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Influences of natural and anthropogenic processes on the nitrogen and phosphorus fluxes of the Yangtze Estuary, China

Received: 10 November 2003 / Accepted: 6 June 2005 / Published online: 3 December 2005
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Abstract Nutrient flux to the sea through the estuary is important to the health of the sea. Combining natural processes with anthropogenic activities, we discuss the influence on the nitrogen and phosphorus fluxes to the Yangtze River basin, to the estuary and to the sea. The fluxes of dissolved inorganic nitrogen (DIN) and dissolved inorganic phosphorus (DIP) to the estuary through the river/estuary interface are obviously higher than those to the sea through the estuary/sea interface of the Yangtze estuary. The changes in nutrient fluxes through different interfaces are largely due to the estuarine hydrological and biogeochemical processes. Household, livestock and agricultural runoff are major sources of nitrogen from human activities, and household and livestock contribute to an increase in the anthropogenic phosphorus. The fluxes of DIN and DIP from economic activities account for about one-third of DIN and DIP fluxes to the sea through the Yangtze estuary.

Keywords Nutrient · Flux · Biogeochemistry · Economic activity · Yangtze estuary

Introduction

The Yangtze River (Changjiang River), one of the largest rivers in the world, carries substantive nutrients through its estuary (Fig. 1) from the Yangtze River

basin (Shen 2001). The concentrations and fluxes of dissolved inorganic nitrogen (DIN) and dissolved inorganic phosphorus (DIP) have substantially increased in the Yangtze River and its estuary in the last 20 years (Zhang et al. 1999; Shen 2001). The additional inputs of nutrients account for the considerable eutrophication and frequent algae booms in this estuary and its adjoining East China Sea in recent years.

Many works concerning the nutrients fluxes in the Yangtze estuary have been done. Yan et al. (2001) and Shen et al. (2001) suggested that utilization of nitrogen fertilizer and nitrogen precipitation should contribute most of the export fluxes of inorganic nitrogen of the Yangtze River (Yan et al. 2001). In the work of Duan et al. (2000), the increasing fluxes of nitrogen and phosphorus at the tidal limit (TL) of the Yangtze estuary were attributed partly to the application of chemical fertilizer in the basin (Zhang et al. 1994). The linkage between the fertilizer utilization and nitrogen inputs to surface waters has been poorly documented (Hobbie 2000). Nevertheless, little work has been done on combining natural processes with anthropogenic activities (Talaue-McManus et al. 2001; Smith et al. 2003) influencing nutrient fluxes in the Yangtze estuary. In this paper, we found that the changes of nutrient fluxes through different interfaces are largely due to the estuarine processes, and the economic activities could contribute much to DIN and DIP fluxes to the sea through the Yangtze estuary.

Materials and methods

The DIP and DIN fluxes through some key interfaces (Fig. 1) were estimated by the method of nutrient budget described by Gordon et al. (1996) based on the data observed in the Yangtze estuary in February and in August 1999 (some information on our nutrient budget is available at <http://data.ecology.su.se/MNODE>). The hydrographic and nutrient data at the TL of the Yangtze estuary were measured at Datong gauging station.

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Fig. 1 A sketch map of the Yangtze estuary. Datong is a gauging station between the Yangtze River and the Yangtze estuary. *TL* tidal limit (looked as river/estuary boundary), *TCL* tidal current limit, *SL* saltwater intrusion limit, *FEL* transitional limit of flood and ebb predominant currents (often located in river mouth), *SDL* lower limit of sediment dispersion (usually overlap plume front)

Anthropogenic inputs of nitrogen and phosphorus to the Yangtze River basin and its estuary were estimated using the land–ocean interactions in the coastal zones project (LOICZ) method as described by Talaue-McManus (1999). Firstly, the relevant economic activities (such as sewage discharge, detergent application, livestock breeding, fertilizing, etc.) and their discharge coefficients of nitrogen and phosphorus were determined; secondly, each activity level was measured; finally, discharges of total nitrogen (TN) and total phosphorus (TP) were estimated as the products of discharge coefficients and activity levels. The data of activity level were derived from National Bureau of Statistics of China (2000) and represented 11 provinces or municipalities in the Yangtze drainage basin. The anthropogenic N and P inputs were calculated as the sum of N and P inputs from each economic activity.

