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Impacts of the Reservoir on the Navigation Conditions of the Downstream Channel: Taking the Three Gorges Reservoir in the Middle Reaches of the Yangtze River as an Example

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Abstract The flow and sediment condition in the middle and lower reaches of Yangtze River (MLYR) was changed a lot after the impoundment of Three Gorges Reservoir (TGR), and further, the evolution process of the sandbars and shoals were affected, both of which have obvious influence on the navigation in the MLYR. Based on the field data, the analysis shows that the changes of flow and sediment favored the waterway condition, which includes the elevation of the lowest water level, the extension of the scour time of shoals, the increase of the erosion speed of shoals caused by the reductive sediment. After the operation of TGR, the frequency of the bank collapse and the sandbar cutting is increasing, and the shoal tends to shrink. However, not all the deformation of sandbars and shoals will obstruct the waterway, only the Critical Width of Returning to Channel (CWRC) is more than the critical river width, the channel will not be unimpeded. The CWRC is about 900–1900m, varying with the navigation base surface and the channel dimension.
Keywords *Navigation Condition; Three Gorges Reservoir; the Middle and Lower reaches of Yangtze River; Channel evolution*

1. Introduction

The main stem of the Yangtze River is a transportation artery communicating East part – West part of China, known as the golden waterway (Gao et al., 2013; Chen et al., 2010; Zhang et al., 2006; Xu et al., 2011). In 2011, striving to build a unimpeded, efficient, safe, green system of modern inland navigation was put forward by the State Council, marking the accelerating development of the inland waterborne and the Yangtze River development has risen to the national strategy. The impoundment of TGR changes the downstream flow and sediment condition and has an influence on the navigation condition of MLYR (Dai et al., 2013; Xia et al., 2014).

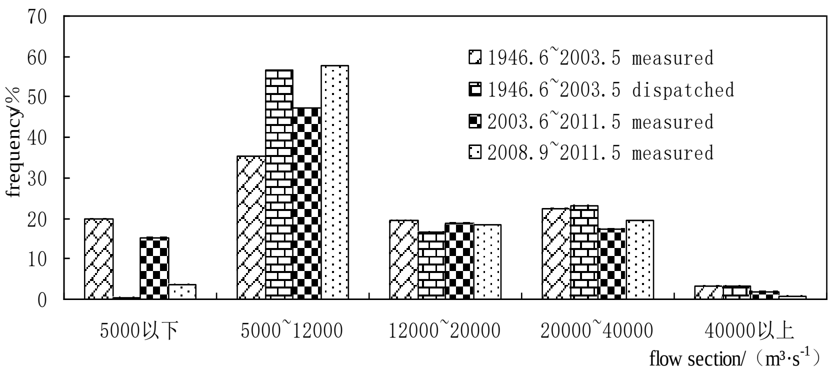
The existing studies mainly have three viewpoints about this: Firstly, the navigation condition changes better because of the riverbed's erosion and downcut, the increment of flow in dry seasons and the reinforcement of shoal scouring caused by reductive sediment after the flood (XIONG et al., 2000). The second view is that the riverbed downcuts meanwhile the bank collapses and the channel broadenings, making the averagely scouring depth of riverbed is not more than the decline amplitude of water level when the flood recedes quickly, and then the navigation depth diminishes and the migration amplitude of the channel increases, all of which cause the navigation condition deteriorates (LI et al., 2004; CAI et al., 2006). The last point is that TGR has both advantages and disadvantages on the navigation condition. On the one hand, with the riverbed scouring and the discharge increasing in dry season, the channel deepens; on the other hand, with the central bar and point bar scouring, the bank collapses and broadens (LIU et al., 2005).

The field data shows that the channel condition in the MLYR turns better as a whole after the impoundment of TGR, though part of them deteriorates. The deformation of sandbars and shoals takes the form of the low sandbar downcut and the bank collapse, but not all of them will cause the navigation obstruction. Thus the evolution process in the MLYR before and after TGR actually still needs further analysis. Based the analysis of the changes of flow and sediment condition and the deformation of sandbars and shoals, combining with the field data before and after the operation of TGR, dissect their impact on the channel condition, so as to provide a reference for the waterway remediation and the upstream reservoir regulation.

