Research on the regulation of Three Gorges Reservoir in response to saltwater intrusion in the Yangtze River Estuary

Recherche sur la régulation du réservoir des Trois Gorges en réponse à l'intrusion d'eau salée dans l'estuaire du fleuve Yangtsé

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Abstract. With the changes of economic society and human activities to the natural environment, the impact of saltwater intrusion becomes more frequent and the degree of harm becomes more serious. The Yangtze River Estuary is a densely populated and economically developed area in China, but in terms of water resources utilization, the Yangtze River Estuary is often suffering from saltwater intrustion in dry season. As the backbone of the cascade reservoirs in the Yangtze River Basin, the scientific operation of the Three Gorges Reservoir plays an active role in reducing the saltwater intrusion in the Yangtze River Estuary. Therefore, based on the analysis of the characteristics of Yangtze River Estuary, this paper sums up the variations of saltwater intrusion and discusses the main dynamic factors of saltwater intrusion. In addition, it explores the internal relationship between the upstream water volume and the saltwater intrusion. It takes the allocation of the fresh water resources by the water resources regulation of the Three Gorges Reservoir as a main discussing point. In the end, this paper focuses on the countermeasures and effect of emergency water replenishment on the saltwater intrusion in the Yangtze River Estuary.

Résumé. Les activités économiques, sociales et humaines ayant modifié l'environnement naturel, l'impact de l'invasion de l'eau salée est devenu plus fréquent et les dégâts sont devenus plus graves. La zone de l'estuaire du fleuve Yangtsé est une zone densément peuplée et économiquement développée en Chine, mais en termes d'utilisation des ressources en eau, la zone de l'estuaire du fleuve Yangtsé est souvent affectée par l'intrusion de marée salée pendant la saison sèche. En tant qu'épine dorsale des réservoirs en cascade dans le bassin du fleuve Yangtsé, le fonctionnement scientifique du réservoir des Trois Gorges a un effet positif sur la réduction de l'intrusion

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de marée salée dans l'estuaire du fleuve Yangtsé. Par conséquent, sur la base de l'analyse des caractéristiques de l'estuaire du fleuve Yangtsé, cet article résume les changements dans l'intrusion de la marée salée et examine les principaux facteurs dynamiques qui affectent ses changements. L'allocation des ressources en eau douce dans l'estuaire du fleuve Yangtsé est le point de départ, et le réapprovisionnement en eau d'urgence est mis en œuvre via le réservoir des Trois Gorges pendant la période d'inversion de la marée salée dans l'estuaire du fleuve Yangtsé. Enfin, cet article se concentre sur les contre-mesures et l'effet de la réalimentation d'urgence en eau sur l'intrusion d'eau salée dans l'estuaire du fleuve Yangtsé.

1 Saltwater intrusion in the Yangtze River Estuary

As a hidden environmental pollution, saltwater intrusion has become one of the serious environmental problems in the Yangtze River Estuary area. It has a non-negligible impact on residential water, agricultural water, and urban industrial production and its development. The section from Datong (about 640 km away from the estuary) to Jiangyin (about 220 km away from the estuary) of the lower Yangtze River is a tidal section, and the section below Jiangyin is an estuary section, which is a tidal current reciprocating area [1]. The saltwater intrusion path of the Yangtze River Estuary is divided into the direct intrusion of the salt tide in the south branch and the indirect intrusion of the salt tide in the north branch. There are four intrusion sources: the north branch, the north channel, the south passage and the north passage, forming a pattern of "three-level bifurcation and four outlets entering the sea"[2].

