Long-term variations and causal factors in nitrogen and phosphorus transport in the Yellow River, China

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ARTICLE INFO

ABSTRACT

This paper is to examine the water quality of the Yellow River basin on the basis of collated data of nitrogen (40 years) and phosphorus (20 years), and also of the relevant chemical fertilizer application, population, and industrial wastewater, etc. Relationship among these elements was discussed in order to explore their causal links, in relation to the temporal variation of nitrogen and phosphorus transportation. Results indicate that the transported nitrogen load in the lower Yellow River has had an increasing trend during the past 40 years but declined considerably in the later 1990s due to the reduction in flow discharge that led to desiccation of the lower reaches of the Yellow River. Whereas, nitrogen contribution to the estuary from Huayuankou to Lijin reach was minus due to the large amount of water diversion from the Yellow River for irrigation purpose. Phosphorus content fluctuated within a certain range without any tendency, but also decreased in the later 1990s due to the desiccation in the lower reaches. Our analysis indicates that nitrogen load in the Yellow River has been mainly impacted by population growth and nitrogen fertilizer application, but showed no statistically significant relationship with wastewater loads. In contrast, total phosphorus content in the Yellow River showed no relationship with population, fertilizer use and wastewater discharge in the basin, but presented significant correlation with suspended solids concentration of the Yellow River. Calculations indicate that the phosphorus content in suspended solids of the Yellow River was 0.54 g/kg, which is quite close to the background value of phosphorus in the soil of the Loess Plateau – the intensive soil erosion area in China, through which the Yellow River flows. Therefore, we conclude that phosphorus transportation in the Yellow River is dominantly controlled by soil erosion from the Loess Plateau. The results are significant for estuarine management in that nitrogen, a key factor in marine eutrophication, is chiefly from anthropogenic sources whereas the large phosphorus loads are controlled by erosion of loess soils.

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1. Introduction

Nitrogen and phosphorus are necessary nutrients for organisms, and are also major elements that cause eutrophication when exceeding the assimilation capacity of receiving waters (Abal et al., 2005). The transportation of nitrogen and phosphorus from the land to sea is an important process component in bio-geochemical cycling (Turner et al., 2003). The study on this subject contributes not only to the knowledge of the mass exchange between the landscape and sea but also to the control of eutrophication of water-bodies, which can provide valuable evidence for assessing contributions of agriculture and urban sources of nutrients. In the past decades, the globe has experienced increased nitrogen in waters (Moffat, 1998). Many studies have indicated that, in China, nitrogen concentration in large rivers also had a significantly increasing trend in the recent years (Zhang, 1995; Chen and Yu, 2004; Chen et al., 2000, 2004; Duan et al., 2000; Li et al., 2007a,b). The loss of nitrogen and phosphorus from the landscape has great impact on water quality of rivers, estuaries, and nearshore zones of adjacent seas. With the rapid economic development, a large amount of nutrients is delivered to the seas and contributes to abnormal proliferation of alga and eutrophication of the seawaters. The frequent occurrence of red tide in Bohai Bay in recent years is closely related to the large amount nutrient inputs from the basin to the sea (Zhao et al., 2002; Jiang et al., 2005). The major rivers that flow to the Bohai Sea include the Yellow River, Haihe River, Luan

River and Liao River. Their total annual discharge is $888 \times 10^8 \, \text{m}^3$, of which nearly 50% is from the Yellow River. Therefore, nutrients transported by the Yellow River exert a major impact on the water quality of the Bohai Sea.

The Yellow River is the second largest river in China, and it is the water source for Northwest and North China. Study on the transport of nitrogen and phosphorus by the Yellow River provides the baseline for environmental assessment and pollution control of nutrients in the river basin and Bohai Sea. Though there already have been many studies on water pollution of the Yellow River (He et al., 2006; Michael et al., 2008; Wang et al., 2009), the analysis of the long-term variation of nitrogen and phosphorus transport by the river and its major impact factors have been rarely reported. In this study, long-term monitored water quality data of the river, and related socio-economic data of the basin are used to assess the variations of nutrient transport in the Yellow River and the controlling factors. Understanding of long-term trends and causal factors can improve the ability to undertake total load control, load allocation and load reduction in the basin and Bohai sea area.

