level propagation time, rise difference coefficient, and rise response time under different dispatch methods for the sections from Zhicheng to Shashi, Shashi to Jianli, Jianli to Luoshan, Luoshan to Hankou, Hankou to Huangshigang, Huangshigang to Matouzhen, Matouzhen to Jiujiang, Jiujiang to Anqing, and Anqing to Datong are presented in Table 7.

Table 7. Statistical Table of Propagation Time for Highest Water Levels, Rise Difference Coefficients, and Rise Response Times in Various Sections of the Main Stream in the Middle and Lower Reaches of the Yangtze River Under Different Dispatch Methods

Section	Initial Flow Rise(m^3/s)	Flow Rising To(m^3/s)	Propagation Time(h)			Rise Difference Coefficient			Rise Response Time(h)		
			Maximum Flow Sustained for Three Days	Maximum Flow Sustained for Five Days	Maximum Flow Sustained for Seven Days	Maximum Flow Sustained for Three Days	Maximum Flow Sustained for Five Days	Maximum Flow Sustained for Seven Days	Maximum Flow Sustained for Three Days	Maximum Flow Sustained for Five Days	Maximum Flow Sustained for Seven Days
Zhicheng ~ Shashi	6000	8000	10	7	7	1.75	1.92	1.94	9	9	9
	6000	10000	8	4	5	1.92	2.11	2.15	8	8	8
	6000	12000	7	4	5	1.98	2.13	2.15	7	7	7
	6000	14000	8	4	5	1.95	2.07	2.09	7	7	7
	6000	16000	7	5	8	1.78	1.91	1.96	7	7	7
	6000	18000	9	7	7	1.70	1.86	1.90	7	7	6
	6000	20000	7	6	2	1.66	1.77	1.79	6	6	6
Shashi ~ Jianli	6000	8000	13	6	7	0.82	0.87	0.89	10	10	7
	6000	10000	13	12	4	0.80	0.85	0.87	9	9	6

	6000	12000	12	9	7	0.81	0.87	0.89	9	9	10
	6000	14000	11	10	7	0.82	0.87	0.88	9	9	10
	6000	16000	11	11	9	0.82	0.84	0.93	8	8	9
	6000	18000	11	9	6	0.80	0.90	0.92	8	8	9
	6000	20000	12	8	8	0.85	0.89	0.91	9	9	9
Jianli ~ Luoshan	6000	8000	21	19	13	0.71	0.80	0.86	9	9	18
	6000	10000	21	16	19	0.73	0.81	0.87	9	9	16
	6000	12000	22	18	15	0.73	0.83	0.89	9	9	11
	6000	14000	23	17	14	0.74	0.85	0.92	8	8	9
	6000	16000	24	19	15	0.76	0.87	0.85	9	9	9
	6000	18000	24	22	18	0.78	0.77	0.83	8	8	8
	6000	20000	26	20	19	0.71	0.78	0.85	9	9	8
Luoshan ~ Hankou	6000	8000	48	34	25	0.84	0.90	0.92	24	24	22
	6000	10000	45	35	30	0.74	0.78	0.82	20	20	22
	6000	12000	40	36	26	0.70	0.75	0.78	18	18	19
	6000	14000	41	34	26	0.68	0.74	0.77	14	14	19
	6000	16000	44	33	27	0.68	0.73	0.77	15	15	18
	6000	18000	42	34	33	0.68	0.74	0.77	15	15	14
	6000	20000	42	37	30	0.67	0.74	0.77	16	16	16
Hankou ~ Huangshigang	6000	8000	22	19	16	0.84	0.87	0.89	12	18	19
	6000	10000	15	18	18	0.87	0.91	0.92	11	18	14
	6000	12000	21	21	18	0.90	0.92	0.93	14	16	13
	6000	14000	18	16	17	0.91	0.92	0.93	14	14	12
	6000	16000	18	14	18	0.91	0.92	0.93	14	14	11
	6000	18000	18	13	15	0.92	0.92	0.93	13	13	11
	6000	20000	20	16	14	0.91	0.93	0.93	10	10	10
Huangshigang ~ Matouzhen	6000	8000	5	7	7	0.88	0.87	0.89	10	10	8
	6000	10000	12	10	3	0.90	0.89	0.89	4	7	7
	6000	12000	5	1	5	0.88	0.87	0.88	6	6	6
	6000	14000	8	9	8	0.88	0.88	0.89	7	7	5
	6000	16000	5	10	7	0.87	0.88	0.89	6	6	5
	6000	18000	7	8	6	0.88	0.89	0.89	6	6	4
	6000	20000	3	9	8	0.87	0.88	0.89	5	5	5
Matouzhen ~ Jiujiang	6000	8000	24	24	19	0.65	0.65	0.66	18	16	17
	6000	10000	22	22	30	0.62	0.65	0.67	18	8	12
	6000	12000	27	24	17	0.64	0.66	0.68	8	8	9
	6000	14000	23	22	25	0.64	0.66	0.69	8	8	7
	6000	16000	25	28	21	0.65	0.67	0.69	6	6	8
	6000	18000	35	30	27	0.64	0.68	0.70	3	3	7
	6000	20000	28	29	30	0.66	0.68	0.71	3	3	5
Jiujiang ~ Anqing	6000	8000	22	18	20	1.07	1.02	0.75	22	22	18
	6000	10000	16	14	24	0.87	0.75	0.70	24	24	16
	6000	12000	19	18	25	0.84	0.73	0.75	14	14	14

