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Nutrient budgets for large Chinese estuaries and embayment

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Abstract

Nutrient concentrations among the Chinese rivers and bays vary 10–75 fold depending on nutrient elements. The silicic acid levels in South China rivers are higher than those from North China rivers and the yields of dissolved silicate increased from the north to the south of China, indicating the effect of climate on weathering. The nutrient levels in Chinese rivers are higher than those from the large and less-disturbed world rivers such as Amazon and Zaire, but comparable to the values for European and North American polluted and eutrophic rivers like the Loire and Po. This may be ascribed to both of extensive leaching and influences from agricultural and domestic activities over the drainage basins of Chinese rivers. DIN:PO_4^{3-} ratios in most of Chinese rivers and bays are higher (up to 2800) than the other rivers in the world. The atomic ratios of DIN to PO_4^{3-} in the major Chinese rivers and embayment decrease in exponential trend with increase in the atomic ratios of PO_4^{3-} to $Si(OH)_4$, indicating that primary production in coastal environments changes with the nutrients transport when the urbanization develops to a certain extent, and the potential limited nutrient elements can be changed from phosphorus to nitrogen limitation, which can modify aquatic food webs and then the ocean ecosystem.

A simple steady-state mass-balance box model was employed. The output shows that the estuaries and embayment behave as a sink or source of nutrients. For the major Chinese estuaries, both residual and mixing flow transport nutrients off the estuaries, and nutrient transport fluxes in summer is 3–4 fold that in winter except comparable for NH_4^+. These fluxes are 1.0–1.7 fold that estimated by timing riverine nutrient concentrations and freshwater discharge. For the major Chinese embayment, nutrient elements are transported to China Seas except PO_4^{3-} and $Si(OH)_4$ in Sanggou Bay and Jiaozhou Bay. Seasonally, nutrients transport fluxes off the bays in the summer are 2.2–7.0 fold that in the winter. In the embayment, the exchange flow dominated the water budgets, resulting in average system salinity approaching the China seas salinity where river discharge is limited. The major Chinese estuaries and embayment

transport 1.0–3.1% of nitrogen, 0.2–0.5% of phosphorus and 3% of silicon necessary for phytoplankton growth for the China Seas. This demonstrates regenerated nutrients in water column and sediments and nutrients transport fluxes between the China Seas and open ocean play an important role for phytoplankton growth. Atmospheric deposition may be another important source of nutrients for the China Seas.

1 Introduction

The coastal ocean represents a surface area of only 10% of the global ocean surface, but accounts for ~25% of global ocean primary production and 80% of global organic carbon burial (Berner, 1982; Smith and Hollibaugh, 1993). Drastic increases in delivery of river-borne nutrients owing to land-use transformation and anthropogenic emission are known to result in eutrophication, hence to modify aquatic food webs and more severe hypoxic events in coastal marine environments (Humborg et al., 1997; Ragueneau et al., 2002; Pahlow and Riebesell, 2000; Turner and Rabalais, 1994; Turner, 2002). High phytoplanktonic productivity at the boundary between terrestrial and marine systems, make the estuary vulnerable to global change in relation to human activities (Valeila et al., 1997). The degree to which estuaries modify the transport of nutrients from land to the ocean can be an important factor affecting the sustainability of near-shore ecosystems, and perhaps over long periods of time, the ocean itself (Nixon et al., 1986).

Riverine transport from China represents ca. 5–10% of total surface runoff and 15–20% of the continental sediment to the global ocean (Table 1). The drainage area of China covers a region of 5–55° latitude in East Asia, with climate changing from tropical to cold temperate. Under tectonic control, most of the major Chinese rivers originate in the western part of the country and flow eastward, emptying into the coast of the Northwest Pacific Ocean. This provides a natural place to deal with the climate influence on the weathering and erosion over the country from the north to the south. The estuaries and embayment along the coast of China mark human disturbance, prominent impacts on the coastal environment and ecosystem have been observed.

The present work summarizes data from biogeochemical surveys of the major Chinese estuaries and embayment, including Changjiang (Yangtze River), Zhujiang (Pearl River), Huanghe (Yellow River), Jiaozhou Bay, etc. So as to understand how the coastal zone of China affects nutrient fluxes to NW Pacific through biogeochemical processes and its relationship to environmental change, gain a better understanding of the cycles of plant nutrient species (N, P, Si).

2 Materials and methods

The present study summarizes data from biogeochemical surveys of a number of large Chinese estuaries, embayment, and adjacent shelf regions (Fig. 1). Riverine and estuarine systems in China include, from the north to the south, the Yalujiang, Liaohe, Shuangtaizihe, Luanhe, Huanghe (Yellow River), Daguhe, Huaihe, Changjiang (Yangtze River), Qiantangjiang, Yongjiang, Jiaojiang, Oujiang, Minjiang, Jiulongjiang, and Zhujiang (Pearl River). Nutrient budgets were focused on Yalujiang, Daliaohe, Huanghe, Changjiang, Minjiang, Jiulongjiang, and Zhujiang. The other Chinese rivers and Han, Keum and Yeongsan from Korea side were included to understand nutrient transport fluxes to the China seas. Table 1 tabulates the drainage areas and long-term water and sediment loads of the major rivers empty into the China Seas. The data for nutrients of the rivers used in this study are basically from scientific investigations. The data were obtained from: the Yalujiang, three cruises in August 1992 and 1994 and May 1996; the Daliaohe, two cruises in May and August 1989 and 1992; the Shuangtaizihe, one cruise in August 1993; the Luanhe, one cruise in August 1991; the Huanghe, four expeditions between 1984 and 1986 and monthly cruises in 2001; the Changjiang, multi-year observations at Nantong since 1997; the Jiaojiang, one cruise in August 1994; the Zhujiang, two cruises in August 2001 and January 2000, and the references for the other rivers.

Embayment along the coast of China includes Taizhou Bay, Sanggou Bay, Hangzhou

Bay, Xiangshan Bay, Sanmen Bay, Jiaozhou Bay, Daya Bay, and Dapeng Bay. And the adjacent shelf regions, that is the Bohai, Yellow Sea, East China Sea and South China Sea. The data sets for the Bohai were obtained from 1998–2001, from 1997–1998 for the Yellow Sea (KORDI, 1998; Liu et al., 2003b), from 1999–2003 for the East China Sea (Zhang et al., 2007b) and the reference for the South China Sea (Zhang and Su, 2006).

Rainwater and aerosol samples were collected in the Changdao at the tip of Shandong Peninsula to the south of Bohai, an island located in Bohai Strait in 1995 (Zhang et al., 2004), from Fulongshan in Qingdao, the west of the Yellow Sea during 2004–2005, Qianliyan Island in the northwest of the Yellow Sea during 2000–2005 and the Shengsi Archipelago in the western East China Sea during 2000–2004 (Bi, 2006; Zhang et al., 2007a).

Water samples were taken on board with Niskin sampler in the China Seas and 2 l acid-cleaned polyethylene bottles attached to the end of a fiber-glass reinforced plastic pole in rivers. After collection samples were filtered immediately through acid cleaned 0.45 µm pore size acetate cellulose filters in a clean plastic tent, and the filtrates were poisoned by saturated $HgCl_2$. All the nutrient data were measured by spectrophotometric method with precision of <3% (Liu et al., 2003a; Zhang et al., 2007b).

3 Biogeochemical modeling approach

Constructing nutrient budgets are essential tools to examine the relative importance of external nutrient inputs versus physical transports and internal biogeochemical processes (Savchuk, 2005), and to assess nutrient retention including denitrification (Gordon et al., 1996; Chen and Wang, 1999; Webster et al., 2000; Hung and Kuo, 2002). The LOICZ guidelines for constructing such budgets concentrate on the simplest case where an estuary or embayment is treated as a single box which is well-mixed both vertically and horizontally and at steady-state (Gordon et al., 1996). Further description and application of the LOICZ approach can be found at http://nest.su.se, Webster et al. (2000), Hung and Kuo (2002), Hung and Hung (2003), de Madron et al. (2003), Souza et al. (2003), and Simpson and Rippeth (1998). Budget for the Yellow Sea (Chung et al., 2000) and Jiulong River estuary (Hong and Cho, 2000), and Pearl River Delta (Cheung et al., 2000) were the product of the LOICZ guidelines.

The LOICZ biogeochemical budget model is a steady-state box model from which nutrient budgets can be constructed from nonconservative distributions of nutrient and water budgets, which in turn are constrained from the salt balance under a steady-state assumption. It is assumed that either water volume remains constant or that the change of water volume through time is known, then net water outflow from the system can be estimated by difference (Gordon et al., 1996). The seawater outflow delivers salt advectively, and the change in salinity of the system results in inward mixing of salt. The salinity of the outflowing seawater is taken to be the average of the system of interest (system 1: designated by subscript syst) and adjacent systems (system 2: designated by subscript ocn) salinity.

The flux of phosphate and dissolved silicate are assumed to be an approximation of net metabolism, because phosphorus and silica are not involved in gas-phase reactions. Nitrogen and carbon both have other major pathways such as denitrification, nitrogen fixation, and gas exchange across the air-sea interface, and calcification. However, the biogeochemical pathways of carbon and nitrogen can be approximated from phosphate and silicate flux and C-N-P-Si stoichiometric ratios of reactive particles coupled with measured flux for carbon and nitrogen. Briefly, under steady-state condition, the water mass balance can be estimated by:

$$V_R = V_{\text{in}} - V_{\text{out}} = V_Q + V_P - V_E + V_G + V_W \tag{1}$$

Where V_R is denoted as residual flow, which is equal to the net input of freshwater; V_Q, V_P, V_E, V_G, V_W, V_{in}, V_{out} are mean flow rate of river water, precipitation, evaporation, groundwater, waste water, advective inflow and advective outflow of water from system 1. V_G is relatively small and negligible in this calculation because over-extraction of groundwater is a feature of the area. V_W is also negligible as no data are available.

