Agricultural water consumption decreasing nutrient burden at Bohai Sea, China

Yindong Tong\textsuperscript{a, b, c, *}, Xuejun Wang\textsuperscript{b, d}, Gengchong Zhen\textsuperscript{e}, Ying Li\textsuperscript{f}, Wei Zhang\textsuperscript{e, **}, Wei He\textsuperscript{b, d}

\textsuperscript{a} School of Environmental Science and Engineering, Tianjin University, Tianjin, 300072, China
\textsuperscript{b} Ministry of Education Laboratory for Earth Surface Processes, Peking University, Beijing, 100871, China
\textsuperscript{c} China-Australia Centre for Sustainable Urban Development, Tianjin, 300072, China
\textsuperscript{d} College of Urban and Environmental Sciences, Peking University, Beijing, 100871, China
\textsuperscript{e} School of Environmental and Natural Resources, Renmin University of China, Beijing, 100872, China
\textsuperscript{f} Department of Environmental Health, College of Public Health, East Tennessee State University, Johnson City, TN, 37614, USA

\textbf{A R T I C L E   I N F O}

Article history:
Received 16 October 2015
Received in revised form 30 November 2015
Accepted 11 December 2015
Available online 13 December 2015

Keywords:
Agricultural water consumption
Huanghe river
Nutrient balance
Nutrient burden
Bohai sea

\textbf{A B S T R A C T}

In this study, we discussed the impacts of human water consumption to the nutrient burden in a river estuary, and used Huanghe River as a case study. The agricultural water consumption from the Huanghe River has significantly decreased the natural water flows, and the amount of water consumption could be almost twice as high as the water entering into the estuary. According to our calculation, agricultural water usage decreased TN outflows by $6.5 \times 10^{4}$ Mg/year and TP outflows by $2.0 \times 10^{3}$ Mg/year. These account for 74% and 77% of the total output loads. It has been widely reported that the majority of the rivers in northern China were severely polluted by nutrients. Its implication on the budget of nutrient in the estuary ecosystem is not well characterized. Our study showed that the discharge of nutrients in the coast waters from polluted rivers was over concerned. Nutrients in the polluted rivers were transported back to the terrestrial systems when water was drawn for human water consumption. The magnitudes of changes in riverine nutrient discharges even exceed the water-sediment regulation trails in the Huanghe River. It has non-negligible impact on estimating the nutrient burden in coastal water ecosystem.

\section{Introduction}

The transport of nutrients from the terrestrial systems to the coastal waters represents a key pathway in the global geochemical cycle (Walsh, 1991; Dai et al., 2011). Anthropogenic activities contribute more than natural process in the transport of nutrients into the seas. Rapid increases in nutrient sources and discharges have greatly changed the nutrient compositions and concentrations in the sea, causing the overabundance of nutrients in the estuarine environment (Mukhopadhyay et al., 2006; Richardson and Jorgensen, 2013; Gao and Wang, 2008; Hessen et al., 2010). This caused the sea water to be more turbid and frequent occurrences of harmful algal blooms (HABs) (Zhang et al., 1999; Wang, 2006). For instance, from 2006 to 2012, HABs occurred approximately 500 times in the coastal waters of China, mainly at the estuaries of large rivers, and an increasing trend of HABs occurrences was observed (China’s State Oceanic Administration, 2012). When considering the negative impacts of human activities on the watersheds, a neglected fact is that, the massive human water consumption from the rivers could also decrease the nutrient burdens at the estuary. Although the negative effects of nutrient discharges to the offshore areas have been widely studied (Zhang et al., 1999; Zhang, 2008; Li et al., 2014), the potential positive effects of human activities have not been well understood. In the wet-climate areas such as Yangtze River Basin, the human water consumption from the river was relatively small. Hence, limited impacts would be imposed to the estuaries from human water consumption (Tong et al., 2015a). However, in the dry-climate areas, river is an important water source for agricultural and industrial usage, and the massive water consumption could decrease the water outflows and nutrient discharges into the estuary significantly.

