# UNIVERSIDADE DO ALGARVE

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## FACULDADE DE CIÊNCIAS E TECNOLOGIA

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# "Trophic Assessment in Chinese Coastal Systems"

**MESTRADO EM GESTÃO DA ÁGUA E DA COSTA**

**(CURSO EUROPEU)**

ERASMUS MUNDUS EUROPEAN JOINT MASTER
IN WATER AND COASTAL MANAGEMENT

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# RESUMO

Eutrofização costeira é definida como "o desenvolvimento de algas estimulado pelo o enriquecimento de nutrientes" em águas costeiras. Desde à duas décadas atrás, começou por ser uma das principais ameaças para as áreas costeiras Chinesas. A enorme quantidade de nutrientes a partir de actividades humanas tem modificado a qualidade natural da água dos estuários, baías e outras zonas costeiras. Como resultado, da sua elevada condição eutrofíca, os sistemas costeiros estão sujeitos a uma serie de impactos negativos com indesejáveis consequências, tais como, a mortalidade de peixes e a interdição da aquacultura de mariscos. Este assunto e de grande interesse na gestão costeira, existindo a necessidade de avaliar e identificar o nível eutrofíco em sistemas costeiros. Neste trabalho, os diferentes métodos de avaliação Chineses são discutidos e comparados com os do Ocidente, tais como, OSPAR, COMPP e ASSETS. ASSETS foi escolhido para dois estudos de (estuário de Changjiang e baía de Fiaozhou) devido à sua solida teoria e aplicações bem sucedidas. A metodologia é baseada no modelo pressão-estado-resposta e 3 índices: Influência humana, Condição Eutrófica, Tendências futuras. Os resultados obtidos para o estuário de Changjiang e a Baía de Fiaozhou, foram "Mau" e "Baixo" embora havia falta de dados, e são mais conclusivos que os resultados obtidos com métodos tradicionais. As comparações das fundamentações por trás das metodologias e dos resultados sugerem que o ASSETS poderá ser um método mais razoável e aplicável para avaliar os sistemas costeiros Chineses.

Palavra-chaves: Avaliação de Eutrofização; ASSETS; Estuário Changjiang; Baía Jiaozhou

## ABSTRACT

Coastal eutrophication, mainly defined as “the enrichment of nutrient stimulating algal growth” in coastal water, has started to be one of the main threats to the Chinese coastal areas since last two decades. The huge amount of nutrient loads from the human activities has modified the natural background of water quality in estuaries, bays and other coastal zones. As a result of elevated eutrophic status, coastal systems are subject to a series of negative and undesirable consequences, such as fish-kills and interdiction of shellfish aquaculture. While much attention is focused on managing this issue, there is a need to assess the eutrophic level in coastal systems and to identify the extent of danger. In this thesis, a variety of traditional Chinese assessment methods are discussed and compared with western ways, such as OSPAR COMPP and ASSETS. Afterwards, ASSETS was chosen to carry out two case studies (Changjiang Estuary and Jiaozhou Bay) due to its solid theory and successful applications. As a process-based method, it set up a pressure-state-response model based on three main indices, i.e., Overall Human Influence, Overall Eutrophic Condition and Future outlook. In spite of the lack of enough data, the results from applying ASSETS to Changjiang Estuary and Jiaozhou Bay are “Bad” and “Low” respectively, while the traditional methods only obtain more ambiguous results. The comparisons of the rationalities behind the methodologies and the results suggest that ASSETS could be a more reasonable and applicable method to assess Chinese coastal systems.


Keywords: Eutrophication assessment; ASSETS; Changjiang Estuary; Jiaozhou Bay

## CONTENTS

# Chapter 1. Introduction and objectives

Eutrophication, considered as one of the major threats to the health of coastal systems for decades, has been redefined in a various ways. The word "eutrophication" has its roots in two Greek words: "eu" which means "well" and "trope" which means "nourishment", while the modern use of the word eutrophication is related to inputs and effects of nutrients in aquatic systems (Andersen et al., 2006). The following paragraphs present some widely accepted definitions that are found in the literature.

a. The definition adopted by U.K. Environment Agency is: "the enrichment of waters by inorganic plant nutrients which results in the stimulation of an array of symptomatic changes. These include the increased production of algae and/or other aquatic plants, affecting the quality of the water and disturbing the balance of organisms present within it. Such changes may be undesirable and interfere with water uses." (U.K. Environment Agency, 1998)

b. The European Commission (EC) Urban Waste Water Treatment (UWWT) Directive defines eutrophication as "the enrichment of water by nutrients, especially nitrogen and/or phosphorus, causing an accelerated growth of algal and higher form of plant life to produce an undesirable disturbance to the balance of organisms in the water and to the quality of water concerned" (91/271/EEC).

c. According to US EPA, eutrophication is a "condition in an aquatic ecosystem where high nutrient concentrations stimulate blooms of algae (e.g., phytoplankton)" (http://www.epa.gov/maia/html/eutroph.html).

d. In the National Estuarine Eutrophication Assessment (NEEA) report conducted by NOAA, eutrophication refers to a process in which the addition of nutrients to water bodies stimulates algal growth (Bricker et al., 1999). And an updated definition from NEEA is a natural process by which productivity of a water body, as measured by organic matter, increases as a result of increasing nutrient inputs. These inputs are a result of a natural process but in recent decades they have been greatly supplemented by various human related activities (Bricker et al., 2004).

