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Characteristics of sediment and nutrient flows in the lower reach of the Yellow River

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Abstract Water shortage and flooding risk are two major concerns in the lower reach of the Yellow River, and both are closely related to the transport of sediment and nutrients. Temporal and spatial change of sediment and nutrient flow in the lower reach are discussed with regard to the possible impacts of the Xiaolangdi Reservoir, which was completed in 2001. A negative sediment flux –1179 kg s^{-1} was found in the lower reach, indicating an erosive state since 2002. Average sediment load measured at Lijin was 16 kg m^{-3} and the highest in the lower reach. Ammonium (NH_4^+) and dissolved oxygen at Huayuankou were found to be temperature dependent, while electrical conductivity (EC) is closely related to discharge. Low EC was observed in the rainy season, while high EC occurs in March and April, due mainly to low discharge and water draining from irrigated upstream areas.

Key words sediment load; water quality; lower reach; Yellow River; nutrient flux

INTRODUCTION

The lower reach of the Yellow River is defined as the range between Huayuankou and Lijin and has a length of approximately 660 km (Fig. 1). The large amount of nutrients and sediment transported through this reach to the delta and the ocean is significant to global water and biogeochemical cycles, especially in the western Pacific. Nevertheless, dyke breaches and major shifts of the reach's course have occurred 26 times in the last 3000 years (Yu, 2002). Today, the 1.7 million people who live inside the dykes are vulnerable to a flooding disaster. Overall, about 87 million people would be affected by a dyke failure. At the same time, water shortages in the Yellow River basin results in reduced flow in the main channel (i.e. the drying up problem) and increased deposition of sediment which elevates the main channel and increases the risk of flooding. It was reported that the river bed at Lijin was raised by about 2.26 m from the 1950s to 1990s (Ye *et al*., 1997). Drying up has not taken place since 1998 due to artificial control of outflow from the dams in the middle and upper reaches.

The objectives of the study are to identify temporal changes of sediment and water quality in the reach by analysing relationships among discharge, sediment and water quality, and estimating the amount of sediment and mass transported to the delta and the ocean.

METHODS

A network monitoring precipitation, discharge, groundwater table depth, sediment load, and water quality has been operating in the lower reach since the 1950s. The main gauging stations in this network are located at Huayuankou, Gaocun, Sunkou, Aishan, Luokou and Lijin (Fig. 1). An automatic monitoring station (AMS) for water quality that measures water temperature (T), dissolved oxygen (DO), electrical conductivity (EC), pH, NH_4^+, and turbidity, has been operating at the Huayuankou station since June 2002. The data set of the AMS for the period of June 2002 to the end of 2005, together with monthly and/or daily discharge and sediment data, was collected and analysed for this study. Sediment load was measured only in the rainy season, i.e. from July to the end of October.

RESULT AND DISCUSSIONS

Sediment

The Yellow River is world famous for its high sediment load. While average loads are about 35 kg m^{-3}, they can be more than 1000 kg m^{-3} in some tributaries (SG, 1984). The annual average

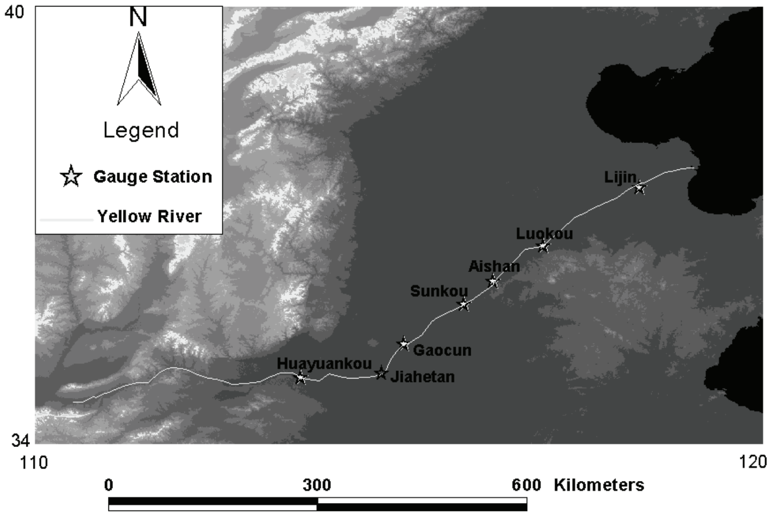

Fig. 1 Location map of the lower reach (defined as from Huayuankou to Lijin) of the Yellow River.

