Response of Erosion and Deposition in Ningxia-Inner Mongolia Reach to the Application of Long-Liu Reservoir on the Upper Yellow River

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Abstract. Along with the global and regional climate change and the intensification of human activities, the run-off of the Yellow River basin has been reduced remarkably, bringing serious problems to the local economy and river ecology. In order to point out important scientific issues of human activities, especially the operation of large-sized reservoirs to the changes of scour and fill of Ningxia-Inner Mongolia reach and the basin management, the paper mainly analyzed the influence of human activities (Longyangxia and Liujiaxia reservoirs are called Long-Liu reservoirs for short) to the scour and fill of Ningxia-Inner Mongolia reach. It used the method of hydrologic and hydrodynamic computation model of Ningxia-Inner Mongolia reach, took the observed silt-discharge data of 1968~2004 to prepare a calculation plan of with or without the joint operation of Long-Liu reservoirs and quantitatively evaluate the influence of the operation of Long-Liu reservoirs to the channel scour and fill amount of Ningxia-Inner Mongolia reach. The outcomes show that the joint operation of Long-Liu reservoirs has increased the sedimentation of the reach. During the joint operation of the period of 1987~2004, comparing with the conditions of with and without Long-Liu reservoirs, the total sedimentation of the reach has increased 170 million tons, of which, 363 million tons increased in flood season and 193 million tons decreased in non-flood season. The research results can provide technical reference to the harnessing of Ningxia-Inner Mongolia reach of the upper Yellow River and have an important role in the Yellow River basin management.

1. Introduction
Since1980’s, the natural runoff of the Yellow River basin has been reduced obviously along with the climate change and the intensification of human activities, especially after the joint operation of Longyangxia and Liujiaxia reservoirs on the upper Yellow River (called Long-Liu reservoirs for short) in 1987. The regulated silt-discharge and flow process coming into the reach certainly will have greater influence to the economy of the both banks on the lower channel and channel scour and fill regulation due to the strong capability of Long-Liu reservoirs. After the operation of Long-Liu reservoirs, the sedimentation of Ningxia-Inner Mongolia reach has become more and more serious, causing channel shrinkage and obvious decrease of channel discharge capacity. Therefore, the
operations of Long-Liu reservoirs are of an important scientific issue to the scour and fill effect of the basin and the research results have significant roles to the river training.

The incoming flow and sediment conditions are closely related to the channel scour and fill. The silt-discharge conditions of Ningxia-Inner Mongolia reach have been remarkably changed and directly affected the channel scour and fill after the operation of Long-Liu reservoirs. The researchers and scholars have done a lot of work on influence of the operation of Long-Liu reservoirs of the upper Yellow River to the silt-discharge conditions of the downstream, showing mainly on the following aspects: a) Influence of joint operation of Long-Liu reservoirs to the silt-discharge conditions of the lower reaches, ZHAO Ye-an, (1992 and 2008) [1-2], CHENG Xiuyan (2002) [3], SHANG Hong-xia (2008) [4], ZHANG Xiao-hua (2008) [5] and ZHENG Yan-shuang (2010) [6]. The outcomes show that the operation of Long-Liu reservoirs has mainly changed the annual distribution of runoff and flow process. The annual proportion of runoff in flood season has been reduced from 60% under the natural condition to 40% after the joint operation of the two reservoirs, the discharge that can transport high sediment concentration reduced and peak discharge decreased. Under such silt-discharge conditions, the channel scour and fill also have corresponding changes. b) There are many research results on influence of the operation of Long-Liu reservoirs to the channel scour and fill of the lower reaches and the outcomes of WANG Yan-cheng (1996) [7], YANG Lai-fei (2002) [8], CHENG Xiuyan (2002) [3], ZHANG Ye-an [2], SHANG Hong-xia (2008) [4], LIU Xiao-yan (2009) [9], HOU Su-zhen [10-11], LI Xue-mei (2009) [12], WANG Sui-j (13), TIAN Shi-min [14], WANG Hai-ting [15], ZHANG Xiao-hua [16-17] and ZHENG Yan-shuang (2009) [18] have analyzed the influence of the construction of Long-Liu reservoirs to the scour and fill of Ningxia-Inner Mongolia reach. Among the above research results, the conclusion of reducing channel sediment concentration and causing channel erosion by reservoir debris-retaining has basically reached common understanding, while there is significant difference on the aspect of effect of regulated silt-discharge by the large-sized reservoir to the channel scour and fill. Most of the research results consider that after the building of the reservoir, it has cut down flood peaks, flatten flood hydrograph, reduced the sediment transporting capacity and the flooding probability of sediment carrying flow, increased the channel deposition, especially changed the distribution of floodplain and channel and reduced the channel flowing capacity. Part of the results considers that the problem of the reach is mainly caused by the changes of silt-discharge which is caused by other factors and the influence of reservoir is smaller. Another part of the results considers that the operation of Long-Liu reservoirs is beneficial to the reach, because during the reservoir operation, it has retained parts of sediment, reduced the quantity of sediment flowing into the river, decreased the sediment concentration of the lower reaches and increased the scouring probability of Ningxia-Inner Mongolia reach. Thus, it is extremely necessary to study the quantitative influence of joint operation for more than 20 years to the scour and fill of the reach from the point of integrated benefits of scientific evaluation of Long-Liu reservoirs operation. The research results have a certain theoretical significance on deepening the evolution of river bed and it also urgently needs to study the issue from the strategic point of view of coordinating silt-discharge process by joint reservoir regulation through establishing silt-discharge regulation and control system of the Yellow River. The research results have provided basic support for exploring and keeping the healthy and scientific operation of the reservoirs on the main Yellow River.

