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CONFLUENCE RATIO AND DEPOSIT BAR DISTRIBUTION IN RESERVOIR CONFLUENCE AREA

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ABSTRACT

River confluences in reservoir area usually create the deposit bars on intersection zone，especially the tributary entrance bar that is quiet adverse to reservoir operation. Take Baishi reservoir confluence located in Northeast china as the representative, Field investigation and model test were reported. Considering the variable confluence ratios and reservoir storage levels, the depth average velocity of cross section along the reach was tested, then the sediment transport capacity was calculated, which could explain the formation mechanism of deposit bar and its distribution character. Results suggest: tributary flow velocity always firstly increased then deceased along the reach, and changed more notable under the greater confluence ratio more than 0.5; the changing characteristic of sediment transport capacity was similar to flow velocity, and it would keep reducing from tributary channel to the downstream confluence when confluence ratio was greater than 0.5. While the situation in mainstream reach is quite different, no matter how big the confluence ratio was, mainstream flow velocity and sediment transport capacity always firstly increased then deceased along the reach, greater confluence ratio means sharper change, and the turning point located in the intersection zone. Due to the inhomogeneous changes of sediment transport capacity, the deposit bar formed in different place, which means the distribution of deposit bars could be deduced according to the confluence ratio during the main sediment transport period in flood seasons. As the result the Discriminate Conditions for deposit bar distribution based on the confluence ratio was established. By using the measured Prototype data, the relationship between the confluence ratio and distribution of deposit bar was verified which is consistent with the research results; As the reservoir water level increased, both flow velocity and sediment transport capacity weakened, as well as the change rate along the reach.

Keywords: Reservoir confluence; deposit bar; confluence ratio; turning point

1 INTRODUCTION

As a typical geomorphic unit in river system, the river confluence plays an important role in human society because of the water transport. When reservoir is built in the lower reaches of the river confluence, the elevation of erosion datum makes the confluence deposit universally. At the same time, overlapping of the water and sediment processes combined with the Morphology change result in the deposit bars which would cause the siltation of the confluence reach to extend upward, and even block the main and tributary rivers. Deposit bars can be divided into tributary bars and mainstream bars according to position (Chen Li et al., 2013). Under the weak hydrodynamic environment in reservoir area, the cumulative development of deposit bars would reduce reservoir storage capacity. The formation of deposit bars in confluence are related to many factors, such as river topography, water storage level, flow and sediment process, confluence angle of tributaries and so on. As one of them, hydrodynamic conditions play a decisive role.

The flow characteristics in confluence reaches have been studied comprehensively, such as the water surface, recirculation and three-dimensional turbulent structure and so on. Field investigation carried out in of confluence of River Bayonne and River Berthier (Pascale Biron et al., 2002) suggested the distinct surface elevation exists in mixing interface and stagnation zone, and a transverse gradient appeared at the edge of the mixing interface. Hydrodynamic characteristics of staggered peak floods in confluence of river Yi and River Luo was calculated by mathematical model (Sun Dongpo et al., 2013), the Y-curve relationship between water level and discharge in the intersection zone was revealed. Flume test was also conducted to study the shape and scale change of separation zone in confluence reach (Mao Zeyu et al., 2004; Wang Xiekang et al., 2006), as well as the relationship between separation zone and confluence ratio. River bed discordance resulted in the upwelling current appeared during the process of tributaries entering the main stream of confluence

(M.Leite Ribeiro,2012）, formed the vertical shear layer, which obviously enhances the three-dimensional turbulence of the flow. Above research focus on natural confluence reach.