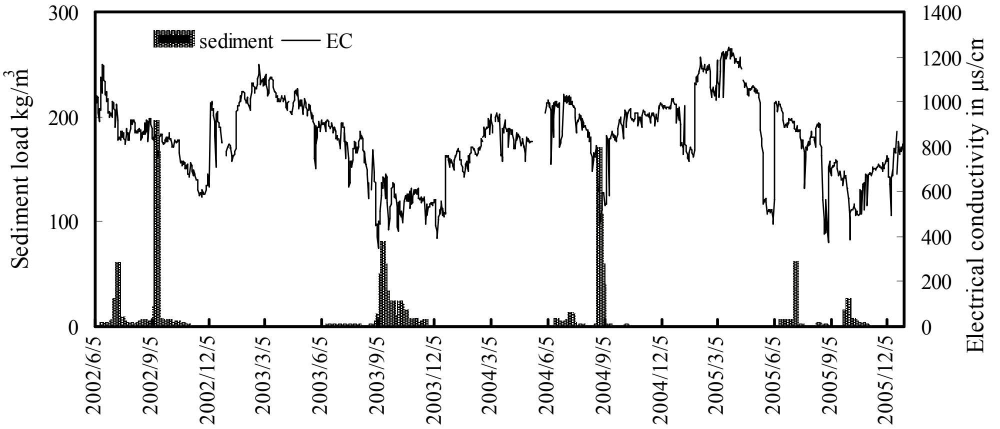

Fig. 2 Change of sediment load and EC at Huayuankou Station from June 2002 to December 2005. Sediment is measured only during the rainy season when sediment load is high.

sediment load transported in the lower reach until 1979 is estimated to be 1.6 × 10^9 tons. Since then it has been sharply reduced by water shortage and low flows in the basin. While the sources, causes and transport characteristics of sediment in the middle and upper reaches are well documented in the Chinese literature, they are less well reported for the lower reach (Ran *et al*., 2000; Liu & Chen, 2001). Total sediment flow at Huayuankou in 2002, 2003, 2004, and 2005 was calculated as the product of flow rate and sediment concentration and was found to be 8.9 × 10^7 tons over 139 days, 1.72 × 10^8 tons over 91 days, 1.43 × 10^8 tons over 39 days and 4.9 × 10^7 tons over 29 days respectively (Fig. 2). The highest sediment load typically occurred in September and most likely corresponds to high sediment flows in the upper stream, which typically start in July and August.

Average sediment load during the period from June 2002 to Dec. 2005 was 9.8, 11.9, 10.8, 11.0, 11.7, 10.8, and 16.0 kg m^{-3} at Huayuankou, Jiahetan, Gaosun, Sunkou, Aishan, Luokou and Lijin stations respectively. The declining flow rate due to water diversion in the lower reach contributes to the downstream increase of sediment load.

The difference in sediment flux (DSF) along the reach between Huayuankou and Lijin, is calculated from the average discharge and the average sediment loads as:

$$DSF = \text{(Lijin discharge)(Lijin sediment load)} - \text{(Huayuankou discharge) (Huayuankou sediment load)}$$
$$= (553.9\ m^3\,s^{-1} \times 16.0\ kg\ m^{-3}) - (784\ m^3\,s^{-1} \times 9.8\ kg\ m^{-3}) = 1179\ kg\ s^{-1}$$

The simple calculation indicates that net erosion could occur in the lower reach. The erosive capacity is then estimated to be 3.72 × 10^7 tons year^{-1}. This phenomenon is best explained by the construction of the Xiaolangdi Reservoir, which was completed in 2001. This reservoir has a total water capacity of 1.265 × 10^{10} m^3 and a design capacity of 1.0 × 10^{10} tons for sediment deposition (YRCC, 2002). Actually, erosion of the riverbed in the lower reach occurred during the period October 1960 to October 1964, immediately after the construction of the Sanmenxia Reservoir which started operation in September 1960 with a total capacity of 9.64 × 10^9 m^3. The total sediment deposition inside this reservoir was estimated to be 4.2 × 10^9 tons in October 1964, with an annual average of about 1.0 × 10^9 tons (SG, 1984), causing the erosion downstream mentioned previously. Sanmenxia Reservoir was thus reformed due to the serious deposition problem. On the other hand, reservoir operations for flushing deposition at Xiaolangdi in June/July could contribute to the change of sediment flow downstream. The sediment load was interpolated based on its relationship with turbidity, and the annual average load in 2002, 2003, 2004, and 2005 is calculated to be 5.5, 4.0, 3.3, and 2.4 kg m^{-3} respectively, indicating a declining trend (Fig. 3). As a result, it is reasonably inferred that the construction of Xiaolangdi causes erosion and a decrease of silt content in the lower reach.