2. The General Situation of Studied Area
The Ningxia-Inner Mongolia reach is located on the lower section of the upper Yellow River with a total length of 1203.8 km from Nanchangtan in Zhongwei County of Ningxia to Mashan Township in Zhunger County of Inner Mongolia. The controlled drainage area is 132,000 km², making up about 22% of the total. The difference of channel characteristics of the reach is obvious due to the different geographic position. The section from Xiaheyan to Qingtongxia is about 124 km long with many twists and turns and channel bars. The width of the section is 200–3300 m and the average gradient is 0.78‰. The length of Qingtongxia ~ Shizuishan section is 194.6 km, the width 200–5000 m and the average gradient 0.20‰. The section from Shizuishan to Wuda Highway Bridge in Inner Mongolia is
gorge-type channel. The average width is 400m and the channel gradient 0.56%. From Wuda Highway Bridge to Sanshenggong is a transitional section with wide and narrow channels and many channel bars. The river length is 105m, the average width 1800m, the main channel width 600m and the channel gradient 0.15%. From Sanshenggong to Sanhuhekou is a wandering section, with a length of 220.7 km. In the section, the channel is straight, wide and shallow cross-section, scattered flow and numerous natural bars in the channel. The average channel width is 3500 m, the mean width of the main channel about 750 m and the channel gradient 0.14%. From Sanhuhekou to Zhaojunfen is a transitional section with the length of 126.4 km, the average width about 4000 m, the average width of the main channel 710 m and the channel gradient 0.117%. On the south bank, there are three larger tributaries flow into the section. From Zhaojunfen to Toudaoguai is a curved section with 173.8 km long. The width of the section is 1200~5000 m, the average width of the main channel 600 m and the channel gradient 0.125%. From Toudaoguai to Hekouzhen is 10.3 km long with the width of 900~2000 m and the gradient 0.156%. Downstream section is gorge-type channel.

The silt-discharge conditions of the reach are more complicated due to the inflow of tributaries of Qingshui, Kushui and other ten major tributaries, diversion and drainage of the irrigated area of Qingtongxia and Sanshenggong reservoirs and the joining of sand blown by the wind of desert. In addition, there are two reservoirs of Long-Liu with bigger regulating storage and stronger capacity on the upper stream of the reach, of which, Luijiaxia Reservoir started storage in October 1968 and the total storage capacity below the designed flood level is 5.7 billion m³, being a partial annual regulating reservoir. Longyangxia Reservoir started storage in October 1986. The normal storage level is 2600 m and corresponding storage capacity is 24.7 billion m³, having pluriennial regulating functions. The basic principle of joint operation of Longyangxia and Luijiaxia reservoirs is joint management and compensational regulation. The operation of the two reservoirs has directly affected the silt-discharge conditions of Ningxia-Inner Mongolia reach on the downstream and then affected the adjustment of scour and fill of the channel.