The Huanghe River, originating from the Qinghai–Tibetan
Plateau at an elevation of 4500 m, is the second longest river in China. The river flows about 5464 km and drains an area of 75.2 × 10⁴ km² before entering into the Bohai Sea, in northern China (Zhang et al., 2013). Most areas of the Huanghe River basin are located in the dry and water-deficient regions. In order to meet the water demand in this region, over 50% of the natural water flows in the Huanghe River was consumed for agricultural irrigation and industrial usage in the basin (Yellow River Conservancy Commission of MWR, 2008–2012). From 1950 s to the early 1990 s, the water consumption from the Huanghe River increased by three-fold (Chen et al., 2005; Wang et al., 2007). The amount of water consumption by human activities (~3 × 10¹⁰ m³) was 1.7 times as the runoff being discharged into the Bohai Sea (~1.8 × 10¹⁰ m³) (Kong et al., 2012; Liu et al., 2012). The over consumption of the Huanghe water in the upstream leads to the frequent occurrences of zero-water flow days in the downstream. Since 2002, the Huanghe River Conservancy Commission implemented the water-sediment regulation (WSR) trail at the beginning of every flood season. Many studies have examined the impact of WSR on the hydrological processes of the Huanghe River. It was reported that WSR kept the Huanghe water discharges at very high levels within a short period, which is expected to affect the nutrient transports, compositions in the ecosystem of the Huanghe estuary and the adjacent sea (Li et al., 2009; Liu et al., 2012; Han et al., 2013). However, very few studies have focused on the potential impacts of massive water consumption along the river.

In this study, a comprehensive analysis of the riverine nutrient concentrations (including nitrogen and phosphorus) and discharges was conducted in the Huanghe River Basin. The potential impacts of anthropogenic water consumption to the nutrient burden at the estuary of Huanghe River (Bohai Sea) was fully discussed. The contributions from various nutrient sources in different sections of the Huanghe River (upper, middle and lower) were identified using a nutrient mass balance model. This study will help the researchers to gain insight into the positive impacts of human activities to the coastal environment. It will also help regulators develop specific strategies to control riverine nutrient discharges and reduce coastal eutrophication in the Bohai Sea.

2. Methods

2.1. Study area

The mainstream of the Huanghe River and its five largest tributaries (Weihe River, Yiluohe River, Jinghe River, Huangshui River, Qinhe River) were considered in this study (shown in Fig. 1). The Huanghe River was divided into four sections based on geographic features. These include the river source section (mainstream before Lanzhou, Gansu Province, with a length of 2504 km), upper section (from Lanzhou to Huhehaote, Inner Mongolia Autonomous Region, with a length of 968 km), middle section (from Huhehaote to Zhengzhou, Henan Province, with a length of 1206 km) and lower section (from Zhengzhou to Jina, Shandong Province, with a length of 786 km).

From 2008 to 2012, the annual water discharge of the Huanghe River into the Bohai Sea was approximately 1.8 × 10¹⁰ m³/year (Tong et al., 2015b). During the wet seasons (from May to October), high levels of precipitation generated water flows of 30–46 × 10⁸ m³/month in the upper Huanghe River, and 16–34 × 10⁸ m³/month at the estuary (Ministry of Water Sources, 2008–2012). During the dry seasons (from December to April of the next year), flows were 17–20 × 10⁸ m³/month in the upper stream, and 5–13 × 10⁸ m³/month at the estuary (Ministry of Water Sources, 2008–2012). The water flows during the WSR trails could account for about 30% of the annual discharges, at the rate of ~40 × 10⁸ m³/year (Kong et al., 2012; Liu et al., 2012). Compared with the upstream, the reduced water flows in the downstream and estuary was mainly caused by the massive human water consumption.