Taking salinity as 0 psu for fresh water (V_Q, V_P and V_E), the salt balance in system 1, therefore, can be derived:

$$S_R V_R = V_X (S_{ocn} - S_{syst}) \quad (2)$$

Where S_R=(S_{syst}+S_{ocn})/2 and S_{syst} and S_{ocn} are mean salinity in system 1 and system 2; V_X is water exchange flow or mixing flow between system of interest and adjacent system. The total water exchange time (τ) of the system of interest can be estimated from the ratio $V_S/(V_R+V_X)$, where V_S is the volume of system 1.

Nutrient budgets are estimated from water budgets and nutrient concentrations. Non-conservative fluxes of phosphate (Δ DIP) can be derived from the following equations:

$$\Delta \mathrm{DIP} = \sum \mathrm{DIP}_{influx} - \sum \mathrm{DIP}_{outflux} = V_Q \mathrm{DIP}_Q + V_P \mathrm{DIP}_P - V_R \mathrm{DIP}_R - V_X \mathrm{DIP}_X \quad (3)$$

where DIP_Q, DIP_{syst}, DIP_{ocn}, DIP_P, DIP_R and DIP_X denote mean phosphate concentration in the river runoff, system 1, system 2, precipitation, residual-flow boundary (DIP_R=(DIP_{syst}+DIP_{ocn})/2) and mixing flow (DIP_X=DIP_{syst}−DIP_{ocn}). A positive non-conservative flux of nutrient components (e.g. Δ DIP) indicates that the system of interest is a sink, and a negative non-conservative flux of nutrients indicates that the system of interest is a source. The other nutrient element flux equations, such as dissolved silicate (DSi) and NO_3^-, are similar to those in DIP in budget derivation.

4 Results and discussion

4.1 Nutrients in the rivers and embayment

4.1.1 Chinese rivers and embayment

Differences in nutrient levels among the Chinese rivers are shown in Table 2a. Variations of nutrient concentrations were 30–60 fold for NH_4^+ and PO_4^{3-}, and 8 fold for

NO_3^- and $Si(OH)_4$. High levels of NO_3^- were observed from the Huanghe, Yalujiang, Daliaohe and Shuangtaizihe; high levels of NH_4^+ were observed from the Huanghe, Zhujiang, Jiulongjiang and Daliaohe; while Huaihe, Yongjiang and Jiaojiang surpasses the others in PO_4^{3-}; and the Jiulongjiang, Minjiang and Yongjiang surpasses the others in dissolved silicate; other rivers (Luanhe, Qiantangjiang and Oujiang) show intermediate values. Evidently, the dissolved silicate levels in South China rivers (e.g. Minjiang) are higher than those from North China rivers (e.g. Daliaohe and Huaihe). This can be related to the effect of climate on weathering, which results in an extensive leaching of silica from drainage areas, followed by higher riverine concentrations in subtropical zones relative to temperate zones. Changjiang and Zhujiang represent more than 80% of total riverine nutrient transport fluxes to the China Seas except PO_4^{3-} in winter, NO_2^- in both winter and summer. Nutrient transport fluxes in summer were higher than those in winter (Table 2b).

Comparison with those in unpolluted rivers, the nutrient levels in Chinese rivers are higher than those from the large and less-disturbed world rivers (Meybeck, 1982) such as Amazon and Zaire, etc., but comparable to the values for European and North American polluted and eutrophic rivers (Liu et al., 2003a) like the Loire, Po, Rhine, Seine etc. This may be ascribed to both of extensive leaching and influences from agricultural and domestic activities over the drainage basins of Chinese rivers. As the ratios of nitrogen to phosphorus fertilizers used in China may be up to 10–20 or even more, and nitrogen is much easier to be leached away from drainage basin than phosphorus. Therefore, N:P ratios in most of Chinese rivers are higher (up to 2800) than the other rivers in the world (Billen and Garnier, 2007), for example N:P ratio is 24 in Amazon River, 13–38 in Po River, Rhine River and Seine River.

The areal yields of nutrients can be estimated by the product of nutrient concentrations with the river discharge divided by the drainage area to illustrate the contribution of nutrients from each drainage areas. Dissolved silicate is mainly delivered via weathering, which is restrained by the interaction of tectonic conditions, rock/soil and climate. The areal yields of dissolved silicate varied from 0.8 to 1270 $mol\,km^{-2}\,day^{-1}$ in large

Chinese rivers. The yields of dissolved silicate in the Jiulongjiang, Minjiang, Oujiang, Zhujiang, Qiantangjiang and Changjiang in the south China were higher than in the Yalujiang, Shuangtaizihe, Daliaohe etc. in the north China (Table 2c). The yields of dissolved silicate increased from the north to the south of China. This can be related to that chemical weathering is much stronger in the hot and wet south than in the cool and dry north watersheds. The increases of rainfall and temperature lead to development of vegetation, enhancing chemical/biological weathering relative to physical denudation (Qu et al., 1993). As a consequence of climate influence on weathering, rivers in the south often have higher values of dissolved silicate than those in the north of China.

The nitrate yields in the Yalujiang, Shuangtaizihe were higher than Qiantangjiang, Minjiang, Zhujiang, Jiulongjiang, Oujiang, Changjiang etc. While the ammonium yields in Jiulongjiang is higher than Minjiang, Zhujiang, Changjiang, Daliaohe; the phosphate yields in Jiulongjiang, Qiantanjiang, Minjiang, Zhujiang, Yongjiang were higher than in Jiaojiang, Haihe and the others (Table 2c). Higher areal yields of dissolved nitrogen and phosphorus in some rivers may indicate that where there are more intensive domestic and agriculture activities and the effects of soil type and agriculture on nutrient levels.

Concentrations of nutrients in major Chinese bays are shown in Table 3. Variations of nutrient concentrations were 55–75 fold for NO_3^-, PO_4^{3-} and $Si(OH)_4$ and ~20 fold for NH_4^+ and NO_2^-. High concentrations of NO_3^-, $Si(OH)_4$ and PO_4^{3-} were observed from Hangzhou Bay, followed by Xiangshan Bay, Sanmen Bay, Taizhou Bay, then Jiaozhou Bay and the other bays; while high concentrations of NH_4^+ were observed in Jiaozhou Bay, followed by Sanggou Bay, then the others. This can be related to the effects of riverine transport, tidal conditions, and biological activities. Nutrient concentrations in Chinese bays are lower compared to Chinese rivers.

The atomic ratios of DIN: PO_4^{3-} were 15–390, indicating that P may be the potential limiting element for phytoplankton growth; the atomic ratios of $Si(OH)_4$:DIN were 0.2–6.7 (Table 3), demonstrating that ratios were higher in Daya Bay and Dapeng Bay (0.6–6.7) although freshwater discharge into Dapeng Bay is quite limited, this is consistent to the above statement: the dissolved silicate levels in South China rivers are higher than those from North China rivers. The atomic ratios of $Si(OH)_4$:DIN were 0.7–1.7 in Hangzhou Bay, Xiangshan Bay and Sanmen Bay, while quite lower (<0.5) in the other bays. The nutrient compositions indicate that P is the potential limiting element for primary production in major Chinese bays, and Si too in Jiaozhou Bay.

As the increase in nitrogen and phosphorus are ascribed to anthropogenic activities, especially agricultural and domestic activities, and nitrogen is much easier to be leached away from drainage basin than phosphorus. In general, phosphate concentrations are higher in the rivers emptying through urban areas due to the effects of domestic wastewater discharge, for example, the concentrations of PO_4^{3-} in wastewater from sewage treatment plants in Qingdao can be more than 80 µM (Liu et al., 2005). While dissolved silicate is mainly delivered via weathering. Therefore, the atomic ratios of PO_4^{3-} to $Si(OH)_4$ can be used to indicate the nutrient contributions from urbanization extent relative to weathering function of the drainage basin. When nutrient elements from the major Chinese rivers and embayment are put together, the atomic ratios of DIN to PO_4^{3-} decrease in exponential trend with increase in the atomic ratios of PO_4^{3-} to $Si(OH)_4$ at $p=0.01$ (Fig. 2). These relationships among the nutrient elements may indicate that primary production in coastal environments changes with the riverine nutrients transport when the urbanization develops to a certain extent, and the potential limited nutrient elements can be changed from phosphorus limitation to nitrogen limitation, which can modify aquatic food webs and then the ocean ecosystem.

4.1.2 Korean rivers empty into the Yellow Sea

The Korean rivers draining into the Yellow Sea has not received sufficient attention and limited data set is available. As the South Korea is relatively small country (99 585 km^2) with rugged terrain leaves only less than 30% of the land is habitable or cultivable, with a large population (48.4×10^6), the land usage is extremely demanding and nutrient load is relatively great among the world rivers. And most agricultural and population centers are concentrated in the lower reaches of the rivers flowing into the Yellow Sea. The concentrations of NH_4^+ and PO_4^{3-} are higher than the Chinese rivers, NO_3^- and

$Si(OH)_4$ are comparable to the Chinese rivers (Table 2a). Regional climate – summer wet monsoon, typhoon in the autumn, dry winter-spring, and uneven rainfall – causes heavy soil erosion of the watershed. Therefore, the concentration of dissolved nutrients as well as other materials in the river increases with water discharge rate (Fig. 3). Recently Millennium Ecosystem Assessment argued that nitrogen fluxes in rivers to the sea over the past four decades have increased 17 folds in the south Korea, mostly due to the application of fertilizers, which is the most largest change in the world (Millennium Ecosystem Assessment, 2005, Table 4-1). Baskin et al. (2002) had also asserted that doubling N content in the Yellow Sea occurs every 3 years during the 1994–1997 due to the human derived N inputs. These two assessments need to be assessed independently for the clear understanding the nutrient dynamics in the Yellow Sea.

