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# Nutrients in the Changjiang and its tributaries

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**Abstract.** Dissolved and particulate, organic and inorganic N, P and Si were measured in the main stream and 15 major tributaries of the Changjiang (Yangtze River) in April–May 1997. The nutrient concentrations are related to water discharge, suspended particulate matter, anthropogenic activities etc. The nutrient levels were quite low in the upper reaches, and significantly increased in the main stream in a region of 2000–3000 km inland from the river mouth. The northern tributaries contribute more nutrients to the Changjiang than the southern tributaries. Based on atomic ratios of N, P and Si, the limiting nutrient in the Changjiang drainage basin was P. The nutrient yields in the Changjiang and its major tributaries indicated high rates of transport of nutrients within the watersheds. Concentrations of nitrate in the Changjiang have increased, but there have been no systematic trends for phosphate and silicic acid since 1980. The DIN/P ratios and DIN/Si ratios increased. The DIN/P and DIN/Si ratios may be expected to continue to increase after construction of the "Three Gorges Dam", which will exercise a great deal of influence on the ecological environment of the Changjiang estuary and its adjacent sea.

## Introduction

Riverine transport is the principal pathway of suspended and dissolved elements from land to the sea. Changes in riverine end-member nutrient concentrations and their ratios may affect coastal ecosystems. One of the potential impacts is to influence phytoplankton production rates (Justic et al. 1995), which leads to a shift of phytoplankton species offshore (Rabalais et al. 1996).

The Changjiang (Yangtze River) is the largest river in Euro-Asian continent, and is ranked third in length (6300 km), fifth in freshwater discharge ($924.8 \times 10^9$ $m^3\ yr^{-1}$) and fourth in sediment discharge ($0.5 \times 10^9$ tons $yr^{-1}$) in the world (Tian et al. 1993). The drainage area is $1.80 \times 10^6\ km^2$. In 1992, about 35% of the national population lived in the Changjiang drainage basin with about 1% of the annual growth rate of population. The drainage basin provides 24% of national arable land, 35% of national crop production, 32% of national gross output of agriculture and 34.5% of national gross output of industry. About $4.5 \times 10^4$ dams were constructed before the 'Three Gorges Dam' (TDG) in the Changjiang drainage basin with a total volume of $1400 \times 10^8$ $m^3$ (National Compilation Committee of Changjiang Almanac 1994–1995). The 'Three Gorges Project' (TGP) in the Changjiang drainage basin is the subject of scientific argument and concern throughout the world (e.g. Liu and Luo (1992); Zhang et al. (1999); Chen (2000)). The well known 'Three Gorges Project' (TGP) of the Changjiang started in 1994, and two cofferdams of the TGD were closed on November 8, 1997. The TGP will have far-reaching effects on environmental and human health issues over the drainage basin and the adjacent East China Sea (Zhang et al. 1999). Six months before the closure of two cofferdams, we took water and sediment samples over the Changjiang drainage basin in April–May 1997. The study was aimed to update background data of nutrient concentrations in the Changjiang drainage basin before the construction of TGD, to evaluate the potential impact of TGD on the estuarine ecosystem, and to assess the impact of weathering and human activity on nutrient concentrations in the Changjiang and its major tributaries.

## Materials and methods

The expedition was performed during April–May 1997 while the value for river discharge was approaching the annual average. Samples were collected down the main channel from upstream to the river mouth over a distance of 3500–4000 km and from 15 large tributaries, i.e. Hanjiang, Jialingjiang, Tuojiang, Minjiang, Fujiang and Daduhe in the north, and Ganjiang, Xiangjiang, Zishui, Yuanjiang, Wujiang, Niulanjiang and Chishuihe in the south (Figure 1). Table 1 tabulates the drainage areas and water and sediment loads of the major tributaries in the Changjiang drainage basin. Water samples were collected by 2 l acid-cleaned polyethylene bottles attached to the end of a 5 m glass-fibre reinforced fishing pole. The filtration was carried out immediately through pre-cleaned 0.45 $\mu$m pore size Millipore filters in a clean plastic tent. The filtrate was acidified to pH $< 2$ with high purity HC1 and stored in the dark.

Nutrients in the filtrate and particulate phosphorus (PP) were analysed using spectrometric methods described by Grassholf et al. (1983). Particulate nitrogen (PN) was determined using a CHN analyser. In this study, the concentration of dissolved inorganic nitrogen (DIN) is the sum of $NO_3^-$ $NO_2^-$ and $NH_4^+$. The concentrations of dissolved organic nitrogen (DON) and dissolved organic phosphorus (DOP) are the difference between total dissolved nitrogen (TDN) and DIN, total dissolved phosphorus (TDP) and phosphate (DIP), respectively. The concentrations of total nitrogen (TN) and total phosphorus (TP) are the sums of PN and TDN, PP and TDP, respectively.

The data quality was monitored by inter-calibrations with the international standard and repeated analyses of samples for nutrients at micromolar level. The precision for dissolved and total nutrients was 5–10% at $< 1$–10 $\mu$mol $L^{-1}$ and 1–5% at 10–100 $\mu$mol $L^{-1}$ or even higher for dissolved and total N and P (Zhang et al. 1995, 1999).