Sediment research in confluence area also made achievement such as mechanism of mainstream deposit bars caused by debris flow (Guo ZhiXue, 2004) and hyper concentrated flow (Wang Ping, 2013). For confluences in reservoir area, researchers mainly concentrated in the tributary deposit bars, also known as entrance bars. Based on the field investigated data, deposit characteristic of tributary deposit bar in XiaoLangDi reservoir (Wang Ting et al., 2011; Zhang JunHua et al., 2013), the classification of tributary deposit bars in DanJiangKou reservoir (Liu Fazhong et al.,2006; Zhang Houyu,2005; Zhang Houyu et al., 2010) were analyzed. hydrodynamic characteristic of the confluence reach in the reservoir area is different from those of the natural confluence reach, the formation mechanism and distribution of the deposit bar is also different.

2 METHOD

A typical confluence reach was selected based on the main influence factors as follow: confluence ratio and storage level. Then according to the similarity law, a physical model was established, and model test method is used to study the hydrodynamic characteristic of the reservoir confluence reaches under the influence of confluence ratio and the storage level. It is demonstrated that the change of sediment transport capacity along the confluence area from increasing to decreasing explains the dynamic mechanism of the formation of deposit bar and its distribution.

2.1 Typical confluence reach in Reservoir area

The long-term effect of sediment-laden flow has formed corresponding river morphology of reservoir confluence, including deposit bars. During this processes confluence ratio and storage level are key factors affecting hydrodynamic conditions, therefore, the selection of the typical confluence reach should focus on making representative of confluence ratio and storage level.

The confluence ratio referred to as R, which is the ratio of tributary discharge to total discharge, reflects the interaction between main and tributary inflows and the situation of flood encounter: the confluence ratio is greater than 0.5 indicates that tributary inflow is dominant, while confluence ratio is less than 0.5 indicates that the main inflow is dominant.

Storage level, which decides the submergence degree of reservoir confluence, could affects the hydrodynamic condition. During the flood season when the storage level decreases, some confluence reaches possibly turn into non-submerge stage, while other confluence reaches in perennial backwater area could maintain the submerge stage. The hydrodynamic conditions of the two cases above are quite different.

In order to study the confluence ratio and deposit bar distribution, the typical confluence reach should have large range of confluence ratio, which means either the mainstream or tributary might be the dominant flow. perennial submerge condition should be considered too. Survey results suggest the confluence of Daling River (D for short) and Mangniu River (M for short) in Baishi reservoir can meet these requirements, see table 1. the physical model was designed according to the background information from Baishi reservoir.

Table 1. Survey of confluence river in reservoir

	Three Gorges reservoir Yangtze-Jia Ling river	**San Menxia reservoir Yellow river-Wei river**	**Dan Jiangkou reservoir Han river-Du river**	**Baishi reservoir D river-M river**
Confluence ratio	0.1-0.6	0.01-0.99	0.01-0.7	0.01-0.99
Submerge condition	Non-perennial submerged	Non-perennial submerged	Perennial submerged	Perennial submerged

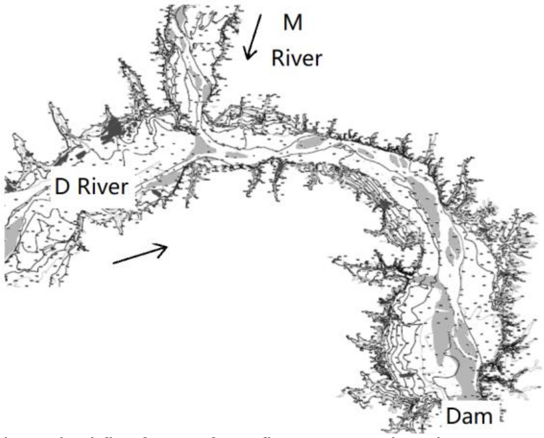
2.2 Typical confluence reach in Reservoir area