4.2 Nutrients in the China Seas

Nutrients in the China Seas are shown in Table 4, which is highly dynamic with different characteristics for various parts from the north to the south. The China Seas change from semi-enclosed shallow water region (i.e. the Bohai) to the epi-abyssal basin (i.e. South China Sea), with vast shelf seas (i.e. Yellow Sea and East China Sea) in between. Nutrient concentrations in the Bohai display short-term variability, imposed on seasonal oscillation and annual change. Nutrient levels are higher in shallow coastal waters than in the Central Bohai (Zhang et al., 2004). Nitrate concentrations increased, but phosphate and silicate levels decreased in the last forty years (Liu et al., 2008). Such a change in nutrient regimes has a profound influence on phytoplankton composition in the Bohai, ratio of diatoms to dinoflagellates was dramatically reduced in the Bohai in recent years (Wang and Kang, 1998; Kang, 1991; Sun et al., 2002).

Concentrations of nutrients are higher in the coastal than the central parts of the Yellow Sea; and seasonal variability of nutrient distribution is observed. The nutrient patterns in the Yellow Sea reflect the effects of the Changjiang effluent plume, surface runoff in the west and east coasts and the circulation. The high concentrations of nitrogen compounds and SiO_3^{2-} in Jiangsu coastal zone and southwest result most likely from convergence of Yellow Sea Coastal Current and the Changjiang effluent. The application of LOICZ model-approach demonstrate the dominance of advection on the nutrient budgetary issues, the active sink/source terms account for >65% of annual input/export flux in the region (Liu et al., 2003b).

The influence of Changjiang on the nutrient dynamics of East China Sea is limited to the inner and middle shelf, whereas the exchange across the shelf edge with Kuroshio, the western boundary current of North Pacific Ocean, is of great importance on the productive fisheries and nutrient budget (Chen and Wang, 1999). The incursion of Kuroshio Sub-Surface Waters (KSSW) can be an important source of nutrients sustaining phytoplankton blooms and peak rates of primary production in spring over the East China Sea Shelf favored by vertical mixing driven by the northeast monsoons starting in late autumn and winter. Also in winter, the riverine influx is at the annual minimum in this region, and circulation drives land-source nutrients southward along the coast of China. In summer the dispersal of river plumes over the shelf increases buoyancy effects, and the southern monsoon induces coastal upwelling. The land-source supplies abundant nutrients with replete nitrogen relative to phosphorus, so that the primary production relies on the contribution and/or compensation by KSSW intrusion that provides with allochthonous sources for phosphate relative to nitrogen (Chen, 2008). This offshore phosphorus source, however, is inhibited by the strong stratification on the shelf in summer. Hence the broad ECS Shelf behaves as a transition region where photosynthesis changes from P-limitation in the coast to the N-limitation further off-shore in the open Kuroshio, particularly in summer when the riverine (e.g., Changjiang) influx is maximum. Revised nutrient box-model budgets for the ECS Shelf indicates that the ECS shelf is a sink of nutrients and hence carbon in terms of material flux from land (i.e., Asia) to the open ocean (i.e., NW Pacific) (Zhang et al., 2007).

The South China Sea comprises of a wide range of sub-ecosystems, such as the shelf, coral reefs, upwelling region and deep basin, with different nutrient dynamics. The coral reefs form a distinctive landscape of the South China Sea, where the nutrients cycle is very efficient within the atoll lagoons; the exchange with open waters is rather limited, however. Nutrient profiles in the deep basin of the South China Sea resemble to other Southeast Asian Basins, being devoid of nutrients at surface and concentration increasing with depth (Zhang and Su, 2006).

Comparison nutrients in different parts of the China Seas, surface concentrations are higher in the Bohai and Yellow Sea, followed by the open shelf of ECS, while South China Sea has low level of nutrients except for the coastal waters affected by the land-source input. In the South China Sea Proper, horizontal gradient of chemical properties is small and vertical processes control the distribution of nutrients. In the Bohai, horizontal movement of water and spatial variations tend to determine the distribution of chemical parameters. While vertical structure of nutrients is concerned, the South China Sea shows the typical open-ocean nutrient profiles with vertical distribution stable and unchanged, while the other China seas change from season to season and with strong signature of inter-annual variability.

4.3 Nutrient budgets in estuaries and embayment

Water and salt budgets for large Chinese estuaries are shown in Table 5a. As freshwater discharge surpass both precipitation and evaporation, the residual flow is off the estuaries and is similar to riverine water discharge. Both residual flow and water exchange flow or mixing flow in summer is higher than that in winter. The total water exchange time of the estuaries is lower than 16 days, and the total water exchange time in winter is 2–5 fold that in the summer.

Water budgets for Chinese embayment are shown in Table 5b. Generally, freshwater discharge into the bays is lower than 10×10^{6} m^{3} day^{-1} except Hangzhou Bay and Taizhou Bay. The residual flow or net water exchange is from the bays to ocean except that in winter, Sanggou Bay, Jiaozhou Bay, Daya Bay and Dapeng Bay are from ocean to the embayment. The exchange flow was 1–48 times the total freshwater inputs. Apparently, the exchange flow dominated the water budgets, resulting in average system salinity, approaching the China seas salinity where river discharge is limited. The total water exchange time of the bays ranged from 13–1042 days, and total water exchange time in winter is higher than that in summer except Sanmen Bay.

The nutrient budgets for large Chinese estuaries are provided in Table 6a. Atmospheric depositions of nutrients are very limited relative to riverine input owing to limited surface area. Both residual and mixing flow transport nutrients off the estuaries. Table 6a illustrates the net source of NO_3^-, PO_4^{3-} and $Si(OH)_4$ in large Chinese estuaries except that PO_4^{3-} in the Huanghe in summer. The model shows that the estuaries behave as a sink of NH_4^+ except that in the Changjiang and Daliaohe in both the winter and summer, in Zhujiang in the summer, in Huanghe and Jiulongjiang in the winter.

The nutrient budgets for major Chinese embayment are shown in Table 6b. Riverine transports are more important than atmospheric deposition for NO_3^-, PO_4^{3-} and $Si(OH)_4$ except Dapeng Bay for NO_3^- and $Si(OH)_4$ and Daya Bay for NO_3^- in summer, in contrast, atmospheric deposition play an important role than riverine input for NH_4^+. From nutrient budgets, nutrients net sink into sediment or transformed into other forms or export off the bays depending on nutrient elements and the bays. However, the result is not conclusive because of the absence of waste load and aquaculture, limited data for riverine inputs.

4.4 Nutrients transport from estuaries and embayment to the China Seas

Eutrophication has been a growing problem in many coastal and estuarine ecosystems around the world (Justi et al., 2003; Rabalais et al., 2002). The transformation of nutrients within estuaries affects the transport of nutrients from land to the ocean and eventually the sustainability of nearshore ecosystems (Nixon, 1995). Nutrients transport from estuaries and embayment to the China Seas are estimated to be the sum of net water flow ($C_R V_R$) and mixing flow ($C_X V_X$) based on nutrients budget as discussed above, that is model results $F_{\text{model}}=C_R V_R+C_X V_X$. Nutrient transport fluxes show conspicuous seasonal variations with higher values in summer and lower values in winter except NH_4^+ in Zhujiang due to wastewater discharge (Table 7a). Totally, nutrient transport fluxes from major Chinese estuaries to coastal areas in summer are 512×10^6 mol day^{-1} for NO_3^-, 24.7×10^6 mol day^{-1} for NH_4^+, 4.77×10^6 mol day^{-1} for PO_4^{3-} and 775×10^6 mol day^{-1} for $Si(OH)_4$, which are 3–4 fold that in winter except comparable for NH_4^+. These fluxes are 1.0–1.7 fold that estimated by timing riverine nutrient concentrations (C) and freshwater discharge (i.e. riverine input $F_{river}=CV_Q$), indicating that estuary processes exist, for example, scavenging and/or regeneration, waste discharge.

Nutrient elements are transported from major embayment to China Seas except PO_4^{3-} and $Si(OH)_4$ in Sanggou Bay and Jiaozhou Bay (Table 7b) based on model output as the concentrations of PO_4^{3-} and $Si(OH)_4$ in the bay are lower than offshore areas. Seasonally, nutrient elements transport fluxes off the bays in the summer are 2.2–7.0 fold that in the winter. Compared with nutrient transports from the riverine input to the bay, model output fluxes off the bay are 1.3–3.0 fold that the riverine input for PO_4^{3-} and NH_4^+, but are comparable to the riverine input for NO_3^- and $Si(OH)_4$. Comparison nutrient fluxes from estuaries with embayment to the China Seas, model outputs show that estuaries transports are 8–56 fold that from embayment.

4.5 The effects of nutrients transport on the ecosystems of the China Seas

Rates of primary productivity in estuaries are among some of the highest on earth. Exchange of matter and energy between estuaries and coastal ecosystems affects phytoplankton growth rates and community composition in offshore ocean. The coastal ocean is a highly dynamic and spatially heterogeneous compartment of the Earth system affected by anthropogenic activities. Primary production in China Seas changes with season and region (Table 8). In both the Bohai and East China Sea, primary production is the highest in the summer and the lowest in the winter. In the Yellow Sea, primary production is the highest in the spring, followed by fall and is the lowest in the winter. In the shelf (bottom depth <200 m) of the northern South China Sea, primary production is comparable in the summer and winter, which are higher than in the spring and fall; in the basin waters (bottom depth >2000 m), primary production is the highest in the winter and the lowest in the summer.