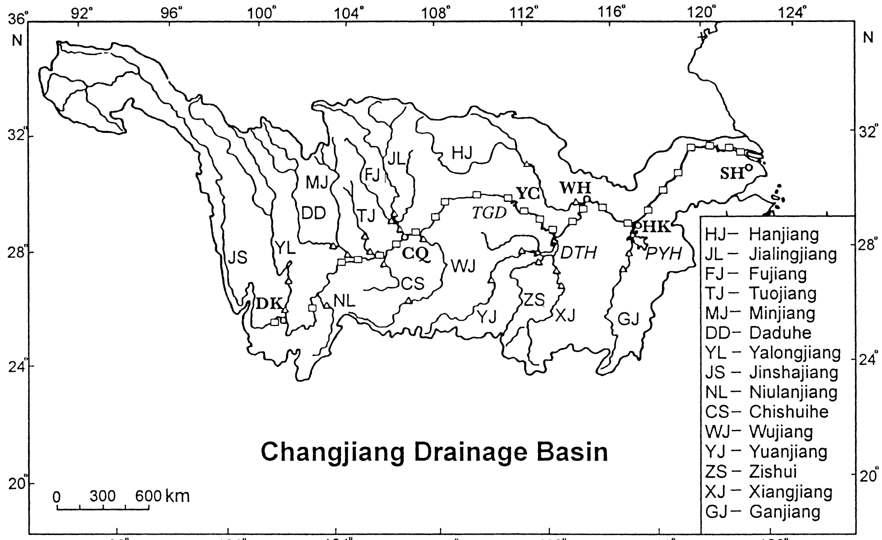


*Figure 1.* Map of the Changjiang drainage basin, which shows the main stream and 15 large tributaries. The sampling sites of water (triangles) along the major stream and tributaries are indicated. Six big cities, namely Shanghai (SH), Wuhan (WH), Chongqing (CQ), Dukou (DK), Yichang (YC) and Hukou (HK) are also shown. The 'Three Gorges Dam' is located ~1950–2000 km inland from the river mouth and ~770 km upstream of Wuhan, and the reservoir extends upstream to Chongquing. Two big lakes, i.e., Dongtinghu (DTH) and Poyanghu (PYH), are illustrated. The Dongtinghu connects the Xiangjiang, Yuanjiang and Zishui with the main channel, the Poyanghu connects the Ganjiang with the main stream.

## Results and discussion

### *Nutrients in the Changjiang and its major tributaries in April–May, 1997*

The concentrations of N, P and Si in the main stream of the Changjiang are in Figure 2, and that of the major tributaries of the Changjiang are in Table 2. The results show that the distributions of $NO_3^-$, DIN, TDN and TN were similar to each other. The nutrient concentrations were quite low in the upper reaches, with 1.10 $\mu$mol $L^{-1}$ for nitrate, 3.5 $\mu$mol $L^{-1}$ for DIN, 3.5 $\mu$mol $L^{-1}$ for TDN and 4.7 $\mu$mol $L^{-1}$ for TN (Figure 2). These results are attributed to the low population density and limited human perturbation of the landscape. The nutrient concentrations increased to 139 $\mu$mol $L^{-1}$ for nitrate, 155 $\mu$mol $L^{-1}$ for DIN, 167 $\mu$mol $L^{-1}$ for TDN, and 180 $\mu$mol $L^{-1}$ for TN in the main stream in a region of 2000–3000 km inland from the river mouth. At the confluence of major tributaries, including the Jialingjiang, Minjiang, Tuojiang and Hanjiang in the north and Wujiang in the south there was a dramatic increase of nutrient concentrations (Table 2). These tributaries are characterised by an intensive anthropogenic perturbation (Zhang et al. 1999). Further downstream, the nutrient concentrations decreased and remained fairly stable, with 70–98 $\mu$mol $L^{-1}$ for $NO_3^-$, 74–100 $\mu$mol $L^{-1}$ for DIN, 78–113 $\mu$mol $L^{-1}$

*Table 1.* Length, drainage areas, long-term water and sediment loads of the major tributaries in the Changjiang drainage basin. See Figure 1 for the locations of individual river systems

| Tributary | Length (cm) | Drainage area $\times 10^4$ km$^2$ | Water discharge ($\times 10^8$ m$^3$ yr$^{-1}$) | Sediment load ($\times 10^6$ tons yr$^{-1}$) |
|---|---|---|---|---|
| Northern tributaries | | | | |
| Hanjiang[a] | 1565 | 15.9 | 557 | 36.2 |
| Jialingjiang[a] | 1120 | 15.8 | 696 | 155.8 |
| Tuojiang[b] | 702 | 2.79 | 127 | 12.4 |
| Fujiang[b] | 700 | 3.64 | 154 | 18.8 |
| Minjiang[a] | 711 | 13.6 | 921 | 50.2 |
| Daduhe[b] | 1062 | 8.27 | 486 | 8.07 |
| Yalongjiang[a] | 1190 | 12.8 | 586 | 12.0 |
| Southern tributaries | | | | |
| Ganjiang[a] | 744 | 8.09 | 664 | 11.2 |
| Xiangjiang[a] | 856 | 9.47 | 759 | 11.6 |
| Zishui[a] | 653 | 2.81 | 239 | 3.03 |
| Yuanjiang[a] | 1033 | 8.92 | 667 | 15.2 |
| Wujiang[a] | 1020 | 8.72 | 530 | 32.9 |
| Chishuihe[b] | 445 | 2.04 | 81.8 | 11.0 |
| Niulanjiang[b] | 423 | 1.32 | 55 | 14.6 |

[a] Data are from National Compilation Committee of Hydrology Almanac, 1990
[b] Data are from Zhu (1993)

for TDN and 81–129 $\mu$mol L$^{-1}$ for TN, respectively. The dilution effect by the tributaries (Xiangjiang and Ganjiang) was observed in the lower reaches down to the river mouth (Figure 2, Table 2).

The concentrations of $NH_4^+$ ranged from 0.2 to 16.4 $\mu$mol L$^{-1}$ with an average of 3.7 $\mu$mol L$^{-1}$ in the Changjiang. Like $NO_3^-$, the concentrations of $NH_4^+$ increased by two orders of magnitude in the main stream in a region 2000–3000 km further inland from the river mouth than the upper reaches, mainly the effects of Jialingjiang, Tuojiang, Hanjiang and Minjiang in the northern part (Figure 2, Table 2). Further downstream, the concentrations of ammonium decreased, with most usually at 0.44–3.37 $\mu$mol L$^{-1}$.

The concentrations of DON were less than 23.4 $\mu$mol L$^{-1}$ with an average of 10.9 $\mu$mol L$^{-1}$ in the river. The distributions of DON were near analytical zero values in the upper reaches and significantly increased to 9.0–23.4 $\mu$mol L$^{-1}$ and remained somewhat stable down to the river mouth over a distance of $\sim$3000 km. The DON concentrations were less than 192 and 68.0 $\mu$mol L$^{-1}$ with averages of 44.2 and 22.4 $\mu$mol L$^{-1}$ in the northern and southern tributaries, and 4 and 2 times higher than in the main stream, respectively. The major tributaries will have much influence on the DON concentrations of the Changjiang (Figure 2, Table 2).

