Study on the total water pollutant load allocation in the Changjiang (Yangtze River) Estuary and adjacent seawater area

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ABSTRACT

With the rapid economic development, the water quality is worsening and red tide takes place frequently in the Changjiang Estuary and adjacent seawaters. To improve the marine water quality, the total inland pollutant load should be controlled effectively. With efficiency and fairness in consideration, the total maximum allowable loads of COD_{Mn}, NH_3–N, inorganic nitrogen and active phosphate to the seawaters were calculated and allocated by the linear programming method based on the water quality response fields of the pollution sources. The maximum allowable loads are 2008×10^3 tons, 169×10^3 tons, 226×10^3 tons and 18×10^3 tons for COD_{Mn}, NH_3–N, inorganic nitrogen and active phosphate when the water quality targets are requested to be achieved in the whole studied region, and 346×10^3 tons and 32×10^3 tons for inorganic nitrogen and active phosphate when the water quality targets to be achieved only in the red tide sensitive area. The cut task of COD_{Mn} and NH_3–N is relatively easy and can be finished by the watershed environmental plan; while the cut task of inorganic nitrogen and active phosphate is tremendous. The coastal provinces should install more denitrification and dephosphorization facilities in the existing waste water treatment plants or build new ones to control the red tides in the concerned seawaters.

1. Introduction

In the recent 30 years, the economy has been developing rapidly in the Changjiang (Yangtze River) Watershed, especially in the Changjiang Delta area. The Changjiang Estuary and adjacent seawaters become one of the most seriously polluted marine areas in China due to the accelerated urbanization and industry development (Wang, 2006; Chen et al., 2007; Zhang et al., 2007; Zhou et al., 2007; Lei et al., 2009). From 2005a to 2006a, the Ministry of Environment Protection (MEP) organized a water quality investigation in this area. According to the monitoring data, the ratios of the surface water areas with the first and second grade of COD_{Mn} water quality standards were 93.0% and 6.9%; the ratios of the surface water areas with the forth and inferior forth grade of active phosphate standards were 33.6% and 14.5%, and the ratio of the areas with the inferior forth grade of inorganic nitrogen standard was 62.6%. The inorganic nitrogen and active phosphate were the primary pollutants.

In order to improve the water quality and ecological environment, the total pollutant load from inland to the seawaters must be controlled. Based on the response relationship between the pollutant load and marine water quality, the total maximum allowable pollutant load was calculated and allocated to the pollution sources for the coastal provinces and upstream region.

2. Study site

The Changjiang River is the longest river in China. It lies in the middle of China and flows from west to east until it impounds into the China East Sea. The Changjiang Estuary and adjacent seawaters (including Qiantangjiang River Estuary) are halfly surrounded by two provinces and one city, i.e. Jiangsu, Zhejiang, and Shanghai.

Based on the marine function zoning programme enacted by the State Environmental Protection Administration (SEPA, former MEP) in 2001 (SEPA, 2002), the water quality standard objectives were set and some modifications were made according to the local water quality standards in Shanghai City and Jiangsu Province. In the inner part of the Changjiang Estuary, the water quality objectives were set by the *Environmental Quality Standards for Surface Water* (GB3838-2002, enacted in 2002) (Fig. 1).