2.2.1 Prototype confluence reaches

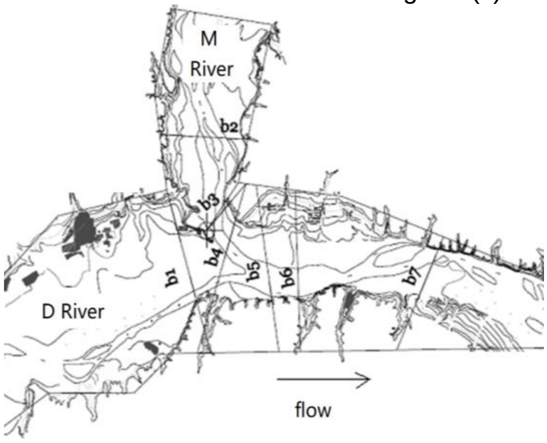
The tributary M River flow into the mainstream D River at 16 km in front of the Baishi dam, formed the Asymmetric confluence, see figure 1(a). According to the Hydrological statistics, the average annual runoff of D River is 1.2 billion m^3, the average annual runoff of M River is 0.283 billion m^3, and Interannual variations of tributary runoff are significant, maximum year up to 1.09 billion m^3 while minimum year only 0.06 billion m^3. The mainstream gradient is about 0.067%, and tributary gradient is about 0.137%, The gradient of tributary is twice as large as that of mainstream river. When the reservoir is in normal storage level, river width of D River and M river in upstream confluence is about 2.46km and 1.39km separately, and downstream confluence the river width is about 1.45km.

2.2.2 Scope of physical model and test condition

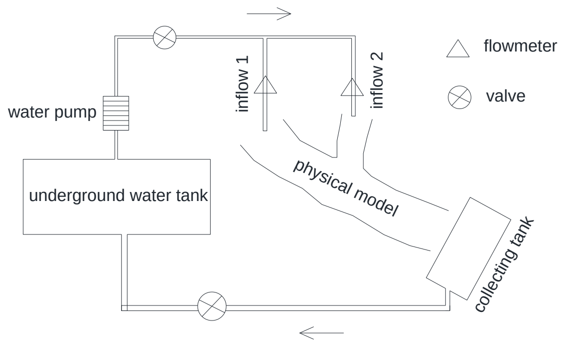
According to the confluence morphology and channel characteristic, the scope of physical scale model could be defined as: the upper boundary of the tributary is 3.5 km above the entrance, the upper boundary of the main stream is 5.5 km above the entrance, and the lower boundary is 6 km below the intersection zone. The scale model is designed according to the similarity theory. The horizontal scale is 300 and the vertical scale is 100. The flow motion satisfies the similarity of inertia force gravity ratio and inertia force resistance ratio. The gauging sections b1-b7 is arranged along the course. The hydraulic characteristic parameters of each section are shown in Table 2. The simulation range and the layout of flow measurement section are shown in Figure 1(b), model test system and regional division of confluence reach in figure1(c) and (d).



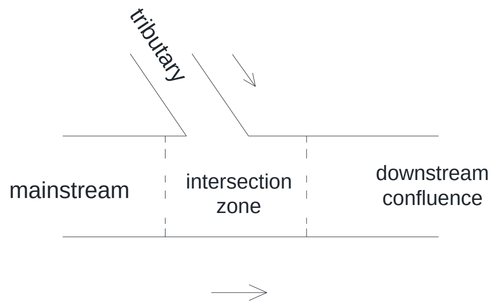
(a) Typical flat form of confluence reaches in reservoir



(b) simulated confluence and gauging sections



(c) test system



(d)confluence model

Figure 1. Prototype and confluence physical model arrangement

Table 2. Hydraulic parameters of gauging sections in 115m storage level

	b1	**b2**	**b3**	**b4**	**b5**	**b6**	**b7**
discharge area A/ 10^4m^2	0.43	0.01	0.16	0.29	0.32	0.52	0.71
wetted perimeter χ/ m	1611	627	499	1323	1012	989	827
water depth h/ m	2.76	0.18	3.26	2.19	3.34	5.51	8.58
Hydraulic radius R_0/ m	2.66	0.17	3.24	2.18	3.21	5.30	8.53

Based on the field measured data of the main and tributary rivers during flood season, five groups of confluence ratios are used to simulate the different flood encounter forms of the main and tributary, and the different submergence degrees of the confluence rivers are simulated by two groups of storage levels corresponding to the significant development of the deposition in the confluence rivers. The test conditions are shown in Table 3.