The concentrations of PN ranged from 1.12 to 18.4 $\mu$mol L$^{-1}$ with an average of 8.2 $\mu$mol L$^{-1}$ in the Changjiang. Again, the PN concentrations showed quite

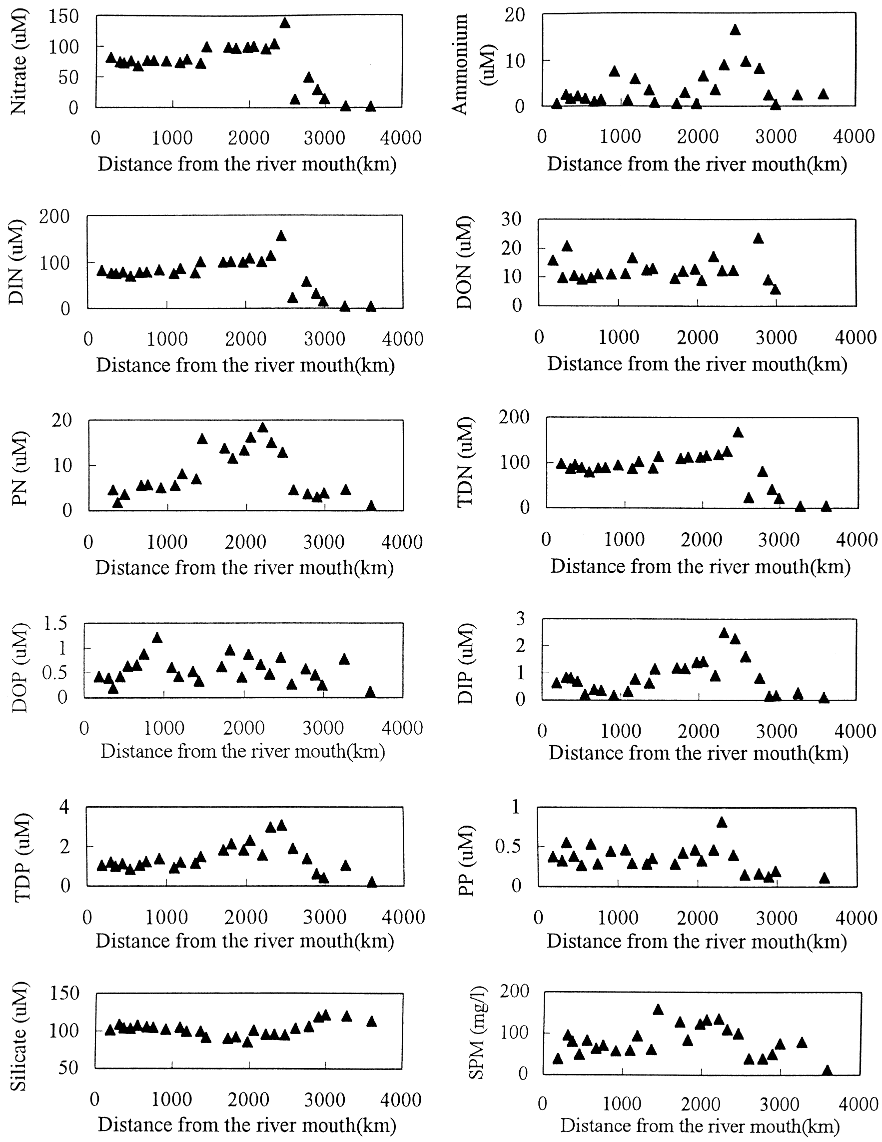


*Figure 2.* Concentrations of nutrients in the main stream of the Changjiang, which are plotted against the distance from the river mouth.

high values in the main stream in a region of 2000 to 3000 km inland from the river mouth (Figure 2). The linear relationships between SPM and PN were significant, with a coefficient of determination $r^2 = 0.736$ ($n = 25$), 0.998 ($n = 11$) and 0.918 ($n = 11$) in the main stream, northern and southern tributaries, respectively. The major tributaries from the north and south contribute large amounts of PN to the main stream (Table 2).

*Table 2.* The concentrations of nutrients ($\mu$mol $L^{-1}$), suspended particulate matter (SPM) (mg $L^{-1}$) and atomic ratios of nutrients in the major tributaries of the Changjiang

| Tributary | SPM | $H_4SiO_4$ | DIP | DOP | PP | $NO_3^-$ | $NH_4^+$ | DON | PN | DIN | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | P | Si |
| Northern tributaries | | | | | | | | | | | |
| Hanjiang | 9.96 | 99.1 | 0.20 | 0.75 | 0.36 | 74.0 | 6.57 | 22.5 | 1.62 | 403 | 0.81 |
| Jialingjiang | 5.2 | 48.4 | 0.99 | 0.27 | 0.21 | 48.7 | 10.5 | 17.0 | 0.72 | 60 | 1.22 |
| Tuojiang | 6.60 | 80.0 | 19.2 | 3.91 | 1.24 | 404 | 171 | 163 | 0.89 | 30 | 7.19 |
| Fujiang | 349 | 76.9 | 0.80 | 0.42 | 1.35 | 92.6 | 28.0 | 22.6 | 64.7 | 151 | 1.57 |
| Minjiang | 5.48 | 91.9 | 1.06 | 0.15 | 0.29 | 75.7 | 4.64 | 24.2 | 0.67 | 76 | 0.87 |
| Daduhe | 8.28 | 81.6 | 0.062 | 0.26 | 0.30 | 30.4 | 16.5 | 24.5 | 1.30 | 756 | 0.57 |
| Yalongjiang | 21.4 | 114 | 0.12 | 0.21 | 0.11 | 13.0 | 0.66 | 4.75 | 1.65 | 114 | 0.12 |
| Southern tributaries | | | | | | | | | | | |
| Ganjiang | 44.1 | 150 | 0.15 | 0.39 | 0.48 | 39.9 | 3.41 | 13.2 | 7.75 | 289 | 0.29 |
| Xiangjiang | 98.1 | 99.1 | 0.23 | 0.61 | 0.50 | 55.5 | 10.7 | 17.1 | 17.9 | 288 | 0.67 |
| Zishui | 10.0 | 94.5 | 0.20 | 0.78 | 0.18 | 74.0 | 4.81 | 24.5 | 1.29 | 394 | 0.83 |
| Yuanjiang | 30.5 | 125 | 0.16 | 0.38 | 0.25 | 19.9 | 10.1 | 7.66 | 3.65 | 188 | 0.24 |
| Wujiang | 45.2 | 68.3 | 6.06 | 0.84 | 0.52 | 91.9 | 0.80 | 34.4 | 5.49 | 15 | 1.36 |
| Chishuihe | 32.3 | 61.8 | 0.015 | 0.25 | 0.45 | 97.0 | 7.10 | 8.86 | 3.46 | 6940 | 1.68 |
| Niulangjiang | 24.0 | 123 | 0.062 | 0.14 | 0.17 | 13.7 | 0.77 | 68.0 | 6.69 | 234 | 0.12 |

The concentrations of DIP, TDP and TP ranged from 0.08 to 2.5, 0.19 to 3.07 and 0.3 to 3.79 $\mu$mol $L^{-1}$ with averages of 0.83, 1.38 and 1.82 $\mu$mol $L^{-1}$, respectively. Like $NO_3^-$, TDN and TN, the nutrient concentrations were quite low in the upper reaches, with 0.08 $\mu$mol $L^{-1}$ for DIP, 0.19 $\mu$mol $L^{-1}$ for TDP and 0.3 $\mu$mol $L^{-1}$ for TP. The nutrient concentrations increased by a factor of 30 for DIP, 13–16 for TDP and TP in the main stream in a region 2000–3000 km inland from the river mouth. Major tributaries, including the Wujiang, Tuojiang and Minjiang were indicated to have significant effects on the main stream (Figure 2, Table 2).