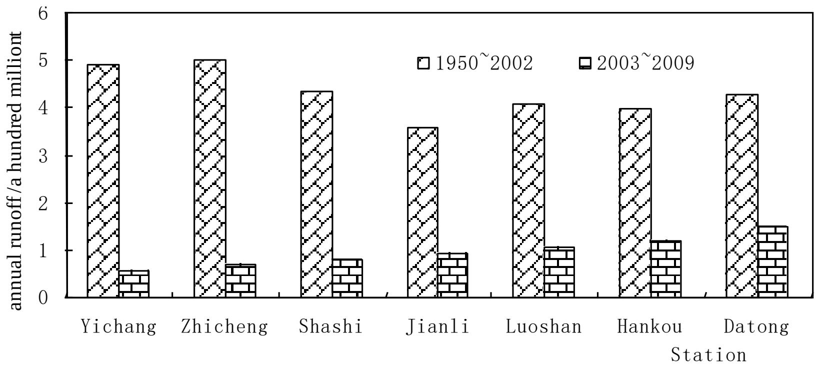
2. The Impact on Flow & Sediment Condition & Sandbar Deformation by Impoundment of TGR

2.1. The Impact on the Flow and Sediment Condition by the Impoundment of TGR

The TGR adopts the mode of ‘ storing clear and discharging muddy water ’. After the impoundment, the flow occurrence frequency at different water levels has adjusted, for instance, the outflow slightly adjusts in the flood period, decreases in the storage period and increases in the dry period. Based on the field flow at Yichang station in the period from June, 1946 to May, 2003, according to the Flood dispatching plan of TGR, the flow occurrence frequency at different levels before and after dispatching is calculated as shown in Figure 1 (a). As can be seen from the graph, the occurrence frequency below 5000 m^3/s falls from 20% to less than 1%, the frequency of 5000–12000 m^3/s increases from 35% to 57%, the frequency above 12000m^3/s decreases slightly. At the same time, the statistical data in the period from June, 2003 to May, 2011 shows that, the frequency below 5000 m^3/s falls from 20% to 15%, the frequency of 5000–12000 m^3/s increases from 35% to 47%, the frequency above 12000 m^3/s decreases significantly.



(a) Change of water flow



(b) Change of sediment load

Figure 1: *Changes of flow and sediment before and after the operation of TGR*

The main reason for the greater difference between before and after TGR has two aspects: Firstly, the watershed has less rainfall after TGR and the flow reduces correspondingly, especially the annual runoff at Yichang station in 2006 is only 284.8 billions m^3, which is accounted for 65% of the average runoff over many years. Secondly, in the period from June, 2003 to September 2008, TGR respectively operates with 135–139m and 144–156m mode, resulting in the lower impounded level and the restricted compensation ability for the flow in dry season. However, the statistical flow process from September 2008 to May, 2011 (operating with 155–175m mode) is basically consistent with the dispatched result. In a word, after TGR the frequency below 5000 m^3/s decreases by a large margin, the frequency of 5000–12000 m^3/s increases evidently, the frequency above 12000 m^3/s decreases slightly.

Under the influence of that the reservoir intercepts sediment, the sediment discharge in the MLYR declines sharply since 2003, descending from 490 millions tons / year before TGR to 57 million tons / year at Yichang station, descending from 430 million tons / year to 150 million tons / year at Datong station, which reduced respectively by 88% and 65%. According to the correlative analysis, in the 40–50 years after TGR, the riverbed of MLYR basically reaches the equilibrium of erosion and deposition. If a series of high dams built in upstream of main Yangtze River are considered, the riverbed of MLYR will be subjected to the erosion effected by the unsaturated water more than 300 years at least.

2.2. The Impact on the Sandbar Deformation by the Impoundment of TGR

With the significant change of the flow and sediment in the MLYR after impoundment of TGR, the sandbars and shoals also have an obvious trend of deformation. Mainly for the more frequent bank collapse and sandbar cutting, also for the low sandbar substantial shrink.

Bank collapse is a common phenomenon in the MLYR, 35.7% of the shoreline in the MLYR has a collapse before TGR. According to statistics, the bank collapse in Jingjiang river happens 15 times per year in 1998–2003, accordingly the collapse length is about 6.6 kilometers per year. Yet there are 26 times per year in 2003–2005, correspondingly the length is about 17.4 kilometers. Compared with 1998–2003, the bank collapse frequency in 2003–2005 is 1.7 times as much as the former, and the length is 2.6 times as much as the former.

