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Scour and silting evolution and its influencing factors in Inner Mongolian Reach of the Yellow River

QIN Yi[1], ZHANG Xiaofang[2], WANG Fenglong[3], YAN Heng[1], HAN Haijun[1]

1. Key Laboratory of North-West Water Resources and Ecology Environment of Ministry of Education, Xi'an University of Technology, Xi'an 710048, China;
2. Zhoushan Water Conservancy Survey and Design Institute, Zhoushan 316000, Zhejiang, China;
3. Harbin Water Conservancy Plan and Design Institute, Harbin 150076, China

Abstract: Rivers with fluvial equilibrium are characterized by bed deformation adjustment. The erosion-deposition area in cross-section reflects this characteristic, which is a base of researching the river scour and deposition evolution by time series analysis. With an erosion-deposition area indicator method proposed in this paper, the time series of erosion-deposition area quantity at Bygl and Shhk stations were obtained with the series duration of 31 years from 1976 to 2006. After analysis of its trend and mutation, three different tendencies about the evolution were observed in general from the quasi-equilibrium phase through a rapid shrinkage to the final new quasi-equilibrium. It is also found that the trend of erosion-deposition area series will change once a big flood occurred in some of the tributaries, and its ever greater influence is due to the decrease of deluge with the completion of upstream reservoirs. Almost all the turning points were coincident with the time when hyper-concentrated sediment flood occurred in some tributaries. With the time series of clear mutations since the late 1990s, the Inner Mongolian Reach has been in a new equilibrium phase. This can be concluded in two aspects. 1. The absence of big floods and sediment transportation from tributaries result in the river shrinkage, and to regain the channel flow-carrying capacity in Inner Mongolian Reach a large flood is needed both of high peak discharge and of lengthy interval to destroy the new equilibrium. 2. The proposed method of erosion-deposition area indicator is of great help to channel scour-deposition evolution analysis because it can demonstrate real time deformation of cross section in quantity.

Keywords: Inner Mongolian Reach of the Yellow River; erosion-deposition area indicator; evolution; equilibrium

The Inner Mongolian Reach is located in the upstream of the lower Yellow River with 10 tributaries of seasonal rivers originating in the Hobq Desert. In recent decades, the deposition rate along this reach has increased with rapid shrinkage of its main channel and a remarkable decrease of its flow-carrying capacity under the influence of the changing climate, reservoir regulation and incoming sediment from its 10 tributaries; the unstableness of river regime, severe bank collapse and the deposition of tributary entrance make it a grim situa-

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Author: Qin Yi (1959–), Professor, specialized in the field of river sediment. E-mail: 13571991500@126.com tion for flood control (Yao *et al*., 2007). Aiming at the flood control and utilization of water resources in this reach, a thorough investigation was made into the water and sediment. In general, three views are presented on the formation of deposition: 1) Serious deposition in this reach has taken place after the operation of Longyangxia Reservoir upstream (Zhao *et al*., 1999). 2) Local coarse sand deposition is the main factor. By analysis of drilling samples, the primary particle size group of river sediment is found greater than 0.1 mm, and 80% is aeolian sand mostly from Ulan Buh Desert and Hobq Desert (Yang *et al*., 2003); 3) Sedimentation volume of the reach from Bayangaole to Toudaoguai is mainly affected by the 10 tributaries, yet it was not large during 1969–1986 due to the favorable condition of incoming water and sediment. While since 1987, the effect of interval sediment on deposition has been intensified in the Inner Mongolian Reach with the regulation of upstream reservoirs and the decrease in precipitation (Liu *et al*., 2009).