The concentrations of DOP varied from 0.12 to 1.21 $\mu$mol $L^{-1}$ with an average of 0.56 $\mu$mol $L^{-1}$ in the Changjiang. The concentrations of PP ranged from 0.11 to 0.82 $\mu$mol $L^{-1}$ with an average of 0.33 $\mu$mol $L^{-1}$. The PP concentrations were low in the upper reaches with 0.11 $\mu$mol $L^{-1}$ for PP, which increased by a factor of 9 in the main stream in a region 2000–3000 km inland from the river mouth and remained stable down to the river mouth (Figure 2, Table 2). The concentrations of PP in the main stream were lower than the southern and northern tributaries. The linear relationships between SPM and PP were not significant. The major tributaries contribute much PP to the main stream.

The concentrations of silicate ranged from 84.7 to 121 $\mu$mol $L^{-1}$ with an average of 102 $\mu$mol $L^{-1}$ in the main channel. The concentrations in the main channel are comparable to those in the southern tributaries (105 $\mu$mol $L^{-1}$) but somewhat higher than those in the northern streams (84.9 $\mu$mol $L^{-1}$). The silicate arises almost entirely from natural weathering and erosion. The tributaries in the south have more extensive leaching of silica from drainage areas than those in the north, followed by higher dissolved silicon concentrations in the south than in the north (Zhang 1996).

On average, particulate N and P were similar in the northern and southern tributaries, while dissolved N and P in the northern tributaries were 2 to 7-fold higher than in the southern tributaries. That higher concentrations of dissolved nutrients in the northern tributaries is probably related to intense soil erosion in the northern part (e.g. Tuojiang, Minjiang) (Zhang et al. 1996), and to paddy-fields being the main agriculture in the southern part (Zhang et al. 1996), which illustrates that nutrients can be mostly retained in the fields without input into the streams.

The concentrations of suspended particulate matter (SPM) ranged from 11.2 to 159 mg $L^{-1}$ with an average of 80.8 mg $L^{-1}$ in the main stream of the Changjiang, which was higher than those in the northern (40.8 mg $L^{-1}$) and southern (45.7 mg $L^{-1}$) tributaries. The sediment load has impacts on nutrient concentrations. With the increasing of SPM concentrations, the concentration of silicate decreased slightly, the concentrations of dissolved inorganic and total N and P increased, while the concentrations of ammonium and dissolved organic N and P had no obvious trend. The distribution features of SPM in the investigation periods is different from the long-term average, that is, owing to higher, steeper, and more poorly vegetated terrain, sediment loads of the upper reaches and northern tributaries are much greater than those of the southern tributaries. The northern tributaries have sediment concentrations one order of magnitude or more greater than those of the southern tributaries (Shi et al. 1985).

*Composition of N and P*

Nitrate accounted for 30% of TDN in the upper reaches and increased up to 86% in a region 2000–3000 km inland from the river mouth, and remained somewhat stable down to the river mouth. Nitrate was 50–80% of the TDN in most of the major tributaries. In contrast to nitrate, ammonium represented more than 60% of TDN in the upper reaches, and decreased significantly to no more than 20% of TDN ~3000 km down to the river mouth. The results also show that DIN accounted for most, at 80–100% of TDN and the DON represented no more than 20% of TDN in the main stream and its tributaries. In the TN, TDN had absolute predominance (> 90%) and the PN was less important (< 10%) in the Changjiang and its major tributaries.

With respect to phosphorus, DIP represented less than 40% of the TDP in the upper reaches, and increased to 80% of the TDP in a region 2000–3000 km inland from the river mouth following the confluences of Yalongjiang, Minjiang, Tuojiang and Jialingjiang in the north and Wujiang in the south. While DIP was a minor species (20%) in the TDP in the main stream in a region ~500–1000 km inland from the river mouth, following the confluence of Hanjiang in the north and Ganjiang, Xiangjiang, Yuangjiang and Zijiang in the south. The TDP accounted for 60–95% of TP, and PP accounted for 10–40% of the TP in the Changjiang and its major tributaries.

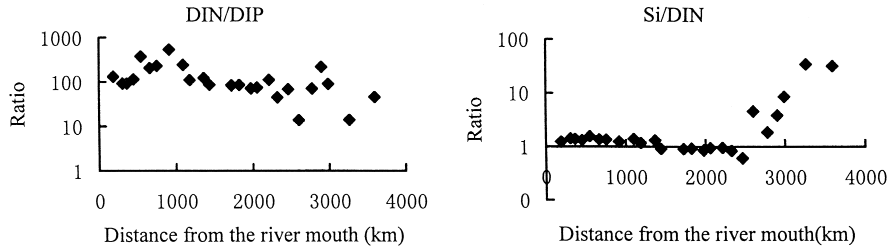


*Figure 3.* Atmoic ratios of N, P and Si species in the Changjiang, which are plotted against the distance from the river mouth.

The compositions of nitrogen species were similar in the main stream and the major tributaries. While the phosphorus species was different, within the TDP, the DIP was the major species (56%) in the northern tributaries, but was minor species (32%) in the southern tributaries. The DOP was the minor composition (44%) in the north part, but major composition (68%) in the south part. The compositions of phosphorus were similar in the main channel and the northern streams.