Not only the river bank collapses, but also the left or right edge of the central bar collapses. The reason for this phenomenon is that, the river bank collapse, which mainly due to that the actual slope ratio is larger than the stability slope ratio caused by the nearshore water erosion (TANG et al., 2012). After impoundment of TGR, the sediment concentration declines sharply, the riverbed erosions generally, the slope ratio increases, so the frequency and the length of bank collapse all increase.

The sandbar cutting is also a pervasive phenomenon in the MLYR. According to statistics, in the Shashi – Chenglingji river reaches, the sandbars in the Majiazui, Zhoutian, Ouchikou, Jianli waterway accumulated are cut 7 times, averagely once two years in 1990–2003. However in 2003–2011 the sandbars accumulated are cut 6 times, averagely twice three years. In addition, some sandbars, such as in the Chibakou waterway, Longkou waterway or Huguang waterway, have remained relatively intact more than 50 years (1950–2002), nevertheless they are all cut after impoundment of TGR. In short, the cutting frequency of sandbar in the MLYR increases and the low shoal is more prone to be cut after the impoundment of TGR.

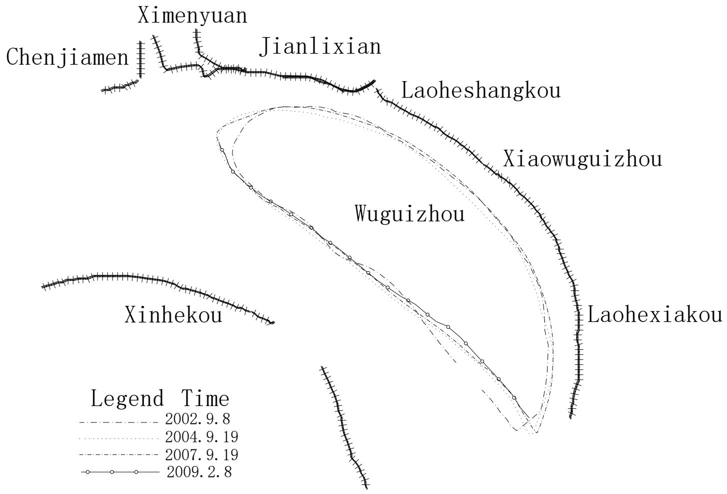


Figure 2: *Bank collapse of Wuguizhou during 2002–2009*

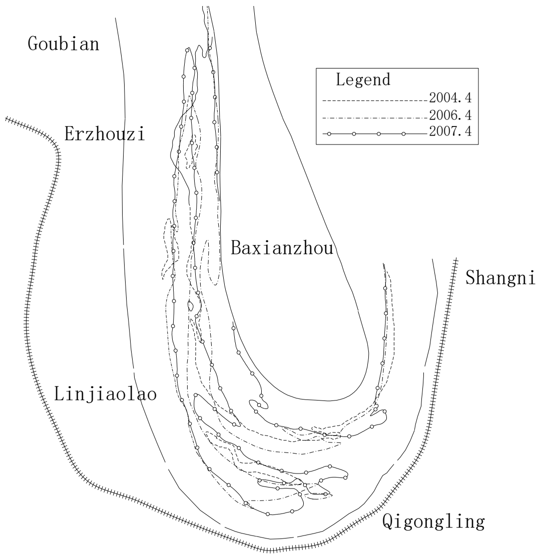


Figure 3: *Cutting of the convex bank sandbar in Chibakou*

The substantial shrink of low shoal is a common phenomenon since the impoundment of TGR. Before the impoundment, because of the fluctuation of flow and sediment and the translocation between the main branch and the second branch, the point bar and central bar scours and deposits frequently, but in a whole they maintains a balance, such as Guniusha bar had no a consistent change trend in nearly 50 years before the TGR (Figure 4). However various types of point bar and central bars all shrink significantly after the impoundment of the TGR.

In the single-thread river reaches, such as the Guangxingzhou bar of the Tiepu waterway, the Luoshan bar of the Jiepai waterway, the Zhaojiaji bar of the Huguang waterway (Figure 5), are substantially shrinking while cutting after TGR. With the upper point bar in Jiepai reach scours promptly, its '0 m' line (Sailing base surface) has washed back to the head of the spur dike in 2010. In curved rivers, such as the Tiaoguan, Fanzui, Hanjinguan, Guniusha waterway, whose convex bars all show greater amplitudes of shrink (Figure 4). In the braided rivers, the concave bars and the low shoals of the sandbar head shrink markly, in some tributary arms the concave bars almost wash over, such as the Bahe bar of the Daijiazhou waterway and the Hongyangshu bar of the Tuqiao waterway.