Table 3. model test conditions

	mainstream		**tributary**		**Confluence ratio**	**Storage level / m**
	Q_m / m^3/s	**P / %**	**Q_t / m^3/s**	**P / %**		
1	3620	10	366	annual average	0.09	
2	3620	10	1240	25	0.26	
3	3620	10	4792	10	0.56	115/118
4	980	25	4792	10	0.83	
5	386	annual average	4792	10	0.92	

2.2.3 Model calibration

Due to limited field data, only the flood trace water level and corresponding flood discharge could be used for calibration. the water surface line was calibrated by comparing the field investigated water profile data with the model test result along the reach, results see table 4, which Indicates the designed physical model could satisfy resistance similarity.

Table 4. verification of hydraulic factor in confluence reach

	gauging section				
	b1	**b2**	**b5**	**b6**	**b7**
Flood Trace Water Level /m	117.06	116.43	114.06	111.38	106.91
Model water level/m	117.13	116.05	113.84	111.76	107.21

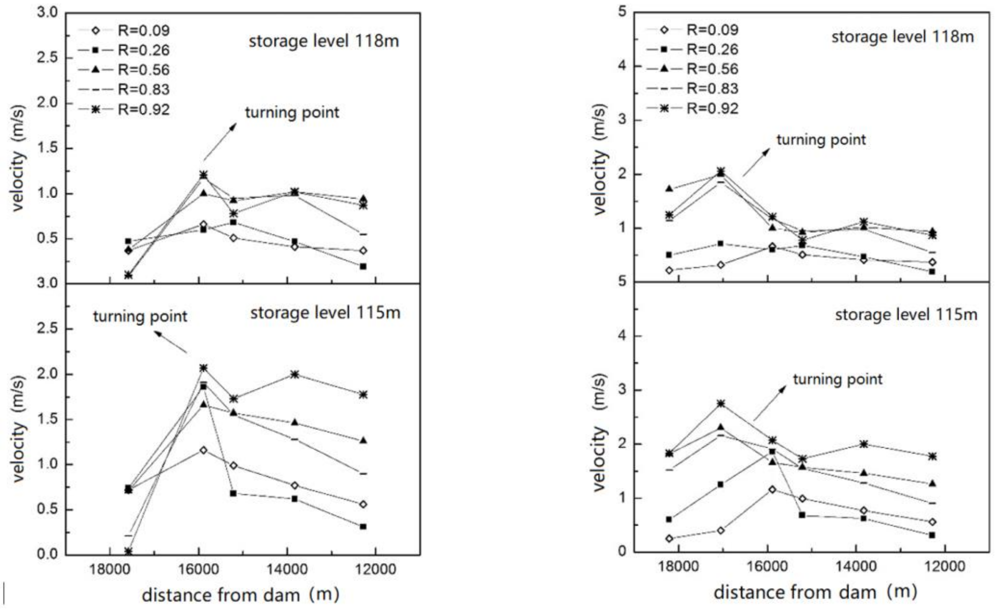
3 RESULTS

3.1 Variation of flow velocity along the reaches

Figure 3 shows the variation of flow velocity from the main and tributary to downstream confluence. Due to the backwater effect, discharge increase and boundary change in intersection zone, flow velocity is totally different than that in single reach. from mainstream to downstream confluence the average flow velocity of cross-section changed first increase then decrease, a clear turning point appeared in intersection zone; With the increase of confluence ratio, backwater effect from tributary increase gradually as well, which would make the flow velocity in mainstream descend and in tributary raise up. As a matter of fact, flow velocity of cross section from mainstream to intersection zone always shows increase and the growth is more significant under the larger confluence ratio. As shown in figure 3(a), under the 115m storage level, the growth of cross section average flow velocity was about 0.44m/s when confluence ratio was 0.09, the growth of cross section average flow velocity could up to 2.03m/s when confluence ratio was rise to 0.92.