2.2. Nutrient data

Total nitrogen (TN) and total phosphorus (TP) concentrations were monitored monthly from 2008 to 2012 at the monitoring stations in the Huanghe River Basin (shown in Fig. 1). Field sampling was carried out according to the “Technical Specifications Requirements for Monitoring of Surface Water and Waste Water, in China (HJ/T 91—2002)” by the Chinese Ministry of Environmental Protection. The water sampling sites were all upstream of the sewage outfall to avoid contamination from the point source. Specifically, the vertical water mixture samples (surface: 50 cm under the surface; middle: 1/2 of the river depth; bottom: 50 cm above the riverbed) were collected and mixed for each sampling site. The sampling equipment was cleaned thoroughly with deionized water between each site to avoid cross contamination. Approximately 0.5–1 L water samples were collected each time. As soon as the samples were collected, H₂SO₄ (GR) was added to make the pH < 2. The samples were kept in the refrigerator before analysis at temperature of 4 °C. The measurement of TN was based on the alkaline potassium persulfate digestion ultraviolet spectrophotometric method (GB 11894–89), with a detection limit of 0.05 mg/L. Measurement of TP was based on flow injection analysis and the ammonium molybdate spectrophotometric method (GB 11893–89), with a detection limit of 0.01 mg/L. The TN was measured by ultraviolet spectrophotometer (Mapada Instrument, Shanghai), and the recoveries of standard solutions were 99.0 ± 6.4%. The TP was measured by spectrophotometer (Mapada Instrument, Shanghai), and the recoveries of standard solutions were 100.0 ± 1.9%.

2.3. Nutrient balance

The nutrient sources and discharges in each section (including river source, upper, middle and lower section) of the Huanghe River were divided into four categories: (i) nutrient flowing-out loads with water discharges; (ii) nutrient flowing-out loads with the human water consumption from the selected river section; (iii) nutrient input from the upstream and tributaries; (iv) other nutrient inputs emitted into the river. Based on the input and output nutrient mass balance, the following equation was established for the upper, middle and lower Huanghe River:

\[ L_{\text{Upstream In}} + L_{\text{Tributary In}} + L_{\text{Other Emission In}} = L_{\text{Downstream Out}} + L_{\text{Water Consumption Out}} \]  

\[ L_{\text{Upstream In}} \] is the nutrient input from the upstream water (Mg/year). For example, for the lower Huanghe River section, \( L_{\text{Upstream In}} \) refers to the nutrient input from the middle Huanghe River section. \( L_{\text{Tributary In}} \) is the nutrient input from the tributaries (Mg/year). \( L_{\text{Other Emission In}} \) refers to the other nutrient emissions discharged into the Huanghe River, and it is the sum of the nutrient emissions from point source, non-point sources, etc. \( L_{\text{Downstream Out}} \) is the nutrient output with water discharges (Mg/year). \( L_{\text{Water Consumption Out}} \) is the nutrient output associated with human water consumption from the river (i.e., agricultural irrigation and
industrial water use). It should be noted that $L_{\text{Water Consumption Out}}$ excludes the water that would be returned into the rivers after usage. $L_{\text{Upstream In}}$, $L_{\text{Tributary In}}$ and $L_{\text{Downstream Out}}$ were calculated based on the monthly water flows ($V_{\text{Runoff}}$, $10^8$ m$^3$/month) and the nutrient concentrations at in-flow and out-flow sites of the river ($C_{\text{Nutrient}}$, mg/L). $L_{\text{Water Consumption Out}}$ was estimated by the volume of water withdrawn from the river ($V_{\text{Water Use}}$, $10^8$ m$^3$/year, excluding the water which would be returned into the river after usage) and nutrient concentrations in the consumed water ($C_{\text{Water Use}}$, mg/L). All of the model terms can be directly calculated except $L_{\text{Other Emission In}}$ (Mg/year). $L_{\text{Other Emission In}}$ was calculated by solving the mass balance equation. Hence, equation (1) could be converted into the following form (equation (2)). The values of the selected parameters in the equation were provided in Table S1.

$$\sum_{i=1}^{12} V_{\text{Runoff}} C_{\text{Nutrient}}(\text{Upstream}) + \sum_{i=1}^{12} V_{\text{Runoff}} C_{\text{Nutrients}} + L_{\text{Other Emission in}} = \sum_{i=1}^{12} V_{\text{Runoff}} C_{\text{Nutrient}}(\text{Downstream}) + V_{\text{Water Consumption}} \times C_{\text{Water Consumption}}$$

(2)