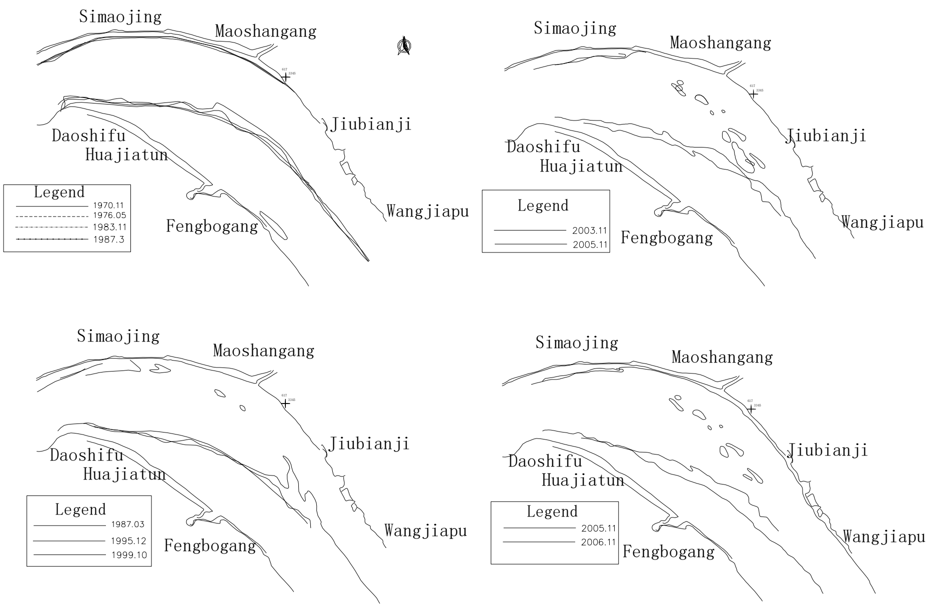


Figure 4: *Changes of convex bank sandbar in Guniusha*

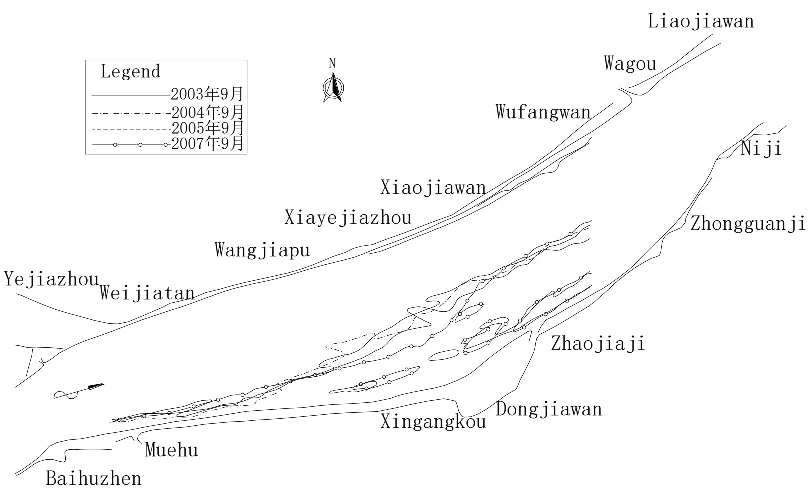


Figure 5: *Changes of Zhaojiaji Sandbar in Huguang*

3. The Impact of the Impoundment of TGR on the Channel in the MLYR

The impoundment of TGR changes the flow and sediment process in the MLYR, and then causes the collapse, sandbar cutting, substantial shrink of low shoal. The former changes the flow and sediment condition of the shoals, the latter changes the boundary condition of the shoals, both of them will affect the channel condition. The followings analyse the changes of channel condition firstly, then inquire into the impact on channel by the change of flow and sediment condition and the sandbar deformation.

3.1. The Impact on the Flow and Sediment Condition by the Impoundment of TGR

The shoal obstruction phenomenon in the MLYR mostly appears in the dry season, and compared with other levels, the change of the shoal depth at the lowest water level within a certain period more reasonably reflects the change of channel condition. Collecting the terrain data of typical shoals in the Jingjiang River in dry season, verifying the depth at the lowest water level of different period within a channel wide range of 150m, the result is shown as Figure 6. From this graph, the shoal depths in the Taipingkou, Majiazui, Zhougongdi, Tianxingzhou, Ouchikou, Jianli waterway increase, yet in Chibakou decreases, that is to say, most shoal depths increase while the channel condition improves, but individual shoal depth decreases.