The thousands of pollution sources in the research area were grouped into 33 conceptual pollution sources to avoid extreme complexity and confusion, including the major rivers such as Changjiang River, Qiantangjiang River, Huangpujiang River, Chaoejing River, Yongjiang River and Jiaojiang River, and 2 direct seawater discharge pollution sources in Jiangsu, 8 in Shanghai and
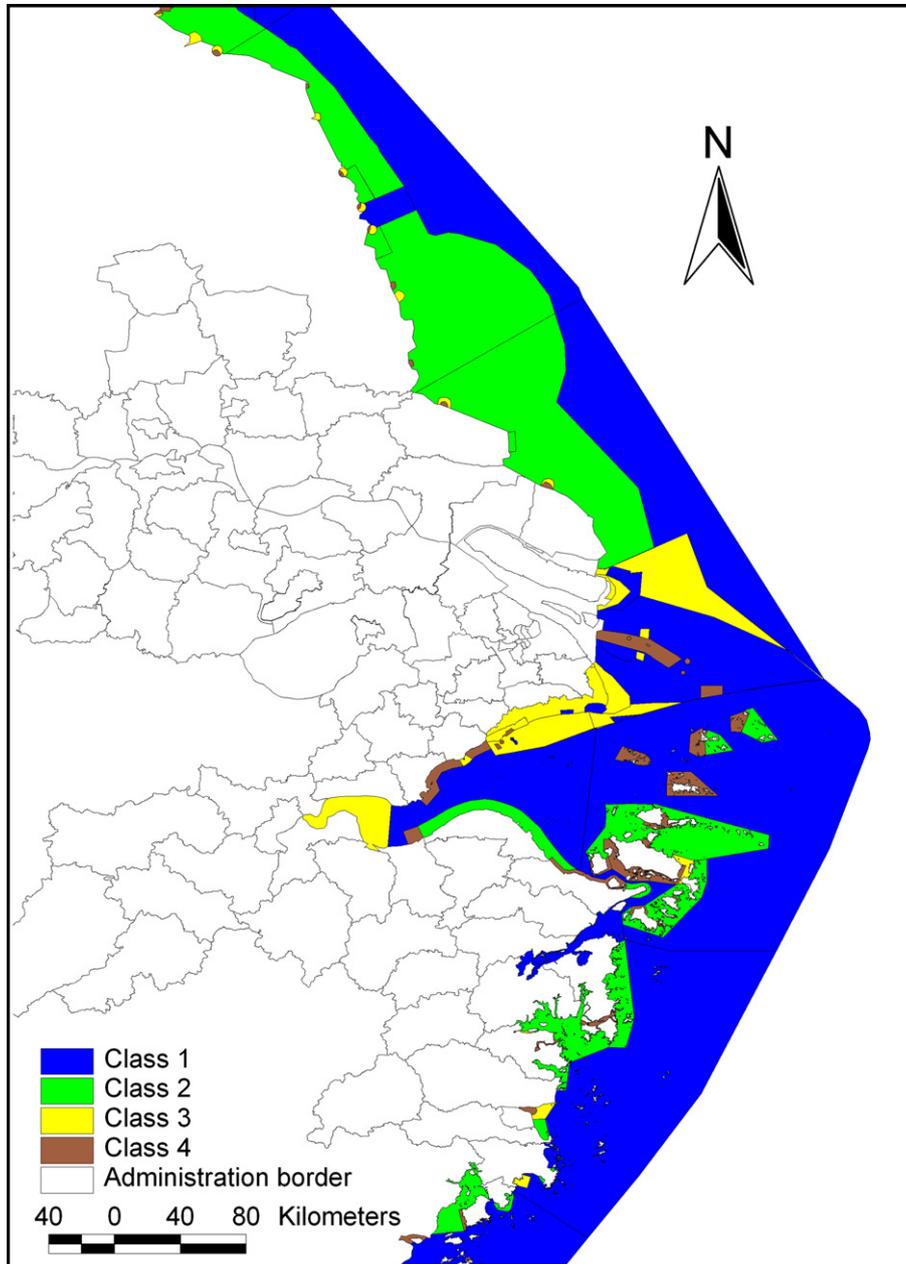

Fig. 1. Marine water quality control objectives in the research area.

17 in Zhejiang (Fig. 2). Totally 2245×10^3 tons COD_{Mn}, 194×10^3 tons NH_3-N, 136×10^3 tons inorganic nitrogen and 82×10^3 tons active phosphate were discharged into the Changjiang Estuary and adjacent seawaters in 2005. The marine aquaculture pollution and atmospheric deposition were treated as environmental background and not considered in the total load allocation in this study.