While eutrophication is getting more and more public and scientific attention all over the world, China is subject to a huge human-induced nutrient modification in coastal systems. One of the most significant changes is the increase of the nutrient inputs from land-source or human-related issues, resulting in the proliferation of phytoplanktonic biomass and algal blooms. Frequent occurrences of HABs (Fig. 1) and eutrophication have become serious issues in Chinese coastal systems (Harrison et al., 1990; Zhang et al., 1999; Huang et al., 2003). In 2003, the national sea waters witnessed altogether 119 cases of marine red tides, added up area bout 14.55 thousand square kilometers.

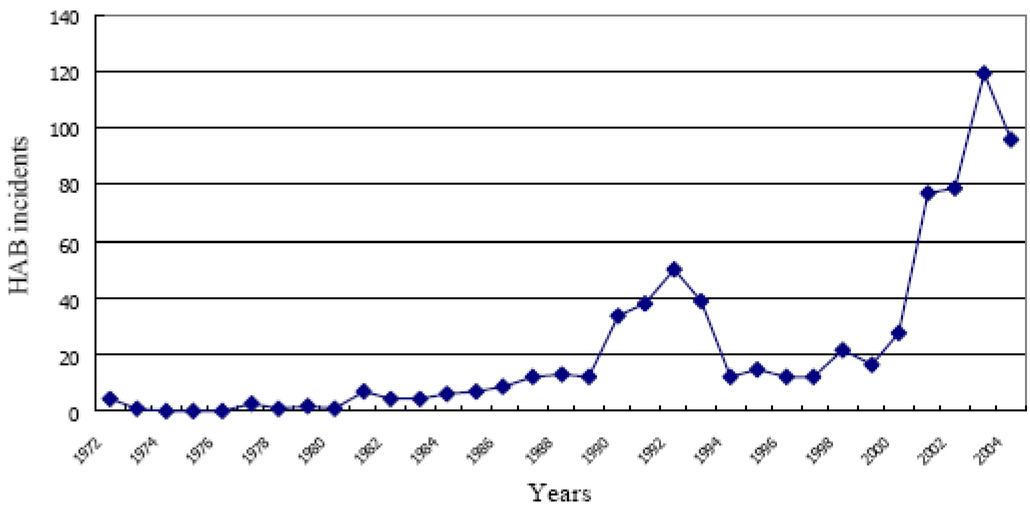


Fig.1. HAB incidents in coastal China from 1972 to 2004 (http://www.china-hab.cn).

Although it is argued that the main reason for this increased HAB incidents is the better national monitoring network, this record is also a clear indicator of more and more serious eutrophication in a national scale. As a result, nutrient enrichment may lead to negative and undesirable consequences, such as fish-kills, interdiction of shellfish aquaculture, loss or degradation of sea grass beds (Bricker et al., 2003). These effects strongly shape public concern and scientific research for better understanding of eutrophication (Cloern, 2001).

Even though there is no specific legislation designed to deal with eutrophication in China, the government has launched a series of laws and regulations to deal with the water-related problem. A list of the legislation related to water quality issues is summarized in Table 1.

Table 1 List of legislation related to water quality issues.

| Title | Objective | Date |
|---|---|---|
| *Regulations of the People's Republic of China on the Prevention of Vessel-induced Sea Pollution* | To Protect marine environment | 1983 |
| *The Water Pollution Control Act of People's Republic of China* | To control Inland water pollution | 1984 |
| *Regulations of the People's Republic of China on Control over Dumping of Wastes in the Seawater* | To regulate dumping of waste | 1985 |
| *Regulations of the People's Republic of China on the Prevention of Pollution Damage to the Marine Environment by Land-sourced Pollutants* | To administrate land pollution sources and to prevent pollution damage to the marine environment by land-sourced pollutants | 1990 |
| *Regulation of the People's Republic of China on Controlling Marine Pollution by Inland Pollutants* | To control marine pollution from inland source | 1990 |
| *Law of the People's Republic of China on the Territorial Sea and the Contiguous Zone* | To define and to protect territorial sea and contiguous zone | 1991 |
| *Decision of the State Council on several issues concerning environmental protection* | To Strengthen the prevention and control of water pollution in rivers and coastal waters | 1996 |

Table 1 (*continued*)

| **Title** | **Objective** | **Date** |
|---|---|---|
| *Decision of the Standing Committee of the National People's Congress on approval of the United Nations Convention on the Law of the Sea* | A full adoption of United Nations Conventions on the Law of the Sea (UNCLOS) treaty norms by China | 1996 |
| *Law of People's Republic of China on the Exclusive Economic Zone and Continental Shelf* | To define the Exclusive Economic Zone and the continental shelf and to specify the jurisdictional powers of China | 1998 |
| *Seawater Quality Standard of the People's Republic of China* | To classify seawater quality into four grades according to the standards set for each grade | 1998 |
| *Marine Environment Protection Act of People's Republic of China* | Marine environment protection | 1999 |
| *Water Act of People's Republic of China* | A general law for management, utilization and protection of water resources | 2002 |

However, before the country sets political priorities for managing and mitigating nutrient enrichment, there is a need for China to make an assessment so as to determine the extent of the problem.

Obviously it needs a lot of work to solve the aforementioned problem, but this thesis is an attempt to go further in terms of understanding this issue. The main objectives in this thesis are:

- To provide an overview of Chinese coasts regarding eutrophication conditions;
- To review the eutrophication assessment methods and to compare them with methods used elsewhere;
- To propose a rational and applicable method to better assess Chinese coastal systems;
- To apply the method to two Chinese systems as a test of its wider applicability in China.