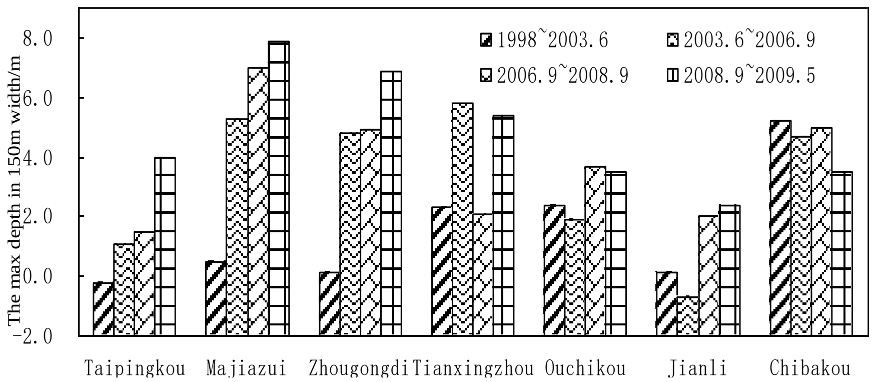


Figure 6: *Changes of shoal water depth in Jingjiang Reach*

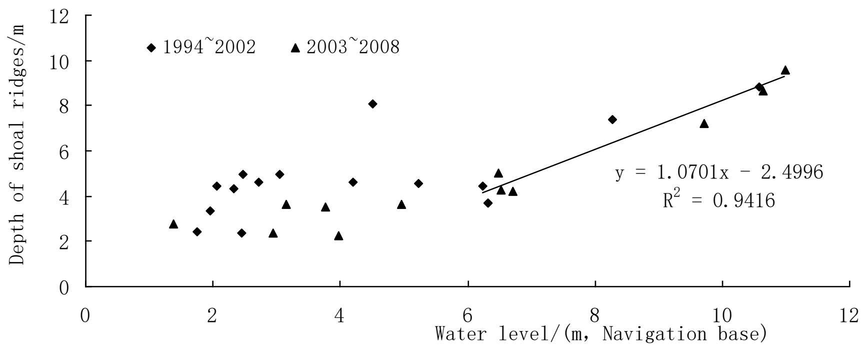


Figure 7: *Relationship between the water depth and the water level at the shoal*

3.2. The Impact of the Change of the Flow and Sediment Condition on Channel

1) *The impact on channel by the change of flow process*

A large number of field data shows that, the most shoals in the MLYR follow the evolution process of "depositing in the flood but scouring in the dry season" within a year. Obviously there is a critical flow. In the flood receding process, when the flow is less than the critical flow, the water returns to deep groove, the shoal begins to scour, the critical flow is called the critical flow of returning to channel (CFRC). Correspondingly the water level and the river width are respectively called the critical water level of returning to channel (CLRC) and the critical river width of returning to channel (CWRC).

Statistics on the relation between the water depth and the water level at the shoal ridges shows that (the relation in Jianli waterway shown as Figure 7), the CLRC in the MLYR is 6 m above the "82" sailing base surface. Further statistics on the relation between the water level and the flow shows that, the CFRC in the Shashi station, Jianli station, Luohan station, Hankou station is respectively 12000 m^3/s, 11000 m^3/s, 14000 m^3/s, 16000 m^3/s (TANG Jinwu et al., 2012). According to the definition, the longer the duration of the CFRC, the more fully the shoal scouring, the better the channel condition will be. Combining with the dispatching calculation result of TGR, the occurrence frequency of the CFRC (the flow below 12000 m^3/s) in the Shashi station increases from 55.2% to 57.1% (Figure 1a). That's to say the flood recedes more slowly after the impoundment of TGR, the scouring time of the shoal increases averagely 7 days per year.

The scouring of shoal is not only related with the during time of CFRC, but also related with the size of channel flow in dry season. The average value of the flow in the dry channel is defined as the channel average scouring flow, which is average value between the CFRC and the lowest flow level, representing the riverbed deformation effect on channel by flow. According to the dispatching calculation result of TGR, statistics and analysis show that, the channel average scouring flow in various reaches of the MLYR increases by about 400 m^3/s–1000 m^3/s after the TGR's regulating, which is about 6%–8% of the channel average flow before TGR. Obviously, this change is favorable for the navigation condition.