Given the surface area of 7.7×10^4 km^2, 38×10^4 km^2, 53×10^4 km^2 and 200×10^4 km^2 over the Bohai, Yellow Sea, East China Sea shelf and South China Sea shelf region at water depths <200 m, respectively, the total primary production would be 3.0, 12.6, 27.3 and 166.0×10^4 t C day^{-1} in the Bohai, Yellow Sea, East China Sea shelf and South China Sea shelf in the summer, respectively; and 1.2, 2.9, 15.7, 164.0×10^4 t C day^{-1} in the Bohai, Yellow Sea, East China Sea shelf and South China Sea shelf in the winter, respectively, with average total primary production of 208.9 and 183.8×10^4 t C day^{-1} in the China Seas in the summer and winter, respectively. Taking into account the Redfield stoichiometric ratio for phytoplankton nutrient elements (C:N:P=106:16:1), primary producers would fix 262.5 and 231.0×10^8 mol day^{-1} of nitrogen, and 16.4 and 14.4×10^8 mol day^{-1} of phosphorus in the summer and winter, respectively. The major Chinese estuaries and embayment transport 811.7 and 236.9×10^6 mol day^{-1} of nitrogen, and 8.35 and 3.08×10^6 mol day^{-1} of phosphorus to the China Seas in the summer and winter, respectively, which account for 1.0–3.1% of nitrogen and 0.2–0.5% of phosphorus necessary for phytoplankton growth. This demonstrates that regenerated nutrients in water column and sediments and nutrients exchange between the China Seas and open ocean play an important role for phytoplankton growth. Atmospheric deposition may be another important source of nutrients for the China Seas, for example in the Yellow Sea, atmospheric deposition represents 51% of nitrogen load (Liu et al., 2003b).

4.6 The effects of silicon transport on the ecosystems of the China Seas

It is well known that with eutrophication, i.e. the addition of N and P and the reduction of water column dissolved silicate, diatom growth and biomass have the potential to be limited by dissolved silicate, which changes the food web dynamics (Conley et al., 1993). In China Seas, phytoplankton species composition changed a lot. For example, in the Bohai, the replacement of diatoms by dinoflagellates was the main feature of phytoplankton community changes in the Bohai in recent years (Wang and Kang, 1998; Kang, 1991; Sun et al., 2002) and the dominant species changed from small cell diatoms and *Chaetoceros* spp. to big cell diatoms coexisting with dinoflagellates between 1958 and 1999 (Sun et al., 2002). In the Yellow Sea, dominant phytoplankton species composition shifted from diatoms to non-diatoms, such as dinoflagellates and cyanophytes, thus increasing the proportion of the small-sized phytoplankton in the size structure of phytoplankton communities (Lin et al., 2005). Frequent harmful algal blooms (*Prorocentrum dentatum* and *Karenia mikimokoi*) exist in coastal waters of the East China Sea (Zhu et al., 1997; Li et al., 2007). Diatom species dominant blooms decreased, but non-diatom species dominant blooms increased (Li et al., 2007). Hypoxia phenomenon is reported off the Changjiang Estuary (Li et al., 2002) and extended from the Changjiang plume ~400 km offshore and ~300 km southward along the coast of the ECS (Chen et al., 2007). On a long view, silicon plays an important role affecting the ecosystems of the China Seas.

Based on nutrient budgets in large Chinese estuaries and embayment, the total $Si(OH)_4$ fluxes to the China Seas are 1070 and 280×10^6 mol day^{-1} in the summer and winter, respectively. For biogenic silica, there are very limited data for these estuaries and embayment (Table 9). In May 2003, dissolved silicate, biogenic silica (BSi) and lithogenic silica (LSi) were measured for the main stream and major tributaries of the Changjiang when the river discharge was approaching the annual average with average concentrations of 88.1 ± 28.4 µmol l^{-1} of $Si(OH)_4$, 2.0 ± 1.6 µmol l^{-1} of BSi and 21.1 ± 12.1 µmol l^{-1} of LSi (unpublished data). With respect to total silicon, $Si(OH)_4$ represented 79%, BSi accounted for 2% and LSi was 19%, in which BSi percent is lower than the values Conley reported (Conley, 1997) due to high sediment load. In the total river discharge and sediment load in China side, the Changjiang represents more than 60% of the total water discharge, and the Huanghe accounts for more than 90% of the sediment load. Suppose the contributions of BSi in the Changjiang is similar to the other major Chinese large rivers, BSi fluxes from large Chinese estuaries to China Seas would be 11.2×10^6 mol day^{-1}. The concentrations of BSi in the bays and shelf regions varies from 0.36–2.42 µmol l^{-1}, the preliminary estimated BSi fluxes from the major embayment to China Seas would be 1.14×10^6 mol day^{-1} based on $Si(OH)_4$ and BSi transport fluxes between Jiaozhou Bay and the Yellow Sea (42.5 and 2.7×10^4 mol day^{-1}, respectively). Therefore, the total $Si(OH)_4$ and BSi fluxes from large Chinese estuaries and embayment would be 523.2×10^6 mol day^{-1}, in which BSi represents 2.3%. Assuming that diatoms account for ca. 75% of the primary production in China Seas and taking into account the Redfield stoichiometric ratio for phytoplankton nutrient elements (C:N:Si=106:16:16), diatom primary producers would fix 185×10^8 mol day^{-1} of silicon. Both $Si(OH)_4$ and BSi fluxes can contribute 3% of silicon necessary for diatom growth. This demonstrates that regenerated silicon in water column and sediments and silicon transport flux between the China Seas and open ocean play an important role for diatom growth.

5 Summary

The present work summarizes data from biogeochemical surveys of the major Chinese estuaries and embayment such as Changjiang and Hangzhou Bay. Nutrient concentrations among the Chinese rivers and bays vary 10–75 fold depending on nutrient elements. The river continuum into the sea experience of lowering residence time and hence increase in plant utilization deplete the level of nutrients in the estuary than in the river. The dissolved silicate levels in South China rivers are higher than those from North China rivers and the yields of dissolved silicate increased from the north to the south of China, indicating the effect of climate on weathering, which results in an extensive leaching of silica from drainage areas, followed by higher riverine concentrations in subtropical zones relative to temperate zones. The nutrient levels in Chinese rivers are higher than those from the large and less-disturbed world rivers such as Amazon and Zaire, but comparable to the values for European and North American polluted and eutrophic rivers like the Loire, Po, Rhine, Seine etc. This may be ascribed to both of extensive leaching and influences from agricultural and domestic activities over the

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drainage basins of Chinese rivers. DIN:PO_4^{3-} ratios in most of Chinese rivers and bays are higher (up to 2800) than the other rivers in the world. As the increase in nitrogen and phosphorus are ascribed to anthropogenic activities, especially agricultural and domestic activities, and nitrogen is much easier to be leached away from drainage basin than phosphorus. While dissolved silicate is mainly delivered via weathering. The atomic ratios of PO_4^{3-} to $Si(OH)_4$ can be used to indicate the nutrient contributions from urbanization extent relative to weathering function of the drainage basin. The atomic ratios of DIN to PO_4^{3-} in the major Chinese rivers and embayment decrease in exponential trend with increase in the atomic ratios of PO_4^{3-} to $Si(OH)_4$ at p=0.01, indicating that primary production in coastal environments changes with the nutrients transport when the urbanization attains to a certain extent, and the potential limited nutrient elements can be changed from phosphorus limitation to nitrogen limitation, which can modify aquatic food webs and then the ocean ecosystem.

For the embayment, the exchange flow dominated the water budgets, resulting in average system salinity, approaching the China seas salinity where river discharge is limited. For large Chinese estuaries, atmospheric depositions of nutrients are very limited relative to riverine input. Both residual and mixing flow transport nutrients off the estuaries. For major Chinese embayment, riverine transports are more important than atmospheric deposition for NO_3^-, PO_4^{3-} and $Si(OH)_4$ except Dapeng Bay for NO_3^- and $Si(OH)_4$ and Daya Bay for NO_3^- in the summer, in contrast, atmospheric deposition play an important role than riverine input for NH_4^+. Nutrient transport fluxes from major Chinese estuaries to coastal areas in the summer are 3–4 fold that in the winter except comparable for NH_4^+. These fluxes are 1.0–1.7 fold that estimated by timing riverine nutrient concentrations and freshwater discharge. Nutrient elements are transported from major Chinese embayment to China Seas except PO_4^{3-} and $Si(OH)_4$ in Sanggou Bay and Jiaozhou Bay based on model output as the concentrations of PO_4^{3-} and $Si(OH)_4$ are lower in the bays than offshore areas. Seasonally, nutrient elements transport fluxes off the bays in the summer are 2.2–7.0 fold that in the winter. Comparison nutrient fluxes from estuaries and embayment to China Seas, model outputs show that estuaries transports are 8–56 fold that from embayment. Taking into account the Redfield stoichiometric ratio for phytoplankton nutrient elements (C:N:P=106:16:1), the major Chinese estuaries and embayment transport 1.0–3.1% of nitrogen, 0.2–0.5% of phosphorus and 3% of silicon necessary for phytoplankton growth. This demonstrates that regenerated nutrients in water column and sediments and exchange between the China Seas and open ocean play an important role for phytoplankton growth. Atmospheric deposition may be another important source of nutrients for the China Seas.

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Table 1. Length, drainage area, long-term average water and sediment loads of large rivers discharging into the China Seas.