# Chapter 2. Review of Chinese coastal systems

With an area of $2.85\times10^5$ $km^2$, roughly equivalent to the area of Portugal, Chinese coastal zones cover 23° of latitude (17°N to 40°N) and 16° of longitude (108°E to 124.5°E). Usually they are highly populated, economically developed, and thus the water bodies are often characterized by important anthropogenic nutrient loads (Table 2).

Out of various pressures to Chinese coastal systems, eutrophication is one of most negative factors influencing ecosystem health. The coastal areas of China that are a concern with harmful algal blooms are (from north to south) the Bohai Sea, the Yellow Sea, the East China Sea, and the South China Sea (Fig. 2). The first documented occurrence of a HAB was in the 1930s, and since then, reports of HABs appear to be increasing over time (Yan et al., 2003).

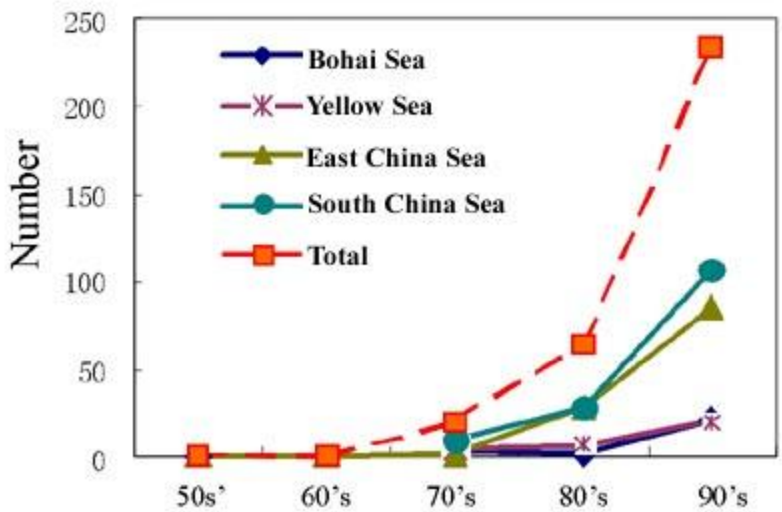


Fig.2. Red tide occurrence number along the Chinese coast (http://www.china-hab.cn).

Table 2 Overview of Chinese coastal zone (adapted after Du et al., 1997; Li et al., 2000; P.R.C. National Bureau of Statistics, 2000).

| | **Unit** | **Mainland** | **Islands** | **Total** | **Percentage of the whole country** |
|---|---|---|---|---|---|
| Coastline | $10^3$ km | 18 | 14 | 32 | % |
| Area of coastal provinces | $10^6$ km$^2$ | 1.248 | 0.36 | 1.608 | 16.75 |
| Population of coastal provinces | $10^6$ | 498.5 | 6.72 (H.K.)<br>21.93 (Taiwan)<br>0.43 (Macao) | 527.6 | 41.9 |
| GDP of the provinces | $10^9$ US$ | 596.83 | 163.57 (H.K.)<br>268.6 (Taiwan)<br>6.16 (Macao) | 1035.16 | 72.5 |
| Coastal vulnerable area | $10^3$ km$^2$ | 143.9 | | 96000 | 1.5 |
| Population of the vulnerable area | $10^6$ | 162.09 | | 1259.09 | 0.13 |
| Population density in vulnerable area | inh km$^{-2}$ | 1126.5 | | | |

At a national scale, 82 red tides were reported in China during 2005 (Table 3) with a cumulative area of 27,070 $km^2$ (State Oceanic Administration, 2006).

Table 3 Red tides reported in Chinese coasts during 2004 to 2005.

| **Sea area** | **Red tide incidents** | | **Cumulative areas ($km^2$)** | |
|---|---|---|---|---|
| | **2004** | **2005** | **2004** | **2005** |
| Bohai Sea | 12 | 9 | 6520 | 5320 |
| Yellow Sea | 13 | 13 | 820 | 1780 |
| East China Sea | 53 | 51 | 17880 | 19270 |
| South China Sea | 18 | 9 | 1410 | 700 |
| Sum | 96 | 82 | 26630 | 27070 |

To understand the individual coastal systems in China, various data on Chinese bays and estuaries are listed as follows based on a series of Chinese documents called “Bays in China”. In this thesis, they are categorized into five groups in terms of areas (extra small, small, medium, large and extra large). Table 4 and 5 present the base data and synthesis data for major coastal systems collected from “Bays in China” (for the smaller systems, see Annexes, Table 1).

Table 4 Background data for Chinese coastal systems.