In addition, owing to the replenishing water function of TGR in dry season, the driest flow increases, the lowest level raises in the downstream of the dam, so as the channel depth. The driest flow at the Shashi station is 3200 m^3/s in the period from May, 1998 to 2003, the lowest level is 30.02 m, but in the period from September, 2008 to August, 2011 after TGR, the driest flow is 5300 m^3/s increased by about 2000 m^3/s, the lowest level is 31.08 m raised by about 1.0 m.

2) *The impact of the sediment discharge on channel*

The change of sediment discharge affects the channel condition by changing the shoal scouring speed. According to the riverbed deformation equation, when the sediment concentration declines, the shoal scouring thickness increases in unit time, the deposition thickness decreases, that's to say the scouring is accelerating but the silting is slowing down, which is undoubtedly advantageous to the navigation condition of MLYR. Numerous field datas also prove this point, like that the duration of the CFRC is basically equal to the channel average flow in the Jianli waterway in the flood receding process of 2001 and 2005, nevertheless the average sediment concentration after the flood is about 0.87 kg/m^3 in 2001, but is only 0.26 kg/m^3 in 2005, correspondingly the shoal scours 0.8 m in 2001, yet 2.0 m in 2005.

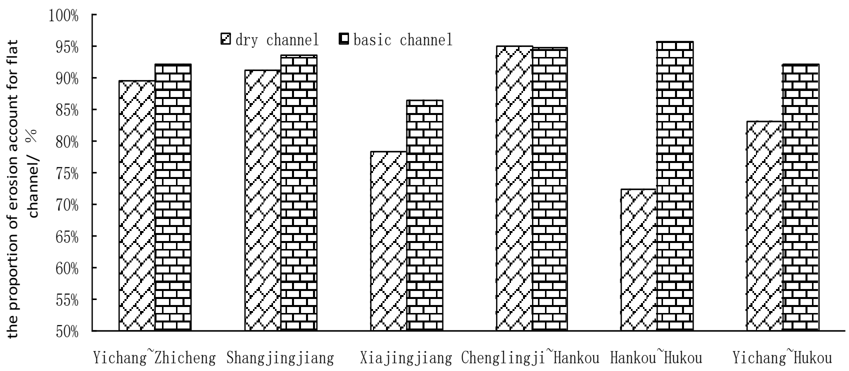


Figure 8: *The percentage of the channel erosion at bankful water level*

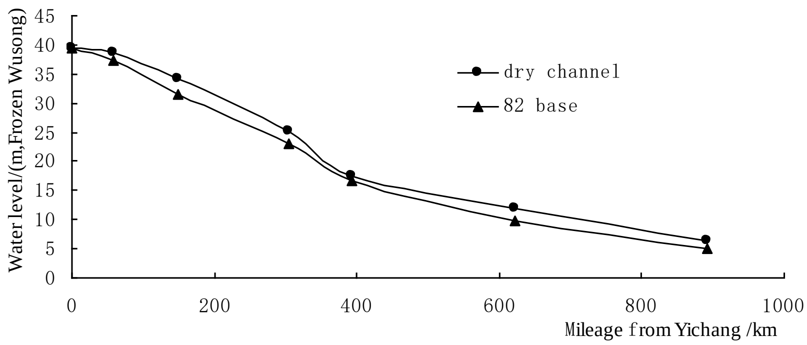


Figure 9: *The low water level and the '82' sailing base level*

Since the impoundment of TGR, under the influence of the sediment reduction, the riverbed in the MLYR scours generally, and the scouring quantity in dry channel accounts for more than 70 % in the flat channel (Figure 8). Figure 9 shows the contrast of the low water level and the '82' sailing base level, from which we can see the difference between above two is small, indicating that the erosion in the MLYR after TGR mainly occurs below the '82' base. With the development of erosion, the channel below '82' base scours continually, the altitude difference between the sandbar (point & central bar) and the channel is magnified, the duration of the CFRC will extend, the channel average flow will increase further, then the channel condition will be further improved.

Therefore, if the sandbar deforms rarely after impoundment of TGR, and the duration of the CFRC turns longer, the channel average flow increases, the lowest water level raises, the shoal deposition slows down but the erosion accelerates, the CFRC also tends to increase, which are all advantageous to the improvement of the channel condition, namely the change of the flow and sediment conditions is favorable for the channel.