Results

DIN and DIP fluxes through different interfaces of the Yangtze estuary

Estuaries, located at the boundary between river and sea, are the sites of significant interactions between land and ocean. In the Yangtze estuary, there are several interfaces (Fig. 1) important to the material fluxes. The Datong gauging station represents the TL in the Yangtze estuary in the dry season and is usually viewed as the river/estuary interface (Shen et al. 2000). The transitional limit of flood and ebb predominant currents (FEL) usually lies in the river mouth of the Yangtze estuary. In most cases, the river mouth is regarded as an interface from the river to the sea. The lower limit of sediment dispersion into the sea (SDL) is often located in front of the submarine delta, which could be more significantly regarded as estuary/sea interface for nutrient exports.

The fluxes of DIN and DIP through some key interfaces were estimated from our nutrient budgets in the Yangtze estuary in dry and flood seasons based on the data observed in 1999. As shown in Table 1, the DIN and DIP fluxes were four to six times higher in flood season than those in dry season due to the large seasonal variation of river discharges. In addition, the fluxes through different interfaces were significantly different and increased from the freshwater end-member to the saltwater end-member in the estuary. Table 1 also shows DIN and DIP fluxes through the river mouth, which were estimated by a flow-weighted mean method to be 1.63×10^{11} and 2.33×10^9 mol/year, respectively.

Sedimentation fluxes of nitrogen and phosphorus in the Yangtze estuary

The Yangtze River carries abundant water and suspended sediments to the estuary, and the suspended sediments would settle at the mixing zone. For example, the sediment filling the Northern Branch (Fig. 1) of the Yangtze estuary amounts to 28.3 million tons/year (Zhang and Cao 1998). The mouth-bar area is the core of the turbidity maximum in the Yangtze estuary, where the sedimentation rate is approximately 3.05 million tons/year, while there are some evidences of slight

Table 1 DIP and DIN fluxes at some key interfaces in the Yangtze estuary in 1999

Interfaces	Dry season (10^6 mol day ⁻¹)			Flood season (10^6 mol day ⁻¹)		
	SL	FEL	SDL	SL	FEL	SDL
DIP	0.5	1.01	1.05	3.3	8.7	4.5
DIN	7.5	102.2	185.6	485	594.1	881.0

Note: *SL* saltwater intrusion limit, *FEL* transitional limit of flood and ebb predominant currents usually located in river mouth, *SDL* lower limit of sediment dispersion

scouring in the riverbed of the South Branch (Fig. 1; Shen 2001).

Particulate phosphorus is the major species of phosphorus, accounting for more than 95% of the total phosphorus in the water (Duan et al. 2000). Similar speciation distribution has been reported for other rivers in the world (Howarth et al. 1996). Particulate phosphorus is retained in the sediments in the mouth-bar area with the sedimentation. The sedimentation rate of the nutrient could be estimated as the sedimentation rate of sediment multiplied by the nutrient concentration in surface sediments (Yanagi et al. 1993; Jickells et al. 2000). According to the concentrations of TP and TN (Liu et al. 2000) in the surface sediments of the Jiuduansha wetland (Fig. 1), the sedimentation fluxes are 2.11×10^7 and 6.1×10^6 kg year⁻¹, respectively. The nutrient inputs to the estuary were estimated as the concentrations of TN and TP (Duan et al. 2000) multiplying yearly mean runoff ($29,500$ m³/s) at the TL of the Yangtze estuary. The results showed that the sedimentation fluxes of TP and TN in the mouth-bar area accounted for 17.5 and 0.35% of their inputs to the Yangtze estuary through the TL, respectively.