| Categories | System | Area | Tidal height | Average salinity | Rainfall | Air temperature | Water temperature |
|---|---|---|---|---|---|---|---|
| | | km$^2$ | m | psu | mm | ℃ | ℃ |
| Extra large (>650 km$^2$) | Changjiang Estuary | 51000.0 | 2.50 | N/A | 1068.7 | 15.5 | 16.9 |
| | Hangzhou Bay | 5000.0 | 2.89 | 13.50 | 1200.0 | 15.9 | 17.1 |
| | Leizhou bay | 1690.0 | 2.07 | 28.69 | 1329.0 | 23.4 | 25.4 |
| | Wenzhou bay | 1473.7 | 4.00 | 27.78 | 1694.6 | 17.9 | 15.3 |
| | Honghai bay | 925.0 | 1.10 | 30.42 | 1723.0 | 22.1 | 20.9 |
| | Taizhou bay | 911.6 | 4.01 | 27.05 | 1435.0 | 16.5 | 14.2 |
| | Haizhou bay | 876.4 | 3.39 | 30.69 | 828.7 | 14.3 | 15.7 |
| | Sanmen bay | 775.0 | 4.02 | 24.88 | 1511.0 | 16.4 | N/A |
| Large (area: 400-650 km$^2$) | Sansha bay | 570.0 | 5.35 | 30.16 | 2013.8 | 20.5 | 20.5 |
| | Pulandian bay | 530.0 | 1.45 | 30.54 | 644.3 | 9.4 | 11.0 |
| | Daya bay | 516.0 | 0.83 | 32.22 | 1722.0 | 22.4 | 21.9 |
| | Zhanjiang Gang | 490.0 | 2.16 | 26.93 | 1689.5 | 23.0 | 25.1 |
| | Yueqing bay | 463.6 | 4.00 | 27.30 | 1411.0 | 17.4 | N/A |
| | Meizhou bay | 423.8 | 5.12 | 32.05 | 1316.6 | 20.2 | 20.5 |
| | Aiwan-Xuanmen bay | 419.3 | 4.00 | 28.28 | 1455.0 | 17.3 | 17.9 |

Table 4 (*continued*)

| **Categories** | **Systems** | **Area** | **Tidal height** | **Average salinity** | **Rainfall** | **Air temperature** | **Water temperature** |
|---|---|---|---|---|---|---|---|
| | | **km$^2$** | **m** | **psu** | **mm** | **℃** | **℃** |
| **Medium (area: 150-400 km$^2$)** | Jiaozhou bay | 397.0 | 2.80 | 32.00 | 732.7 | 12.5 | 13.8 |
| | Qinzhou bay | 380.0 | 2.40 | 28.24 | 2091.0 | 22.0 | 23.1 |
| | Jinzhou bay (Dalian) | 342.0 | 1.45 | 31.51 | 599.7 | 10.3 | 11.2 |
| | Dapeng bay | 335.0 | 1.38 | 31.61 | 1899.0 | 22.2 | 24.5 |
| | Xinghua bay | 250.0 | 4.16 | 32.62 | 1289.5 | 20.2 | 27.5 |
| | Xiamen bay | 230.1 | 3.99 | 26.07 | 1143.5 | 20.9 | N/A |
| | Fuzhou bay | 223.6 | 1.38 | 31.19 | 642.7 | 9.3 | 14.0 |
| | Luoyuan bay | 179.6 | 4.98 | 27.04 | 1649.5 | 19.0 | 17.4 |
| | Dalian bay | 174.0 | 2.13 | 30.30 | 639.8 | 10.2 | 11.2 |
| | Yalu Jiang estuary | 170.0 | N/A | N/A | 1019.0 | 8.5 | 11.3 |
| | Sanggou bay | 163.2 | 1.10 | 31.76 | 819.6 | 11.1 | 13.3 |
| | Qingduizi bay | 156.8 | 4.09 | 27.04 | 815.2 | 11.3 | 11.3 |
| | Jinzhou bay (Jinzhou) | 151.5 | 2.06 | 24.88 | 637.6 | 8.9 | 13.6 |

Table 5 Synthesis data for Chinese coastal systems.

| Systems | $NH_4$ | $NO_2$ | $NO_3$ | $PO_4$ | N/P | Chl *a* | PH | COD |
|---|---|---|---|---|---|---|---|---|
| | μmol $l^{-1}$ | μmol $l^{-1}$ | μmol $l^{-1}$ | μmol $l^{-1}$ | | mg $m^{-3}$ | | mg $l^{-1}$ |
| Changjiang Estuary | 1.4-20 | 0.10-2.5 | 68.000 | 20.645 | 3.366-3.512 | 1.13 | 6.9-8.6 | 0.3-55.5 |
| Hangzhou Bay | 9.857 | 1.714 | 112.143 | 1.129 | 109.576 | N/A | 8.09 | 2.94 |
| Leizhou bay | N/A | 0.393 | 2.336 | 0.126 | N/A | N/A | 8.18 | 0.26 |
| Wenzhou bay | 1.410 | 0.390 | 14.200 | 1.170 | 13.675 | 1.54 | 8.28 | 0.80 |
| Honghai bay | 2.500 | 0.230 | 5.300 | 0.240 | 33.458 | 3.12 | 8.31 | 0.82 |
| Taizhou bay | N/A | 0.400 | 27.260 | 0.650 | N/A | 2.15 | 8.24 | 0.71 |
| Haizhou bay | 0.750 | 0.100 | 1.500 | 0.110 | 21.364 | N/A | 8.15 | 0.77 |
| Sanmen bay | 1.357 | 0.357 | 16.071 | 0.935 | 19.012 | 1.47 | 8.00 | 1.33 |
| Sansha bay | 1.100 | 1.020 | 11.190 | 0.660 | 20.167 | 0.79 | 8.22 | N/A |
| Pulandian bay | N/A | 0.286 | 2.200 | 0.258 | N/A | 5.68 | 8.07 | 1.31 |
| Daya bay | 0.210 | 0.200 | 0.560 | 0.200 | 4.850 | 1.70 | 8.22 | N/A |
| Zhanjiang Gang | N/A | 0.643 | 9.286 | 0.139 | N/A | N/A | 8.12 | 0.32 |
| Yueqing bay | 0.800 | 0.270 | 31.130 | 0.720 | 44.722 | 1.40 | 8.15 | 0.86 |
| Meizhou bay | 1.140 | 0.750 | 7.200 | 0.330 | 27.545 | 1.70 | 8.19 | 0.77 |
| Aiwan-Xuanmen bay | 1.250 | 0.480 | 14.87 l | 0.720 | 23.057 | 1.00 | 8.20 | 0.72 |
| Jiaozhou bay | N/A | 3.357 | 3.357 | N/A | N/A | N/A | 8.15 | 1.40 |