3. Data sources and Research Method

3.1. Sources of data

The observed data of mean daily discharge and average daily sediment delivery rate of the stations on the main river in 1968~2004 period used for the study all come from the observed data of Hydrological Bureau of Yellow River Conservancy Commission, i.e. the hydrological data of the Yellow River basin of the Hydrological Yearbook of the People’s Republic of China. The analyzed and computed hydrometric stations on the main river are Tangnaihai, Guide, Xunhua and Xiaochuan, which are the inlet and outlet stations of Longyangxia and Luijiaxia reservoirs and Xiaheyan, Qingtongxia, Shizuishan, Bayangaole, Sanhuhekou and Toudaoguai, which are situated in Ningxia-Inner Mongolia reach. The used data of tributaries mainly are from the stations of Hongqi of Taohe River and Zheqiao of Daxia River which are the inlet tributaries of Luijiaxia Reservoir and inflow tributaries of the reach of Quanyanshan of Qingshui River and Guoqiaqiao of Kushui River. Among the ten major tributaries in Inner Mongolia, three of Tugerige Station in Maobulagou, Longtouguai in Xilinou and Xiangshawan in Hantaihua have observed data. The observed data of tributaries in the period of 1968~1990 comes from hydrologic data of the Yellow River basin of the Hydrological Yearbook of the People’s Republic of China. The observed data of 1991~2004 period are mainly from planning projects of the Yellow River basin [20] and the observed data of tributaries are provided by the relevant departments of local cities and provinces.
3.2. Research method

3.2.1. Establishing model. The study mainly adopted hydrology and hydrodynamics model to calculate the channel scour and fill situation of the reach under the conditions of with and without Long-Liu reservoirs. It adopted the method of linear multivariate regression in establishing calculation formula of sediment delivery rate. The detailed calculation method of the model is shown in ZHENG Yan-shuang (2012) [6] and TIAN Shi-min (2013) [14]. Based on the existing hydrologic model, it had been further revised and improved, i.e. it had considered the calculation formula of sediment delivery rate when the mean daily discharge in the normal period of each station was greater than 3000 m$^3$/s during the calculation of sediment delivery rate of outlet section. The calculation formula of sediment delivery rate in the normal period of each station is as follows:

\[
\text{Shizuishan Station } \begin{align*}
Q_{Shi} &\geq 3000 \text{m}^3/\text{s}, \quad Q_{SShi} = 11.836S_{Qing}^{0.1674} \\
\text{Bayangaole } \begin{align*}
Q_{Ba} &\geq 3000 \text{m}^3/\text{s}, \quad Q_{SBa} = 2.7862S_{Shi}^{18.563} \\
\text{Sanhuhekou } \begin{align*}
3000 \text{m}^3/\text{s} &\leq Q_{San} < 4000 \text{m}^3/\text{s}, \quad Q_{SSan} = 19.65S_{Ba}^{0.2964} \\
Q_{San} &\geq 4000 \text{m}^3/\text{s}, \quad Q_{SSan} = 32.064S_{Ba}^{0.1386} \\
\text{Toudaoguai } \begin{align*}
Q_{Tou} &\geq 3000 \text{m}^3/\text{s}, \quad Q_{STou} = 2.0947S_{San}^{7.997}
\end{align*}
\end{align*}
\]

Of which, $Q_{Shi}$ and $Q_{SShi}$ are discharge and sediment delivery rate of Shizuishan Station, $Q_{Ba}$ and $Q_{SBa}$ are discharge and sediment delivery rate of Bayangaole Station, $Q_{San}$ and $Q_{SSan}$ are discharge and sediment delivery rate of Sanhuhekou Station, $Q_{Tou}$ and $Q_{STou}$ are discharge and sediment delivery rate of Toudaoguai Station, $S_{Qing}$, $S_{Shi}$, $S_{Ba}$, and $S_{San}$ are sediment concentration of stations of Qingtongxia, Shizuishan, Bayangaole and Sanhuhekou respectively.

3.2.2. Model verification. In order to verify the rationality of the model, it computed the amount of yearly and accumulated channel scour and fill of each section of the reach (shown in Table 1, Fig.1 and Fig.2) and compared the computed data with the observed data by taking the observed data of silt-discharge in 1968~2004 as a basis. It showed that the computed data and the observed data of scour and fill of the whole reach and each section were basically the same and the computed data and the observed data of yearly and accumulated scour and fill were also basically identical, showing the model could rationally reflect the characteristics of scour and fill of the reach and could be used for long-term channel scour and fill calculation.