For making river-controlling strategies, it is of great importance to probe into the deposition characteristics and its main causes of the Inner Mongolian Reach (before an agreement is reached). Sediment concentration from the upper river is not always in conformity to the carrying capacity in the current flow because of the diversity and complexity of the drainage area, according to Qian *et al*. (1987), hence the temporary change to the river channel. Therefore, the mobile bed of alluvial channel is forever in the state of deformation and development but the self-adjustment of the river bed has been promoting the deformation to stop or even disappear. Thus, possibly it may be in a relative equilibrium phase when the river reach stays stable. Souring or deposition, its geometry remains almost the same with the recoverable channel. Only when a big change occurs to the incoming water and sediment load, can this balance be destroyed (Shao and Wang. 2005) and this feature is certainly reflected in the trend of channel evolution. Consequently, the characteristic of channel evolution and its causes may be explored from the evolution trend of the channel section.

1 Time series of scour and silting evolution of channel section

Traditionally, deposition-scouring analysis is conducted by study of the information out of water table under same discharge in different periods of time (from the past till now). A higher water table represents deposition and the lower scoring. This method is quite effective but is impossible to predict the detailed fluvial process because the plot can only express a limited observed data on time axis. Zhang (2005) put forward a new method from using grid-net or contour map for determination of quantitative analysis for river bed sedimentation amount. According to test, the method is thought to have characters of high accuracy and fast speed. But it does not break away from the same shortage with the water table discharge method mentioned above. In order to analyze the characteristic of channel scour and silting evolution fully and its causes from the evolution trend of the channel section, the key lies in the time series reflecting the trend. In this paper, the erosion-deposition area index method is proposed for calculation of erosion-deposition area of channel section which results in the time series, and specific approaches are as follows: A_0, Z_0, and B_0 denote the channel cross-sectional area, the water table and width at a certain time t_1, and the three variables changed would be A_0', Z_0', and B_0' by t_2 (see Figure 1).

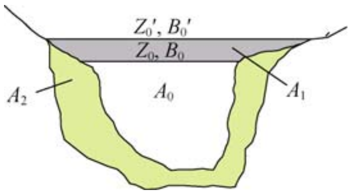

Figure 1 Schematic diagram of erosion-deposition variation in cross section

A_0' can be calculated as:

$$A_0' = A_0 + A_1 + A_2 \tag{1}$$

where A_1 is caused by water table changes due to changing discharge and A_2 is caused by channel evolution. In this way, A_2 can be presented as:

$$A_2 = A_0' - A_0 - A_1 \tag{2}$$

A_1 is calculated approximately by trapezoid planimetry; the value of A_2 is negative when the channel is in deposition and positive in scouring. After a period $T = \sum_{i=1}^{m}(t_2 - t_1)_i = \sum_{i=1}^{m}\Delta t_i$, the erosion-deposition area can be illustrated as $\sum_{t=t_0}^{T} A_{2,t}$. A comparison is made in order to examine the validation of this method between the change of estimated and measured values in sectional area (Table 1).

Table 1 Changes of sectional area before and after seasonal floods

Year	Hydrometric station	Beginning and ending time of $\sum A_2$ (Month/Date)	Maximum water table of the duration Z_m/m	Cross sectional area relevant to Z_m/m^2		Difference value	$\sum A_2$	Relative error/%
				Beginning	Ending			
1978	Huaxian	6.17–11.26	338.8	1549	1451	–98	–90	8.89
1990	Sanhuhekou	5.7–8.20	1018.55	1025	1172	147	154	4.55
2000	Toudaoguai	7.6–9.17	987.23	725	746	22	24	8.33

Table 1 shows the relative error is less than 10% either in the Yellow River or Weihe River, and the error gets slightly larger only with occurrence of over-bank floods. Take the big flood in 1981 as an example: the real cross-sectional area increased by 1629 m^2 whose relative error was 13.3%. In other words, the real value A_{2r} is closely related to the computed value A_2, namely, $A_{2r} = cA_2$. In a single channel $c \approx 1$ and $c > 1$ for a compound channel. Considering the difference between the real and the computed values, we believe A_2 is an indicator of cross-sectional scour and silting evolution, and the time series is obtained with those indicators.

Obviously the proposed method differs from the traditional one in real time deformation of cross section in quantity, which is helpful for analysis of channel scour-deposition evolution.