Table 5 (*continued*)

| Systems | $NH_4$ | $NO_2$ | $NO_3$ | $PO_4$ | N/P | Chl *a* | PH | COD |
|---|---|---|---|---|---|---|---|---|
| | μmol $l^{-1}$ | μmol $l^{-1}$ | μmol $l^{-1}$ | μmol $l^{-1}$ | | mg $m^{-3}$ | | mg $l^{-1}$ |
| Qinzhou bay | N/A | 0.071 | 2.786 | 0.645 | N/A | N/A | 7.77 | 0.78 |
| Jinzhou bay (Dalian) | N/A | 0.003 | 0.003 | 0.548 | N/A | 3.17 | 8.19 | 0.65 |
| Dapeng bay | 2.530 | 0.140 | 4.570 | 0.090 | 80.444 | 2.25 | 8.20 | 0.92 |
| Xinghua bay | 0.400 | 0.220 | 1.020 | 0.100 | 16.400 | 2.34 | 8.22 | N/A |
| Xiamen bay | 3.860 | 1.430 | 8.940 | 0.480 | 29.646 | 4.55 | 8.22 | 1.23 |
| Fuzhou bay | N/A | 0.107 | 0.107 | 0.419 | N/A | 2.28 | 8.00 | 1.15 |
| Luoyuan bay | 1.480 | 0.970 | 8.680 | 0.290 | 38.379 | 2.01 | 8.23 | N/A |
| Dalian bay | N/A | 3.386 | 7.786 | 1.000 | N/A | N/A | 8.16 | 1.27 |
| Yalu Jiang estuary | N/A | N/A | N/A | 0.460 | N/A | N/A | 8.02 | 2.34 |
| Sanggou bay | N/A | 92.857 | 457.143 | 403.226 | N/A | N/A | 8.20 | 1.20 |
| Qingduizi bay | N/A | 0.386 | 2.093 | 0.516 | N/A | N/A | 8.11 | 1.41 |
| Jinzhou bay (Jinzhou) | N/A | N/A | N/A | N/A | N/A | 3.10 | 8.00 | 1.30 |
| Quanzhou bay | 5.700 | 1.020 | 29.300 | 0.300 | 120.067 | 1.43 | 7.94 | 1.08 |
| Tong-an bay | 4.150 | 0.720 | 14.200 | 0.200 | 95.350 | 2.00 | 8.25 | 1.02 |
| Shidao bay | 0.571 | 0.500 | 3.643 | 0.032 | 146.143 | N/A | 8.08 | 1.32 |
| Dayao bay | N/A | 0.150 | 0.793 | 0.419 | N/A | N/A | 8.19 | 0.78 |

Table 5 (*continued*)

| **Systems** | **$NH_4$** | **$NO_2$** | **$NO_3$** | **$PO_4$** | **N/P** | **Chl *a*** | **PH** | **COD** |
|---|---|---|---|---|---|---|---|---|
| | **μmol $l^{-1}$** | **μmol $l^{-1}$** | **μmol $l^{-1}$** | **μmol $l^{-1}$** | | **mg $m^{-3}$** | | **mg $l^{-1}$** |
| Shantou Gang | 6.800 | 4.200 | 38.000 | 0.490 | 100.000 | 4.50 | 7.84 | 2.02 |
| Rongcheng bay | N/A | 1.143 | 0.043 | 0.452 | N/A | N/A | 8.13 | 0.80 |
| Xiaoyao bay | N/A | 0.236 | 1.193 | 0.355 | N/A | N/A | 8.19 | 0.81 |
| Anpu Gang | N/A | 0.279 | 0.214 | 0.084 | N/A | N/A | 8.85 | 0.63 |
| Dongshan bay | 0.870 | 0.420 | 6.070 | 0.380 | 19.368 | 3.22 | 8.24 | 1.07 |
| Guanhe mouth | N/A | N/A | 0.910 | 1.300 | N/A | N/A | 8.20 | N/A |
| Hai He estuary | N/A | N/A | N/A | N/A | N/A | N/A | 8.00 | N/A |
| Huang He estuary | 0.927 | 0.429 | 5.556 | 0.197 | 35.086 | N/A | 8.25 | 1.62 |
| Laoshan bay | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A |
| Liao He estuary | 0.001 | 0.006 | 0.086 | 0.790 | 0.118 | N/A | 7.91 | 3.06 |
| Lingshan bay | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A |
| Luan He estuary | 0.570 | 0.230 | 1.270 | 0.510 | 4.059 | N/A | 8.20 | N/A |
| Majia He estuary | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A |
| Minjiang estuary | 6.400 | 1.310 | 44.200 | 1.500 | 34.607 | 2.40 | 7.60 | 2.53 |
| Pearl River estuary | N/A | N/A | N/A | 0.980 | N/A | N/A | 8.15 | N/A |
| Tuhai He estuary | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A |
| Wuleidao bay | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A |
| Xiaoqing/ZiHe estuary | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A |

Although a national trophic assessment of Chinese coastal systems has not conducted yet, it is highly suspected that most of coastal areas and estuaries are suffering from overloaded nutrients. The available literature suggests that those undergoing most severe eutrophication include Bohai Bay, Changjiang Estuary, Hangzhou Bay and Pearl River Estuary (Zou et al., 1985; Peng & Wang, 1991; Pei & Ma, 2002; Chai et al., 2006).