Anthropogenic N and P fluxes to the sea through the Yangtze estuary

The N and P inputs to the Yangtze River basin from each economic activity were estimated using the discharge coefficient multiplied by the level of each activity (Table 2). Since 1959, anthropogenic N inputs to the Yangtze River basin have doubled, while anthropogenic

Fig. 2 Long-term changes of anthropogenic inputs of nitrogen and phosphorus to the Yangtze River basin

P inputs have increased but not as much (Fig. 2). Assuming ratios of N and P in organic waste materials recommended by LOICZ: DIN/TN=0.38, DIP/TP=0.5 (San Diego-McGlone et al. 2000), the anthropogenic inputs of DIN and DIP to the basin could be estimated as 7.7×10^{10} and 1.44×10^{10} mol/year, respectively, in 1999 (Fig. 3).

Assuming that 25% of anthropogenic DIN and DIP inputs to the basin were discharged into the estuary (Smith et al. 2000) and they would be redistributed between particles and water in the estuary, the anthropogenic DIN and DIP exports to the sea must not equal

Table 2 Estimations of nitrogen and phosphorus inputs to the Yangtze River basin from economic activities in 1999

Economic activities	Discharge coefficients ^a		Activities levels ^b	TN inputs (10 ⁷ kg year ⁻¹)	TP inputs (10 ⁶ kg year ⁻¹)
	N	P			
Household activities (kg person ⁻¹ year ⁻¹)					
Solid waste	1.86	0.37	5.17×10 ⁸ person	96.2	191
Domestic sewage	4	1	5.17×10 ⁸ person	207	517
Detergent	—	1	5.17×10 ⁸ person	—	517
Urban runoff (mg L ⁻¹)	1.9	0.4	1.1 m year ⁻¹ (precipitation) 21,525 km ² (urban area)	3.44	7.23
Livestock (kg ⁻¹ head ⁻¹ year ⁻¹)					
Cattle	43.8	11.3	4.94×10 ⁷ head	216	558
Horses	95.3	16.4	2.73×10 ⁶ head	26	44.8
Sheep	4	21.5	5.18×10 ⁷ head	20.7	1110
Piggery	7.3	2.3	2.15×10 ⁸ head	157	494
Aquaculture (kg t ⁻¹ year ⁻¹)					
Prawn	5.2	4.7	5.10×10 ⁵ t	0.27	2.39
Milkfish	2.9	2.6	8.40×10 ⁶ t	2.43	21.8
Non-point agricultural runoff (kg t ⁻¹ year ⁻¹)	1.68	0.04	2.40×10 ⁹ t	403	96
Total inputs				1,130	3,570

^aReferring to LOICZ Web Pages: <ftp://data.ecology.su.se/wasteload-4.xls>

^bThe activities levels in 1999 from National Bureau of Statistics of China (2000). Urban runoff was estimated as mean precipitation multiplied by urban area. Non-point agricultural runoff was estimated from the data of soil erosion

Fig. 3 The composition of anthropogenic inputs of DIN and DIP to the Yangtze River basin in 1999

the inputs to the estuary. According to the observation data of two surveys in 1999, DIP accounted for 5~7.5% of TP and DIN accounted for 60~80% of TN in the Yangtze estuary. Based on this assumption and observation data, the anthropogenic DIN and DIP fluxes to the sea through the Yangtze estuary (here river mouth was used as an interface between estuary and sea) were estimated as 5.38×10^{10} (calculated as 70% of TN) and 8.64×10^8 mol/year (calculated as 6% of TP), respectively. The anthropogenic DIN and DIP fluxes from the Yangtze River basin accounted for 32.9 and 37.1% of their fluxes exporting to sea, respectively.