Two types of pollutants were considered. The first was the organic pollutants, including COD_{Mn} and NH_3-N. The second was the eutrophication pollutants, including dissolved inorganic nitrogen and inorganic phosphate. The *Marine Water Quality Standard* (GB 3097-1997) was adopted to set the water quality target for the above pollutants.

The design flow condition was also set differently for the above two types of pollutants. The lowest monthly average flow was selected as the design flow condition for COD_{Mn} and NH_3-N to ensure that the water quality standards can be met in most of the year. The annual average flow of multiple years was selected as

design flow condition for inorganic nitrogen and active phosphate as the eutrophication is closely relative to the substance accumulation in a long time rather than the worst hydraulic condition.

The total loads of all pollutants, i.e. COD_{Mn}, NH_3-N, inorganic nitrogen and active phosphate, were firstly allocated under the condition that the water quality targets were to be met in whole research region. Then the total loads of inorganic nitrogen and active phosphate were allocated under the condition that the water quality targets were only to be met in the red tide sensitive area. The red tide sensitive location was determined by Qi's research (Qi, 2003).

3. Method description

The linear programming method based on response field of pollution source was used in the total pollutant load allocation. Firstly the response field of each pollution source was calculated through water hydraulic and quality modeling, and the response
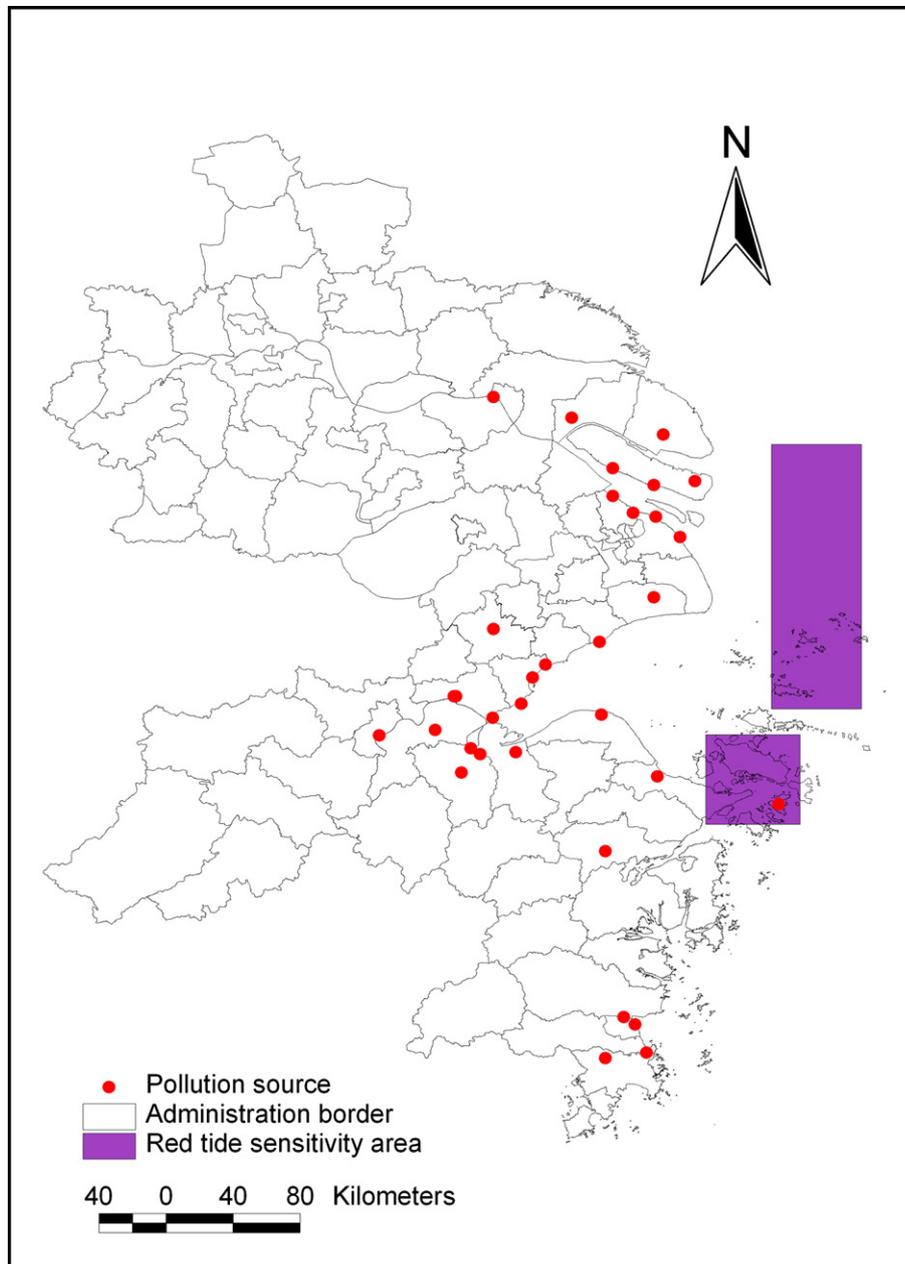
Fig. 2. Location of the conceptual pollution sources (river included). *The rectangle area is the red tide sensitive area in the research area.