2 Survey and data

2.1 Introduction

Running 673-km long with its river slope about 0.17‰, the Inner Mongolian Reach, from

Shizuishan to Hekouzhen, is located in the upstream of the lower Yellow River (Wang and Jia, 2009). Close to the mouth slope, it is the alluvial channel with no extra sediment carrying capacity. The four hydrometric stations along the mainstream are Shizuishan, Bayangaole, Sanhuhekou and Toudaoguai (herein after as “Szs, Bygl, Shhk and Tdg” for short), see Figure 2. There are different sources respectively for water and sediment in the upper Yellow River, 98% water up above Lanzhou and 54% of sediment from below the city (Wang *et al.*, 1996). Since 1961, water control projects have been built one after another like Yanguoxia, Sanshenggong, Qingtongxia, Liujiaxia and Longyangxia reservoirs at upstream of the Inner Mongolian Reach. Along with other irrigation measures, there is quite a different adjustment of incoming water and sediment load in the reach. After the completion of the Longyangxia Reservoir in particular, the wet season water quantity in this reach was reduced by 54% compared with the previous period and the peak flow decreased from 2000–4000 m^3/s (1969–1986) to 1000–1500 m^3/s (Liu *et al.*, 2009). Deserts of developed aeolian landform are around the reach: to the west of it is Ulan Buh Desert from Wuhai to Dengkou; from Dengkou to Hekouzhen are Hobq Desert and 10 tributaries (called KongDui in Mongolia) distributed to the south. The total area of these tributaries is 10,767 km^2 with fragile eco-environment. Sudden deluge of high concentration sediment takes place every time with heavy rainfall in the wet season. The flood peak of Xiliugou, one of the tributaries, in 1998 was 1600 m^3/s and its sediment concentration reached 1150 kg/m^3, bringing large amount of sediment into the Yellow River to form sand barriers and clog rivers. The annual sediment load from 10 tributaries into the Yellow River is 2711×10^4 t, according to Feng *et al.* (2009), in which more than 60% is coarse sand with a diameter greater than 0.05 mm. Table 2 illustrates those recorded years of disasters from the 10 tributaries.

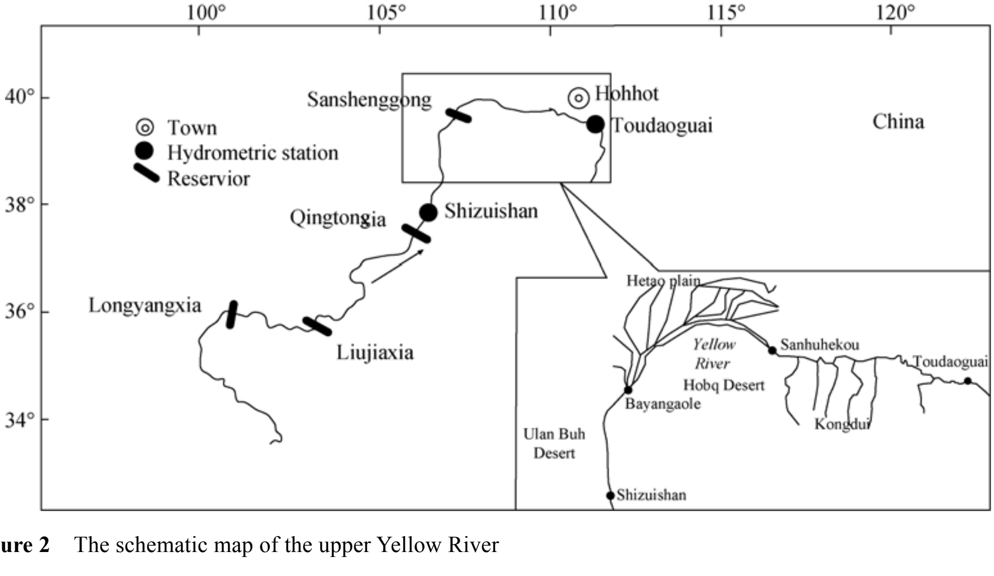

Figure 2 The schematic map of the upper Yellow River

Table 2 Years with disasters from 10 tributaries recorded in history

Period	1950s	1960s	1970s	1980s	1990s	Since 2000
Year	1959	1960 1961	1973 1976 1978 1979	1982 1989	1994 1998	2003