4. Research Achievements

4.1. Silt-discharge comparison of Ningxia-Inner Mongolia reach under the conditions of with and without Long-Liu reservoirs
Table 1. Comparison of observed and computed data of total scour and fill of each station in different periods of the reach Unit: $10^8$ t

| Period     | Item                     | Qingtongxia-Shizuishan | Shizuishan-Bayangaole | Bayangaole-Sanhuheko | Sanhuheko-Toudaoguai | Qingtongxia-Toudaoguai |
|------------|--------------------------|------------------------|-----------------------|----------------------|-----------------------|------------------------|
| 1968-1986  | Observed data            | -2.91                  | 0.62                  | -2.03                | -2.45                 | -6.77                  |
|            | Computed data            | -2.92                  | 0.50                  | -1.66                | -2.35                 | -6.43                  |
| 1987-2004  | Observed data            | -0.26                  | 2.61                  | 3.49                 | 3.51                  | 9.35                   |
|            | Computed data            | -0.11                  | 3.05                  | 2.96                 | 3.00                  | 8.89                   |
| 1968-2004  | Observed data            | -3.17                  | 3.23                  | 1.46                 | 1.06                  | 2.57                   |
|            | Computed data            | -3.03                  | 3.54                  | 1.30                 | 0.65                  | 2.46                   |

Figure 1. Comparison of observed and computed data of yearly scour and fill of Qingtongxia-Toudaoguai section.

Figure 2. Comparison of observed and computed data of accumulated scour and fill of Qingtongxia-Toudaoguai section.

In order to compare the silt-discharge flowing into the reach under the conditions of with and without Long-Liu reservoirs, it reduced the silt-discharge condition of the reach without Long-Liu reservoirs. The reduction method was to recalculate the difference of discharge and sediment delivery rate of inlet and outlet hydrometric stations of Longyangxia Reservoir (Tangnaihai and Guide) and inlet and outlet hydrometric stations of Liujiaxia Reservoir (Xunhua of inlet, Hongqi, Zheqiao and Xiaochuan of outlet) into Qingtongxia Reservoir based on travel time. The assumed streamwise silt was not adjusted because the silt adjustment of Lanzhou-Qingtongxia section was minor. The travel time of outlet discharge of Longyangxia Reservoir to Qingtongxia Reservoir was 4 days and the travel time of outlet discharge of Liujiaxia Reservoir to Qingtongxia Reservoir was 2 days. The reduction of discharge and sediment delivery rate is shown in formula 1-5 and 1-6. The reduced silt-discharge condition of Long-Liu reservoirs obtained by this method is shown in Table 2.
Table 2. Silt-discharge characteristics of Qingtongxia Station in different periods with and without Long-Liu reservoirs.

| Item                      | Period               | Runoff (10^8 m³) | Silt discharge (10^8 t) | Sediment concentration (kg/m³) | Max. discharge (m³/s) |
|---------------------------|----------------------|------------------|-------------------------|--------------------------------|------------------------|
|                          |                      | Flood season     | Annual total            | Flood season                   | Year                   |                      |
| Original (with reservoir) | 1968-1986           | 2583.4           | 4767.5                  | 13.9                           | 15.3                   | 5.4                  | 3.2                  | 5540                |
|                          | 1987-2004           | 1300.2           | 3121.2                  | 12.7                           | 14.5                   | 9.8                  | 4.6                  | 2900                |
| Reduced (without reservoir) | 1968-1986        | 3113.4           | 4790                    | 23.3                           | 26.5                   | 7.5                  | 5.5                  | 5779                |
|                          | 1987-2004           | 2093.7           | 3223.7                  | 17.8                           | 21.2                   | 8.5                  | 6.6                  | 4408                |
| (2) - (1)                | 1968-1986           | 529.9            | 22.5                    | 9.4                            | 11.2                   | 2.1                  | 2.3                  | 239                 |
|                          | 1987-2004           | 793.5            | 102.5                   | 5.1                            | 6.7                    | -1.3                 | 2                    | 1508                |

\[ Q = Q_0 + (Q_1 - Q_2) + (Q_3 - Q_4) \]  \hspace{1cm} (5)  
\[ Q_s = Q_{s0} + (Q_{s1} - Q_{s2}) + (Q_{s3} - Q_{s4}) \]  \hspace{1cm} (6)