relationship between the pollutant emission and water quality was built up; secondly the optimization target function and water quality constraint equations were formulated, and the linear programming method was used to calculate the environmental capacity; lastly the total maximum allowable load was allocated with the fairness among the pollution sources in consideration. The water quality model, linear programming model and total pollutant load allocation model were used respectively in the three steps.

3.1. Water quality model

The MIKE21 model was used in this research. The basic pollutant transportation equation is convection–diffusion equation (Barettaa et al., 1994; Chubarenko and Tchepikova, 2001; Lin et al., 2008):

$$\partial C/\partial t + u\, \partial C/\partial x + v\, \partial C/\partial y = D_x \partial^2 C/\partial x^2 + D_y \partial^2 C/\partial y^2 + s + KC$$

where C – pollutant concentration (mg/L); t – time (s); x,y – the latitudinal and longitudinal coordination (m); u,v – velocity component in x,y direction (m/s); D_x,D_y – turbulent diffusion coefficient in x,y direction (m^2/s); K – comprehensive degradation coefficient; s – source and sink item.

The response field of each pollution source was calculated with the above water quality model under the load with concentration of 1.0 mg/L of COD$_{Mn}$, NH$_3$–N, inorganic nitrogen and active phosphate respectively.

3.2. Linear programming model

The maximum environmental capacity was calculated only considering the environmental dilution and purification ability. The fairness among the pollution sources was not considered in this step. The formulas of the linear programming used in the capacity optimization calculation are (Appan, 1989; Zhang, 2007):

$$\max z = C^T X$$
$$\text{st.} \begin{cases} AX + B \leq S \\ X_l \leq X \leq X_u \\ X \geq 0 \end{cases} \tag{1}$$

where, z – objective function, C – coefficient vector. When the total pollutant load is considered, set $C = [1, 1, ..., 1]^T$.

A is the response matrix:

$$A = \begin{bmatrix} a_{11} & \cdots & a_{12} \\ \vdots & a_{ij} & \vdots \\ a_{m1} & \cdots & a_{mn} \end{bmatrix} \tag{2}$$

where a_{ij} – response concentration of the jth pollution source on the ith water quality control point, which was calculated by MIKE21 model in this study; m – number of the water quality control points; n – number of the pollution sources.