The relationship between confluence ratio and flow velocity change from tributary to downstream confluence is more complicated. In general when the confluence ratio was less than 0.5, cross section flow velocity from tributary to downstream confluence first increased then decreased, the turning point appeared in the tributary entrance position instead of intersection zone , when confluence ratio is close to 0.5, the total discharge in downstream is larger than other conditions, Inertia enables flow velocity value decreasing with a slow rate along the downstream confluence.

With the rise of storage level, discharge area expands, the overall flow velocity decrease. In figure 3(a), after the water level rose, maximum flow velocity descended from 2.07m/s to 0.72m/s in intersection zone，flow velocity decreasing rate in downstream confluence was slowing down，the similar situation also occurred from tributary to downstream confluence, see figure 3(b).



（a）mainstream to downstream confluence （b）tributary to downstream confluence

Figure.3 Variation of cross section flow velocity along the reach

3.2 Variation of sediment transport capacity along the reaches

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Deposit bar formed or not, as well as the formed position, decided by the ratio of sediment concentration to sediment transport capacity. under certain flow and sediment condition, the region in reservoir confluence reaches with the small value of sediment transport capacity means serious deposition possibly occur, even form deposition bars, as a result, sediment transport capacity plays a vital role in process of sediment deposition. Zhang Ruijin's equation of sediment transport capacity is used to analyze the variation of sediment transport capacity along the course of flow.

$$S_* = K\left(\frac{U^3}{\mathrm{gR}_0\omega}\right)^{\mathrm{m}} \qquad [1]$$

Where *U*- average velocity of cross-section flow
R_0- hydraulic radius of section
g- gravity acceleration
***ω*-** settling velocity of bed sand in suspended load
K- coefficient
m- Index number

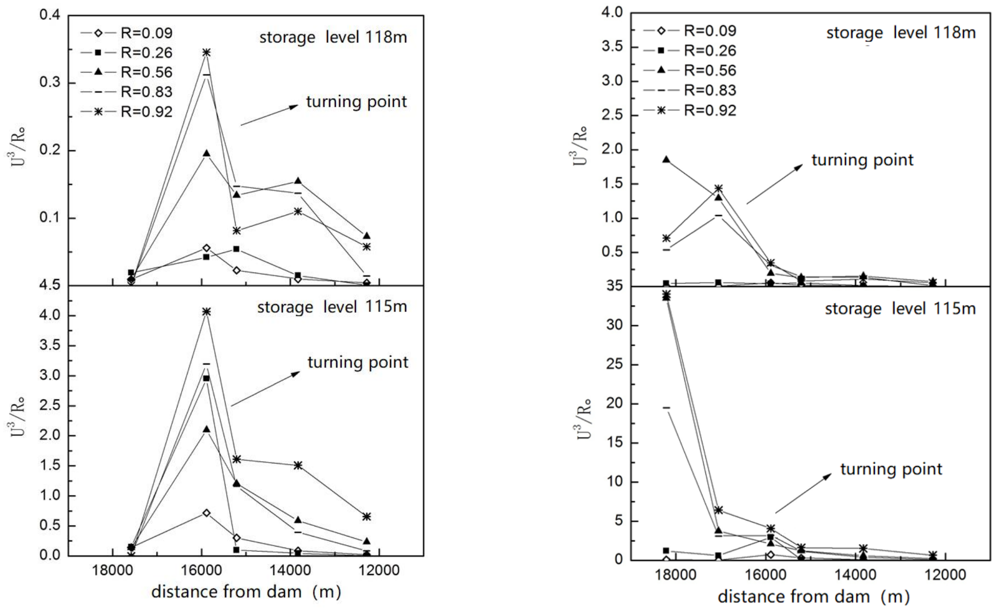
the coefficient K, index number m vary with $U^3/(g R_0\boldsymbol{\omega})$ change. In a given river section, the value of K， m does not change much. For the convenience of analysis, assuming that the value of ω, g, K, m remain unchanged, average flow velocity of cross section together with the hydraulic radius of section determine the sediment transport capacity of cross section in reservoir confluence area. As a result, define the ratio of U^3 to R_0 as the sediment transport capacity factor:

$$S_* = K\left(\frac{U^3}{\mathrm{gR}_0\omega}\right)^{\mathrm{m}} \propto \frac{U^3}{\mathrm{R}_0} \qquad [2]$$

Sediment transport capacity is closely related to the cubic of flow velocity, there is a certain consistency between them. Figure 4(a) shows sediment transport capacity factor change from mainstream to downstream confluence, demonstrates the turning point from increase to decrease, while in figure 4(b) the sediment transport capacity factor from tributary to downstream confluence shows a single change of reduction along the reach when confluence ratio was larger than 0.56.

With the increase of confluence ratio, sediment transport capacity growth raised up along the reach from mainstream to downstream confluence, and sediment transport capacity decline range raised up as well along the reach tributary to downstream confluence. By comparing the cross-section sediment transport capacity factor above and below the intersection zone, it was believed change range of sediment transport capacity in two zones are both great.

Under submerge condition, the rise of storage level would not affect the variation law of sediment transport capacity of along the reach, but the flow velocity and sediment transport capacity of flow decreases significantly due to increase of parameters such as discharge area, wetted perimeter and hydraulic radius. Take figure 4(a) for instance, when storage level was 115m, the corresponding sediment transport capacity factor in intersection zone was 4.0, when storage level rose up to 118m, the corresponding sediment transport capacity factor in intersection zone was 0.35.the variation of storage level could also affect the sediment transport capacity in downstream confluence.



（a）mainstream to downstream confluence （b）tributary to downstream confluence

Figure 4. Variation of sediment transport capacity factor along the reach

4 DISCUSSION

4.1 Hydrodynamic mechanism of deposit bar formation

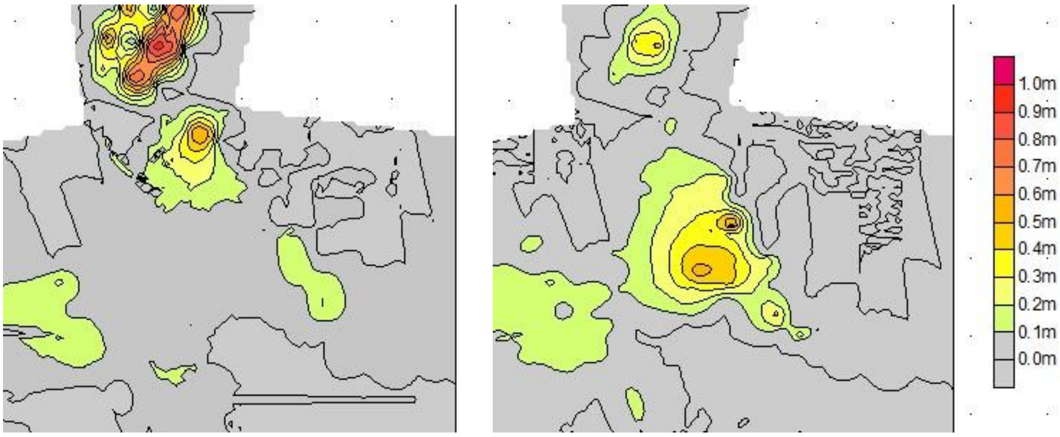
Both cross section flow velocity and sediment transport capacity in reservoir confluence reach exhibited the characteristic of increasing first and then decreasing, and different confluence ratio usually means different decreasing range， in addition when the confluence ratio was larger than 0.5, sediment transport capacity always showed the decreasing character from tributary to confluence downstream. Analysis of variation of sediment transport capacity can reflect the characteristics of non-uniform sediment deposition in reservoir confluence, which means when the sediment transport capacity of current increases, the sediment deposition is relatively small. When sediment transport capacity of the current decreases, the sediment begins to accumulate in large quantities, and sediment would deposit along the course with the decrease of the sediment transport capacity. In the section where the sediment transport capacity of current varies dramatically, the change of sediment scouring and silting is also dramatic. The above-mentioned characteristic is precisely the hydrodynamic mechanism of the formation of deposit bars.