2. Data source and manipulation

2.1. Data source and study station

Monthly flow and nitrogen (dissolved inorganic nitrogen, $DIN = NO_3^- \text{-N} + NO_2^- \text{-N} + NH_4^+ \text{-N}$) data from 1960 to 2003 were collected from the Yellow River Conservancy Commission (YRCC, 1960–2003). Monthly phosphorus (orthophosphate and total phosphorus form involved in this study) and suspended solid data were taken from the Global Environmental Monitoring System (GEMS/water program, 1980–1996) and YRCC (1997–1998) at Luokou Station. Turner, et al. (2003) introduced this program and data set in their paper. For these phosphorus data, orthophosphate was monitored twice a month from 1980 to 1984 and once in a month from 1985 to 1993; total phosphorus (TP) was monitored once per month from 1985 to 1998.

For each province in the Yellow River basin (Qinghai, Sichuan, Gansu, Ningxia, Inner Mongolia, Shaanxi, Shanxi, Henan, and Shandong; Fig. 1), nitrogen and phosphorus fertilizer application data (converted to elemental N and P) from 1980 to 2000 were taken from China Agriculture Statistic Yearbook (China Agriculture Yearbook Compilation Committee, 1980–2000); population data for each province in the basin were from the China Statistic Yearbook (China Statistic Yearbook Compilation Committee, 1980–2000); wastewater discharge data for each province from 1989 to 2000 were from China Environment Yearbook (China Environment Yearbook Compilation Committee, 1989–2000).

In this paper, according to the study needs and data availability, we selected major downstream stations of the Yellow River (Huayuankou, Luokou and Lijin) as the study sites (Fig. 1). Huanyuankou Station is an important monitoring section in the lower reaches of the mainstream, representing 95% of the entire drainage area. We examined the correlation of water quality parameters and socio-economic data in terms of this station. Luokou Station, around 400 km downstream of Huayuankou Station, is another major station at the river, and the monitoring station used in the global GEMS/water project. As the monthly data of phosphorus and suspended solid are only available at Luokou station, the correlation analysis was conducted at this station with data from 1985 to 1998. The station of Lijin, representing the entire drainage area, is the most downstream monitoring station on the mainstream, some 100 km from the estuary (Fig. 1).

2.2. Data manipulation

Fertilizer application and population for the entire basin were calculated by adding each province's data, which were weighted by the area of each province that falls within the Yellow River basin. Monthly nitrogen and phosphorus concentrations were used to display the long-term variation. Annual nitrogen flux was calculated by summing monthly loads to ensure adequate accuracy (Fu, 2003).
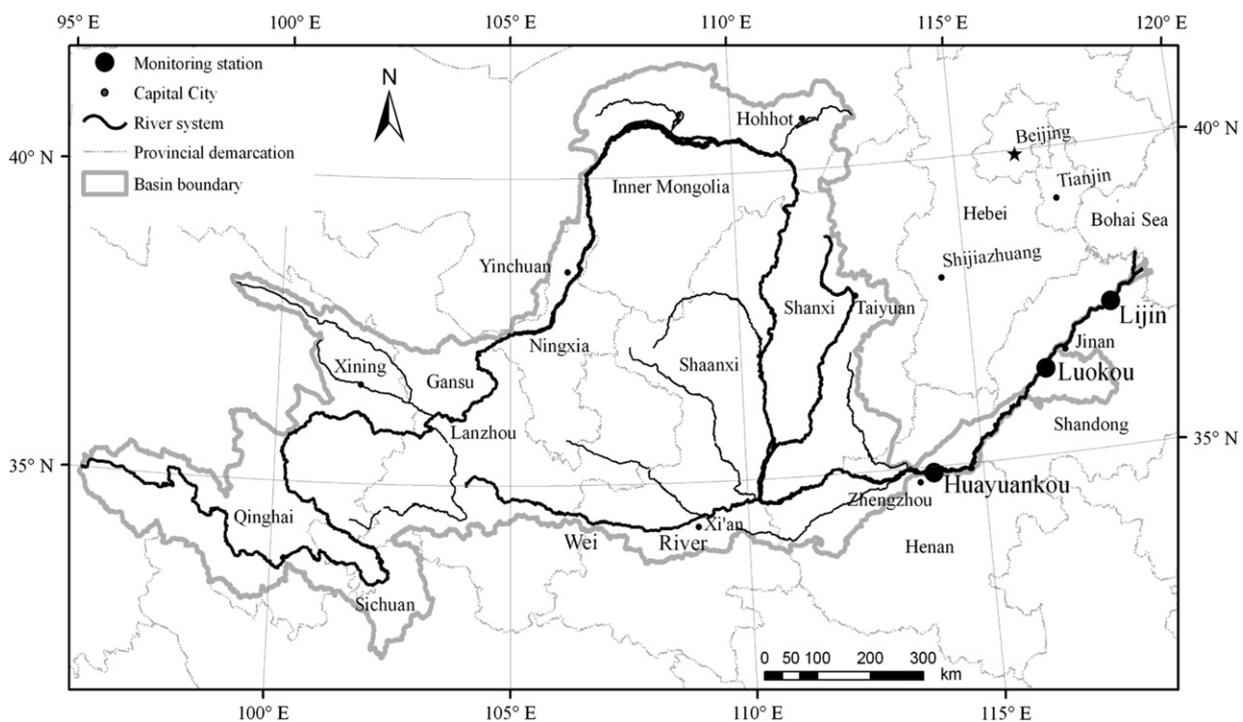