Ice-jam flood formation is another feature of this reach. Located in the most northern part of the Yellow River reach, the river is in ice season of 4–5 months every year in which a freezing-melting process is observed (Wang *et al.*, 2006; Yao *et al.*, 2007). Since water flows from the lower latitude (37º17′) to the higher one (40º51′), the freeze starts downstream and progresses up while melting occurs in the opposite direction. In this way the upper discharge is greater than the lower one during ice melting season, so easily a serious ice-jam flood happens. Under the co-influence of hydrodynamic and thermodynamic factors, the adjusting process of water, sediment and bed form to accommodate each other is far more complicated than in the summer flood season (Fang *et al.*, 2007; Ke *et al.*, 2000).

2.2 Data

As for the Inner Mongolian Reach, the most serious sedimentation reach has been observed from Bygl to Shhk, located above the 10 tributaries. The changing trend of cross section in these two places may well reflect the influence of incoming water and sediment from upstream and of 10 tributaries. So measured data from the two hydrometric stations (1976–2006) is used for analysis. Due to data absence at Bygl in 1989 and 1990, Shhk is the primary subject. The initial cross-sectional area A_0 was 1080 m^2 recorded on February 2, 1976, and the accumulated indicator (the change value relative to the initial area), $\sum_{t=t_0}^{T} A_{2,t}$, calculated by formulas (1) and (2) is collected at the end of each month during the period 1976–2006. Finally, a time series with a length of 372 is generated.

3 Channel evolution and its causes

3.1 Characteristics of channel evolution

Figures 3 and 4 show a similar variation trend of three-phase changes at Bygl and Shhk, from a stable phase through a change phase into the new stable. 1976–1990 for Shhk was a relatively stable period with the river bed remaining almost unchanged although it is in scouring in flood season and silting in non-flood season. The accumulated indicator value is small at the end of a year (Figure 4): Point A represents the value of maximum area change (scouring) in flood season, 1200 m^2 larger than the initial value in 1976 and it was approximately 190 m^2 till the end of the year 1981 (see Point B in the same figure), from which it can be seen that the river had remarkably recoverable behavior. During 1991–1999, with the constant decrease of both fluctuation of the area change value and its mean, the channel began to silt through a dramatic adjustment when the river is in a disequilibrium phase. Followed by equilibrium after the year 2000, this new phase has witnessed the recoverable river bed again but the cross-sectional area is roughly 400 m^2 smaller than that in 1976. Another thing remarkable is the turning point at Bygl 3–4 years ahead of Shhk.

The cross-section evolution is the interaction of incoming water and sediment and the river bed boundary. The analysis of the incoming water and sediment at Shhk revealed that the incoming sediment coefficient during 1976–1990 stayed around 0.004 $kg{\cdot}s{\cdot}m^{-3}$ and increased continuously till it reached 0.010 $kg{\cdot}s{\cdot}m^{-3}$ in 1997. From then on, the coefficient remained around 0.009 $kg{\cdot}s{\cdot}m^{-3}$, corresponding to the three-phase characteristics of cross section.