3.3. The Impact of by Sandbar Deformation on Channel

Systematically arranging of the field terrain data in the MLYR and combining the change of navigation condition over the years, analysis shows that the effect on the channel by sandbar deformation can be divided into two kinds: the channel condition obstructs the navigation after the deformation as well as doesn't impede navigation after the deformation. Even if the same extent of the bank collapse or the low sandbar shrink, the change of the channel condition is not identical. The right margin of the Wuguizhou in the Jianli waterway collapses back about 200 m in 1996–1998, meanwhile the channel condition deteriorates sharply, only in the dry period of 1998–1999, the dredging quantity is more than

110000 m^3. However it collapses back about 200m in 1994–1996, the channel condition has little change (TANG et al., 2012).

According to its definition, the CFRC means the flow when the shoal begins to scour after the flood. The smaller the CWRC, the larger the flow in unit width, the more fiercely the riverbed scours, consequently the CWRC heavily determines the shoal erosion intensity. Therefore, there exists a CWRC, when the actual CWRC is smaller than it, no matter what kind of riverbed deformation, the channel won't appear the obstructing sailing phenomenon; on the contrary, when the actual CWRC is larger than the critical value, the channel condition likely worsens and obstructs navigation.

From the viewpoint of the physical essence, the CWRC is, under the design water level, the minimum value of the WRC, when the maximum depth meets the maintenance depth within a range of channel width. Therefore, the method to determine the CWRC can be summarized as: according to the terrain data, adding up the relation between the maximum depth and the WRC under the design level within a range of channel width, from which we can find, when the actual water depth is equal to the maintenance depth, the minimum value of WRC is precisely the CWRC. Considering most shoals in the MLYR follow the discipline of "depositing in flood and scouring in dry season", and the obstructive period focuses on the dry season, so the CWRC summarized by the above method, using the terrain data in the early days after flood (e.g. October), is relatively safe and can be used in practical engineering.

Collecting the terrain data after flood of MLRY in October of 1996 or 1998 or 2002, according to the above method, adds up the relation between the channel depth and the CWRC, the relationship of Group Five (the combination of the planning channel dimension in 2020 and the design water level in 2023) in Chenglingji – Hankou Reaches is shown in Figure 10. According to the under enveloping curve of the relationship, combining the channel maintenance depth, the various groups of CWRC in the different reaches are obtained, shown as Figure 11. As we can see from this graph, the CWRC in Shashi–Ouchikou Reaches, Ouchikou–Chenglingji Reaches, Chenglingji–Hankou Reaches, Hankou–Hukou Reaches, is respectively about 1300–1500 m, 900–1100 m, 1500–1700 m, 1800–1900 m.