Of which, (1) \( Q \) is reduced discharge of Qingtongxia Station, \( Q_0 \) is original discharge of Qingtongxia Station, \( Q_1 \) and \( Q_2 \) are inlet and outlet discharge of Longyangxia Reservoir and \( Q_3 \) and \( Q_4 \) are inlet and outlet discharge of Liujiaxia Reservoir. The flow routing had considered the travel time. In formula (2), \( Q_s \) is reduced sediment delivery rate of Qingtongxia Station, \( Q_{s0} \) is original sediment delivery rate of Qingtongxia Station, \( Q_{s1} \) and \( Q_{s2} \) are inlet and outlet sediment delivery rate of Longyangxia Reservoir, \( Q_{s3} \) and \( Q_{s4} \) are inlet and outlet sediment delivery rate of Liujiaxia Reservoir.

It can be seen from the comparative analysis of silt-discharge characteristics of with and without Long-Liu reservoirs that in the flood season of 1968~1986, the total amount of runoff and sediment had been increased 52.99 billion m³ and 940 million t respectively and sediment concentration increased 2.1 kg/m³ under the conditions of no Long-Liu reservoirs. Because Liujiaxia Reservoir makes up water to the channel in non-flood season, thus the runoff in non-flood season without Liujiaxia Reservoir is reduced. Therefore, the total amount of annual runoff and sediment without Liujiaxia Reservoir was only increased 2.25 billion m³ and 1.12 billion t and sediment concentration increased 2.3 kg/m³. Comparing with the reservoir, the maximum annual discharge without Liujiaxia Reservoir was increased by 239 m³/s. The joint operation of Long-Liu reservoirs has greater capability on runoff regulation, especially in flood season. It can be seen from Table 1-2 that in the flood season of 1987~2004 without Long-Liu reservoirs, the runoff and sediment had been increased by 79.35 billion m³ and 510 million t respectively and sediment concentration increased 2 kg/m³. The reduced annual maximum discharge was 1508 m³/s more than that of the original.

4.2. Computation results of hydrologic model under the different conditions of plans

In order to analyze the quantitative influence of the operation of Long-Liu reservoirs to the channel scour and fill of the reach, it computed the scour and fill of the reach under the exiting two different silt-discharge conditions of with and without Long-Liu reservoirs section by section and period by
period by using hydrologic model. The calculation results of the two plans are shown in Table 3. It can be seen that during 1968~1986 when only Liujiaxia Reservoir was in operation, the sedimentation of the reach was reduced, the total sediment reduction of Qingtongxia-Toudaoguai section was 578 million t, in addition, the sedimentation of each section was reduced and Qingtongxia-Shizuishan section was the maximum reduction of 401 million t. During 1987~2004 of joint operation of Long-Liu reservoirs, the sedimentation of the reach was increased. The total increase was 170 million t, of which, 363 million t increased in flood season and 193 million t decreased in non-flood season (Table 4).

4.3. Rationality analysis of computation results

It computed the influence of the storage operation of Long-Liu reservoirs to the scour and fill of the reach by using hydrologic model. The outcomes show that during the single operation of Liujiaxia Reservoir, the sedimentation of the reach is decreased, while during the joint operation of Long-Liu reservoirs, the sedimentation of the reach is increased. It is identical on nature with the computation results of mathematical model mentioned in a special report of Analysis on Function and Operational Mode of a Regulated Discharge Regime of Heishanxia Reservoir of the Yellow River [19] drafted by Yellow River Engineering Consulting Co, Ltd. The main analyzed reasons are that during the single operation of Liujiaxia Reservoir, the discharge adjustment is smaller and less storage, but the coming sediment from tributaries of Taohe and Daxia rivers are more and the sediment retaining of Liujiaxia Reservoir is greater, showing obvious function of sediment retaining, especially in July and August. Therefore, the function to the reach is sediment reduction. While the operation of Longyangxia Reservoir is in the period of low water with less sediment and it has greater function of storage. Storing water in flood season can reduce flow coming into the reach, regulate flow process, make the flood hydrograph of the reach flat (Fig.4) and reduce greater discharge that transport sediment. In addition, because the silt-discharge of the region mainly comes from the source area of clear water with less silt and the function of reservoir trap is smaller, thus, it has increased the sedimentation of the reach. The computation results of hydrologic model are reasonable from quantitative point of view.