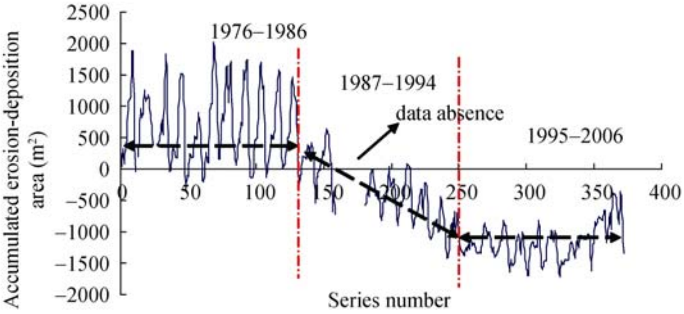

Figure 3 Changes of erosion-deposition area at Bygl Station in 1976–2006

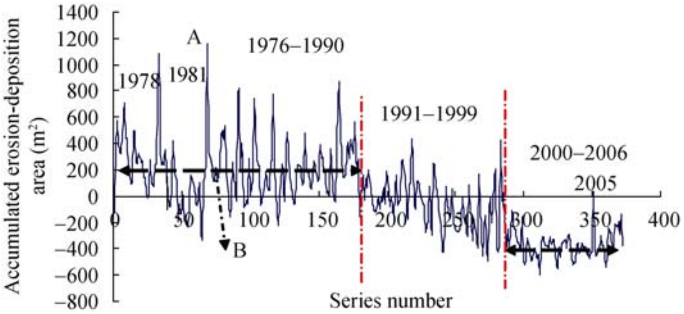

Figure 4 Changes of erosion-deposition area at Shhk Station in 1976–2006

3.2 Mutation analysis

The time at which sudden transition of a trend of channel evolution happened is called mutation point, suggesting the existence of some important factors coming into effect. Methods of residual mass curve, Mann-Kendall hypothesis test and heuristic segmentation test (Pedro *et al*., 2001; Wang *et al*., 2009) were applied to carry out the mutation analysis.

Figure 5 is the results of residual mass curve method. It shows the significant change of the trend at the series number 48 (year 1979), 68 (year 1981), 188 (year 1991) and 240 (years 1995 and 1996).

Figure 6 (for Mann-Kendall test) shows *UF* curve in positive chronological order exceeds the lower critical boundary at the sequence number around 200 (year 1993), and *UB* curve in inverted chronological order crosses the *UF* curve at the sequence number around 246 (year 1996). By this method, those sequence numbers are the mutation points.

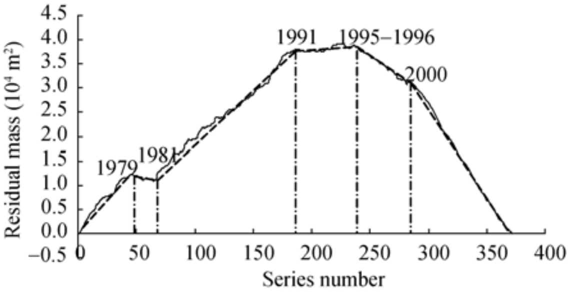

Figure 5 Residual mass curve of erosion-deposition area

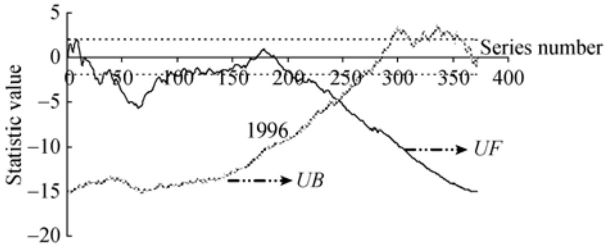

Figure 6 Statistic series curve obtained by Mann-Kendall Method which is used for the test, where the dotted line represents the upper and lower critical boundary at 5% significance level

The statistic value T was used to quantify the mean difference of the two series before and after a certain time i by means of heuristic segmentation method. T_1 and T_2 present the statistic values from series before and after the time i. Here the critical value $P_0 = 0.90$. In Figure 7, there are two mutation points at the sequence number 238(year 1995) for T_1 and 293 (year 2000) for T_2 with significance level $P(T_{\max1}) = 0.995 > P_0$ and $P(T_{\max2}) = 0.936 > P_0$ respectively.

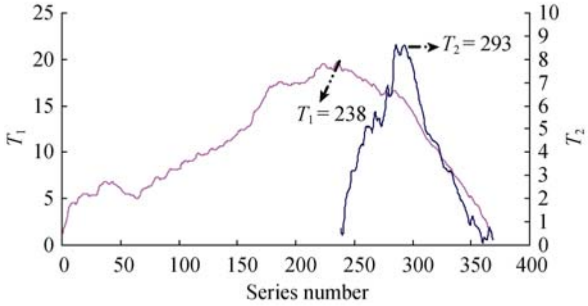

Figure 7 Diagram for the heuristic segmentation test method

The above analysis by three different methods results in conclusion that the mutation time of cross-section evolution is around 1995 and 2000. Extraordinary change of the trend also took place in 1979, 1981 and 1991.