	6000	14000	22	19	16	0.76	0.69	0.70	20	20	20
	6000	16000	19	21	28	0.73	0.65	0.73	22	22	19
	6000	18000	22	20	23	0.68	0.65	0.72	18	18	18
	6000	20000	26	17	23	0.74	0.71	0.72	17	17	17
Anqing ~ Datong	6000	8000	10	9	10	1.67	0.81	1.26	10	10	10
	6000	10000	9	9	9	1.14	0.89	0.77	9	9	9
	6000	12000	10	9	8	0.93	0.77	0.66	10	10	10
	6000	14000	10	9	10	0.92	0.78	0.83	10	10	10
	6000	16000	9	11	8	0.88	0.88	0.70	10	10	10
	6000	18000	10	10	8	1.07	0.91	0.71	9	9	10
	6000	20000	9	10	6	0.96	0.86	0.73	9	9	9

4 Conclusions

(1) After the construction of the Three Gorges Reservoir, the runoff propagation times have all decreased by varying degrees, and the degree of smoothing has been enhanced to varying degrees in the river section from Yichang to Zhicheng, Zhicheng to Shashi, Shashi to Jianli, the propagation times and the degree of smoothing virtually remained no change in the section of the river below Jianli.

(2) Before and after the construction of the Three Gorges Reservoir, the propagation times of low water are generally longer than that of flood water in each section from Yichang to Luoshan along the middle reaches of the Yangtze River.

(3) Through the simulation of low-water runoff evolution under different dispatch methods, it is generally observed that the larger the maximum discharge flow and the longer the duration of the maximum flow, the shorter the propagation time of the highest water level; The larger the maximum discharge flow, the shorter the response time to rise; The longer the duration of the maximum flow in the section above Jiujiang, the greater the coefficient of increase. However, the variation pattern of the coefficient of increase in the section from Jiujiang to Datong under different scheduling methods is not obvious.

This study calculated the historical measured data from different stations along the mainstream of the middle and lower reaches of the Yangtze River, built the hydraulics model of the middle and lower reaches of the Yangtze River based on MIKE11, and analyzed the evolution of runoff in middle and lower reaches of Yangtze River under low water conditions. However, this study only considered the runoff propagation law of the middle and lower reaches of the Yangtze River, and the analysis of the impact of tributaries, as well as the inflow of Dongting Lake and Poyang Lake, is insufficient. Further in-depth research is needed in the future.

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