# Chapter 3. Review of eutrophication assessment methods

Eutrophication assessment, began with classical freshwater approach (Carlson, 1977; Morihiro et al., 1981), has developed through two "phases" (Cloern, 2001). These nutrient-based classification systems are termed as a "Phase I" approach due to developing through the measurement of variables such as transparency, nutrients and chlorophyll *a*. Over the last few decades, the increase in research effort and discussion on coastal eutrophication processes has advanced our understanding of the problems, and increasingly effective "Phase II" methods have been developed to explore cause/effect relationships, such as the Oslo-Paris (OSPAR) Convention for the Protection of the North Sea Comprehensive Procedure (OSPAR COMM), US EPA's National Coastal Assessment (NCA) water index method and Assessment of Estuarine Trophic Status (ASSETS) method (Weisberg et al., 1993; Lowery, 1996; Madden and Kemp, 1996; Bricker et al., 1999; Dettmann, 2001; EPA, 2005).

In the Chinese history of eutrophication assessment, there are a number of eutrophication assessment methods proposed in China, such as the nutrient index and fuzzy analysis. As they mainly focus on the pressures to the systems by chemical tools, these methods are usually cited as "Phase I" approaches (Wang, 2005; Yao, 2005). A subset of these methods which are commonly used is reviewed in this chapter, such as Nutrient Index Method, Primary Component Analysis and Fuzzy Analysis.

In addition, three other methods, the OSPAR-COMPP (developed by the OSPAR signatories), NCR Water Quality Index (US EPA National Coastal Report) and ASSETS (US NOAA) are outlined as well. Even though they have only incompletely been applied to Chinese systems, these approaches might be helpful to present a different way to look at Chinese eutrophication issues.

## 3.1. Nutrient Index Method I

The method suggested by Chinese National Environmental Monitoring Center is based on nutrient index.

Nutrient Index ($N_I$) in seawater (Lin, 1996) is calculated by Eq.1:

$$N_I = C_{COD}/S_{COD} + C_{TN}/S_{TN} + C_{TP}/S_{TP} + C_{Chla}/S_{Chla} \quad \text{(Eq. 1)}$$

where: $C_{COD}$, $C_{TN}$, $C_{TP}$ *and* $C_{Chla}$ are measured concentrations of COD, total nitrogen, total phosphorus (in mg $l^{-1}$) and chlorophyll *a* (in µg $l^{-1}$) in sea water, respectively. $S_{COD}$, $S_{TN}$, $S_{TP}$ and $S_{Chla}$ are standard concentrations of COD, total nitrogen, total phosphorus and chlorophyll *a* in sea water, respectively (Table 6).

$N_I$, if larger than 4, indicates the sea water is eutrophic.

Table 6 Seawater eutrophication assessment standards (Lin, 1996).

| $S_{COD}$ | $S_{TN}$ | $S_{TP}$ | $S_{Chla}$ |
|---|---|---|---|
| 3.0 mg $l^{-1}$ | 0.6 mg $l^{-1}$ | 0.03 mg $l^{-1}$ | 10 µg $l^{-1}$ |

## 3.2. Nutrient Index Method II

Adapted from Japanese assessment methods (Okaichi, 2004), Zou and his colleagues proposed one other nutrient index method (Zou et al., 1985).

Nutrient Index ($N_I$) in seawater:

$$N_I = (C_{COD} \times C_{DIN} \times C_{DIP} \times 10^6) / 4500 \quad \text{(Eq. 2)}$$

where $C_{COD}$, $C_{DIN}$, $C_{DIP}$ are measured concentrations of COD (in mg $l^{-1}$), dissolved inorganic nitrogen and phosphorus in seawater, respectively.

$4500/10^6$ in Eq. 2 is mean product of standard concentrations of COD, DIN and DIP, as it is believed that the critical value for COD is 1-3 mg $l^{-1}$, DIN 0.2-0.3 mg $l^{-1}$ and DIP 0.01-0.02 mg $l^{-1}$ (Chen et al., 2002).

$N_I$, if larger than 1, indicates the sea water is eutrophic.

These two limnology-originated methods mentioned above are simple to carry out, with parameters easy to sample. While they are widely used in Chinese coastal systems, research in the past decades has identified key differences in the responses of lakes and coastal-estuarine ecosystems to nutrient enrichment (Cloern, 2001). In addition, it is widely accepted nowadays that nitrogen and phosphorus concentration are not necessarily indicative of coastal eutrophication.

## 3.3. Principal Component Analysis (PCA)

The basic philosophy underlying this method is that traditionally sampled eutrophic parameters are correlated to each other, and there is a need to find out the principal components out of various variables. Two main types of trophic indicators have been and are still being used in eutrophication assessment, i.e., biological factors and physico-chemical factors (Parinet el al., 2004). Even though the specific cause and effect relation between these factors are not clear yet, it’s obvious that they are connected to each other (Strain & Yeats, 1999). Given the complexity of the system, the aim of this method is to apply linear regression to make up a set of information that could provide a more reliable way to characterize the state of the aquatic system than variables themselves.