3.3 Causes of channel evolution

Analysis of water and sediment situation at the mutation time has proved the fact that the evolution trend changes after a big deluge from some of those 10 tributaries with the exception of the year 1981 whose trend change was caused by a disastrous flood (Table 2) from the upper mainstream. Large amount of sediment load from the tributaries into the mainstream resulted in so serious sedimentation to form a sandy barrier in 1989, 1994 and 1998. Sedimentation stagnated the main channel flow and water table increased. The resulted backwater reduced the upper flow velocity as well as its sediment carrying capacity. All of these have led to retrogressive deposition (Wang *et al.*, 2010). Sediment deposition is impossible to be washed away without high and lasting flows, and the river channel will conduct its self-adjustment. The boundary form and incoming water and sediment will readjust to each other with disappearance of the previous equilibrium. An apparent channel deformation happens later since the adjustment takes some time. In this area, the reach around Zhaojunfen Station (located in outfall area of the tributaries between Shhk and Tdg) plays the key role in local erosion base level to its upper reach. Due to the hysteretic nature of feedback mechanism of channel deformation, effects of the tributaries in 1989, 1994 and 1998 appeared respectively in 1991, 1996 and 2000. Although a great quantity of sediment came from the tributaries in 1979 and 1982, the period of 1981–1984 was one of the wet year groups. Each year the flow of over 2000 m^3/s lasted for nearly 30 days, and the big flood in 1981 even lasted 50 days. Therefore, sediment deposition from the tributaries was washed away whose effect was eliminated and the river channel was relatively stable after 1981 (Figure 3).

Since the 1990s, partly due to the Yellow River drought period, and partly to the regulation of reservoirs, the big flood occurring frequency and its duration have significantly decreased (Ran *et al*., 2010; Hou *et al*., 2010) with greater influence seeing the serious channel shrinkage. The river bed changes were also presented in water table changes under the same flow (Figure 8). These conclusions were consistent with those achieved by Liu *et al*. (2009). Besides, it is interestingly observed that during 1976–1979, the river channel was deposited because of the unfavorable incoming water and sediment (small discharge with heavy sediment load), and even the 1978 big flood made the cross-sectional area 1079 m^3 larger than that in 1976, it did not change the deposition trend in the period. On the contrary, favorable water and sediment in the following four years after 1981 guaranteed the stable channel for about 10 years, indicating the river does not readjust itself unless there is long lasting and huge discharge incoming water.

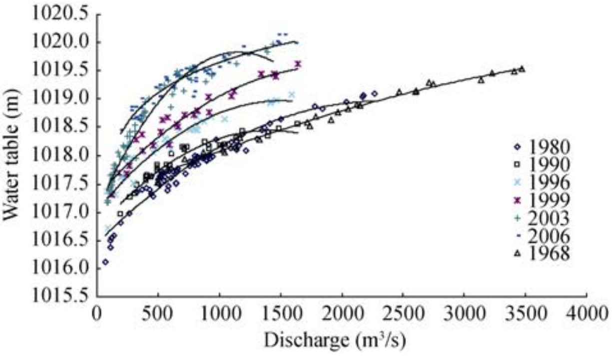

Figure 8 The relationship between discharge and water table at Shhk in flood season (July to October during 1968–2006)