1.1 Main influencing factors

Salt tide usually occurs at the confluence of rivers and oceans. When the seawater level at the estuary is higher than the river level, the seawater will flow back into the river, and the salt tide will continue to expand from the estuary to the upstream along the river. The main influencing factors of saltwater intrusion are as follows: (1) tidal current. Tides and tidal currents are the vertical fluctuation of sea surface and the horizontal flow of seawater caused by the tidal force of celestial bodies. They are the "power sources" of the mixing of saltwater and fresh water and have a significant impact on the saltwater intrusion. (2) Runoff. Salt tide back irrigation usually occurs in the dry season of dry years with less water from upstream, generally from November to April of the next year. The results show that there is an obvious negative correlation between the chlorine value of the Yangtze River Estuary and the flow of Datong station. In dry season, when the discharge is normal or dry, the salt water in the open sea can reach Wusongkou, Baozhen or above. (3) Wind stress. Wind has great influence on saltwater intrusion. Different wind speed and wind direction will lead to different intensity of rising and falling tide in estuary area, and the influence on saltwater intrusion in estuary area will also be different. (4) River regime changes. With the continuous intensification of human activities such as river dredging and channel dredging, a large number of sediment mining and large-scale waterway regulation have made the river channel in the estuary area generally cut down and the deep channel of the main tidal channel deepened. (5) Sea level change. Based on the change of sea level on decades and longer time scale, the variation of the average tide level in the open sea affects the strength of high concentration saltwater in and out of the estuary area, thus affecting the distribution of freshwater resources in the Yangtze River Estuary [3].

1.2 Law of temporal and spatial variation

As a geographical environment phenomenon mainly caused by natural factors, saltwater intrusion in the Yangtze River Estuary has a certain evolution law in time and space. (1) On the time scale, the saltwater intrusion in the Yangtze River Estuary has semi diurnal, semi monthly, seasonal and annual variations, which are mainly controlled by tides and runoff. In the short half day and half month time scales, the saltwater intrusion in the Yangtze River Estuary is mainly affected by tides, while in the longer seasonal and annual time scales, the saltwater intrusion in the Yangtze River Estuary is mainly affected by runoff. (2) On the spatial scale, the saltwater intrusion in the Yangtze River Estuary has longitudinal, transverse and vertical variations. In the longitudinal direction, from the mouth of the North Branch to the fork of the South Branch, the saltwater intrusion weakened along the way. During the spring tide, the saltwater intrusion in the southern branch (including the north channel and south channel) is characterized by high at both ends and low in the middle. Horizontally, the intensity of saltwater intrusion in the North Branch, the south passage, the north channel and the north passage weakens in turn in the estuary of the Yangtze River. Vertically, in the estuary, the saltwater intrusion has obvious vertical change, which is more significant during neap tide than during spring tide [4].

Fig. 1. Locations of the Yangtze River basin in China.

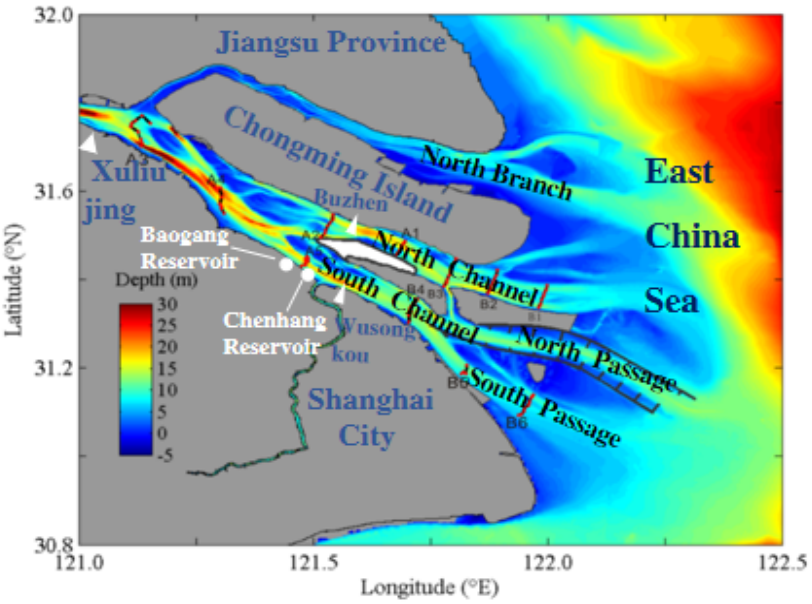

Fig. 2. Topography around the Yangtze River Estuary and Tide monitoring cross section (red strips).

2 Response relationship between saltwater intrusion and upstream discharge

2.1 Numerical model of saltwater intrusion

ECOM-si is a three-dimensional numerical model developed based on POM (Princeton Ocean Model), which has been widely used in estuary saltwater intrusion [5]. The model can set various dynamic factors including wind, wave, tidal current and runoff. Based on the control equations of ECOM-si model, the initial conditions and boundary conditions (sea surface and seafloor for the vertical boundary, shore and water for the horizontal boundary) of the research object are selected, and the dynamic boundary process of tidal flat is processed by using the dry wet discrimination method [6]. According to the numerical solution method, the calculation range of the model is set and calculated. Finally, the observation data are selected to verify the simulated estuary water level, tidal current and salinity, and the rationality of the model results is evaluated.