4.2 verification for deposit bar distribution

The relationship between the distribution of deposit bar and the confluence ratio could be verified by the experimental data in the reference (Yan Tao et al., 2014). Figure 5 shows the distribution of deposition in the confluence area after the mainstream and tributary floods under the storage level 115m. during the flood period the sediment inflow from the mainstream accounts for 35% of the total amount of the sediment inflow，the tributary sediment accounts for 65%. The confluence ratio in the main sediment transport period in figure 5(a) was 0.34, and in figure 5(b) was 0.96, represent the hydraulic dominant position of the mainstream and the dominant position of the tributaries respectively.

When the confluence rate was 0.34, the maximum value of sediment transport capacity appeared in intersection zone, where the sediment deposit volume was minimum. Most of the sediment incoming deposited in the upper reaches of the confluence area, because the tributary sediment account for 65%, so the deposit bar appeared in the tributary channel, see figure 5(a).

When the confluence ratio was 0.94, turning point of sediment transport capacity appeared from mainstream to downstream confluence, while sediment transport capacity from tributary to downstream confluence decreasing along the reach, and there was a drastic decline in intersection zone. as a result, most of the sediment from tributaries is deposited in the intersection zone, while the sediment from the mainstream is deposited in the upper reach of the confluence area. since the tributary sediment is dominant, deposit bar appeared in the intersection zone，see figure 5(b).



（a）deposit bar when R=0.34 （b）deposit bar when R=0.96

Figure 5 deposit bar distribution with different confluence ratio

5 CONCLUSIONS

(1) Due to the reflection from tributary backwater, discharge increase and boundary change, the flow velocity of cross-section along the reach from mainstream(D river) to the downstream confluence changed, which shows the characteristics of first increasing and then decreasing, and a turning point appears in the intersection zone, however the same phenomenon from tributary (M river)to downstream confluence only appeared when the confluence ratio is less than 0.5. With the increase of confluence ratio, the flow velocity in the mainstream decreases, the flow velocity in the tributary and confluence area increases. When the reservoir storage level rises up, the average velocity of the section decreases, and the attenuation rate of the velocity along the downstream confluence decreases significantly.

(2) sediment transport capacity from mainstream to downstream confluence shows the characteristic of first increasing and then decreasing as well, while the sediment transport capacity from tributary to downstream confluence shows a single change for reduction when confluence ratio larger than 0.5. With the increase of the confluence ratio, the variation range of sediment transport capacity is more significant, and the variation rate along confluence area increases. Rise of the storage level lead to Increase of parameters such as discharge area, wetted perimeter and hydraulic radius, then the flow velocity of cross section decreases, as well as the sediment transport capacity of flow, whose rate of change also slowing down.

(3) The sediment transport capacity of flow from mainstream to downstream confluence increases first and then decreases, and the sediment transport capacity of flow decreases from tributary to downstream confluence when the confluence ratio is greater than 0.5. all above mentioned reasons lead to uneven sediment deposition. In the section where the sediment transport capacity of flow varies dramatically, the change of sediment scouring or silting is also dramatic. These changes are the hydrodynamic mechanism of the formation and distribution of deposit bars in reservoir confluence reaches.

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