One reason for deposition at Bygl ahead of Shhk is sediment ejection from Qingtongxia Reservoir, according to Wang and Qin *et al.* (2010). During this desilting period, flow with high sediment coefficient resulted in downstream channel deposition along the reach from Bygl to Tdg when more severely-deposited reach is seen from Bygl to Shhk. What is more, out of temperature reduction in ice season mentioned above, the low-temperature effect (Hong *et al*., 1983; Chen *et al*., 2006) produces the increase of both bed-layer sediment concentration and the uniformity of the concentration profiles, leading to higher sediment discharge. Complicated is the adjusting process in the ice flood season mentioned in Section 2.1, the cross-sectional area of Bygl decreased dramatically in 1987, and at the discharge of 400 m^3/s, the water table before 1987 wet season is one meter higher than that of 1986 after the flood season, namely, the river channel was heavily deposited in the non-flood season (Hou *et al*., 2010). In general the earlier the river freeze-up date, the larger the corresponding discharge and the sediment load of this reach, therefore the more deposition volume, since flow velocity swiftly reduces once river is freeze-up. According to the data presented in the book of Compilation of Ice Status Data and Its Characteristics Analysis (written by Hydrographic Bureau of Yellow River Conservancy Commission in 2006), the ice flood season characteristics of 1986–1987 were as follows: earlier freeze-up date than in the previous years with lower temperature. Temperatures decreased rapidly under the influence of strong cold air on November 13th. The average daily temperature of Dengkou began to decline from 7.2℃ on 12th to –11℃ on 14th, ranging 18.2℃. Drifting ice appeared at Tdg on 14th, and this reach began to freeze up on 15th, 29 days earlier than usual. Shhk and Bygl began to freeze up on November 27th and 30th, respectively, 7 and 13 days earlier whereas on January 4th as usual at Szs. Freeze-up firstly took place at Shhk Station with much smaller flow velocity and sediment transport rate (0.1 t/s more or less when frozen). Measured data showed a sudden increase of sediment transport rate at Bygl Station in the period from November 15th to freezing-up time (the mean value in Nov. is 1.61 t/s); the rate of Shhk was smaller (the mean value in November is 0.396 t/s). This shows the output sediment is less than the input.

Because coarse sand is easy to suspend in low temperature water (Qin, 2009), sediment load is larger in ice flood season than in summer with the same discharge. As a result, once the lower river reach began to freeze, the coarse sand transportation of large amount (compared with summer) halted with decrease of flow velocity which would produce unavoidable deposition in the channel (Hou *et al.*, 2010; Ran *et al.*, 2010). Apart from these, the joint operation of the two reservoirs of Longyangxia and Liujiaxia reduced the maximum peak flow of Szs to be only 1350 m^3/s being much smaller than historical records. By the characteristics of summer flood that the greater is the peak flow of Szs, the more severe is the erosion along the lower reach, it is concluded that the deposition in ice flood and absence of the big summer flood have caused the earlier deposition of Bygl.

4 Conclusions

(1) Based on the analysis of the variation change and the mutational characteristics of the time series out of cross section erosion-deposition area indicator at Bygl and Shhk stations, it was found that the reach has undergone a process of three phases: a relatively stable phase into a new equilibrium one with rapid deposition in between. The sectional area of Bygl began to decline ahead of Shhk in 1987 chiefly because of low-temperature effect.

(2) The main reason of deposition in this reach is severe incoming sediment from 10 tributaries. Since water and sediment come respectively from different places, shortage of big flood out of reservoir operation have caused the ever-increasing effect of 10 tributaries on channel deposition. Consequently, it is possible for this river to shrink again unless hyper-concentrated flow would not occur in this area.

(3) For the preceding reasons, it is of necessity to take various measures to control the 10 tributaries while other sediment releasing techniques (auto-desiting gallery for instance) are to be adopted. Man-made flood is no doubt a strategy. However, the river reach is currently in a new equilibrium phase. The feedback mechanism of the river channel will automatically eliminate deviation from equilibrium when great changes hardly take place either in material

composition of the riverbed and bank or in the situation of incoming water and sediment. For the coarse sediment in the Inner Mongolian Reach, man-made flood to regain the channel flow-carrying capacity deserves further study, including the value of peak-flow and flood duration. Meanwhile, guarantee of water resources and coarse sediment movement are equally worthy of further research.

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