2.2 Relationship between saltwater intrusion and discharge

Based on the established three-dimensional numerical model of saltwater intrusion in the Yangtze River Estuary, the saltwater intrusion in the Yangtze River Estuary is simulated under the conditions of 11500 m^3/s, 10000 m^3/s, 9000 m^3/s and 8000 m^3/s, and the response relationship between saltwater intrusion and runoff at Datong station is analyzed.

According to relevant data, in the past 60 years, the average discharge of Datong in January is 11300 m^3/s, and that in February is 11650 m^3/s. therefore, the discharge is set at 11500 m^3/s to simulate the saltwater intrusion in the Yangtze River Estuary under the condition of average flow in dry season. The monthly average flow of Datong station corresponding to 6 days of continuous unsuitable water intake at Chenhang reservoir is

selected as the critical flow to ensure the safety of water supply in Shanghai. In order to find out the corresponding critical flow, the simulation also set the Datong station flow of 10000 m^3/s, 9000 m^3/s, 8000 m^3/s for scenario simulation. As result shows, 5, 5.8, 8.2, 10.2 days for the Longest continuous time not suitable for taking water corresponds to the 11500, 10000, 9000, 8000 m^3/s for the Datong station discharge.

2.3 Determination of critical discharge

According to historical data, saltwater intrusion occurs in most years in the water source area of the Yangtze River Estuary. When a short-term saltwater intrusion occurs, the normal water supply will not be affected due to the water storage in the reservoir. Only when the saltwater intrusion is serious and the duration of saltwater intrusion exceeds the maximum water supply capacity of the reservoir, the water supply security problem will appear. According to the simulation results of the model scenario, when the discharge of Datong station is 9000 m^3/s, the longest continuous time of not taking water at the intake of Chenhang reservoir is about 8.2 days, and the time of not taking fresh water is obviously longer than that of taking fresh water. When the storage capacity of Chenhang reservoir is full, if Baogang reservoir is not used, the longest water supply can only be 6 days. When the discharge of Datong station is 10000 m^3/s, the longest continuous unfit water intake time of Chenhang reservoir is 5.8 days, so it can be approximately considered that the critical discharge of Datong station corresponding to the continuous unfit water intake time of Chenhang reservoir is 10000 m^3/s.

3 Influence of Three Gorges Reservoir operation on Yangtze River Estuary water resources

3.1 Runoff comparison analysis of Datong station

Datong station is an important hydrological station in the lower trunk stream of the Yangtze River, and is also the tidal boundary of the Yangtze Estuary. There is abundant water in the estuary of the Yangtze River. The Datong hydrological station located in the main stream of the Yangtze River is selected as the analysis station. According to the measured data, the runoff variation characteristics of the basin above Datong in the dry season (from December to March) are analyzed, and the spatial distribution and the annual and inter annual variation rules are analyzed.

Among the runoff sources of Datong, the catchment area above Yichang accounts for 59% of Datong, and the annual average annual runoff accounts for 48.2% of Datong. The catchment area above Hankou accounts for 87.3% of Datong, and the average annual runoff accounts for 79.2% of Datong. The catchment area of Poyang Lake system in Jiangxi rainstorm area account for 9.5% of Datong respectively. The runoff of Poyang Lake system account for 16.8% of Datong.

Fig. 3. Sketch map of main water systems of Yangtze River**.**

3.2 Runoff variation in dry season of Datong station

According to the statistics of runoff data of Datong station from 1960 to 2015, the average annual discharge is 28000 m^3/s. Compared with the 1960-2002 series, the average discharge of Datong station from 2003 to 2015 decreased by 1400 m^3/s, with a reduction rate of 4.93%. For the period from December to March, the average flow of Datong station from 2003 to 2015 was 15200 m^3/s, an increase of 2000 m^3/s compared with that of 1960-2002, with an increase rate of 15.2%. The most significant increase was in March, with the monthly average flow increasing by 3200 m^3/s, with an increase rate of 20.1%. The smallest increase range was in December, with the monthly average flow increasing by 700 m^3/s, with an increase rate of 4.86%. See Table 1 below for details.