River	Length (km)	Drainage area ($\times 10^4$ km^2)	Water discharge ($\times 10^9$ m^3 yr^{-1})	Sediment load ($\times 10^6$ t yr^{-1})
Huanghe	5463[a]	75.2[a]	42.6[d]	1089.3[d]
Luanhe	877[a]	5.4[b]	4.7[e]	22.2[e]
Daliaohe	1390[a]	21.9[a]	3.8[f]	17.1[f]
Shuangtaizihe	1390[a]	6.0[j]	43.0[j]	20.0[j]
Yalujiang	795[g]	6.3[b]	32.8[b]	1.1[b]
Huaihe	1000	27	26.4[h]	9.87
Daguhe	179	0.56[c]	0.5[c]	0.96[c]
Changjiang	6300	180.9[b]	928.2[h]	500[h]
Han	469.7[i]	2.62[i]	20.9[i]	12.42[i]
Keum	401.4[i]	0.99[i]	5.8[i]	3.95[i]
Yeongsan	115.8[i]	0.28[i]	2.1[i]	1.24[i]
Qiantangjiang	494[l]	4.1[j]	34.2[j]	4.4[j]
Yongjiang	121[l]	0.43[k]	1.02[k]	0.36[k]
Jiaojiang	198	1.0[j]	2.30[j]	1.2[j]
Oujiang	376	1.79[k]	14.6[k]	2.67[k]
Minjiang	577	6.1[j]	53.6[j]	7.5[j]
Jiulongjiang	258	1.5[b]	11.7[j]	2.5[j]
Zhujiang	2214	59.0[j]	482.1[j]	95.9[j]

[a] Ren et al. (2002); [b] Zhang (1996); [c] Liu et al. (2005); [d] National Compilation Committee of River and Sediment Communiqué (2000); [e] Feng and Zhang (1998); [f] National Compilation Committee of Hydrology Almanac (1982); [g] Liu and Zhang (2004); [h] Liu et al. (2003a); [i] Hong et al. (2002); [j] Zhang (2002); [k] Ministry of Hydrology Power of People's Republic of China (2004); [l] Gao et al. (1993)

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Table 2a. Concentrations (µM) of various nutrient species in major Chinese and Korean rivers transport to the China Seas.

River	Season	NO_3^-	NH_4^+	NO_2^-	PO_4^{3-}	$Si(OH)_4$	Reference
Daliaohe	May 1992	159.2	17.1	12.1	1.19	71.2	Jiang et al. (1995)
Daliaohe	Aug 1992	52.1	3.14	8.56	1.71	34.2	Jiang et al. (1995)
Shuangtaizihe	Aug 1993	181	3.0	0.05	0.40	105	Zhang (2002)
Luanhe	Aug 1991	74.4		0.2	0.51	87.2	Zhang (1996)
Huaihe	Dec 2004–Feb 2005	76.3	16.5	1.71	4.02	38.1	Unpublished data
Huanghe	Winter	238	36.8	7.42	0.62	115	Zhang (1992)
Huanghe	Summer	225	5.14	3.93	0.33	99.8	Tan (2002)
Yalujiang	Aug 1992, 1994	268	2.38	0.37	0.30	127	Liu and Zhang (2004)
Yalujiang	May 1996	76.3	5.78	0.17	0.09	146	
Daguhe	Mar 2002, 2004	142.8	0.65	16.6	0.08	11.5	Liu et al. (2005, 2007)
Daguhe	Aug 2002, 2005	156.5	0.60	15.7	0.58	101.1	
Han	Jun 1992	57.1	75.8	2.0	3.5	36.9	Hong, unpublished
	Jun 2000	97.6	217.5	12.7			Kim et al. (2004a)
Keum	1997–1998	160	26.5	1.5	1.4	85	Yang et al. (1999a)
Yeongsan	1998–2000		37.1		3.9	72.2	Cha and Cho (2002)
Changjiang	Jan 1997–2001	62.7	16.0	0.61	0.49	112.0	Unpublished data
Changjiang	Jul 1997–2001	70.2	4.64	0.07	0.34	100.2	
Qiantangjiang	Aug 2004	101	0.70	1.54	1.00	128	Unpublished data
Yongjiang	May 2002	119		11.1	3.2	183	Unpublished data
Jiaojiang	Oct 1994	123	0.59		2.21	162	Zhang (2002)
Oujiang	Aug 2004	72.3	3.21	0.44	0.30	150	Unpublished data
Minjiang	Winter	65	4.13	1.65	1.45	208	Hu et al. (1996)
Minjiang	Summer	45	3.61	0.84	0.50	156	
Jiulongjiang	Summer	36.2	10.70		0.61	261	Chen et al. (1985, 1997),
Jiulongjiang	Winter	36.2	19.60		0.91	279.4	Wang et al. (2006)
Zhujiang	Aug 1999	78.6	2.15	1.71	0.85	116.3	Unpublished data
Zhujiang	Jan 2000	58.1	22.0	2.06	0.66	106.2	

Table 2b. Nutrient transport fluxes ($\times 10^6$ mol/day) from rivers to the China Seas.

River	Season	NO_3^-	NH_4^+	NO_2^-	PO_4^{3-}	$Si(OH)_4$
Daliaohe	May 1992	0.75	0.08	0.057	0.006	0.34
Daliaohe	Aug 1992	1.10	0.07	0.181	0.036	0.72
Shuangtaizihe	Aug 1993	21.3	0.35	0.006	0.047	12.4
Luanhe	Aug 1991	0.96		0.003	0.007	1.12
Huaihe	Dec 2004–Feb 2005	5.52	1.19	0.12	0.29	2.76
Huanghe	Winter	1.23	0.19	0.038	0.003	0.59
Huanghe	Summer	2.54	0.058	0.044	0.004	1.12
Yalujiang	Aug 1992, 1994	29.2	0.26	0.040	0.033	13.8
Yalujiang	May 1996	4.81	0.37	0.011	0.006	9.21
Daguhe	Mar, Aug 2002, 2004	0.22	0.001	0.024	0.0005	0.08
Han	Jun 1992	3.3	4.3	0.11	0.20	2.1
	Jun 2000	5.6	12.5	0.73	–	–
Keum	1997–1998	2.5	0.4	0.02	0.02	1.4
Yeongsan	1998–2000	–	0.2	–	0.02	0.4
Changjiang	Jan 1997–2001	65.9	16.8	0.64	0.51	117.7
Changjiang	Jul 1997–2001	277.4	18.3	0.28	1.34	395.9
Qiantangjiang	Aug 2004	9.46	0.066	0.14	0.094	12.0
Yongjiang	May 2002	0.33		0.031	0.009	0.51
Jiaojiang	Oct 1994	0.78	0.004		0.014	1.02
Oujiang	Aug 2004	2.89	0.13		0.012	6.00
Minjiang	Winter	4.48	0.28	0.11	0.10	14.3
Minjiang	Summer	12.5	1.00	0.23	0.14	43.2
Jiulongjiang	Summer	2.6	0.78	52.1	0.04	19.1
Jiulongjiang	Winter	0.5	0.30	19.7	0.01	4.2
Zhujiang	Aug 1999	117.1	3.20	2.55	1.27	173.3
Zhujiang	Jan 2000	17.2	6.51	0.61	0.20	31.4

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Table 2c. The areal yields of nutrients ($mol\,km^{-2}\,day^{-1}$) in major Chinese rivers.

River	Season	NO_3^-	NH_4^+	NO_2^-	PO_4^{3-}	$Si(OH)_4$
Daliaohe	May 1992	28.36	3.05	2.16	0.212	12.7
Daliaohe	Aug 1992	41.39	2.49	6.8	1.358	27.2
Shuangtaizihe	Aug 1993	355.4	0.10	5.89	0.785	206.2
Luanhe	Aug 1991	17.7	0.05		0.122	20.8
Huaihe	Dec 2004–Feb 2005	20.4	0.46	4.42	1.077	10.2
Huanghe	Winter	1.63	0.05	0.25	0.004	0.79
Huanghe	Summer	3.37	0.06	0.08	0.005	1.50
Yalujiang	Aug 1992, 1994	463.7	0.64	4.12	0.519	219.7
Yalujiang	May 1996	76.4	0.17	5.79	0.093	146.2
Daguhe	Mar, Aug 2002, 2004	39.2	4.23	0.16	0.086	14.7
Han	Jun 1992	125	166	4	8	81
	Jun 2000	213	475	28	–	–
Keum	1997–1998	257	43	2	2	136
Yeongsan	1998–2000	–	76	–	8	148
Changjiang	Jan 1997–2001	36.4	0.35	9.30	0.285	65.1
Changjiang	Jul 1997–2001	153.3	0.15	10.13	0.743	218.8
Qiantangjiang	Aug 2004	230.8	3.51	1.60	2.29	292.5
Yongjiang	May 2002	77.3	7.23		2.08	118.9
Jiaojiang	Oct 1994	77.5		0.37	1.39	102.1
Oujiang	Aug 2004	161.6		7.17	0.670	335.2
Minjiang	Winter	73.4	1.86	4.66	1.64	234.9
Minjiang	Summer	204.3	3.81	16.39	2.27	708.1
Jiulongjiang	Summer	176.2		52.1	2.97	1270.2
Jiulongjiang	Winter	36.4		19.7	0.916	281.3
Zhujiang	Aug 1999	198.5	4.32	5.43	2.15	293.7
Zhujiang	Jan 2000	29.1	1.03	11.0	0.33	53.3

Table 3. Concentrations (µM) of nutrient species in major Chinese bays.