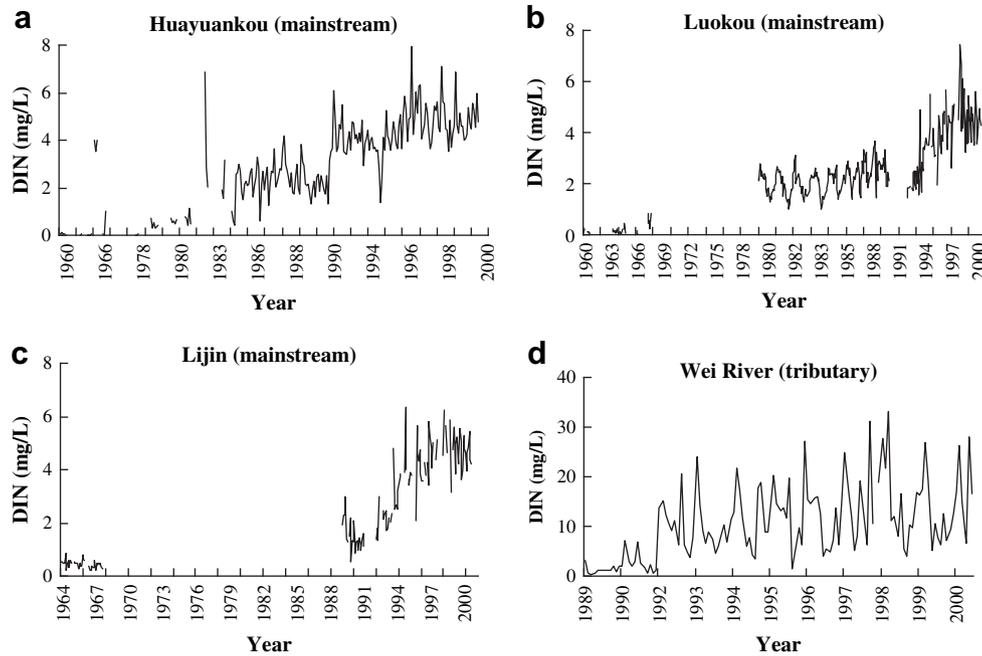Fig. 1. The Yellow River basin and the monitoring stations used in this paper.

Fig. 2. Variations of dissolved inorganic nitrogen concentration in the Yellow River.

Since Shandong Province is downstream of Huayuankou station, when we examine the relationship between water quality parameters and socio-economic factors at Huayuankou station, the socio-economic data of Shandong Province is not counted. In addition, as the socio-economic data are yearly statistic in China's various yearbooks, we correspondingly used yearly averaged water quality data to conduct correlation analysis.

Different statistic methods and tests were used to reveal the varying trend, with consideration of different characteristics of data distribution. A significance level of 0.01 was selected. The calculation and statistic work were performed in EXCEL and SPSS.