Table 1. Average flow of Datong station in different periods and its variation.

category		Discharge and its change (discharge: m^3/s, percentage: %)					
		Annual mean	Dec.	Jan.	Feb.	Mar.	Mean from Dec. to Mar.
1960～2015		28000	14500	11400	12000	16600	13600
①1956～2002		28400	14400	11000	11500	15900	13200
②2003～2015		27000	15100	12900	13600	19100	15200
Comparison of ① and ②	discharge	-1400	700	1900	2100	3200	2000
	percentage	-4.93	4.86	17.3	18.3	20.1	15.2

From January 1950 to May 2003 before the operation of the Three Gorges project, the number of days when the daily average flow of Datong station was less than 10000 m^3/s was 1905 days, accounting for 10% of the total days of the period. From June 2003 to September 2008, the Three Gorges Project began to play the function of storing abundant and regulating dry seasons, and the number of days when the daily average discharge of Datong station was less than 10000 m^3/s was 44 days, accounting for only 2% of the total days of the period. In October 2008, the Three Gorges project entered the experimental water storage period As of December 31, 2016, the measured minimum daily average discharge of Datong station was 10400 m^3/s, and there was no case that the daily average flow was less than 10000 m^3/s. See Table 2 for details.

Table 2. Statistical table of days with daily average flow less than 10000 m^3/s at different time periods of Datong station.

period	Days of less than 10000 m^3/s (d)	Total days(d)	Proportion
1950.1~2003.5	1905	19509	10%
2003.6~2008.9	44	1949	2%
2008.10~2016.12	0	2014	0

3.3 Influence of regulation of Three Gorges Reservoir on discharge of Datong station

Based on the critical discharge of Datong station, the frequency of monthly average discharge less than 10000 m^3/s in 1970-2015 and planning target year is counted respectively. Through comparison, the impact of regulation of Three Gorges Reservoir on saltwater intrusion is preliminarily analyzed.

According to the statistics of monthly average discharge data measured at Datong station, the monthly average discharge of each month from October to April from 1970 to 2015 was less than 10000 m^3/s, and the statistical results are shown in Table 3. According to the statistics of the frequency of monthly average discharge less than 10000 m^3/s before and after the construction of the Three Gorges reservoir, it can be seen that the number of times when the monthly average discharge of Datong station is less than 10000 m^3/s after 2003 is obviously reduced, only once in February 2004.

Table 3. Statistics of times of monthly average discharge less than 10000 m^3/s at Datong station under different conditions.

Level year	Period	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	Total
Measured discharge year	1970~2002	0	3	13	12	2	0	30
	2003~2015	0	0	0	1	0	0	1
	Total	0	3	13	13	2	0	31
Planning target year	1970~2002	0	3	5	5	0	0	13
	2003~2015	0	0	0	1	0	0	1
	Total	0	3	5	6	0	0	14

It can be seen from the above table that after the construction and operation of the Three Gorges reservoir, replenishing water in dry season has a certain impact on the discharge of Datong station in dry season. Under the planning level year, the average monthly discharge of each month in the dry season (December to March) from 1970 to 2015 is 14 times less than 10000 m^3/s. Compared with the actual situation, the number of times when the monthly average discharge of Datong station is less than 10000 m^3/s is obviously reduced, among which the decrease in January and February is more significant, 8 times and 7 times respectively. It can be seen that the operation of the Three Gorges reservoir can increase the average discharge of Datong station in dry season to a certain extent, and then help to slow down the saltwater intrusion in the Yangtze River Estuary.

4 Effect analysis of water replenishment operation in Three Gorges Reservoir

4.1 Timing of water replenishment

At present, there are three ways to replenish freshwater and release the pressure of saltwater.The diagram of dispatching mode is shown in Figure 4 below.