B is the background concentration vector, $B = [b_1, b_2, ..., b_m]^T$. S is the water quality standard vector, $S = [s_1, s_2, ..., s_m]^T$. X, X_l and X_u are the pollutant load, the upper and lower load limit vectors, $X = [x_1, x_2, ..., x_n]^T$, $X_l = [x_{l1}, x_{l2}, ..., x_{ln}]^T$, $X_u = [x_{u1}, x_{u2}, ..., x_{un}]^T$

3.3. Total pollutant load allocation model

To make the allocation more acceptable for the polluters, the principles of fairness and efficiency were considered at the same time on the basis of the environmental capacity estimation. 6 factors were considered in this step, i.e. environmental capacity, water resource, population, agriculture and economic development. The ratio of the allocated load of each pollution source should be close to its ratios of the above six factors as much as possible. So the total pollutant load allocation was a multiple objective problem. The weighted average method was used to calculate the share ratio of each pollution source (Fu et al., 2006; Meng, 2008):

$$r_i = \sum_{k=1}^{6} w_k r_{ki} \tag{3}$$

where, r_i is the share ratio of allocated load of the ith pollution source; $w_1, w_2, ..., w_6$ are the weights for the environmental capacity, existing discharge load, water resource, population, agriculture land area and economic added value, $\sum_{i=1}^{6} w_i = 1$, $w_i \geq 0 (i = 1, 2, ..., 6)$; $r_{1i}, r_{2i}, ..., r_{6i}$ are the share ratios of the 6 factors for the ith pollution source.

In this study, the weights of the 6 factors were 0.421, 0.079, 0.184, 0.103, 0.122, and 0.092 based on the more than 20 investigation tables in the two provinces and one city.

Set R as the ratio vector of the pollution sources, $R = [r_1, r_2, ..., r_n]$. The pollution source load can be expressed as:

$$Y = \alpha R \tag{4}$$

where, α – the scalar parameter, Y – pollution load vector, $Y = [y_1, y_2, ..., y_n]$. Then the vector Y can be replaced into the formula (1):

$$\alpha AR + B \leq S \tag{5}$$

The value of α can be obtained as:

$$\alpha = \min_{1 \leq i \leq m} \left[(s_i - b_i)/(AR)_i \right] \tag{6}$$

So the load estimation of ith pollution source is:

$$y_i = r_i \min_{1 \leq i \leq m} \left[(s_i - b_i)/(AR)_i \right] \tag{7}$$

Herein the allocation load of each pollution source can be solved directly.