3. Results and discussion

3.1. Long-term variations of nitrogen transport by the Yellow River

The long-term variations of monitored nitrogen at the three mainstream stations (Huayuankou, Luokou, and Lijin) are shown in Fig. 2. It is indicated from the available data that, in the early 1960s, the dissolved inorganic nitrogen (DIN) concentrations were generally lower than 1 mg/L, and, in the reported period, the nitrogen concentration had a significantly increasing trend (Kendall correlation coefficient: $r = 0.733$, $P = 0$ for Huayuankou Station; $r = 0.636$, $P = 0$ for Luokou Station; $r = 0.818$, $P = 0$ for Lijin Station). In addition, from the figure it can be observed that, two obvious step changes in nitrogen concentration occurred in the early 1980s and early 1990s at Huayuankou Station (Fig. 2a); and a step increase in the early 1990s at Luokou and Lijin Station (Fig. 2b,c).

Available data exhibit the similar variation of DIN in tributaries. For example, in the Wei River, the largest tributary of the Yellow River (Fig. 1), the increasing trend is significant through the study period ($r = 0.58$, $P = 0 < 0.01$), and a sharp increase also occurred in the early 1990s (Fig. 2d).

By contrasting DIN concentration in the mainstream and tributaries of the Yellow River, we find that the inorganic nitrogen content in tributaries is much higher than that in the mainstream. For instance, the average DIN in Wei River was 10.35 mg/L (from 1989 to 2000, $n = 125$), while it was 4.10 mg/L at the Huayuankou

station (from 1989 to 2000, $n = 132$). Other researchers have evaluated the nitrogen contamination in the Yellow River and reached the conclusion that many tributaries were more polluted than the mainstream (Xia et al., 2001; Zhang et al., 2003).

We also calculated the annual nitrogen fluxes (loads) at the three stations (Fig. 3). It is shown from Fig. 3 that, before 1997 nitrogen fluxes had an obvious increasing trend, but after that year they apparently decreased, mostly due to the intensified river-channel desiccation or drying-up at the lower reaches of the Yellow River in the mid-late 1990s (Qian et al., 2001; Li et al., 2007a,b). The severest situation occurred in 1997, in which there was no flow in the downstream of the Yellow River for 226 days (Qian et al., 2001). Consequently, the nitrogen flux fell to its lowest historical level in that year. In addition, it can be observed from Fig. 3 that, the pattern of variation of nitrogen fluxes at the three stations is quite synchronous. However, the nitrogen fluxes at upstream station of Huayuankou are consistently higher than those at the downstream stations of Luokou and Lijin. Similarly, nitrogen load values at Luokou station (downstream of Huayuankou and upstream of Lijin) are higher than those at Lijin station (Fig. 3). This is inconsistent with usual cases, in which the pollutant load in the upper reaches is
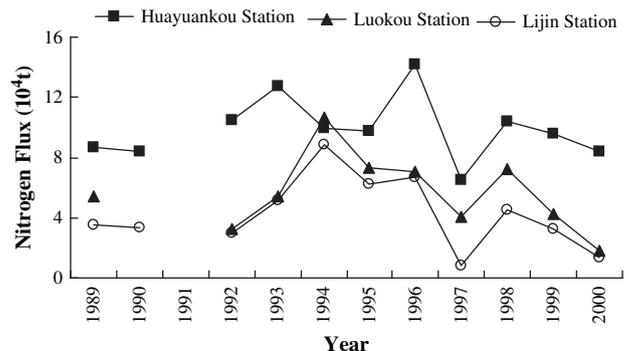

Fig. 3. Nitrogen flux variations of the three downstream stations from 1989 to 2000.
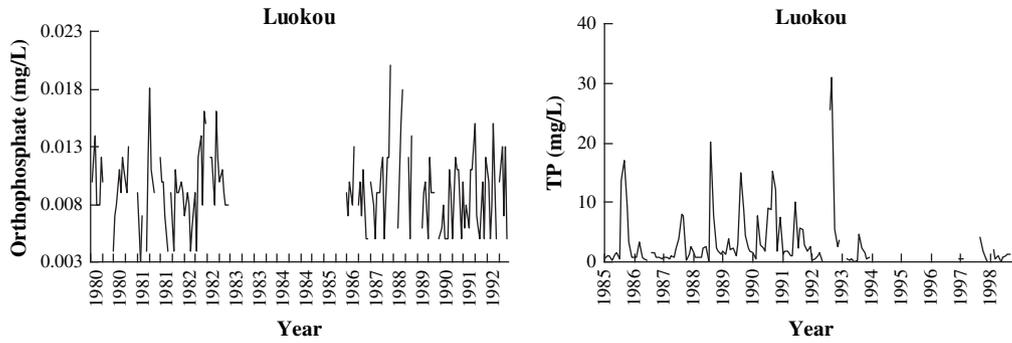
Fig. 4. Variations of orthophosphate and total phosphorus (TP) in the Yellow River.