*Nutrient ratio*

Ratios of dissolved nutrients were compared with typical values for uptake of phytoplankton in order to determine which nutrient would first be depleted. The DIN: DIP ratios were between 14–200 with most of the values at 40–100 in the upper reaches to ∼1000 km inland from the river mouth, increased to 200–500 in the main stream in a region ∼500–1000 km inland from the river mouth, and remained at 90–130 downstream (Figure 3). The high ratios were also observed in most of the tributaries (Table 2). While it is difficult to give definite results from the references as to which nutrient in the Changjiang is the limiting element for phytoplankton growth, it is possible to estimate which nutrient is potentially limited. Kahlert (1998), based on a literature survey, proposed that N:P > 32 for P limitation and N:P < 12 for N limitation for freshwater periphyton. Hu et al. (1990) showed, by bioassay in laboratory experiments of, that in the Changjiang Estuary N limits phytoplankton production if N:P < 8, while P is the limiting nutrient if N:P > 30. This indicates that biological activity is strongly P limited in the Changjiang and its tributaries.

It can be expected that part of the suspended particulate matter will be trapped within the reservoir after construction of the TGD, and the nitrogen levels will continue to increase following the population increase and economic growth over the drainage basin, as well as atmospheric deposition, while phosphorus is particle active compared to N in an aquatic environment. The P limitation, therefore, will be more serious than at present. Zhang et al. (1999) expected by model calculation that the N:P ratio of the river would reach 300–400 after the year 2010.

The ratios of silicate to DIN were quite high in the upper reaches, with SI: DIN ratios up to 34 (Figure 3), owing to low concentrations of DIN in the upper reaches (Figure 2). The Si: DIN ratios remained stable at 0.7–2 downstream to the river

*Table 3.* Comparison of the nutrient concentrations in the Changjiang with other national and world rivers ($\mu$mol $^{-1}$)

| River | $NO_3^-$ | $NH_4^+$ | $H_4SiO_4$ | DIP | DIN | DON | DOP | Reference |
|---|---|---|---|---|---|---|---|---|
| Yalujiang | 129 | 1.4 | 156 | 0.16 | 130 | | | Zhang et al. (1998) |
| Daliaohe | 7.5 | 12.5 | 29.2 | 1.71 | 20.0 | | | Zhang (1996) |
| Luanhe | 74.6 | | 87.2 | 0.51 | | | | Zhang (1996) |
| Huanghe | 122 | | 296 | 0.36 | | | | Zhang (1996) |
| Changjiang | 70.3 | 3.7 | 102 | 0.83 | 74.1 | 10.9 | 0.56 | This study |
| Zhujiang | 68 | 15.8 | 150 | 0.75 | | | | Lin et al. (1995) |
| Loire | 184 | 3.8 | 163 | 2.55 | 187 | 64.3 | 1 | Meybeck et al. (1988) |
| Po | 150 | 24.4 | 120 | 4.6 | 174 | | 0.35 | Degobbis and Gilmartin (1990) |
| Rhine | 106 | 37.9 | 55.5 | 6.77 | 144 | | 0.3 | van der Weijden and Middelburg (1989) |
| Seine | 429 | | 183 | 32.3 | | | | Garnier et al. (1995) |
| Brittany | | | | 3.91 | 466 | 34.1 | 0.79 | Wafar et al. (1989) |
| Rhone | | | | 0.13 | 111 | | | Denant and Saliot (1990) |
| Zaire | 6.5 | | 165 | 0.8 | | | | Bennekom et al. (1978) |
| Amazon | 10 | | 115 | 0.7 | 16.7 | | | DeMaster and Pope (1996) |
| | | | | | | | | Edmond et al. (1981) |

mouth (Figure 3). The results also show that high Si: DIN ratios were observed in Yalongjiang, Yuanjiang, Ganjiang and Niulanjiang from the north and south of the watersheds (Table 2). While the removal of N within the reservoir is expected to be compensated by the anthropogenic inputs downstream of the dam, this may lead to silica limitation in the Changjiang estuary and its coastal areas.

*Comparison with other rivers*

Differences in nutrient concentrations exist among the Chinese rivers (Table 3). High levels of $NO_3^-$ and silicate were observed from the Huanghe and Yalujiang, whereas the Daliaohe exceeds the others in DIP and $NH_4^+$, other rivers show intermediate values. Evidently, the silicate levels in South China rivers (e.g. Zhujiang) are higher than those from North China rivers (e.g. Daliaohe and Luanhe). 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 (Zhang 1996).

Compare the nutrient level of Changjiang with those in large and less disturbed world systems, the $NO_3^-$, DIP and $NH_4^+$ levels in the Changjiang are 10, 2 and 3 times, respectively, higher than those from large and less disturbed world systems (Meybeck 1982). This may be ascribed to both extensive leaching and influences from agricultural and domestic activities over the drainage basin (Zhang 1996). The nutrient levels in the Changjiang are higher than those of the large and less disturbed world rivers such as the Amazon and Zaire, etc., but comparable to values for European and North American polluted and eutrophic rivers like the Loire, Po, Rhine, Seine, etc. (Table 3).

As the weight ratios of nitrogen and phosphorus fertilizers used in China may be up to 10–20 or even more, and nitrogen is much easier to leach away from the drainage basin than phosphorus (Zhang et al. 1995). Therefore, N: P ratios in most Chinese rivers are higher (up to 100–800) than the other rivers of the world, for example N: P ratio is 24 in the Amazon, 13–38 in the Po, Rhine and Seine rivers (Table 3).

*Nutrient denudation within the Changjiang drainage basin*

Riverine ion compositions can be affected by climate, vegetation, geographic and tectonic conditions, that form the basic setting of weathering in the drainage basin. However, anthropogenic activities (e.g. fertilizer application) are imposed. The weathering products can be carried away by surface runoff or other transport means (e.g. underground water). For the chemical erosion, uncertainty arises from the variations of discharge and ion compositions, other sources like atmospheric deposition, migration by biological processes, pollution drainage, and the recycling of chemical substances in the drainage basin, all have obvious influences on the chemical erosion rate. With the limited water discharges of the main stream of the Changjiang and its tributaries, the areal yields, in this study defined as element concentration times the long-term average river discharge, divided by the drainage area, illustrate the contribution of elements from tributary drainage areas (Figure 4, Table 4).

Silicate is mainly delivered via weathering, which is restrained by the interaction of tectonic conditions, rock/soil and climate. The areal yields of silicate varied from 33.8 to 51.9 mmol $m^{-2}$ $yr^{-1}$ with an average of 41.9 mmol $m^{-2}$ $yr^{-1}$ in the Changjiang, which slightly increased from upper to lower reaches. The silicate yields in the Ganjiang, Xiangjiang, Zijiang and Yuanjiang in the southern tributaries were 2 times higher than in the main stream, but have less influence on the main stream due to the regulation of Dongtinghu and Poyanghu (Figure 4, Table 4). The silicate yields increased by a factor of 2 from the northern to the southern part of the Changjiang. This can be related to chemical weathering which is much stronger in the hot and wet south than in the cool and dry north of the watersheds (Qu et al. 1993). As a consequence of climate influence on weathering, tributaries in the south often have higher values of silicate than those in the north of the Changjiang (Table 2).