Bay	Season	NO_3^-	NO_2^-	NH_4^+	PO_4^{3-}	$Si(OH)_4$	Reference
Sanggou Bay	Spring	2.62	0.41	0.98	0.11	1.34	Unpublished data
	Summer	2.93	1.44	15.0	0.15	3.95	
	Fall	8.20	1.62	5.56	0.68	6.90	
	Winter	5.82	0.38	4.83	0.31	5.36	
Jiaozhou Bay	Spring	5.5	0.88	13.5	0.45	3.7	Liu et al. (2005, 2007)
	Summer	16.5	2.4	10.0	0.28	4.4	
	Fall	4.9	2.4	7.3	0.44	6.5	
	Winter	11.0	1.14	8.35	0.41	5.02	
Hangzhou Bay	Spring	55.3	0.24	1.09	0.94	67.9	
	Summer	64.4	1.02	2.95	1.00	94.7	
	Fall	56.7	0.27	1.32	1.57	98.6	
	Winter	58.1	0.5	2.64	1.54	60.3	Gao et al. (1993)
Xiangshan Bay	Summer	43.4	1.56	2.43	1.05	32.8	Zhang et al. (2006),
	Winter	47.4	0.50	1.88	1.66	47.3	Zhang et al. (2003)
Sanmen Bay	Jul 2005	30.9	1.87	1.90	0.66	41.8	
	Apr 2005	35.4	0.25	2.37	0.70	38.6	Wang et al. (2007)
Taizhou Bay	Summer	7.08	0.68	1.78	0.42		Chinese Compilation
	Winter	24.1	0.39	0.85	1.17		Committee of Embayment (1993)
Daya Bay	Spring	1.12	0.10	1.27	0.17	16.7	
	Summer	2.16	0.41	1.87	0.16	25.2	
	Fall	1.80	0.50	2.62	0.17	21.7	
	Winter	2.17	0.24	2.20	0.30	16.1	Qiu et al. (2005)
Dapeng Bay	Summer	3.86	0.59	1.86	0.28	12.0	Li et al. (2004),
	Winter	2.50	0.93	2.91	0.11	3.72	Chinese Compilation Committee of Embayment (1998)

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Table 4. Nutrient concentrations (µM) for the China seas.

Sea	Season/Area	NO_3^-	NH_4^+	PO_4^{3-}	$Si(OH)_4$
Bohai[a]					
	Summer	1.19±1.60	1.76±0.89	0.329±0.21	7.20±4.98
	Winter	4.19±1.96	2.05±0.68	0.66±0.21	7.86±3.65
Yellow Sea[b]					
	Summer	0.51–5.75 (2.96)	0.13–2.5 (0.91)	0.11–0.60 (0.47)	2.75–12.0 (11.9)
	Winter	0.73–9.1 (4.1)	0.01–1.9 (0.99)	0.15–0.78 (0.43)	0.2–17.8 (8.5)
East China Sea Shelf[c]					
	Summer	0.5–6.1 (3.5)	0.32–1.1 (0.71)	0.07–0.38 (0.17)	5.95–13.2 (6.0)
	Winter	2.4–8.8 (5.6)	0.32	0.23–0.65 (0.44)	6.0–16.0 (11.0)
South China Sea Shelf[d]					
	Surface	6.5	3.5	0.25	2
	Near-bottom	4.5	3	3.5	7.5
South China Sea Proper[d]					
	Surface	0.25	0.45	0.15	2
	Near-bottom	45		2.65	150

[a] Li et al. (2003); [b] KORDI (1998), Liu et al. (2003b); [c] Zhang et al. (2007); [d] Zhang and Su (2006)

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Table 5a. Water and salt budgets for the Chinese estuaries. Area is in km^2, average depth in m, volume in $\times 10^6$ m^3, water fluxes in $\times 10^6$ m^3 day^{-1}, salinity in psu, and τ in days. In the table, positive values indicate transport into the studied system; negative data show the export off the studied system.

Estuary	Season	Area	Depth	Volume	S_{syst}	S_{ocn}	V_Q	V_P	V_E	V_R	V_X	τ
Yalujiang	Aug 1992, 1994	170	6	1020	5.59	24.45	113.9	1.3	0.80	−114.4	91	5.0
	May 1996	170	6	1020	7.42	26.78	63.1	0.1	0.20	−63	55.6	8.6
Daliaohe	Aug 1992	39.4	4	157.6	14.30	29.49	21.13	0.18	0.27	−21.0	30.3	3.1
	May 1992	39.4	4	157.6	10.46	28.14	4.74	0.011	0.047	−4.7	5.1	16.0
Huanghe	Summer	3.6	2	7.2	27.00	31.20	11.67	0.015	0.038	−11.6	81	0.1
	Winter	3.6	2	7.2	26.86	30.70	5.33	0.0007	0.0066	−5.3	40	0.2
Changjiang	Summer	3094	5	15 470	7.66	26.91	3951	13.4	18	−3946.4	3544	2.1
	Winter	3094	5	15 470	13.98	28.81	1051	4.6	5.8	−1049.8	1515	6.0
Minjiang	Summer	114	2	228	23.11	33.60	276.9	0.6	0.7	−276.8	748	0.2
	Winter	114	2	228	25.91	33.60	68.9	0.2	0.3	−68.8	266	0.7
Jiulongjiang	Summer	85	6.47	550	27.40	33.97	73.0	0.6	0.7	−72.9	341	1.3
	Winter	85	6.47	550	28.30	32.23	15.1	0.1	0.1	−15.095	116	4.2
Zhujiang	Aug 1999	1180	7	8260	6.30	30.00	1490	11.4	7.4	−1494	1144	3.1
	Jan 2000	1180	7	8260	20.60	33.30	296	1.4	4.4	−293	622	9.0

Table 5b. Water and salt budgets for the Chinese embayment. Area is in km^2, average depth in m, volume in $\times 10^6\ m^3$, water fluxes in $\times 10^6\ m^3\ day^{-1}$, salinity in psu, and τ in days. In the table, positive values indicate transport into the studied system; negative data show the export off the studied system.

Embayment	Season	Area	Depth	Volume	S_{syst}	S_{ocn}	V_Q	V_P	V_E	V_R	V_X	τ
Sangguo Bay	Summer	163.2	7.5	1224	30.27	31.79	1.44	0.92	0.941	−1.41	28.9	40
	Winter	163.2	7.5	1224	32.05	32.72	0.10	0.067	0.348	0.18	8.8	142
Jiaozhou Bay	Summer	390	6.26	2440	30.84	31.79	5.51	1.753	1.92	−5.34	176.1	13
	Winter	390	6.26	2440	31.90	32.72	0.379	0.154	0.594	0.06	2.4	1042
Hangzhou Bay	Summer	5000	8	40 000	10.59	23.80	190.1	21.8	30.2	−181.7	236.5	96
	Winter	5000	8	40 000	12.15	24.40	50.4	9.2	9.3	−50.3	75.0	319
Xiangshan Bay	Summer	563	8	4504	25.95	24.92	5.5	3.3	3.3	−5.50	135.1	32
	Winter	563	8	4504	22.03	27.40	1.5	1.1	1.1	−1.50	6.9	536
Sanmen Bay	Jul 2005	775	8	6200	24.21	25.13	3	1.6	1.7	−2.90	77.8	77
	Apr 2005	775	8	6200	27.74	30.55	11.5	5.1	4.3	−12.3	127.6	44
Taizhou Bay	Summer	911.561	10	9116	31.95	26.37	28.5	4.6	4.8	−28.3	147.9	52
	Winter	911.561	10	9116	24.94	29.37	7.5	2.1	2.2	−7.40	45.4	173
Daya Bay	Summer	432.9	9	3896	31.60	33.46	0.843	4.9	3	−2.74	48.0	77
	Winter	432.9	9	3896	32.16	34.28	0.175	0.5	1.9	1.23	19.2	217
Dapeng Bay	Summer	166.76	15	2501	31.76	33.46	0	3.6	1.9	−1.70	32.6	73
	Winter	166.76	15	2501	31.84	34.28	0	0.4	1.2	0.80	10.8	249

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Table 6a. Box model outputs of nutrient budgets in the Chinese estuaries. The concentrations of nutrients in the systems (C_{syst}) and offshore oceans (C_{ocn}) are in µM, atmospheric nutrients deposition ($V_P C_P$), riverine input ($V_Q C_Q$), the net nutrients transport ($V_R C_R$), mixing exchange fluxes of nutrients ($V_X C_X$) and nutrients sink and/or source (Δ) are in $\times 10^6$ mol day^{-1}. In the table, positive values indicate transport into the studied system; negative data show the export of nutrients off the studied system.

		C_{syst}				C_{ocn}				$V_R C_R$				$V_X C_X$			
Estuary	Season	NO_3^-	NH_4^+	PO_4^{3-}	$Si(OH)_4$	NO_3^-	NH_4^+	PO_4^{3-}	$Si(OH)_4$	NO_3^-	NH_4^+	PO_4^{3-}	$Si(OH)_4$	NO_3^-	NH_4^+	PO_4^{3-}	$Si(OH)_4$
Yalujiang	Aug 1992, 94	268	2.46	0.53	103	2.96	0.91	0.47	11.9	−15.5	−0.193	−0.057	−6.57	−24.1	−0.14	−0.005	−8.30
Yalujiang	May 1996	49.5	3.804	0.164	95.5	4.1	0.973	0.29	8.5	−1.7	−0.150	−0.014	−3.28	−2.53	−0.16	0.007	−4.84
Daliaohe	May 1992	155.6	7.85	1.52	54.1	77.8	5.57	1.55	9.62	−0.5	−0.031	−0.007	−0.15	−0.40	−0.01	0.000	−0.23
Daliaohe	Aug 1992	47.1	1.00	1.42	22.1	13.6	0.64	0.90	5.34	−0.6	−0.017	−0.024	−0.29	−1.02	−0.01	−0.016	−0.51
Huanghe	Summer	63.2	2.88	0.20	41.1	9.54	2.29	0.3	24	−0.4	−0.030	−0.003	−0.38	−4.3	−0.05	0.008	−1.38
Huanghe	Winter	69.8	8.0	0.54	30.0	4.19	2.05	0.48	8.15	−0.2	−0.027	−0.003	−0.10	−2.6	−0.24	−0.002	−0.87
Changjiang	Summer	62.8	3.38	0.68	93.0	31.6	0.71	0.57	38.7	−186.3	−8.070	−2.467	−259.8	−110.7	−9.46	−0.390	−192.4
Changjiang	Winter	56.7	7.94	0.79	74.8	26	0.32	0.63	29.6	−43.4	−4.333	−0.747	−54.80	−46.5	−11.5	−0.247	−68.47
Minjiang	Jun 1986	22.3	3.14	0.52	91.5	3.5	0.71	0.17	6.0	−3.6	−0.533	−0.096	−13.50	−14.1	−1.82	−0.262	−64.0
Minjiang	Oct 1986	35	1.96	0.88	99.4	5.6	0.32	0.44	11.0	−1.4	−0.078	−0.045	−3.80	−7.83	−0.44	−0.117	−23.54
Jiulongjiang	Summer	17.3	4.08	0.32	153.3	3.05	0.57	0.2	38.4	−0.7	−0.169	−0.019	−6.99	−4.84	−1.19	−0.041	−39.13
Jiulongjiang	Winter	17.4	2.47	0.74	123.4	12.44	0.39	0.53	57.7	−0.2	−0.022	−0.010	−1.37	−0.58	−0.24	−0.024	−7.64
Zhujiang	Aug 1999	79.2	1.85	0.80	99.1	5.3	1.06	0.19	12.9	−63.1	−2.174	−0.740	−83.69	−84.5	−0.90	−0.698	−98.67
Zhujiang	Jan 2000	34.6	15.1	0.35	56.1	0.38	1.57	0.09	2.13	−5.1	−2.436	−0.064	−8.53	−21.2	−8.39	−0.162	−33.57

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Table 6a. continued.