generally lower than that at the downstream sections due to more tributaries discharging into the mainstream. This situation can be explained by two factors: (a) the Yellow River-channel topography. It is well known that the reach downstream from Huayuankou is called a "suspended river" (Zeng, 2004), which means the river level is higher than the surrounding ground level due to hundreds of years of sedimentation in the lower reaches of the Yellow River (from Huayuankou and downstream). Consequently, there are few tributaries discharging into this reach, therefore leading to less loads into the reach. (b) water transfer in this reach. There are vast areas of farmland, about 2800 km^2, in Henan and Shandong Province of the lower Yellow River reaches, and these farmlands are irrigated with water withdrawn from the Yellow River. The yearly averaged water transfer from the river for irrigation amounts to 10^{10} m^3 (Ren and Tang, 1998). Calculated with the yearly averaged nitrogen concentration of 4.10 mg/L from 1989 to 2000 at Huayuankou station, the annual nitrogen load diverted from Huayuankou to Lijin is estimated at $>4 \times 10^4$ tons. This leads to the reduced nitrogen load downstream from Huayuankou. Therefore, contrary to the other reaches of the entire watershed, the nitrogen contribution to the estuary from Huayuankou to Lijin is negative. This finding is useful when planning nitrogen pollution control in the Yellow River basin and its estuary.

3.2. Long-term variations of phosphorus transport by the Yellow River

According to monitored phosphorus records, the average orthophosphate concentration from 1980 to 1992 was 0.009 mg/L ($n = 131$); the average total phosphorus (TP) concentration from 1985 to 1998 was 3.095 mg/L ($n = 134$) at Luokou station. Compared with world rivers (Meybeck, 1982), the Yellow River is the richest in total phosphorus. However, as the orthophosphate concentration is less than 1% of the total phosphorus concentration, the phosphorus in the Yellow River mainly appears in the particulate-bound form. The long-term variations of the two forms of phosphorus in the Yellow River are presented in Fig. 4. Unlike nitrogen variation, both forms of phosphorus had no continuous tendency in the reported period, but fluctuated within a certain range. The orthophosphate variation is smaller ($\mu = 0.0092$ mg/L, $s = 0.0034$, $n = 131$). Similar to nitrogen, the concentration of total phosphorus also significantly decreased due to the desiccation. This is because the phosphorus is mainly combined to suspended solids, with the water flow decreasing, particulates transport correspondingly reduced and therefore the concentration of the total phosphorus became lower. In contrast, the concentration of soluble chemicals was less impacted by the drying-up of the Yellow River. For example, the concentration of total inorganic nitrogen had no such a sudden decline in the late 1990s (Fig. 2).

3.3. Impact factors of nitrogen transport in the Yellow River basin

Using Huayuankou station as the controlling section, we summarized the change of population, nitrogen and phosphate fertilizer application, and wastewater discharge in the river basin (not including downstream Shandong Province) for the past 20 years (Fig. 5). It can be seen from Fig. 5 that the population, nitrogen and phosphate fertilizer application in the basin presented an obvious increasing trend over the period ($r = 1$, $p = 0$ for population; $r = 0.93$, $p = 0$ for nitrogen fertilizer; $r = 0.95$, $p = 0$ for phosphate fertilizer), whereas the available data for industrial wastewater discharge (1989–2000) showed no significant change during the study period ($r = -0.12$, $p = 0.53 > 0.01$).

We explored the correlation between these indexes and nitrogen fluxes at Huayuankou station. The statistical analysis indicates that the nitrogen flux has a positively significant correlation to the basin population (Fig. 6a, $r = 0.643$, $P = 0.003$, $n = 19$), and also has a similar relationship with fertilizer application in the basin (Fig. 6b, $r = 0.628$, $P = 0.004$, $n = 19$).