3. Results and discussion

3.1. Spatial variations in nutrients

TN and TP concentrations in the Huanghe River and tributaries in 2012 are presented in Fig. 3A and B, respectively. Generally, the nutrients in the Huanghe River reflected the characteristic of “high TN and low TP concentration”. The TP concentrations in the majority of the selected rivers were low (lower than the V limit according to the China Surface Water Quality Standard of 0.4 mg/L), but TN concentrations were extremely high. In 2012, the minimum TN concentration was observed in the river source section, with a median of 1.39 mg/L, while the maximum was observed in the Fenhe River, with a median of 24.06 mg/L. The TN concentrations in all sections but the river source section have greatly exceeded the V limit of the China Surface Water Quality Standard (GB 3838-2002) of 2.0 mg/L, indicating these waters have been severely contaminated by nitrogen. A longitude increase of TN concentrations was observed along the Huanghe River (Fig. S1A). The average TN concentration in the lower Huanghe River was 3.05 (range = 0.89—7.92) mg/L, higher than those in the upper Huanghe River (2.54, range = 0.62—6.97) mg/L (Fig. S1A). The maximum TN concentrations occurred at the sampling sites near the Jinan city, with a value of 5.07 (range = 3.16—7.92) mg/L. The TN concentrations in the Huanghe River were much higher than the reported values in the Yangtze River, where the average was less than 2 mg/L (Tong et al., 2015a).

The minimum TP concentrations were also observed in the river source section, whereas the maximum concentrations were observed in the Fenhe River. The maximum concentration did not exceed the V limit of China Surface Water Quality Standard of 0.4 mg/L, indicating the phosphorus pollution in the Huanghe River Basin was not serious. The longitudinal variation of TP concentrations along the Huanghe River was provided in Fig. S1B, and site-specific high TP concentration was observed at the sampling site of Huhehaote, as high as 0.15 (range = 0.10—0.18) mg/L. In the upper Huanghe River at Lanzhou, the TP concentration was 0.04 (range = 0.01—0.09) mg/L, while in the lower section, the corresponding concentration was 0.07 (range = 0.02—0.18) mg/L. The sources of nitrogen and phosphorus in the Huanghe River have been discussed by previous studies. The excessive riverine nitrogen is derived from increase in population, cropland use, fertilizer application, and municipal sewage discharge over the drainage basin, while phosphorus transportation in the Huanghe River was dominated by the soil erosion from the Loess Plateau (Meng et al., 2007; Liu et al., 2012). The nitrogen fertilizers used in the Huanghe
Fig. 2. Discharges of the Huanghe River (A) and fraction of different water uses (B). A: River source; B: Upper section; C: Middle section; D: Lower section; E: Weihe; F: Yiluohe; G: Huangshui; H: Fenhe; I: Qinhe.

*The contributions of various water uses were presented based on the data in 2009.*

Fig. 3. TN (A) and TP (B) concentrations in the Huanghe River mainstream and the main tributaries in 2012. V limit in TN based on Chinese water quality standards (2.0 mg/L) V limit in TP based on Chinese water quality standards (0.4 mg/L)

A: River source; B: Upper section; C: Middle section; D: Lower section; E: Weihe; F: Yiluohe; G: Huangshui; H: Fenhe; I: Qinhe
River Baisn is about $1.5 \times 10^6$ tons. A significant relationship between nitrogen fertilizer usage and nutrient transport of Huanghe River was observed (Meng et al., 2007; Liu et al., 2012; Liu, 2015). The phosphorus content in suspended solids of the Yellow River was quite close to the phosphorus background value in the soil from the Loess Plateau (Meng et al., 2007). Generally, the phosphate concentrations are comparable to other Chinese rivers and they are at the pristine level of the global river data (Liu et al., 2009, 2012; Liu, 2015). The different nutrient sources probably lead to the difference of TN and TP concentrations in the Huanghe River and the spatial distribution. For instance, the higher TP concentrations generally occurred in the middle section of Huanghe River, where flows through Loess Plateau (Fig. S1B).

3.2. Temporal variations in nutrients

For the majority of the selected rivers, a decrease in TN concentrations was observed from 2008 to 2012 (Table 1). In detail, the TN concentrations in the middle main stream decreased by 22% (from 4.06 mg/L in 2008 to 3.16 mg/L in 2012). For the lower section, the TN concentrations decreased from 4.35 mg/L in 2008 to 3.11 mg/L in 2012, by 29%. However, for certain rivers, an opposite trend in TN concentrations was observed, such as the Qinhe River and upper Huanghe River (Table 1). The TP concentrations in the Huanghe River were low and remained stable during the study period, although a slight decrease occurred in the tributaries such as the Yiluohe, Huangshui and Fenhe River (Table 2).