Table 3. Computation results of annual total scour and fill under the different conditions of silt-discharge of the reach.

| Item         | Period     | Qingtongxia- Shizuishan | Bayangaole- Sanhuhekou | Shizuishan- Toudaoguai | Qingtongxia- Toudaoguai |
|--------------|------------|-------------------------|-------------------------|-------------------------|-------------------------|
| With reser.  | 1968-1986  | -2.92                   | 0.5                     | -1.66                   | -2.35                   | -3.51                   | -6.43                   |
|             | 1987-2004  | -0.11                   | 3.05                    | 2.96                    | 3                       | 9                       | 8.89                    |
| Without reser. | 1968-1986 | 1.09                    | 1.02                    | -0.5                    | -2.25                   | -1.73                   | -0.65                   |
|             | 1987-2004  | -1.94                   | 2.05                    | 3.49                    | 3.6                     | 9.13                    | 7.19                    |
| ①-②         | 1968-1986  | -4.01                   | -0.52                   | -1.16                   | -0.1                    | -1.78                   | -5.78                   |
|             | 1987-2004  | 1.83                    | 1                       | -0.53                   | -0.6                    | -0.13                   | 1.7                     |
Table 4. Distribution of Annual total scour and fill of the reach during 1987~2004 joint operation of Long-Liu reservoirs.

| Item     | Period          | Total scour and fill of Qingtongxia-Toudaoguai section (10^4 t) | Flood season | Non-flood season |
|----------|-----------------|----------------------------------------------------------------|--------------|------------------|
| With ①   | 1987~2004       | 10.23                                                        | -1.34        |                  |
| Without ② |                 | 6.61                                                         | 0.58         |                  |
| ②-①     |                 | -3.63                                                       | 1.93         |                  |

5. Discussion

It used hydrologic channel scour and fill model of the reach to calculate the quantitative influence of Long-Liu reservoirs operation to the channel scour and fill of the reach. The model was established based on a series of simplification of flow continuity equation, flow momentum equation and sediment equilibrium equation and obtained sediment delivery equation and the exchange process of silt-discharge of floodplain and channel according to the analysis of observed data. The calculation precision of the model was related to the rationality of equation simplification, the accuracy of empirical formula and the generalization accuracy of actual process to a certain extent. Although the results of the model computation basically could simulate the characteristics of the channel scour and fill of Ningxia-Inner Mongolia reach, some factors had not been fully considered, such as the influence of coarse and fine sediment and degree of sandstorms to the channel scour and fill of the reach due to not in-depth understanding of the laws of sediment transport and scour and fill of the reach. Thus, the study on the aspects of methodology and the characteristics of scour and fill of the reach need to be further improved and deepened.

6. Conclusion

The mathematical model of hydrologic channel scour and fill of Ningxia-Inner Mongolia reach used by the study can simulate and compute the characteristics of the scour and fill of the reach to a certain extent, quantitatively evaluate the influence of different conditions of silt-discharge to the scour and fill of the reach, quite well reflect the actual situation of scour and fill of the reach and deepen the understanding on the laws of channel scour and fill and river-bed evolution.

(1) It has quantitatively studied the influence of Long-Liu reservoirs operation to the reach. The single reservoir operational period of Liujiaxia is in 1968~1986. Comparing with and without reservoir, the total sediment reduction of the reach (Qingtongxia~Toudaoguai section) is 578 million t, mainly happening in Qingtongxia~Shizuishan section. The joint operation of Long-Liu reservoirs is in 1987~2004. Comparing with and without reservoir, the total sedimentation of the reach increases 170 million t, of which, 363 million t is increased in flood season and 193 million t decreased in non-flood season.

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References

[1] Zhao, Y., Hou S.Z., and Li, Y., (1992). “Brief Account of Scour and Fill of Ningxia-Inner Mongolia Reach on the Upper Yellow River in 1980’s.” Yellow River, 4, 20-23.

[2] Zhao, Y., et al (2008). “Study on Key Techniques of Regulating Runoff and Sediment of Reservoirs on the Main Yellow River and Study on Adjustment of Operational Mode of Longyangxia and Liujiaxia Reservoirs.” Yellow River Hydraulic Research Institute.

[3] Cheng, X-W., Qian, Yi-ying., and Fu, Chong-jin., (2002). “Analysis on Variation of Silt-Discharge of the Upper Yellow River and Channel Scour and Fill Evolution of Ningxia-
Inner Mongolia Reach, Variation of Silt-Discharge Study of the Yellow River.” the Yellow River Water Conservancy Press.