Given that the population and fertilizer application were growing during the study period (Fig. 5), both factors have significant impact on the nitrogen increase in the Yellow River. However, due to the narrow difference between the two correlation coefficients (0.643 and 0.628), existing data are unable to discriminate between the influence of population and agricultural use of nitrogen fertilizer.

In addition, we also examined the relationship between industrial wastewater discharge data of 1989–2000 in the basin (excluding Shandong Province) and nitrogen flux (Fig. 6c). The statistical test shows that they are not statistically correlated ($r = -0.394$, $P = 0.26 > 0.01$, $n = 11$). This may suggest that industrial discharges are not a factor in the trend or, more likely, that the
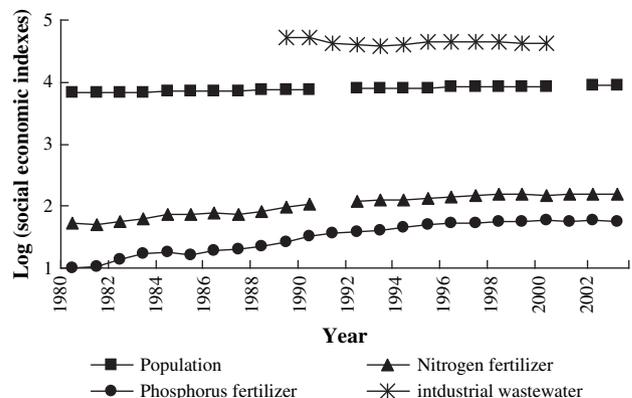

Fig. 5. Change of the population, nitrogen and phosphate fertilizer and wastewater discharge in the Yellow River basin from 1980 to 2003.
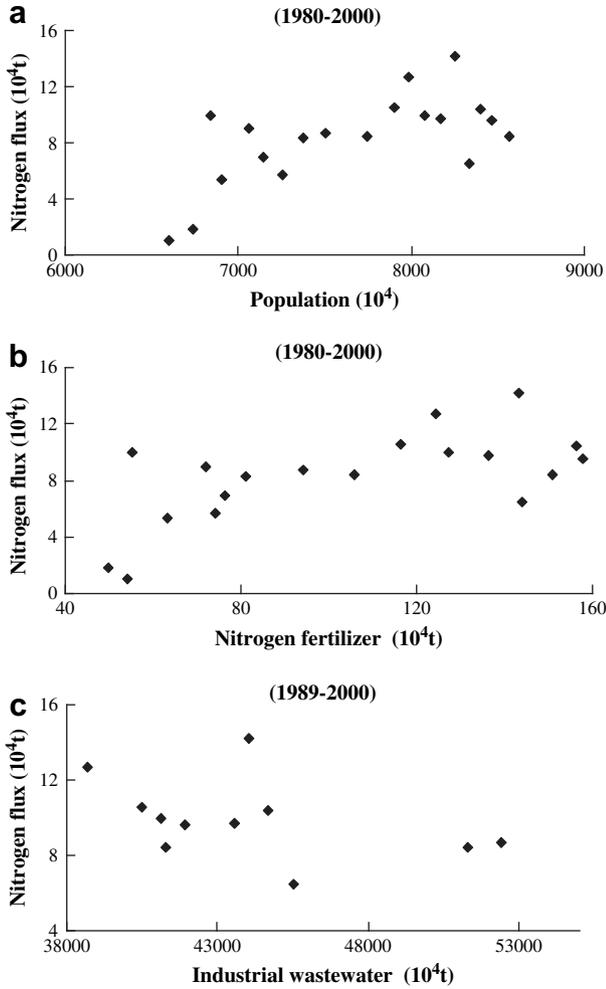
Fig. 6. Relationship between nitrogen flux and population (a), nitrogen fertilizer (b), industrial wastewater (c) in the Yellow River basin, at Huayuankou.

Fig. 7. Relationship between total phosphorus concentration and population (a), phosphate fertilizer application (b), wastewater discharge (c) in the Yellow River basin, at Luokou.

proportion of industrial wastewater is not sufficiently large relative to other sources to impact on the total nitrogen load.

Many studies have shown that, major factors contributing to nitrogen input in the basin include industry, agriculture (fertilizer) and population (Meybeck and Helmer, 1989; Benjamin et al., 1991; Xing and Zhu, 2000; Gregory et al., 2001). In the Yellow River basin, most areas are agriculture-dominated, and the industries in the Yellow River are not so developed as in the Yangtze basin. Therefore, the nitrogen transportation is mainly impacted by the population growth and fertilizer use, but less influenced by industrial discharges.