The seasonal variations of nutrient concentrations in the Huanghe River and its tributaries were presented in Fig. 4. Previous studies have revealed that the runoff caused by the precipitation could affect the nutrient concentrations in the waters significantly (Chen et al., 2000; Meng et al., 2007). In this study, for the middle section, most of the high TN and TP concentrations occurred during the wet seasons (from June to October), and a significant relationship was observed between the nutrient concentrations and water flows (for TN, $p = 0.001$, $n = 55$; for TP, $p = 0.024$, $n = 56$). The higher nutrient concentrations in the rivers may be caused by nutrient release from non-point sources (Chen et al., 2000). In wet seasons, soil loss caused by precipitation may transport more soil nutrients to the rivers and increase nutrient concentrations (Chen et al., 2000). However, the relationship between nutrient concentrations and water flows was not significant in the lower Huanghe River (for TN, $p = 0.206$, $n = 48$; for TP, $p = 0.206$, $n = 51$), implying that these rivers may have a mixture of diffuse sources, point sources and non-point sources (Chen et al., 2000).

3.3. Nutrient balance in mainstream

The nutrient sources and discharges in the upper, middle and lower Huanghe River were presented in Fig. 5A and B, respectively. For the upper section, the upstream TN input (water discharge before Lanzhou) was $7.7 \times 10^4$ Mg/year, and the other TN input (including non-point source, point source, atmospheric deposition, etc.) was $8.5 \times 10^3$ Mg/year, much lower than the upstream inputs. For the middle section, the upstream TN input was $5.4 \times 10^4$ Mg/year, and the other TN input was $7.1 \times 10^3$ Mg/year. The largest tributary TN input was observed in the Weihe River, with a value of $3.6 \times 10^4$ Mg/year. For the Fenhe River and Yiluohe River, the corresponding TN input was low. The TN concentrations in the Fenhe River were the highest in the basin, due to the low water flows, the TN discharges from Fenhe into the Huanghe River was not significant, indicating the nutrient pollution in the Fenhe was not diffused.

### Table 1

<table>
<thead>
<tr>
<th>Yearly TN concentrations (2008-2012) in the Huanghe River and its main tributaries (average (min-max), mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008</td>
</tr>
<tr>
<td>2009</td>
</tr>
<tr>
<td>2010</td>
</tr>
<tr>
<td>2011</td>
</tr>
<tr>
<td>2012</td>
</tr>
</tbody>
</table>
Massive nutrient loads in the Huanghe River were returned to the terrestrial systems with the human water consumption (Fig. 5A and B). The total TN output flux with the water consumption from the Huanghe River was about 8.8 \times 10^4 Mg/year, much higher than the riverine TN loads being discharged into the estuary (Tong et al., 2015b). The TN output load with water consumption from the upper and lower section was about 3.2 \times 10^4 and 3.2 \times 10^4 Mg/year, respectively, higher than those from the middle section, with a value of 2.4 \times 10^4 Mg/year. The TN output load with the water consumption accounted for 58% of the total TN outputs, indicating the majority of the TN output loads has been restricted in the terrestrial systems.

For the upper section, the upstream input of TP (from river source section) was about 1.5 \times 10^2 Mg/year. For the middle section, the upstream input of TP was 1.6 \times 10^2 Mg/year, while the tributary input from the Weihe, Yiluohe and Fenhe rivers was about 1.0 \times 10^3, 1.3 \times 10^2 and 7.75 Mg/year, respectively, lower than the upstream inputs (Fig. 5B). The total TP output load with the water consumption from the Huanghe River was 2.6 \times 10^3 Mg/year, and the maximum flux was observed in the lower Huanghe River, with a value of 1.2 \times 10^3 Mg/year.