It is known as "stable discharge" type without peak scheduling and discharging with constant flow. "Stable discharge" means that the discharge of the reservoir keeps the same throughout the tidal cycle, that is, the increased daily discharge of the reservoir remains unchanged during the tidal period. "start and finish" means selecting the two most sensitive periods of flow when the salt tide changes from strong to weak and from weak to strong. The discharge of reservoir is increased to suppress salt tide, and the discharge is reduced in other periods, which makes the discharge process form a saddle shape, thus prolonging the water intake time of main reservoirs in the estuary. "Avoid rising and suppress dropping" is to avoid the period with the strongest salt tide intensity, increase the discharge when the salt tide is about to ebb, and reduce the discharge in other periods, so that the discharge process forms a step type, which is conducive to the formation of stable water intake period in the period with weak salt tide intensity.

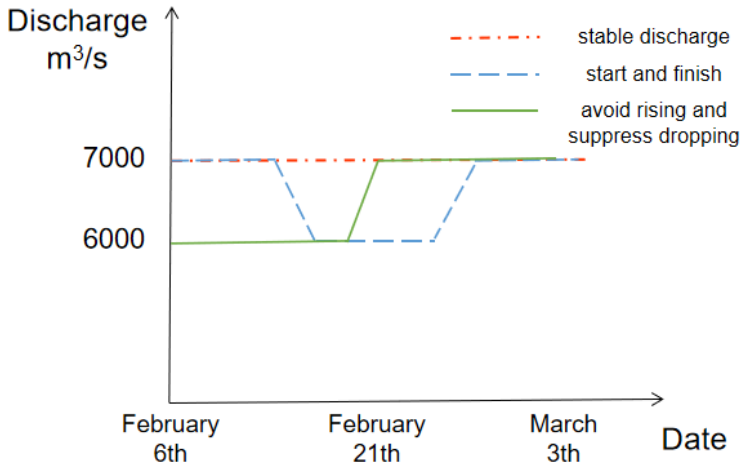

Fig. 4. Schematic diagram of Three Gorges Reservoir dispatching modes.

4.2 Selection of replenishing discharge

From the current situation, the situation that the discharge of Datong is less than 10000 m^3/s will be improved through the replenishment of the Three Gorges reservoir. However, due to the complicated causes of saltwater intrusion, even if the discharge of the Three Gorges reservoir is increased to 6500 m^3/s, it is still unable to guarantee that there will be no saltwater intrusion in the Yangtze River Estuary. Therefore, under the condition of basically meeting the saltwater pressure requirements of the Yangtze River Estuary, the discharge capacity of the Three Gorges Reservoir during normal operation should not be increased too much, and a certain amount of water storage should be reserved to meet the water demand in special emergency situations and avoid the great impact on other comprehensive utilization. If necessary, it is suggested that the discharge of the Three Gorges reservoir should be controlled at 6000 m^3/s during the saltwater intrusion. If the Three Gorges reservoir needs to start the emergency operation scheme in a particularly dry year, the following discharge is 7000 m^3/s for 10 days (assuming that the emergency plan is put into operation from December to march of the next year, and the minimum discharge of the Three Gorges has been increased to 6000 m^3/s), the additional water replenishment is about 864 million m^3 per start-up.

4.3 Evaluation of water supplement effect

Taking the saltwater intrusion from February to March 2014 as an example, on February 21, the Three Gorges project launched an emergency plan to increase the discharge to 7000 m^3/s, and ended on March 3. The regulation of replenishing freshwater was maintained for 11 days. The Three Gorges Reservoir added 1.85 billion m^3 of water to the downstream, of which 950 million m^3 was specially added for the Yangtze Estuary. During this period, the diversion volume below Datong was about 350 million m^3, accounting for the additional water supply for the Yangtze Estuary 36.8% of the total.

From the point of view of water supplement effect, although the saltwater intrusion has been alleviated to some extent, from the water quantity, only about 600 million m^3 of water discharged from the Three Gorges project is added to the Yangtze River Estuary, accounting for 63.2% of the total water replenishment for the Yangtze River Estuary. The water intake along the line below Datong accounts for 36.8% of the total water supply for the Yangtze River Estuary, which affects the effect of the water replenishment to a certain extent, and makes the boundary benefit of replenishing freshwater by Three Gorges Reservoir poor. It is suggested that during the period of saltwater intrusion, water-saving should be controlled in this area, and the domestic water consumption of residents should be given priority. Some industrial production water should be limited, high water consumption industries should be stopped, and some underground water reserve deep wells should be used. On this basis, the upstream reservoir group can select the ebb tide period according to the actual situation to replenish water. The make-up discharge should be determined according to Datong discharge and regional water demand.