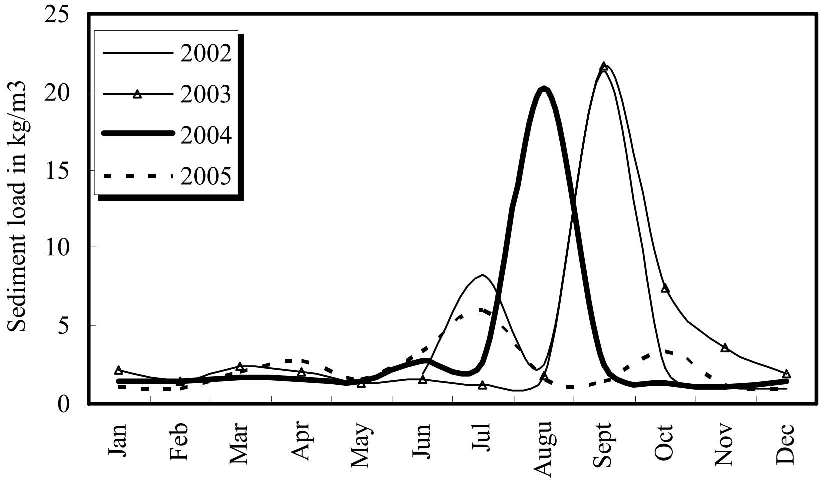

Fig. 3 Average monthly sediment load at Huayuankou station from June 2002 to the end of 2005.

Mass flow at Huayuankou station

Monitoring from the AMS indicated that EC reaches its lowest level as discharge increases in the rainy season (Fig. 2). The highest levels occur during the dry season of March and April when water is diverted for irrigation in the middle and upper reaches of the river and in the North China Plain (CDCID, 2002). The seasonal pattern of water quality is opposite to that of discharge and sediment. Return flow to the main channel, either from the drainage canal of irrigation field or from groundwater discharge upstream, contributes to a high EC and pH in the river water of the lower reach. Irrigation was found to be the main reason for the increase of major ions in the river water in the last 50 years (Chen *et al.*, 2003).

Monthly EC data collected at Huayuankou confirms the temporal pattern collected, i.e. high EC values in March and April, low values in the rainy season till October, and medium values in the winter (Fig. 4). In contrast, high monthly NH_4^+ occurs from January to April when the water temperature is low (Fig. 5). Since 2003 the time of peak NH_4^+ values has shifted by one month. Annual average EC, water temperature, NH_4^+, and discharge in 2002, 2003, 2004 and 2005 are given in Table 1. The NH_4^+ content is inversely related to T (Fig. 5). Both DO and NH_4^+ are temperature dependent and have similar temporal patterns (Fig. 6). EC and pH at Huayuankou are poorly correlated with T.

An empirical relationship between EC (in ms m^{-1}) and total anions, TAN (meq L^{-1}), was found within the study area (Chen *et al*, 2002): $TAN = 0.1241 \times EC - 0.706$, with $R^2 = 0.9895$. This relationship was used to calculate TAN at Huayuankou. Mass flow (meq s^{-1}) was then estimated as

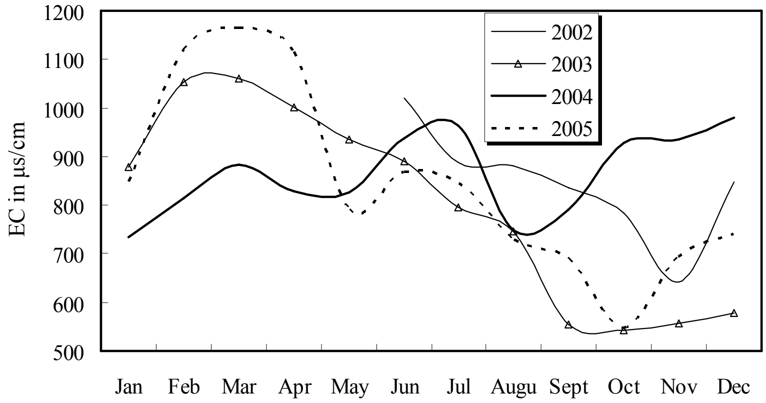

Fig. 4 Average monthly EC at Huayuankou station from June 2002 to the end of 2005.