Studies of the Mississippi River have revealed TN and TP loads of 5.6 \times 10^1 and 3.3 \times 10^2 Mg/km²/year, respectively, with corresponding total discharges of 1.8 \times 10^6 and 1.1 \times 10^5 Mg/year (Turner et al., 2003a, 2003b). In the Red River, the TN and TP loads were 8.6 \times 10^1 and 3.3 \times 10^1 Mg/km²/year, with totals of 1.3 \times 10^3 and 5.1 \times 10^2 Mg/year, respectively (Quynh et al., 2005). In the Huanghe River, TN and TP discharges for the entire Yangtze Basin were 9.0 \times 10^1 and 1.1 \times 10^1 Mg/km²/year, respectively (Tong et al., 2015b). The total nutrient discharges of the Huanghe River were comparable to previously reported values in the literature (Turner et al., 2003a, 2003b; Quynh et al., 2005; Tong et al., 2015b). The annual nitrogen fluxes per square kilometer in the river basins were much higher in the lower Huanghe (Table S2). In the present study, the corresponding value for the lower Huanghe River was 2.63 Mg/km²/year, much higher than the nitrogen inputs in the upper streams and other large rivers. Although the nitrogen loads delivered in the lower Huanghe River were relatively high, the TP discharges were smaller than other rivers, which was consistent with the “high TN and low TP concentrations” characteristic in the Huanghe River.

4. Discussion

The Huanghe River Basin is located in a middle-latitude region with an arid and semiarid climate, and the water flow is largely affected by the human activities along the river (Yellow River Conservancy Commission of MWR, 2008–2012). Due to the dry climate, the water of the Huanghe River was increasingly being used to meet the water needs of the cities along the river (Fig. 2). With the human water consumption, large amount of nutrient load has been transported back to the terrestrial systems (Fig. 6). In this study, the nutrient output load with agricultural irrigation was calculated to be 6.5 \times 10^4 Mg/year for TN and 2.0 \times 10^3 Mg/year for TP, accounting for 74% and 77% of the total output loads (Fig. 6). It was reported that the riverine TN and TP discharges of the Huanghe River into the estuary were about 2 \times 10^4 and 1000 Mg/year (Tong et al., 2015b), respectively, lower than the output discharges with the water consumption. The majority of the nutrient loads in the Huanghe River have been restricted to the terrestrial systems. Therefore, the impact of nutrient pollution in the Huanghe River was not diffused into the coastal waters. In 2009, the sewage emission in the Huanghe River Basin was estimated to be 42 \times 10^8 Mg (Yellow River Conservancy Commission of MWR, 2008–2012). According to the sewage discharge standard in
China (GB18918-2002), the TN concentration in the sewages is limited to be 20 mg/L. Hence, less than $8.4 \times 10^4$ Mg of TN was emitted into the Huanghe River through sewage emissions in 2009, which was also lower than the TN output discharges with the water consumption (with a value of $8.7 \times 10^4$ Mg/year).

It has been widely reported that the majority of the rivers in the North China were severely polluted by nutrients, such as Haihe River, Huaihe River, Huanghe River etc. (Ministry of Environmental Protection, 2006–2012). However, the case of Huanghe River implied that the nutrient pollution in the polluted rivers may not be discharged into the coastal waters, but transported back to the terrestrial systems with the consumed water, especially in the dry-climate areas. Hence, the negative impacts of these polluted rivers to the offshore areas were lower than previously estimated. In

---

**Fig. 4.** Monthly variations of TN and TP concentrations in the Huanghe River mainstream and tributaries (mg/L).
contrast to the Huanghe River, the Yangtze River, which was located in the wet regions of China, presented a totally different characteristic of nutrient transport (Tong et al., 2015a). The nutrient output flux with the human water consumption in the Yangtze River was $8.8 \times 10^4$ Mg/year for TN and $5.7 \times 10^3$ Mg/year for TP, respectively, accounting for only 5% and 3% of the nutrient load discharged into the East China Sea (Tong et al., 2015a). This result indicated that in the Yangtze River Basin, the majority of the nutrient loads in the river, which were mostly emitted by anthropogenic activities, have been transported into the coastal systems, rather than restricted in the terrestrial systems. The massive riverine nutrient discharges of the Yangtze River have
resulted in frequent occurrences of HABs at the estuary (Dai et al., 2011; Li et al., 2014).