The chemical yields were 0.35 to 42.3 mmol $m^{-2}$ $yr^{-1}$ with 27.1 mmol $m^{-2}$ $yr^{-1}$ on average for $NO_3^-$, 0.99 to 43.3 mmol $m^{-2}$ $yr^{-1}$ with 28.6 mmol $m^{-2}$ $yr^{-1}$ on average for DIN, 0.99 to 49.8 mmol $m^{-2}$ $yr^{-1}$ with 33.4 mmol $m^{-2}$ $yr^{-1}$ on average for TDN, and 2.27 to 55.3 mmol $m^{-2}$ $yr^{-1}$ with averages of 36.1 mmol $m^{-2}$ $yr^{-1}$ for TN, respectively. The yields were much lower in the upper reaches and increased by a factor of more than 3 in the main stream in a region 3000–4000 km from the river source, then remained stable downstream. This can be related to high

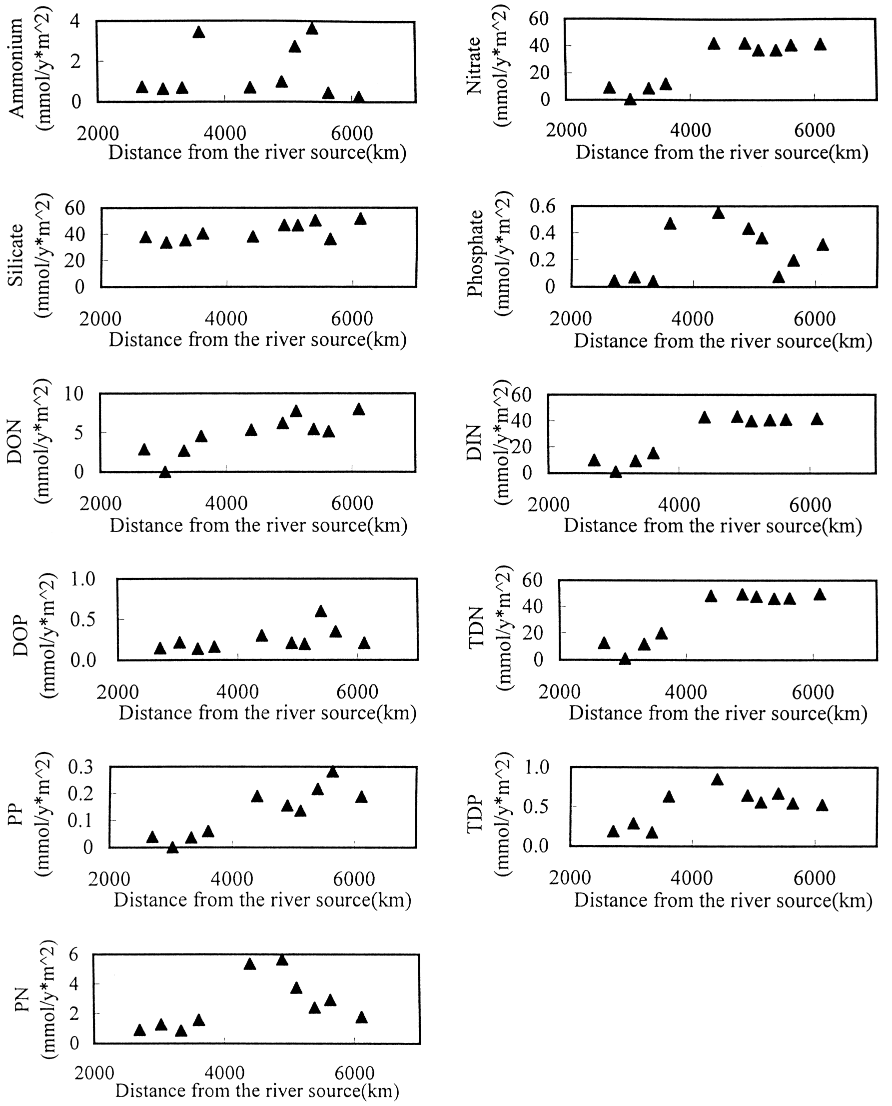


*Figure 4.* Areal yields of nutrient species in the main stream of Changjiang, which are plotted against the distance from the river source.

yields in major tributaries like Minjiang, Jialingjiang, Wujiang and Zishui, and intense anthropogenic activities, e.g. applying fertiliser, draining waste discharge.

The ammonium yields ranged from 0.25 to 3.65 mmol $m^{-2}$ $yr^{-1}$ with an average of 1.43 mmol $m^{-2}$ $yr^{-1}$ in the Changjiang. The DON yields were less than 8.01 mmol $m^{-2}$ $yr^{-1}$ with an average of 4.82 mmol $m^{-2}$ $yr^{-1}$, which increased by a factor of 4 from the upper to the lower reaches. The DON yields in almost all of the tributaries were higher than in the main stream.

*Table 4.* The areal yields of nutrients (mmol $m^{-2}$ $yr^{-1}$) in the major tributaries of the Changjiang

| Tributary | $H_4SiO_4$ | $NO_3^-$ | $NH_4^+$ | DON | PN | DIP | DOP | PP |
|---|---|---|---|---|---|---|---|---|
| Northern tributaries | | | | | | | | |
| Hanjiang | 36.2 | 28.6 | 1.55 | 9.80 | 0.848 | 0.097 | 0.375 | 0.147 |
| Jialingjiang | 24.2 | 41.6 | 7.22 | 15.0 | 0.348 | 0.455 | 0.229 | 0.106 |
| Tuojiang | 27.2 | 218.9 | 72.3 | 87.3 | 0.255 | 11.0 | 2.03 | 0.196 |
| Minjiang | 62.3 | 51.3 | 3.15 | 16.4 | 0.454 | 0.721 | 0.102 | 0.197 |
| Yalongjiang | 53.4 | 6.02 | 0.401 | 2.43 | 1.20 | 0.070 | 0.082 | 0.073 |
| Southern tributaries | | | | | | | | |
| Ganjiang | 123.1 | 32.7 | 0.681 | 10.8 | 6.35 | 0.120 | 0.320 | 0.394 |
| Xiangjiang | 79.4 | 44.5 | 8.56 | 13.7 | 14.3 | 0.185 | 0.485 | 0.397 |
| Zishui | 80.3 | 62.9 | 4.09 | 20.8 | 1.09 | 0.170 | 0.662 | 0.153 |
| Yuanjiang | 81.1 | 1.41 | 3.70 | | 1.07 | 0.185 | 0.195 | 0.120 |
| Wujiang | 45.9 | 40.0 | 0.286 | 13.4 | 6.93 | 1.23 | 0.358 | 0.565 |
| Chishuihe | 24.7 | 38.8 | 2.84 | 3.55 | 2.22 | 0.006 | 0.100 | 0.18 |