Here are two examples of principal components selected through PCA method from the literature:

a. Lin and her colleagues analyzed data from Zhelin Bay (Guangdong Province, China) and selected four parameters, i.e., water temperature, salinity, concentration of $PO_4$ and $SiO_3$, which represent up to 91.46% of the total variance of the observance (Lin et al., 2004).
b. In Parinet's work done in 2004, the data base for 18 eutrophic variables from ten lakes in Ivory Coast were interpreted and it was suggested that four parameters, conductivity, pH, permanganate index and UV absorbance, were possible to make a precise description without impairing its quality (Parinet et al., 2004).

The conduction of PCA obtains a few variables with which the system is able to be simplified to assess with not missing main information. After being calibrated, the selection of principal parameters could be extended to a larger area of water systems.

The advantage of this method is obvious, that is, it needs fewer parameters to be sampled after making principal components analysis. While it's common that most of coastal systems face data gaps, it allows scientists or managers to better make use of data available. Combined with Nutrient Index Methods, PCA is able to find out the most important parameters related to the eutrophic conditions, which provides a more flexible way than using the parameters from Nutrient Index methods themselves. However, since it is based on statistic calculation, PCA does not have solid scientific basis in coastal science, but only empirical statistical rationality. This is probably the main reason that it has not been commonly applied to Chinese system.

## 3.4. Fuzzy Analysis

The main advantage that fuzzy theory has is its ability to deal with imprecise, uncertain or ambiguous data or relationship, which is clearly fit to the study of ecological and environmental issues (Metternicht, 2001).

In most conventional methods, a variety of threshold values are used to give a classification for parameters when evaluating the system status. However, a discrepancy frequently arises from the lack of a clear distinction between the uncertainty in the quality criteria employed and the vagueness or fuzziness embedded in the decision-making output values (Chang et al., 2001). Owing to inherent imprecision, difficulties always exist in describing eutrophic conditions through distinct numbers used as thresholds for various variables.

In early developed eutrophication index methods, such as Calson's index, tended to divide eutrophication level by discrete numbers (Calson, 1977). For example, Trophic State Index values of 49 and 50 are in different classes while 41 falls into the same category with 49, even though it sounds much more reasonable to put 49 and 50 together. In this case, Fuzzy theory seems to be a possible solution to deal with the ambiguity within eutrophication assessment. Although the theory had existed for decades, to apply fuzzy theory to assess water quality began in the 1990s (Peng et al., 1991; Kung et al., 1992; Salski, 1992; Lu & Lo, 2002; Marchini & Marchini, 2006).

### 3.4.1. Determination of membership function

Suppose there are $n$ sampling sites, which collected $m$ parameters, such as dissolved inorganic nitrogen, chlorophyll *a* and dissolved oxygen. Then the dataset could be written down as the following matrix:

Multivariable data:

$$X = \begin{vmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \cdots & \cdots & \cdots & .. \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{vmatrix} = (x_{ij}) \qquad \text{(Eq. 3)}$$

where $i = 1, 2, \ldots, m$; $j = 1, 2, \ldots, n$.

Assume that water quality standards are divided into $c$ categories, for example, trophic levels like *low*, *medium* and *high*. Then the multivariable index can be written as the following matrix.

Multivariable index:

$$Y = \begin{vmatrix} y_{11} & y_{12} & \cdots & y_{1c} \\ y_{21} & y_{22} & \cdots & y_{2c} \\ \cdots & \cdots & \cdots & .. \\ y_{m1} & y_{m2} & \cdots & y_{mc} \end{vmatrix} = (y_{ih}) \qquad \text{(Eq. 4)}$$

where $i = 1, 2, \ldots, m$; $j = 1, 2, \ldots, n$; $h = 1, 2, \ldots, c$.

To define the membership of multivariable index as following, respectively, increasing ($y_{i1} < y_{ic}$) and decreasing ($y_{i1} > y_{ic}$):

$$\mu_{ih} = \begin{cases} 0, & h = 1 \\ (y_{ih} - y_{i1})/(y_{ic} - y_{i1}), & 1 < h \leq c \\ 1, & h = c \end{cases} \qquad \text{(Eq. 5)}$$

and

$$\mu_{ih} = \begin{cases} 0, & h = 1 \\ (y_{ih} - y_{ic})/(y_{i1} - y_{ic}), & 1 < h \le c \\ 1, & h = c \end{cases} \quad \text{(Eq. 6)}$$

Named $\theta_{ij}$ the general membership function for $x_{ij}$, it can be obtained as the following analytical expressions, respectively, increasing ($y_{i1} < y_{ic}$) and decreasing ($y_{i1} > y_{ic}$):

$$\theta_{ij} = \begin{cases} 0, & x_{ij} \le y_{i1} \\ (x_{ij} - y_{i1})/(y_{ic} - y_{i1}), & y_{i1} < x_{ij} < y_{ic} \\ 1, & x_{ij} \ge y_{ic} \end{cases} \quad \text{(Eq. 7)}$$

and

$$\theta_{ij} = \begin{cases} 0, & x_{ij} \le y_{ic} \\ (x_{ij} - y_{ic})/(y_{i1} - y_{ic}), & y_{ic} < x_{ij} < y_{i1} \\ 1, & x_{ij} \ge y_{i1} \end{cases} \quad \text{(Eq. 8)}$$

### 3.4.2. Determination of weights

The over standard weight of $x_{ij}$ ($o_{ij}$) is calculated by the following formula:

$$o_{ij} = x_{ij} / \overline{y_i} = x_{ij} / (\frac{1}{c} \cdot \sum_{h=1}^{c} y_{ih}) \quad \text{(Eq. 9)}$$