The massive water consumption in the Huanghe River region led to a significant decrease of riverine nutrient discharges into estuary, and finally alleviated the nutrient concentrations at the estuary. Under current condition, the riverine TN load flowing into the Bohai Sea was about $1.2 \times 10^{4}$ Mg/year. However, if the agricultural irrigation was prohibited in the Huanghe River basin, the riverine TN discharge would increase by $6.5 \times 10^{4}$ Mg/year, respectively, about 4 times the current discharge. Dissolved inorganic nitrogen (DIN) is the most important nitrogen species in the rivers. According to Zhang et al. (2010) and Meng et al. (2007) study, the DIN accounted for approximately 80% of the TN discharges in the Huanghe River (Meng et al., 2007; Zhang et al., 2010). Hence, additional $5.2 \times 10^{4}$ Mg/year of DIN would be discharged into the estuary if agricultural irrigation was prohibited. The direct consequence of increase in riverine DIN discharges is the significant increase of DIN concentrations at the estuary.

In the previous studies related to the hydrological process in the Huanghe River, WRS was believed to be the major factor in determining the nutrient transport from the human interference (Liu et al., 2012; Liu, 2015). Since 2002, WSR trail has been carried out by the Yellow River Conservancy Commission at the beginning of every flood season. The water flows during the WRS could account for about 30% of the annual riverine discharges ($4 \times 10^{8}$ m$^3$). However, compared with the human water consumption along the river ($-3 \times 10^{10}$ m$^3$), the water discharges caused by the WSR were relatively small. In Liu’s studies, during the regulation trial in 2009, which lasted for 20 days, total freshwater discharge were 25% of annual water discharge and dissolved nutrient fluxes represented 22–35% of annual nutrient fluxes (Liu, 2015). WSR would not only increase the nutrient inputs to the coastal ecosystem, but also result in nutrient imbalance, affecting phytoplankton production and composition (Liu et al., 2012; Liu, 2015). The changes of nutrient discharges to the estuary by the WSR were much smaller than the nutrient reductions caused by the human water consumption. Another major difference which should be noted between these activities is that the WSR is a sudden and quick process (usually lasts for 20 days in one year), while the water consumption is a long and durable process. It is difficult to assess which activity’s impact to the Huanghe River and its estuary is greater. However, the positive impacts of massive water consumption should not be neglected considering the huge amounts of water consumption and the significant decrease of riverine nutrient discharges at the estuary.

5. Conclusions

1. Generally, the nutrients in the Huanghe River reflected the characteristic of “high TN and low TP concentration”. The TP concentrations in the majority of the selected rivers were low, but TN concentrations were extremely high. For the majority of the selected rivers, a decrease in TN concentrations was observed from 2008 to 2012. However, TP concentrations remained relatively stable during the study period.

2. The total TN and TP output fluxes with the water consumption from the Huanghe River were about $8.8 \times 10^{4}$ and $2.6 \times 10^{4}$ Mg/year. The nutrient output loads with agricultural irrigation were calculated to be $6.5 \times 10^{4}$ Mg/year for TN and $2.0 \times 10^{4}$ Mg/year for TP. These account for 74% and 77% of the total output loads. Our data showed agricultural irrigation discharge is higher than the riverine discharges into the Bohai Sea.

3. It has been widely reported that the majority of the rivers in northern China were severely polluted by nutrients. However, this study showed that the nutrients discharges from the polluted rivers into the coastal waters would be overestimated, if the transportation back to the terrestrial systems with the consumed water was not considered. The massive water consumption in the Huanghe River region led to a significant decrease of riverine nutrient discharges into estuary, and eventually decreased the nutrient concentrations at the estuary.

Acknowledgments

This project was funded by the National Natural Science Foundation of China (41130535, 41501517, 41471403). Yindong Tong was also partly sponsored by the open fund of “Ministry of Education Laboratory for Earth Surface Processes, Peking University”. We also appreciate for the help from Miss Hu Xindi (Harvard T.H. Chan School of Public Health) in the polishing of the language.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.ecss.2015.12.006.

References

Tong, Y.D., Wang, X.J., Zhen, G.C., Chi, J., Liu, X.H., Lu, Y.R., Yao, R.H., Zhan, Y.,

Y. Tong et al. / Estuarine, Coastal and Shelf Science 169 (2016) 85–94