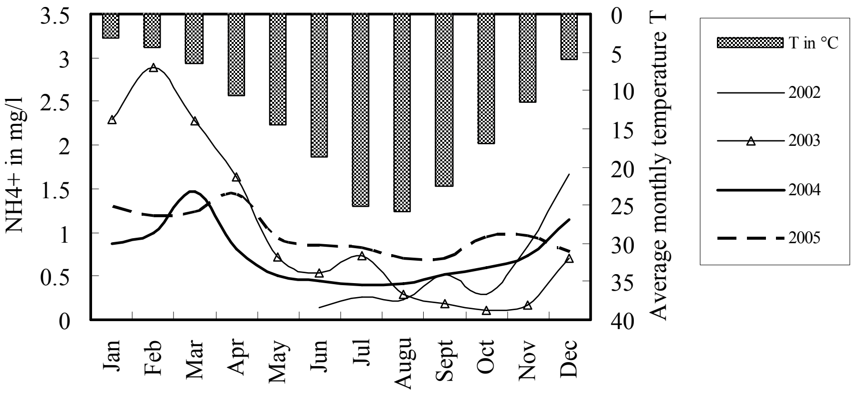

Fig. 5 Average monthly NH4+ from June 2002 to the end of 2005 and water temperature at Huayuankou.

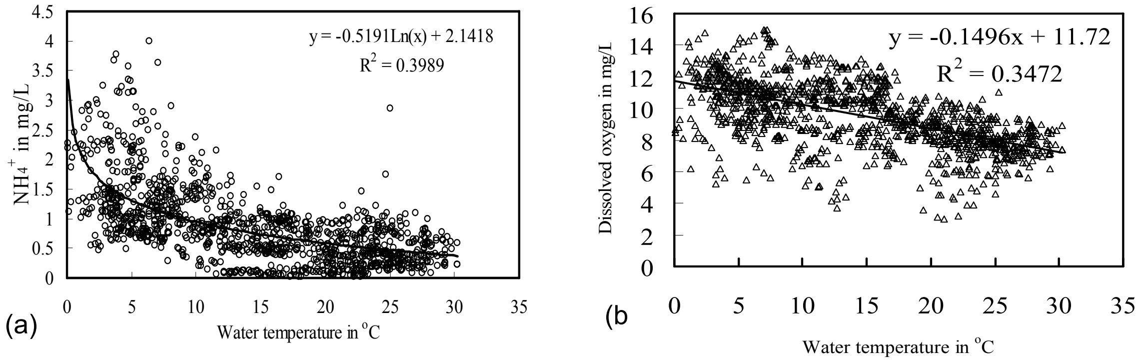

Fig. 6 Relationships of NH_4^+ and DO with water temperature at Huayuankou station, y refers to NH_4^+ and DO in (a) and (b) respectively, while *x* refers to water temperature.

Table 1 Annual average water temperature, EC, NH_4^+ and discharge at Huayuankou.

Year	T (°C)			EC (µs cm^{-1})			NH_4^+ (mg L^{-1})			Discharge (m^3 s^{-1})		
	Sample size	Mean	Std	Sample size	Mean	Std	Sample size	Mean	Std	Sample size	Mean	Std
2002*	204	18.3	7.8	205	842.6	124	204	0.56	0.58	210	654	546
2003	364	14.1	7.9	360	798.8	205.8	355	1.04	0.96	365	862	789
2004	342	13.7	7.6	342	864.8	108.1	317	0.74	0.37	366	756	563
2005	362	13.7	8.3	362	845.8	218	361	0.99	0.28	365	806	652

*No data available from January to May in 2002. Std refers to standard deviation of the means.

the product of TAN and discharge. Using this technique for 2002, 2003, 2004, 2005 the mass flow was found to be 4.34×10^{16} meq (during the period of 5 June–31 December), 7.46×10^{16} meq, 8.12×10^{16} meq, and 8.73×10^{16} meq for each year, respectively. Since chloride accounts for about 22% of TAN, annual Cl^- flux transported to the ocean can also be estimated.

The impacts of Xianlangdi Reservoir on water quality are an interesting issue. Though it is difficult to give a conclusive remark regarding the impacts of the reservoir on EC and water temperature, mass flux defined as the product of TAN and discharge shows a trend of increase. The hydrological regime has been modified by the construction of the Xiaolangdi Reservoir, and the possible upsurge of nutrient release in the reservoir due to fragmentation and flow regulation could contribute to the potential change of EC and the increase of mass flux in the lower reach, similar to that reported in the other rivers of the world (Nilsson *et al*., 2005).

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