It should be pointed out that the conclusion was drawn from the perspective of the entire basin. It does not deny that, in some tributaries of the Yellow River, industry has a dominant impact on the water quality, for example, the Sushui River, tributary of the Yellow in Shanxi Province, where the river is mainly wastewater, especially in dry seasons.

3.4. Impact factors of phosphorus transport in the Yellow River basin

Similarly, we examined the relationship between phosphorus transportation and major factors that potentially contribute to phosphorus input to the Yellow River. Because of data availability, the study period was from 1985 to 1998 at the GEMS/Water Luokou
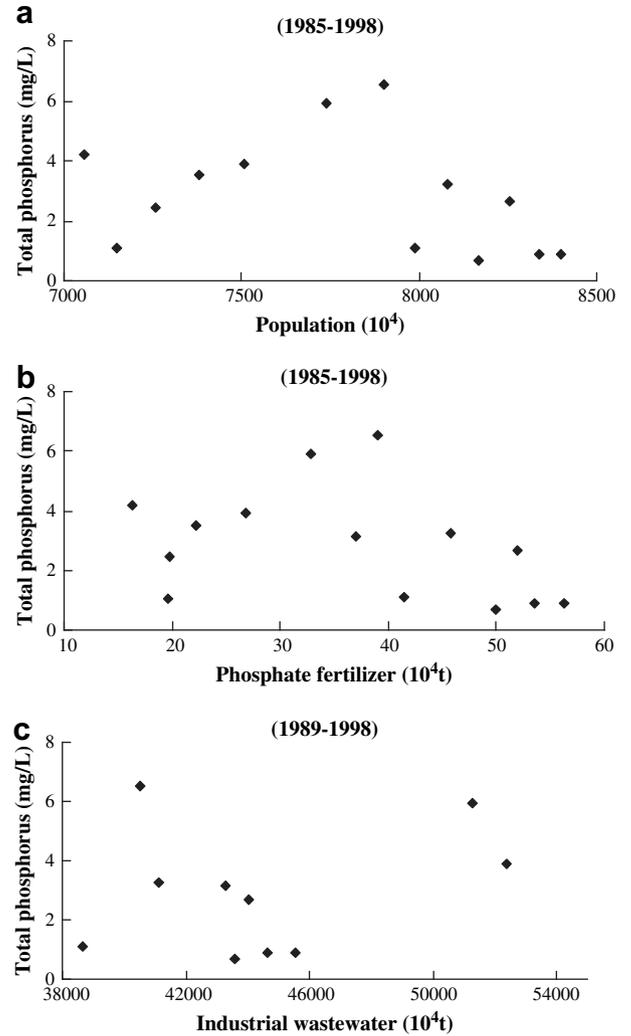
station, around 400 km downstream from Huayuankou (Fig. 1). The statistical results show that phosphorus transport by the Yellow River has no correlation with population (Fig. 7a, $r = -0.306$, $P = 0.309 > 0.01$, $n = 13$), with phosphate fertilizer application (Fig. 7b, $r = -0.359$, $P = 0.208 > 0.01$, $n = 13$), and with industrial discharge in the basin (Fig. 7c, $r = 0.654$, $P = 0.078 > 0.01$, $n = 10$). This indicates that none of these factors are major controlling factors for phosphorus input to the river. This is distinctly different from the nitrogen situation.

To further explore the potential causal factor for phosphorus in the Yellow River we analyzed the correlation between total phosphorus and suspended solid data. The result shows that they are significantly positively correlated (Fig. 8, $r = 0.965$, $P = 0 < 0.01$). To elucidate this phenomenon and explore the impact factor of phosphorus in the Yellow River, we conducted further statistical analysis.