The PN yields were between 0.85 and 5.67 mmol $m^{-2}$ $yr^{-1}$ with an average of 2.66 mmol $m^{-2}$ $yr^{-1}$. The PN yields were rather low in the upper reaches, and significantly increased by a factor of 5 in the main stream at $\sim$4000 km from the river source, and decreased further downstream. The PN yields in the main stream were much higher than in the northern tributaries, but only half of those in southern tributaries. The increased rainfall and temperature lead to development of vegetation, thus enhancing chemical/biological weathering relative to physical denudation (Qu et al. 1993).

The chemical yields of DIP, TDP and TP ranged from 0.042 to 0.55, 0.18 to 0.85 and 0.21 to 1.04 mmol $m^{-2}$ $yr^{-1}$ with averages of 0.26, 0.51 and 0.71 mmol $m^{-2}$ $yr^{-1}$, respectively. Like nitrogen, the yields of dissolved phosphorus were rather low in the upper reaches, increased by a factor of 3–10 in the main stream in a region 3000–4000 km from the river source, and decreased slightly further downstream. The major tributaries, including Tuojiang, Minjiang and Jialingjiang in the north and Wujiang in the south have significant impacts on the phosphorus yields in the main stream (Figure 4, Table 4).

The yields of DOP and PP varied from 0.14 to 0.60 and 0.036 to 0.28 mmol $m^{-2}$ $yr^{-1}$ with averages of 0.25 and 0.15 mmol $m^{-2}$ $yr^{-1}$, respectively. The DOP and PP yields increased by a factor of 4 to 7 from upper to lower reaches, respectively. The major tributaries (Tuojiang and Wujiang) have quite heavy impacts on the yields of DOP in the main stream (Figure 4).

The average areal yields of $NO_3^-$, $NH_4^+$, DIP and silicate in the main stream of the Changjiang were 27.1, 1.43, 0.26 and 41.9 mmol $m^{-2}$ $yr^{-1}$, respectively, while they were 41.5, 0.25, 0.32 and 51.9 mmol $m^{-2}$ $yr^{-1}$ respectively in the river mouth (Figure 4). Edmond et al. (1985) calculated areal yields for $NO_3^-$, DIP and silicate for the Changjiang, based on data from the 1980–1981 cruises in the estuary, which were higher than this study except for $NO_3^-$. Zhang (1996) obtained higher yields for $NH_4^+$, similar yields for DIP and silicate, lower yields for $NO_3^-$ relative to this study. The comparison with the nutrient yields from the Amazon suggests a serious removal and loss of nutrients from the Changjiang watersheds (Edmond et al. 1985), which again reflects intense agricultural and domestic activities in China.

The areal yields of dissolved nitrogen and phosphorus increased by a factor of 2–7 from the south to the north tributaries of the watersheds (Table 4). This demonstrates more intensive domestic and agricultural activities in the northern than in the southern part of Changjiang, and the effects of soil type and agriculture on nutrient levels as discussed above.

Human activities like dam construction have impacts on nutrient yields. It is known that the Danjiangkou Dam on the Hanjiang in 1968 has reduced annual suspended sediment discharge by about 90%; the Gezhou Dam has also significantly changed the sediment transport in the Changjiang (Shi et al. 1985). The silicate load of the Danube has been reduced by about two-thirds since dam construction in the early 1970s, which has been instrumental in causing the observed changes in Black Sea surface waters (Humborg et al. 1997). Nutrient concentrations have seasonal variation in the Changjiang (Edmond et al. 1985; Shen 1993), thus nutrient yields will be changed after the construction of the TGD.

*Historical trends*

The data collected since 1980 indicate that concentrations of $NO_3^-$ increased in the Changjiang. In the same period, concentrations of phosphate and silicate showed no systematic trends, thus the N/P and N/Si ratios increased (Figure 5). It has also been reported that levels of nitrogen species ($NO_3^-$ and $NH_4^+$) in the Changjiang, from observations close to the river mouth but unaffected by seawaters, have doubled from 1980 to 1992 (Zhang et al. 1995).

In the Changjiang drainage basin, crop production increased from $112 \times 10^6$ tons in 1980 to $170 \times 10^6$ tons in 1996 (Figure 6). Population rose from $3.4 \times 10^8$ in 1980 to $4.1 \times 10^8$ in 1996 (Figure 6), which corresponds to a crop population level of 320 kg per person in 1980 and 410 kg per person in 1996, respectively. At the same time, cultivation areas for crop production decreased from $35.8 \times 10^7$ ha in 1980 to $34.1 \times 10^7$ ha in 1996. Some cultivated areas have become deserts, but in most cases cultivated areas have been allocated for industrial and domestic uses.

Clearly, in order to sustain the growing populations within the limited agricultural areas in China, a direct and simple strategy has always been to increase crop production, which demands more chemical fertilisers. Figure 6 shows the consumption of chemical fertilisers in the Changjiang drainage basin. It should be kept in mind that chemical fertiliser consumption has increased by a factor of 3, i.e. from $302 \times 10^4$ tons in 1980 to $937 \times 10^4$ tons in 1996 (Figure 6). Crop production increased by a factor of 1.5 from 1980 to 1996, corresponding to an increase by a factor of 3 for fertiliser consumption. Taking into account the data for water chemistry, riverine chemistry trends for nutrients are in agreement with the use of chemical ferilisers in the catchment areas, and waste discharges increased from 7.7 ×