Estuary	Season	$V_Q C_Q$				$V_P C_P$				Δ			
		NO_3^-	NH_4^+	PO_4^{3-}	$Si(OH)_4$	NO_3^-	NH_4^+	PO_4^{3-}	$Si(OH)_4$	NO_3^-	NH_4^+	PO_4^{3-}	$Si(OH)_4$
Yalujiang	Aug 1992, 94	29.2	0.26	0.033	13.8	0.024	0.048	0.000	0.001	10.4	0.03	0.03	1.0
Yalujiang	May 1996	3.88	0.083	0.0059	7.42	0.014	0.018	0.000	0.000	0.33	0.21	0.00	0.7
Daliaohe	May 1992	0.75	0.08	0.01	0.34	0.002	0.005	0.001	0.001	0.19	−0.04	0.00	0.04
Daliaohe	Aug 1992	1.10	0.07	0.036	0.72	0.009	0.020	0.001	0.001	0.54	−0.06	0.00	0.07
Huanghe	Summer	2.54	0.06	0.004	1.12	0.001	0.001	0.000	0.000	2.2	0.02	−0.01	0.6
Huanghe	Winter	1.23	0.36	0.003	0.59	0.000	0.000	0.000	0.000	1.59	−0.10	0.00	0.4
Changjiang	Summer	277.4	18.3	1.34	395.9	0.188	0.402	0.001	0.024	19.5	−1.20	1.51	56.3
Changjiang	Winter	65.9	16.8	0.51	117.7	0.357	0.641	0.001	0.009	23.6	−1.59	0.48	5.6
Minjiang	Jun 1986	12.5	1.00	0.14	43.2	0.007	0.015	0.000	0.001	5.2	1.34	0.22	34.3
Minjiang	Oct 1986	4.48	0.28	0.10	14.3	0.013	0.024	0.000	0.000	4.7	0.21	0.06	13.0
Jiulongjiang	Summer	2.64	0.78	0.04	19.1	0.005	0.011	0.000	0.001	2.9	0.57	0.02	27.1
Jiulongjiang	Winter	0.55	0.30	0.014	4.22	0.010	0.018	0.000	0.000	0.25	−0.05	0.02	4.8
Zhujiang	Aug 1999	117.1	3.20	1.27	173.3	0.072	0.153	0.000	0.009	30.5	−0.28	0.17	9.1
Zhujiang	Jan 2000	17.2	6.51	0.20	31.4	0.136	0.245	0.000	0.003	9.0	4.07	0.03	10.7

Table 6b. Box model outputs of nutrient budgets in the Chinese embayment. The concentrations of nutrients in the systems (C_{syst}) and offshore oceans (C_{ocn}) are in µM, atmospheric nutrients deposition ($V_P C_P$), riverine input ($V_Q C_Q$), the net nutrients transport ($V_R C_R$), mixing exchange fluxes of nutrients ($V_X C_X$) and nutrients sink and/or source (Δ) are in $\times 10^5$ mol day^{-1}. In the table, positive values indicate transport into the studied system; negative data show the export of nutrients off the studied system.

		C_{syst}				C_{ocn}				$V_R C_R$				$V_X C_X$			
Embayment	Season	NO_3^-	NH_4^+	PO_4^{3-}	$Si(OH)_4$	NO_3^-	NH_4^+	PO_4^{3-}	$Si(OH)_4$	NO_3^-	NH_4^+	PO_4^{3-}	$Si(OH)_4$	NO_3^-	NH_4^+	PO_4^{3-}	$Si(OH)_4$
Sanggou Bay	Summer	2.93	15.0	0.15	3.95	2.96	0.91	0.47	11.9	−0.042	−0.112	−0.004	−0.11	0.01	−4.06	0.09	2.29
	Winter	5.82	4.83	0.31	5.36	4.1	0.99	0.43	8.5	0.009	0.005	0.001	0.013	−0.15	−0.34	0.01	0.28
Jiaozhou Bay	Summer	16.5	10.0	0.28	4.37	2.96	0.91	0.47	11.9	−0.519	−0.290	−0.020	−0.435	−23.79	−15.92	0.33	13.3
	Winter	11.00	8.35	0.41	5.02	4.1	0.99	0.43	8.5	0.0046	0.003	0.000	0.004	−0.17	−0.18	0.00	0.08
Hangzhou Bay	Summer	64.4	2.95	1.00	94.7	19	2.01	0.64	36.8	−75.8	−4.51	−1.49	−119.4	−107	−2.22	−0.85	−137
	Winter	58.1	2.64	1.54	60.3	23.8	1.92	1.07	45.0	−20.6	−1.15	−0.66	−26.5	−25.7	−0.54	−0.35	−11.4
Xiangshan Bay	Summer	43.4	2.43	1.05	32.8	34.1	0.32	0.52	20.1	−2.13	−0.076	−0.043	−1.45	−12.6	−2.85	−0.72	−17.1
	Winter	47.4	1.88	1.66	47.3	25.1	0.71	0.65	21.4	−0.54	−0.019	−0.017	−0.52	−1.54	−0.08	−0.07	−1.79
Sanmen Bay	Jul 2005	30.9	1.90	0.66	41.8	17.6	0.32	0.29	9.29	−0.70	−0.032	−0.014	−0.74	−10.4	−1.23	−0.29	−25.2
	Apr 2005	35.4	2.37	0.70	38.6	24.1	0.71	0.51	21.00	−3.66	−0.189	−0.074	−3.66	−14.4	−2.12	−0.24	−22.4
Taizhou Bay	Summer	7.08	1.78	0.42		5.34	0.32	0.16	3.64	−1.76	−0.297	−0.082		−2.57	−2.16	−0.38	
	Winter	24.1	0.85	1.17		22.7	0.71	0.87	19.4	−1.73	−0.058	−0.075		−0.62	−0.06	−0.13	
Daya Bay	Summer	2.16	1.87	0.16	25.2	1.83	1.06	0.14	9.86	−0.05	−0.040	−0.004	−0.48	−0.16	−0.39	−0.009	−7.4
	Winter	2.17	2.20	0.30	16.1	0.38	1.57	0.09	2.13	0.02	0.023	0.0024	0.11	−0.34	−0.12	−0.040	−2.7
Dapeng Bay	Summer	3.86	1.86	0.28	12.0	1.83	1.06	0.14	9.86	−0.048	−0.025	−0.0036	−0.19	−0.66	−0.26	−0.046	−0.7
	Winter	2.50	2.91	0.11	3.72	0.38	1.57	0.09	2.13	0.012	0.018	0.0008	0.02	−0.23	−0.14	−0.0022	−0.2

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Table 6b. continued.

		$V_P C_P$				$V_Q C_Q$				Δ			
Embayment	Season	NO_3^-	NH_4^+	PO_4^{3-}	$Si(OH)_4$	NO_3^-	NH_4^+	PO_4^{3-}	$Si(OH)_4$	NO_3^-	NH_4^+	PO_4^{3-}	$Si(OH)_4$
Sanggou Bay	Summer	0.23	0.46	0.004	0.010	2.25	0.23	0.008	1.45	−2.4	3.5	−0.100	−3.6
	Winter	0.13	0.17	0.001	0.003	0.14	0.02	0.000	0.01	−0.1	0.15	−0.012	−0.3
Jiaozhou Bay	Summer	0.56	1.10	0.010	0.023	8.63	0.87	0.032	5.57	15.1	14.25	−0.350	−18.4
	Winter	0.31	0.41	0.001	0.007	0.54	0.06	0.000	0.04	−0.69	−0.3	−0.002	−0.1
Hangzhou Bay	Summer	3.03	6.50	0.013	0.383	222.4	9.5	1.901	275.5	−42.3	−9.2	0.427	−19.6
	Winter	5.77	10.4	0.021	0.141	51.6	1.70	0.968	59.8	−11.0	−10.4	0.021	−22.0
Xiangshan Bay	Summer	0.34	0.73	0.001	0.043	6.46	0.27	0.055	8.00	7.95	1.9	0.708	10.5
	Winter	0.65	1.17	0.002	0.016	1.49	0.05	0.028	1.73	−0.06	−1.1	0.057	0.6
Sanmen Bay	Jul 2005	0.47	1.01	0.002	0.059	13.5	0.57	0.115	16.66	−2.9	−0.3	0.184	9.3
	Apr 2005	0.89	1.61	0.003	0.022	3.07	0.10	0.058	3.56	14.05	0.6	0.252	22.5
Taizhou Bay	Summer	0.55	1.19	0.002	0.070	7.75	0.04	0.139	10.21	−4.0	1.2	0.325	
	Winter	1.05	1.89	0.004	0.026	7.75	0.04	0.139	10.21	−6.5	−1.8	0.066	
Daya Bay	Summer	0.26	0.56	0.001	0.033	0.04	0.01	0.014	0.71	−0.09	−0.1	−0.003	7.1
	Winter	0.50	0.90	0.002	0.012	1.02	0.23	0.102	0.36	−1.2	−1.0	−0.066	2.2
Dapeng Bay	Summer	0.10	0.22	0.000	0.013	0.00	0.00	0.000	0.00	0.6	0.07	0.049	0.87
	Winter	0.19	0.35	0.0007	0.005	0.00	0.00	0.000	0.00	0.03	−0.2	0.00068	0.1

Table 7a. Nutrient transport fluxes ($\times 10^6$ mol day^{-1}), i.e. model output ($V_R C_R + V_X C_X$) from major Chinese estuaries to China Seas. In the table, positive values indicate transport into the studied system; negative data show the export off the studied system.