[4] Shang, Hong-xia., Z,Y-S., and Zhang, Xiao-hua(2008). “Influence of Reservoir Operation to the Silt-Discharge Conditions of Ningxia-Inner Mongolia Reach.” Yellow River, 30,28-30.

[5] Zhang, X-H., Z ,Y-S (2008). “Analysis on the Laws of Scour and Fill and Affecting Factors of Ningxia-Inner Mongolia Reach.” Zhengzhou, Yellow River Hydraulic Research Institute.

[6] Zheng,Y-S., Tian, S-M(2012). “Study on the Function of Long-Liu Reservoirs Operation to the Scour and Fill Evolution of Ningxia-Inner Mongolia Reach.” Zhengzhou, Yellow River Hydraulic Research Institute.

[7] Wang, Y-C., Feng, X-W., (1996). “Influence of Reservoirs on the Upper Yellow River to the Inner Mongolia Section.” Yellow River,1, 5-10.

[8] Yang, L-F., Lu,Y-H.and Wang,H (2002). “Characteristics of Channel Scour and Fill and Its Variation Trend Forecasting of Lanzhou–Hekouzhen Section After Building a Large-Sized Reservoir on the Upper Yellow River.”Variation of Silt-Discharge Study of the Yellow River, Volume 1 (Part 2), the Yellow River Water Conservancy Press.

[9] Liu, X-Y., Hou, S-Z, et al(2009). “Reasons and Countermeasures for the Main Channel Shrinking in Inner Mongolia Section of the Yellow River.” Journal of Hydraulic Engineering.40,1048-1054.

[10] Hou, S-Z, Wang Ping(2005). “Analysis on Flood Carrying Indexes and Runoff Conditions of Ningxia-Inner Mongolia Reach of the Yellow River.”Yellow River.27,24-27.

[11] Hou, S-Z., Chang ,W-H, Wang, Ping., and Wei-bin(2007). “Characteristics and Cause of Formation of Channel Shrinking in Inner Mongolia Section of the Yellow River.” Yellow River, (1) 40,30-35.

[12] Li, X-M., Lin,Y-P., and Wang,Ling(2009). “Genetic Analysis on Sedimentation of Bayangaole~Toudaoguai Section in Recent 20 Years.”Yellow River, 31,12-15.

[13] Wang, S-j., Fan, X-l., and Zhao, X-k (2010). “Geographic Research on Temporal and Spatial Variation of Suspended Load Scour and Fill and Its Affecting Factors of Ningxia-Inner Mongolia Reach of the Yellow River.”29,1779-1887.

[14] Tian, S-M., Deng, C-X., Xie, B-f, and Zhang, X-H (2013). “Influence of Joint Operation of Long-Liu Reservoirs to the Channel Scour and Fill of Ningxia-Inner Mongolia Reach.” Advances in Science and Technology of Water Resources.10,33-36.

[15] Wang, H-B., Jia X-P (2009). “Channel Erosion and Sedimentation Process of Inner Mongolia Section under the Conditions of A Large-Sized Reservoir Operation.” Journal of Desert Research, 29,189-192.

[16] Zhang,X-H., Shang, H-X., Zheng, Y-S., et al(2008).“Channel –Reforming Process of the Upper and Lower Reaches after Building A Large-Sized Reservoir on the Main Yellow River .” Zhengzhou: the Yellow River Water Conservancy Press.

[17] Zhanga,X-H., Zheng, Y-S., Zhang, Min(2008), “Characteristics of Recent Channel Scour and Fill and Laws of Scour and Fill and Sediment Transport of Ningxia- Inner Mongolia Reach on the Upper Yellow River.” Journal of Tianjin University.20-23.

[18] Zheng, Y-S., Zhang,X-H., and Shang, H-X., (2009).”Analysis on Characteristics and Causes of Recent Adjustment of Ningxia-Inner Mongolia Reach of the Yellow River.”Yellow River, 31,50-53.

[19] Duan, G-Y., Chen, S-W., Qian, Y. et al(2010). “Special Report of Analysis on Function and Operational Mode of a Regulated Discharge Regime of Heishanzia Reservoir of the Yellow River.” Yellow River Engineering Consulting Co., Ltd., October 2010.