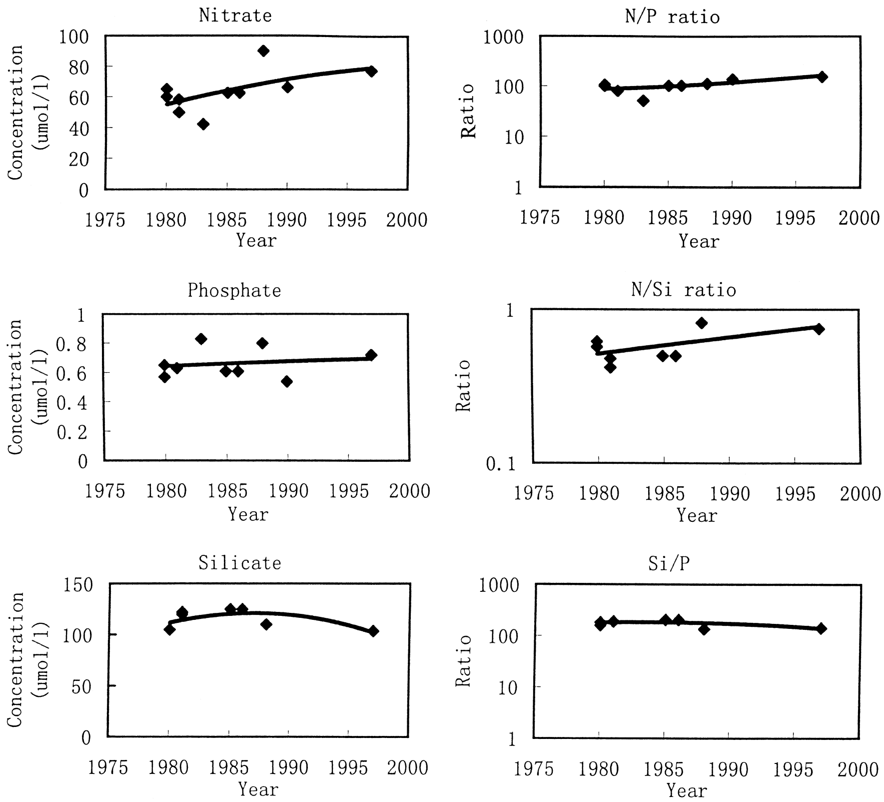


*Figure 5.* Concentrations and ratios of nutrients in the Changjiang since the last twenty years. The data are from Edmond et al. (1985); Wang et al. (1983); Huang et al. (1986); Shen et al. (1987); Shen (1993); Tian et al. (1993); Lin et al. (1984); and this study.

$10^9$ tons in 1980 to 9.1 × $10^9$ tons in 1995 (National Compilation Committee of Environmental Almanac 1996). The nutrient levels can be augmented due to low tillage skills and irrational application of chemical fertilisers. For example, it was estimated that 45.4 mg of nitrogen may be leached from every kilogram of soil in the Changjiang drainage basin, thus increase the nutrient concentrations in the watersheds (Huang et al. 1994).

Alternatively, the historical increase in nutrients in the Changjiang may result from serious erosion and/or reduction in water load. An increase in weathering and erosion may induce leaching of nutrients from soil and hence augment riverine nutrient concentrations. The area of soil erosion increased by 55% from 117 × $10^6$ ha in 1973 to 183 × $10^6$ ha in 1996.

With the limited water discharges of the major tributaries, the fluxes of dissolved nutrients input into the main stream were calculated. The fluxes of dissolved N and P increased by a factor of 2–3 in tributaries from the south to north, while the dissolved silicon fluxes were higher in the south than the north. This illustrates that

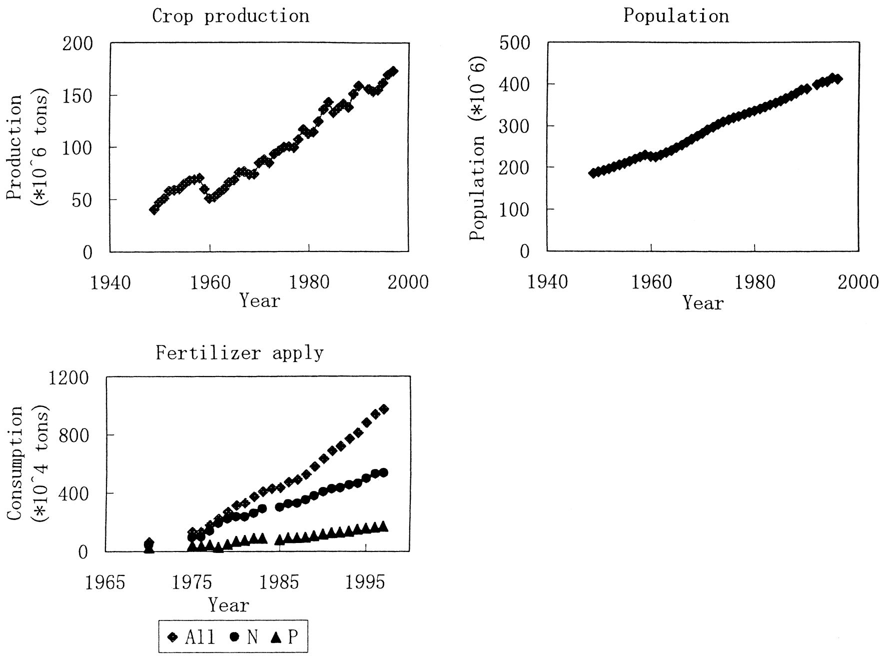


*Figure 6.* Population (× $10^4$), crop production (× $10^4$ tons) and fertiliser consumption (× $10^4$ tons) in the Changjiang drainage basin. The data show the variation of population and crop production since 1949, and the consumption of all agricultural fertiliser, nitrogen fertiliser and phosphorus fertiliser since 1970. Data are from National Compilation Committee of Changjiang Almanac (1997); National Compilation Committee of Agricultural Almanac (1997).

the silicon has mainly come from the upper reaches, and southern streams contribute more silicon to the main stream than the northern streams. While dissolved N and P in the main stream mainly comes from the norhtern tributaries.

## Conclusions

As discussed above, nutrient levels in the Changjiang depend on climate and geographic and tectonic conditions, as well as anthropogenic activities. The N and P levels were quite low in the upper reaches, and significantly increased in the main stream in a region 2000–3000 km inland from the river mouth, which shows that the northern streams contribute more nutrient burdens than the southern tributaries. Nutrient levels in the Changjiang are expected to continue to increase in the near future owing to leaching from inundated soils and intensive human activity after completion of the TGD.

The concentrations of nutrients in the Changjiang were similar to those of the other major Chinese rivers, and comparable to Europe and North American rivers. Since 1980, the concentrations of $NO_3^-$ in the Changjiang have slightly increased, while the concentrations of phosphate and silicate has no systematic trend. Phosphorus is the limiting species for phytoplankton growth in the Changjiang and its tributaries. The calculated yields show the intense agricultural and domestic origins of nutrients in the Changjiang.

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