Estuary	Season	NO_3^-	NH_4^+	PO_4^{3-}	$Si(OH)_4$
Yalujiang	Aug 1992, 94	−39.6	−0.33	−0.063	−14.9
Yalujiang	May 1996	−4.2	−0.31	−0.0073	−8.1
Daliaohe	May 1992	−1.0	−0.04	−0.007	−0.4
Daliaohe	Aug 1992	−1.7	−0.03	−0.040	−0.8
Huanghe	Summer	−4.8	−0.078	0.005	−1.8
Huanghe	Winter	−2.82	−0.26	−0.005	−0.97
Changjiang	Summer	−297	−17.5	−2.86	−452
Changjiang	Winter	−89.9	−15.9	−0.99	−123
Minjiang	Jun 1986	−17.6	−2.4	−0.36	−77.5
Minjiang	Oct 1986	−9.23	−0.52	−0.16	−27.3
Jiulongjiang	Summer	−5.58	−1.4	−0.060	−46.1
Jiulongjiang	Winter	−0.81	−0.26	−0.034	−9.0
Zhujiang	Aug 1999	−148	−3.1	−1.44	−182
Zhujiang	Jan 2000	−26.4	−10.8	−0.23	−42.1

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Table 7b. Nutrient transport fluxes (×10^5 mol day^{-1}), i.e. model output ($V_R C_R + V_X C_X$) from major Chinese embayment to China Seas. In the table, positive values indicate transport into the studied system; negative data show the export off the studied system.

Embayment	Season	NO_3^-	NH_4^+	PO_4^{3-}	$Si(OH)_4$
Sanggou Bay	Summer	−0.034	−4.17	0.088	2.18
	Winter	−0.14	−0.33	0.011	0.29
Jiaozhou Bay	Summer	−24.3	−16.2	0.31	12.8
	Winter	−0.16	−0.17	0.001	0.088
Hangzhou Bay	Summer	−183.2	−6.73	−2.34	−256.2
	Winter	−46.3	−1.69	−1.01	−37.9
Xiangshan Bay	Summer	−14.7	−2.93	−0.77	−18.6
	Winter	−2.09	−0.10	−0.087	−2.31
Sanmen Bay	Summer	−11.1	−1.26	−0.30	−26.0
	Winter	−18.0	−2.31	−0.31	−26.1
Taizhou Bay	Summer	−4.33	−2.46	−0.47	
	Winter	−2.35	−0.12	−0.21	
Daya Bay	Summer	−0.21	−0.43	−0.013	−7.84
	Winter	−0.33	−0.098	−0.037	−2.57
Dapeng Bay	Summer	−0.71	−0.29	−0.049	−0.88
	Winter	−0.22	−0.13	−0.001	−0.15

Table 8. Seasonal primary production (mg C m^{-2} day^{-1}) in China Seas.

Region	Spring	Summer	Fall	Winter	Reference
Bohai	300±73	390±201	232±72	161±33	Fei et al. (1991); Lü et al. (1999); Sun et al. (2003)
Yellow Sea	2066 (66–5303)	331 (67–1020)	702 (281–1341)	75 (15–221)	Yang et al. (1999b)
East China Sea	307±156	515±315	371±154	297±121	Gong et al. (2003)
Northern South China Sea					
Shelf (<200 m)	620±220	830±420	450±240	820±40	Chen and Chan (2006)
Basin (>2000 m)	440±300	310±140	320±140	530±190	

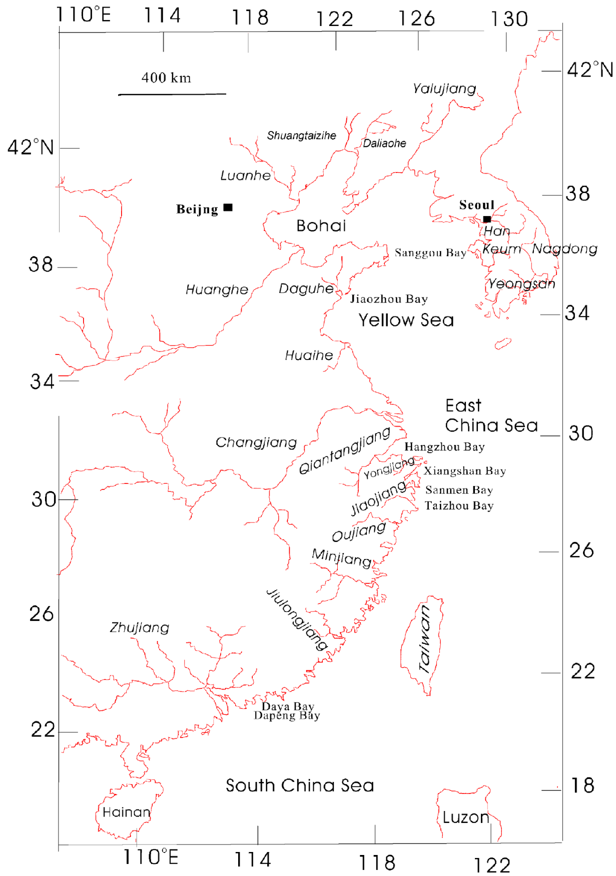

Fig. 1. Map of the east China and the west of South Korea, showing the location of large rivers and embayment in this study and adjacent shelf region from north to south of the China Seas.

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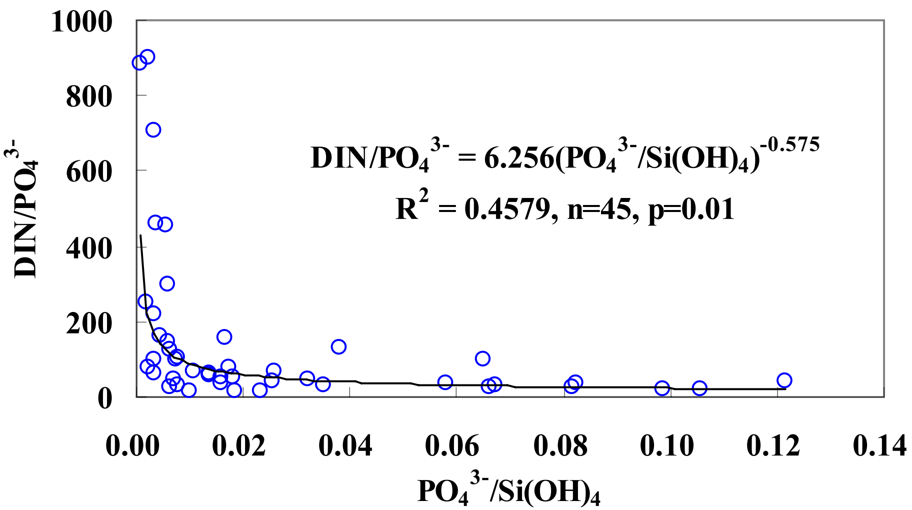

Fig. 2. The atomic ratios of DIN to PO_4^{3-} versus PO_4^{3-} to $Si(OH)_4$ in large Chinese estuaries and embayment.

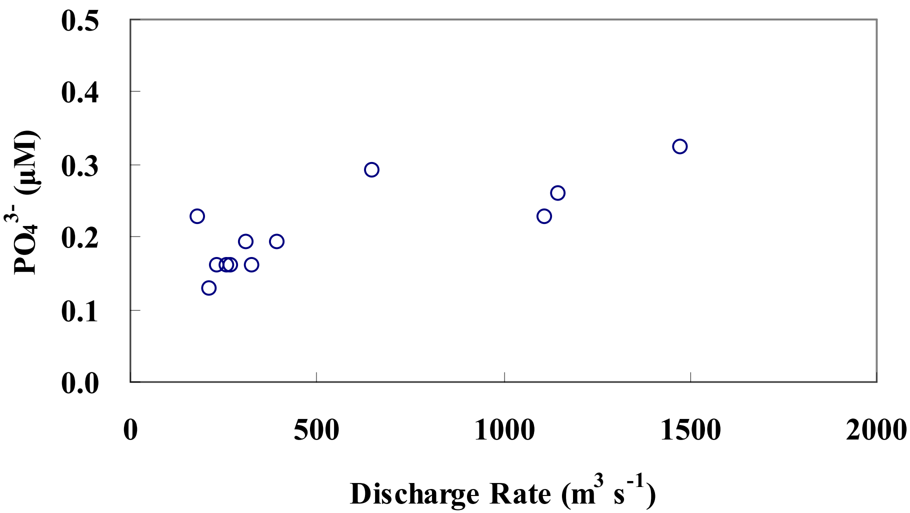

Fig. 3. Nutrient concentration (PO_4^{3-}) and discharge rate of the Han River over the year, an example for the Korean rivers (Data was taken from Kim et al., 2004b).

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