Discussion

Natural processes

Hydrographic processes

Hydrographic processes are the most important natural processes influencing nutrient fluxes in the Yangtze River basin. The river runoff had a small variation from 1956 to 1988 and had a tendency to increase from 1989 to 2000 (Shen 2001), which could contribute to the similar variation of annual fluxes of nitrate and DIN through the tidal limit of the estuary from the Yangtze River basin. These had only a slight increase from 1950s to 1970s, while their values have increased significantly in the next 20 years (Table 3). Highest flux of phosphate was recorded in the 1960s (Table 3). However, P fluxes have had a slight tendency to increase since 1970s. Liu

Table 3 Long-term variation of nutrient flux to the Yangtze estuary through the river/estuary interface

Period	PO_4^{3-} (10^8 mol year $^{-1}$)	NO_3^- (10^{10} mol year $^{-1}$)	DIN (10^{10} mol year $^{-1}$)
1959	8.47	1.44	1.45
1960s	2.73	1.13	1.73
1970s	1.1	1.22	1.86
1980s	2.2	4.47	5.31
1990s	2.42 ^a –3.39 ^b	8.19	10.2 ^c

^aFu et al. (2002)

^bEstimated roughly from the figure data of Zhang et al. (1999)

^cDerived from nitrate fluxes provided the ratio between nitrate and DIN is 80% (73.9–95.5%, Fu et al. 2002)

and Shen (2001) reported that the concentrations of phosphate in some months (e.g. October) in 1959, 1964 and 1965 were several tens of times higher than normal, which contributed to obviously high values of estimated fluxes. Furthermore, we thought it also depended on the hydrographic conditions. For example, the highest sediment transport rate at Datong since 1959 occurred in 1964 (about 680 million tons), and the runoff was 14% higher than the long-term mean runoff. Data at Hankou and Yichang, two gauging stations in the middle and upper reaches of the Yangtze River, showed similar patterns. The yearly mean concentration of sediment at Datong was 0.60 kg/m^3 in the 1960s (up to 0.89 kg/m^3 from July to September), while only 0.27 kg/m^3 in the 1990s.

Besides the annual variation, the nutrient fluxes had seasonal variation and monthly variation (Liu and Shen 2001; Fu and Shen 2002b; Liu et al. 2002). For example, nitrogen and phosphorus fluxes in the flood season were usually much higher than those in the dry season (Table 1), which were largely attributed to the variation of the river discharges.

Atmospheric deposition

Atmospheric deposition, including wet (e.g. rainfall) and dry depositions, was another important natural process influencing the nutrient flux of the Yangtze River. Most runoff of the Yangtze River came directly from rainfall, which accounted for 70~80% of the runoff yearly; about 20~30% of the runoff was supplied by groundwater (Shen et al. 2001). The water discharges through the Datong station correlated well with the rainfall ($r=0.817$, $n=144$). Floods, often occurring in the seasons of excessive rainfall, would result in heavy soil erosion and nutrient leaching. Moreover, the rainfall directly carried the atmospheric nutrient into the estuary. As far as the Yangtze estuary was concerned, the local rainfall contributed to 0.74% of the DIN influxes in dry season and 0.64% of the DIN influxes in flood season in 1999 based on our nutrient budget. But for the whole Yangtze River basin, the rainfall contributed much to the nutrient fluxes, especially for DIN (Shen

et al. 2001). The nitrate fluxes to the estuary from the Yangtze River basin, correlated well with the mean rainfall ($r=0.80$; $n=144$), increasing with increasing rainfall in the basin.

Compared to nitrogen, wet deposition often played a minor role in the process of P deposition. Phosphorus in the atmosphere, often in particulate form, was derived from the floating dust. There was a less dissolved phosphate in the raindrops in the clouds. Though dry deposition generally contributed little to the nutrient deposition, e.g. nitrogen deposition, it could also be very important in cases of heavy particle deposition (Pryor and Barthelmie 2000). Recently, storms accompanied by blowing sand and dust have occurred frequently in North China. In the last 10 days of March 2002, some cities including Beijing suffered from the biggest dust event of the last decade, which also had a great influence on the Yangtze River basin. A shower of mud also appeared in the Yangtze Delta. If such weather occurred frequently in the Yangtze River basin, atmospheric nutrient deposition would be enhanced and possibly become another important source of nutrient (e.g. phosphorus) entering into the lakes, rivers and estuaries of the basin.