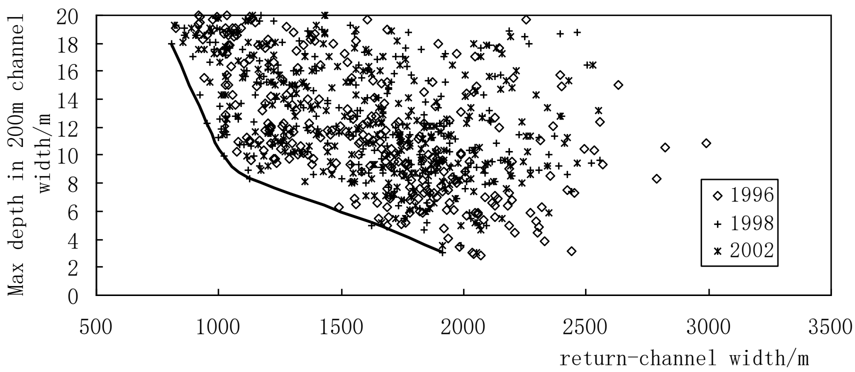


Figure 10: *Relationship between CWRC and channel depth*

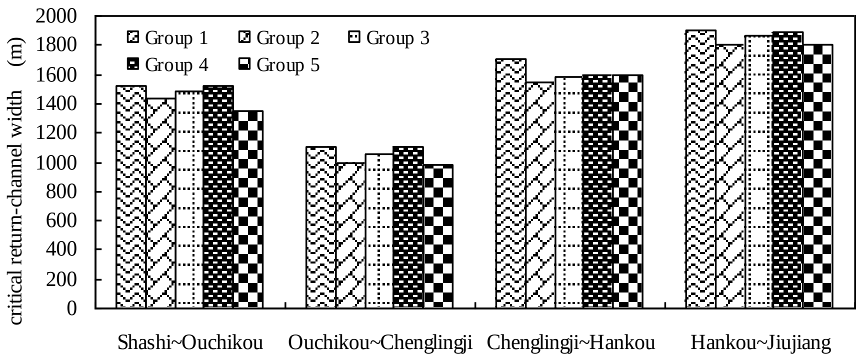


Figure 11: *The critical CWRC of different combinations*

As mentioned before, the right margin of the Wuguizhou in the Jianli waterway retreats back about 200 m, yet no obstructive navigation appears, the main reason lies in that the CWRC increases from 800 m to 1000 m, but is always less than the CWRC. However in 1996–1998 the right margin retreats back about 200m again, the CWRC increases to 1200m, more than the critical value, unfortunately the channel condition deteriorates and obstructs navigation. The right point bar of Nianziwan waterway deposits and accretes in 1996–1998, the CWRC constricts from 1200 m to 900 m, so the obstructive phenomenon disappears. The CWRC in the Majiazui, Jianli, Chibakou, Luxikou waterway are all larger than the critical values, thus the channel conditions obstruct navigation after sandbar cutting. Nevertheless the CWRC in the Longkou waterway is larger than the critical value, so its navigation condition is always better even though the convex sandbar cutting.

The CWRC in the Guniusha waterway before TGR is similar to the critical value, about 1900m. With the impoundment of TGR, the Guniusha bar gradually shrinks, until 2007 the CWRC increases to 2200 m, correspondingly the obstructive navigation occurs. However, although the point bars in Tiaoguan, Fanzui waterway shrink evidently too, their CWRC are still less than the critical value, consequently not yet obstructive navigation occurs. It is thus clear that, the CWRC analyzed in this paper is reasonable, which can be used to identify whether the obstructive navigation will occur or not, after the collapse, Sandbar cutting, low sandbar shrink substantially.

Based on the analysis above, after the impoundment of TGR, the change of flow and sediment process is favorable for the navigation condition, the deterioration of navigation condition mainly due to the fierce sandbar deformation, such as collapse, sandbar cutting, low sandbar shrink substantially. Owing to that the riverbed in the MLYR is subjective to the erosion of the less saturated flow in future for a long time, the low point bar and central bar will shrink further, and the nearshore riverbed scours, the slope ratio increases, the bank without the revetment will collapse further, when the CWRC caused by the sandbar deformation is larger than the critical value, the channel that originally not obstructs navigation will appear obstructive phenomenon.

Therefore, the channel regulation should guard timely the sandbar whose CWRC approaches or exceeds the critical value, avoiding of getting into the extremely passive situation of obstruction navigation. The longer the duration of CFRC, the more sufficiently the shoal scours. Thus the cascade reservoir dispatching in upstream should try to extend the duration of the CFRC (the flow below 12000 m^3/s in Yichang station) in the MLYR as far as possible.

4. Conclusions

This paper analyzes the change of the flow and sediment process in the MLYR and the characteristics of sandbar deformation, combining with the field data before and after TGR, dissects their effect on channel in the MLYR, the main conclusions are as follows:

1) After the impoundment of TGR, the flow below 5000 m^3/s basically disappears, the occurrence frequency in 5000–12000 m^3/s increases substantially, the occurrence frequency above 12000 m^3/s reduces a little, meanwhile the sediment concentration decreases sharply. After the TGR, both the frequency and the length of bank collapse increase significantly, the frequency of the low sandbar cutting increases and the low sandbars shows a trend of shrink.
2) After TGR, the change of flow and sediment process is favorable for the channel condition, concretely represented as the duration of the shoal scouring extends, the scouring intensity strengthens, the driest flow increases, the lowest water level raises, the reduction of sediment discharge causes the shoal deposition slows down, but the erosion accelerates.
3) After TGR, the channel condition deteriorates mainly due to the fierce sandbar deformation, such as collapse, sandbar cutting, low sandbar shrink substantially. Whether the channel obstructs navigation or not, depends on the size of the CWRC. When the CWRC is smaller than the critical value, the channel won't appear obstructive phenomenon, yet when the width is larger than the critical value, the waterawy is likely to obstruct sailing.

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