4.4 Suggestions on emergency dispatching mode

Through comparison, it is found that the stable discharge can better increase the fresh water intake time of main reservoirs in the estuary, but from the perspective of power generation of upstream reservoir, compared with the other two schemes, the discharge volume of stable discharge is about twice of the other two schemes, which is not conducive to the effective utilization of water resources from the perspective of water resources development and utilization. Considering the formation mechanism and influencing factors of saltwater intrusion in the Yangtze River Estuary, the saltwater source of Chenhang reservoir is

completely from the upstream North Branch salt water back irrigation. Generally, the best saltwater pressure period is the ebb period of neap tide, so the proposed the scheme ("Avoid rising and suppress dropping") is the recommended scheme for the timing of saltwater pressure and replenishment in the Yangtze River Estuary.

According to relevant studies, the time when the discharge of Datong reaches its peak is about 15 days after the discharge of the Three Gorges is increased. According to the above time relationship, the upper half axis of the ordinate is the discharge time of the Three Gorges, and the lower half axis is the time when the discharge reaches the peak at the Yangtze River Estuary. The diagram of dispatching time is shown in Figure 5 below.

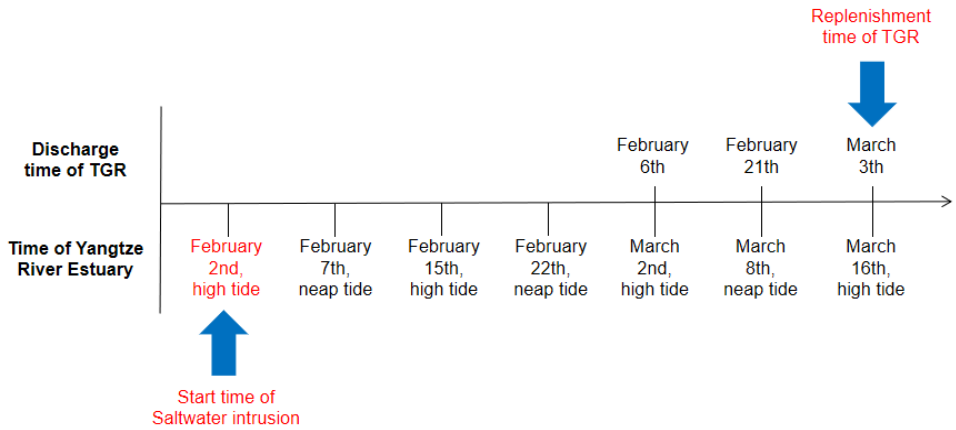

Fig. 5. Schematic diagram of discharge time selection of Three Gorges Reservoir.

Taking the saltwater intrusion period from February to March 2014 as an example, February 2 is the start time of saltwater intrusion. After the beginning of intrusion, after February 2, the occurrence time of spring tide and neap tide in the Yangtze River Estuary is shown in the figure. According to the time of spring tide and neap tide forward 15 days, the discharge time of the Three Gorges reservoir is obtained. After February 2, the discharge time of the Three Gorges reservoir is divided into February 6, February 21 and March 4. According to the regulation mode of "avoid rising and suppress dropping", the time when the peak discharge of the Three Gorges reservoir reaches the Yangtze River Estuary needs to avoid the spring tide period and start to discharge in the neap tide period. Considering comprehensively, the discharge time is February 21.

5 Conclusion

With the normal operation of the Three Gorges reservoir, the average discharge of Datong station in dry season has been increased to a certain extent, which has a positive practical role in slowing down the saltwater intrusion in the Yangtze River Estuary. When the saltwater intrusion occurs seriously in the Yangtze River Estuary and the emergency water replenishment operation of the Three Gorges reservoir is needed, the Three Gorges reservoir can adopt the "avoid rising and suppress dropping" regulation mode to deal with the saltwater intrusion. At this time, the discharge of the Three Gorges reservoir is reasonably controlled from 6000 to 7000 m^3/s. According to the condition of saltwater intrusion intensity, it is suggested that the reservoir groups in the upper trunk stream of the Yangtze River should share the increased discharge of the Three Gorges Reservoir in proportion, and select the

period of neap tide ebb to discharge and replenish water. The make-up discharge should be determined according to the discharge of Datong and the regional water demand.

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