Taking suspended solids at Luokou station as the independent variable, and the total phosphorus as the dependent variable, we conducted regression analysis, and drew the regression equation as following:

$$\lg P = 0.999 \lg SS - 3.285 \tag{1}$$

where, P is total phosphorus content (mg/L), SS is suspended solid content (mg/L). The coefficient of determination of the regression
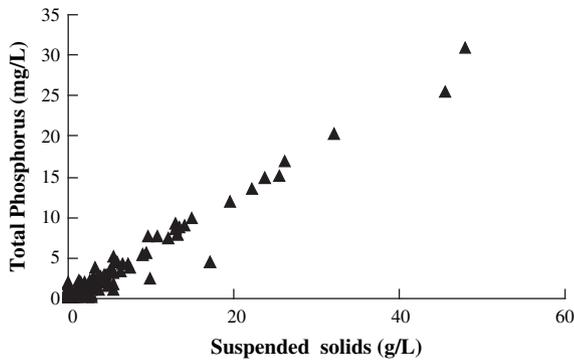
Fig. 8. Relationship between total phosphorus content and suspended solids at Luokou.

equation is $r^2 = 0.934$, and F-test for the equation indicates that the regression result is statistically significant ($F = 1494.97$, $p = 0$). T-test for the regression coefficient indicates that it is statistically significant at the confidence level of 0.001.

With the long-term average suspended solid concentration of 35 000 mg/L in the Yellow River (Water Ministry, 2003) and using the Equation (1), we can calculate the total phosphorus content of suspended solids of the Yellow River, which is equal to 0.54 g/kg. This calculated value is quite close to the phosphorus background value of the soil from the Loess Plateau. According to the investigation of approximately two thousand soil samples from Shan'xi, Gansu, Ningxia, and Shanxi Province, the average soil phosphorus content is 0.65 g/kg (National soil survey office, 1995), the relative error to which is only 17% compared with our calculated value. As we know that the Yellow River has the highest suspended solid concentration of world rivers, and that the large amount of suspended solids transported by the Yellow River is mainly from the soil loss from the Loess Plateau, located in the several provinces mentioned above. The source of the soil loss in the Yellow River basin is comparatively simple, so the total phosphorus of the Yellow River presents significant correlation to the suspended solids. This can also explain why the Yellow River is the most abundant in phosphorus of all World Rivers. However, this does not imply that other phosphorus sources are unimportant, only that that soil loss component so dominates P transport in this river that any other source such as agriculture or human use of phosphates as in, for example, detergents, in the Yellow River are masked by the abundance of soil-related phosphorus.

4. Conclusions and summary

While there have been some reports on nitrogen variations in the Yellow River, the long-term variation of phosphorus transport by the Yellow River are rarely reported (Xia et al., 2001; Chen and Yu, 2004; Chen et al., 2004). In this paper, we examined both nitrogen and phosphorus variations in the lower reaches of the Yellow River, and discussed their causal factors. Our analysis leads to the following conclusions:

(1) Nitrogen transport by the Yellow River had been continuously increasing in the past decades; however, due to the drying up in the lower reaches of the river, it was drastically reduced in the late 1990s, while the orthophosphate and total phosphorus concentrations presented no trend change during the study period.
(2) Because of the unique geomorphic characteristic of this "suspended river" downstream from Huayuankou station, and because of the large amount of water transfer from the reach

between Huayuankou and Lijin for the irrigation purpose every year, the nitrogen contribution in this reach to the estuary is negative.
(3) Nitrogen concentration in the lower reaches of the Yellow River is positively and significantly correlated to population and nitrogen fertilizer use in the basin, but has no correlation with industrial discharge in the basin. Therefore it is believed that the population growth and fertilizer use are major causal factors in nitrogen flux trends. However, the current data are unable to identify which factor plays a more dominant role in impacting the nitrogen load in the Yellow River, and this issue is worthy of further exploring.
(4) Total phosphorus transport by the Yellow River is not subjected to the population growth, phosphate fertilizer usage, or industrial discharge in the basin, but is significantly correlated to the suspended solid content of the river water. The similarity in phosphorus concentration of river sediments and of soils from the Loess Plateau strongly suggests that phosphorus transport of the Yellow River is mainly influenced by the soil loss from the Loess Plateau.

In summary, the fact that nitrogen is mainly influenced by anthropogenic sources whereas phosphorus is mainly influenced by soil erosion, provides important evidence on control options for pollution control both for the lower Yellow River and for nutrient input to the Yellow River estuary and to the Bohai Sea. We also note that efforts by YRCC to increase river discharge in the lower reaches as a means of mobilizing bed sediments to increase channel capacity for flood control purposes, will have the effect of increasing both nitrogen and phosphorus loads to the Bohai Sea.

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