4. Results

The 2-dimensional MIKE21 model was used to build the relationship matrix between the pollutant load and the water quality response. To overcome the effects of the errors in the initial field, the stable calculation time duration was 2 years. More than 5 h were needed to calculate the response field for each pollution source on the computer. So the nonlinear optimization method was infeasible in the total pollutant load allocation in the Changjiang Estuary and adjacent seawaters. The linear programming method based on the response field was used in this study. The water
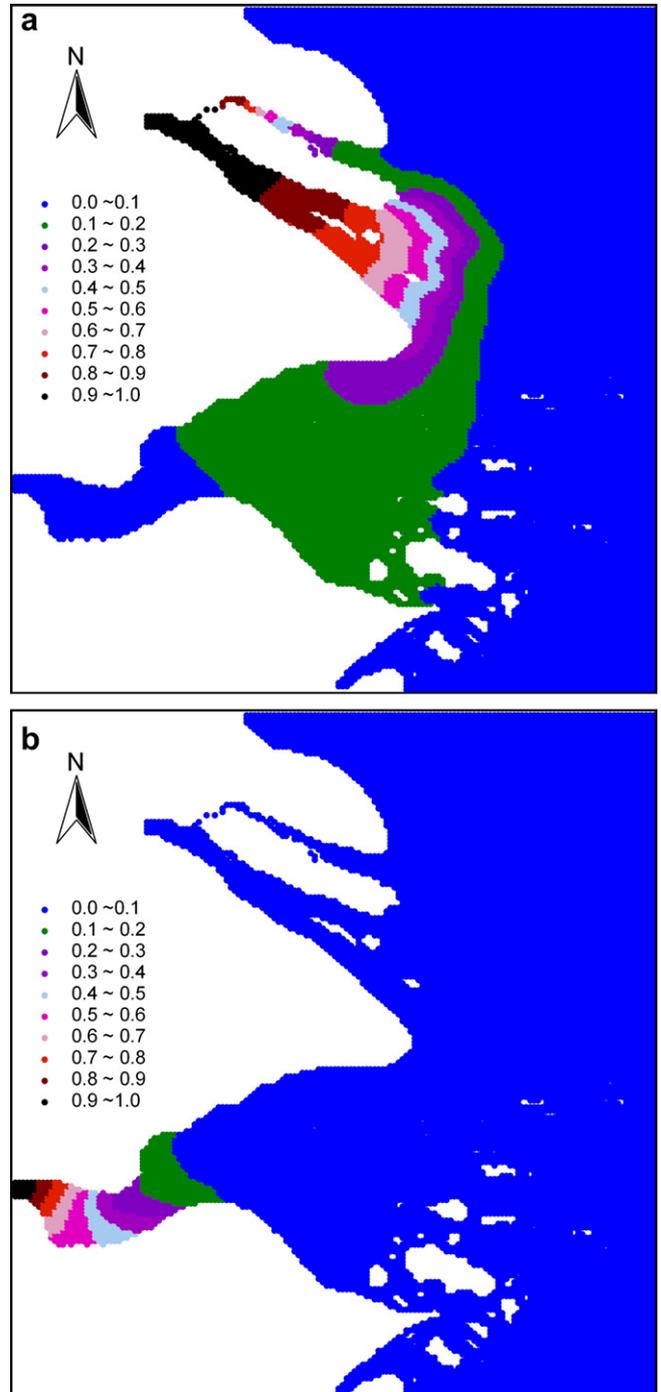

Fig. 3. Response fields of the pollution sources (mg/L). (a) COD for Changjiang River. (b) COD for Qiangtiangjiang River.
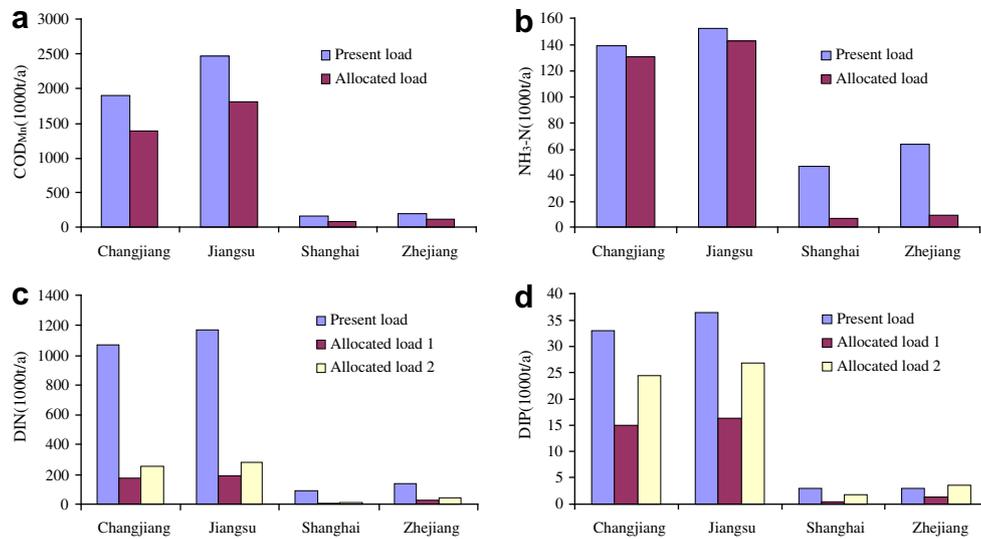
Fig. 4. Comparison of the allocated loads and the present loads in 2005. *Allocated load 1 means the loads were allocated to meet the water quality targets in the whole research region; allocated load 2 means the loads were allocated to meet the water quality targets only in the red tide sensitive area. (a) COD_{Mn}. (b) $NH_3–N$. (c) Inorganic nitrogen. (d) Active phosphate.

quality of the research field was the summary of the individual response fields of all the pollution sources. So the complexity of the calculation was greatly simplified. The COD_{Mn} response fields of Changjiang River and Qiantangjiang River see Fig. 3.