Estuarine processes

Estuarine processes, e.g. physical mixing, sediment absorption/desorption, chemical exchange and biological transfer, etc., can influence the nutrient exports (Schubel and Kennedy 1984). The turbidity maximum, estuarine plume front and intertidal zone are the zones which are most important to these processes (O'Donnell 1993; Shen 2001).

In the turbidity maximum of an estuary, abundant suspended sediments coming from river and sea were captured by the saltwater intrusion and density confluence (Li and Zhang 1998; Shen and Pan 2001; see Fig. 4). Thus, the absorption/desorption between sediment and water could influence the behaviour of nitrogen and phosphorus in the estuary. Froelich (1988) reported that the dissolved phosphate in natural rivers and estuaries were controlled by the buffering mechanism of suspended sediments.

The intertidal zone provides available space for sedimentation of the suspended particles (Fig. 1), where nutrient elements such as C, N and P could be effectively stored. In fact, such storage enhances the sedimentation fluxes of particulate nutrients and decreases their export to sea. In addition, nutrients interact in the complicated biogeochemical processes in the intertidal belts. For example, the intertidal zones could be the important place to denitrify and to fix nitrogen. Our previous work showed that nitrogen fixation is strong in the mouth-bar area (Shen 2001), and which could be contributed by the wetlands in the intertidal zones.

The estuarine front had a significant impact on the nutrient fluxes of key interfaces of the estuary, e.g. river/estuary boundary (Morris et al. 1995). Luxury nutrients were detected in the plume (Fig. 4). The photic depth increased with the decreasing turbidity, favouring primary production, an important process in biogeochemical cycles (Hu et al. 1995; Gong et al. 1996). The bottom water under the front in the Yangtze estuary exhibited low levels of dissolved oxygen, less than 2 mg/L (saturation is less than 30%, Tian et al. 1991), which could be attributed to the decomposition of sedimenting organisms. Simultaneously, nutrients were also released and recycled to the surface water with the circulation or upwelling and which sustained the primary production (Huang and Ji 1994; Fu and Shen 2002a).

Anthropogenic activities

In the past 40 years, the population and its density in the Yangtze River basin had doubled so that the development of cities and industry were enhanced. Increasing anthropogenic activities would certainly enhance the loads of nitrogen and phosphorus to the soils, rivers and lakes in the Yangtze River basin. In 1999, household, livestock and agricultural activities contributed to most of the anthropogenic nitrogen inputs, accounting for 26.8, 37.1 and 35.6%, respectively. Household and livestock activities contributed to most of the anthropogenic phosphorus inputs, accounting for about one-third and two-thirds, respectively (Fig. 5). Economic activities contributed about 37.1% of DIP and 32.9% of

Fig. 4 A conceptual model of estuarine processes (revised from Jickells 1998)

Fig. 5 The percentage distribution of DIN and DIP fluxes from economic activities

DIN fluxes to the sea from the Yangtze River basin. Similar results are observed in the watershed of Ling-ayen Bay by Talaue-McManus et al. (1999).

Conclusions

Hydrographic factors combined with atmospheric deposition, and estuarine processes contributed to temporal variation and spatial variation of DIN and DIP fluxes in the Yangtze estuary, respectively. Household, livestock and agriculture activities were the main sources of anthropogenic nitrogen; household and livestock activities were the main sources of anthropogenic phosphorus. The substantially increasing nitrogen fluxes and slightly increasing phosphorus fluxes to the Yangtze estuary through the river/estuary interface could be greatly attributed to the anthropogenic activities. The anthropogenic DIP and DIN fluxes from the Yangtze River basin accounted for one-third of the total dissolved inorganic fluxes to the sea. Consequently, enhanced economic activities could threaten the health of the aquatic environment of the Yangtze River basin and its adjacent coast.

Acknowledgements The authors appreciated the assistance of colleagues from the Monitoring Center of East China Sea for their analytical and field work. This study was supported by the National Natural Science Foundation of China (40231017), and partially by Chinese Academy of Sciences (KZCX1-SW-12-II-32). The authors also thank two anonymous reviewers for their helpful review comments.

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