With the above method, the total load was allocated among the 33 pollution sources (Fig. 4). The maximum allowable loads are 2008×10^3 tons, 169×10^3 tons, 226×10^3 tons and 18×10^3 tons for COD_{Mn}, $NH_3–N$, inorganic nitrogen and active phosphate when the water quality targets are requested to be met in the whole region, and 346×10^3 tons and 32×10^3 tons for inorganic nitrogen and active phosphate when the water quality targets to be met only the red tide sensitive area.

The cut rates of the pollutants grouped by region see Table 1.

For the Changjiang upstream region, the cut rates for COD_{Mn} and $NH_3–N$ are relatively low, but the cut task for inorganic nitrogen and active phosphate is still heavy. The control emphasis for the upstream provinces is inorganic nitrogen and phosphate removal. The status of Jiangsu province is similar to the Changjiang upstream region. The emphasis is inorganic nitrogen and active phosphate removal as well. For Shanghai, besides the cut task of inorganic nitrogen and active phosphate is heavy, the COD_{Mn} and $NH_3–N$ cut task is not easy either. For Zhejiang, the cut task for $NH_3–N$, inorganic nitrogen and active phosphate is prominent.

5. Discussion

The allocation results show that the cut task for COD and $NH_3–N$ is relatively low. The control countermeasures are suggested to be

listed in the watershed programme. For the pollution sources with huge direct discharge, the COD and $NH_3–N$ should also be controlled under mixing zone constraints.

The inorganic nitrogen and active phosphate are the major control pollutants. As the nitrogen and phosphate are mainly from agriculture, the treatment emphasis should be paid more on non-point sources, such as reduction of fertilizer usage gradually, establishment of ecological agriculture, and enhancement of Natural Reservation Area protection, artificial wetland protection and control of water and soil loss. The urban sewage treatment plants should be equipped with nitrogen and active phosphate removal facilities, or new denitrification and dephosphorization waste water treatment plants must be built in the future.

It is very interesting to find that the active phosphate concentration does not increase obviously when the history data of 1959 and 1957 was compared with the observation data in 2005 and 2006. It is probably due to that although the phosphate load from the inland is increasing, the marine fishery production has been growing at the same time in these years, so more phosphate is absorbed and the new balance is built up.

In this sense, the nitrogen removal is even more urgent than phosphate. So recently the emphasis will be focused on nitrogen removal. The active phosphate should also be controlled to prevent the red tide comprehensively. As the nitrogen load removal task is tremendous especially in the Changjiang upstream region, it will take a long-term to realize the expected targets of nitrogen control.

Acknowledgements

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Table 1
Cut rates of the pollutant loads (based on 2005 data) to meet the water quality targets by region.

Region	COD_{Mn}	$NH_3–N$	Inorganic nitrogen		Active phosphate	
			Whole control[a]	Red tide sensitive area control[b]	Whole control[a]	Red tide sensitive area control[b]
Changjiang	26.6%	5.7%	83.4%	76.0%	54.5%	26.3%
Jiangsu	27.5%	12.1%	83.5%	75.7%	58.5%	28.4%
Shanghai	47.1%	85.2%	91.2%	82.5%	88.8%	44.6%
Zhejiang	47.3%	86.0%	83.1%	65.9%	57.5%	0.0%
Total	29.2%	39.7%	83.9%	75.4%	57.1%	23.8%

[a] To meet the water quality standards in the whole research area.
[b] To meet the water quality standards only in the red tide sensitive area in Fig. 2.

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