On the other hand, different variables are of various importance to water quality. For example, nitrogen concentration and phosphorus concentration might be more clear indicators than the water clarity for some aquatic systems in terms of eutrophication. Named $v_i$ the weight of parameters $i$, the synthesis weight set derives from the product of $o_{ij}$ and $v_i$.

$$W = \begin{vmatrix} v_1 & & & \\ & v_2 & & \\ & & \cdots & \\ & & & v_m \end{vmatrix} \bullet \begin{vmatrix} o_{11} & o_{12} & \cdots & o_{1n} \\ o_{21} & o_{22} & \cdots & o_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ o_{m1} & o_{m2} & \cdots & o_{mn} \end{vmatrix} \quad \text{(Eq. 10)}$$

A normalized matrix is determined by normalizing the initial matrix $W$ column by column.

$$W = \begin{vmatrix} w_{11} & w_{12} & \cdots & w_{1n} \\ w_{21} & w_{22} & \cdots & w_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ w_{m1} & w_{m2} & \cdots & w_{mn} \end{vmatrix} = (w_{ij}) \qquad \text{(Eq. 11)}$$

where $w_{ij}$ is the normalized synthesis weight for $x_{ij}$.

### 3.4.3. Fuzzy synthetic evaluation

When membership function and weight are given, fuzzy synthetic evaluation for site $j$ to Level $h$ can be performed as follows:

$$e_{jh} = 1 \Bigg/ \sum_{k=1}^{c} \left[ \frac{\sum_{i=1}^{m} (w_{ij} |\theta_{ij} - \mu_{ih}|)^{p}}{\sum_{i=1}^{m} (w_{ij} |\theta_{ij} - \mu_{ik}|)^{p}} \right]^{2/p} \qquad \text{(Eq. 12)}$$

Then the overall trophic level can be presented by a matrix:

$$E = (e_{jh}) = \begin{vmatrix} e_{11} & e_{12} & \cdots & e_{1c} \\ e_{21} & e_{22} & \cdots & e_{2c} \\ \cdots & \cdots & \cdots & \cdot\cdot \\ e_{n1} & e_{n2} & \cdots & e_{nc} \end{vmatrix} \qquad \text{(Eq. 13)}$$

where $P$ is the fuzzy distance constant, equal to 1 (Hamming distance) or 2 (Euclidean distance) (Xiong & Chen, 1993).

For example, Lin and his colleagues' work applied the fuzzy analysis in Fujian sea area, China (Lin et al., 2002). In Xunjiang River, surface water samples were taken from five sampling sites, with four parameter studied, i.e., concentrations of $PO_4$, DIN, chlorophyll a and COD. The water quality standards used in this study were adopted from Chinese national seawater standards (Table 7).

Table 7 Assessment standard values.

| Trophic level | COD | DIN | $PO_4$ | Chl *a* |
|---|---|---|---|---|
| | $mg\ l^{-1}$ | $mg\ l^{-1}$ | $mg\ l^{-1}$ | $mg\ l^{-1}$ |
| I (Oligotrophic) | 1 | 0.2 | 0.01 | 1 |
| II (Mesotrophic) | 3 | 0.4 | 0.03 | 3 |
| III (Eutrophic) | 5 | 0.5 | 0.05 | 5 |

Setting P=1, the result of eutrophic level membership of surface water at Xunjiang River is shown as following matrix:

$$E = \begin{vmatrix} TrophicLevel & Site1 & Site2 & Site3 & Site4 & Site5 \\ I & 0.072 & 0.069 & 0.056 & 0.055 & 0.286 \\ II & 0.0699 & 0.891 & 0.867 & 0.903 & 0.644 \\ III & 0.229 & 0.040 & 0.077 & 0.042 & 0.070 \end{vmatrix}$$

The probabilities for these five sampling sites ranged from 64.4% to 90.3%, which suggested that studying area fell into the category of Level II.

Despite the great efforts in developing the application of fuzzy theory based on ecological models, the progress is still frustrating for mainly two reasons (Kompare et al., 1994; Chen & Mynett, 2003). The first one is large and redundant ruleset in high dimensional systems, the size of which grows exponentially with the number of variables. The other one is difficulties in defining membership functions and inference rules.

## 3.5. OSPAR COMPP

A Common Procedure has been adopted by OSPAR for the identification of eutrophication status of the OSPAR Maritime Area (OSPAR, 2003). As a stepwise method, the OSPAR COMPP comprises two main procedures: the Screening Procedure and the Comprehensive Procedure. The Screening Procedure, as a "broad-brush" approach, is designed to identify obvious non-problem areas with regard to eutrophication. Areas that are not identified as obvious non-problem areas in the first procedure are to be subjected to the Comprehensive Procedure to be classified into problem areas, potential problem areas or non-problem areas. These three types of areas with regard to eutrophication are defined as following:

a. "Problem areas with regard to eutrophication" are those areas for which there is evidence of an undesirable disturbance to the marine ecosystem due to anthropogenic enrichment by nutrients;

b. "Potential problem areas with regard to eutrophication" are those areas for which there are reasonable grounds for concern that the anthropogenic contribution of nutrients may be causing or may lead in time to an undesirable disturbance to the marine ecosystem due to elevated levels, trends and/or fluxes in such nutrients;

c. "Non-problem areas with regard to eutrophication" are those areas for which there are no grounds for concern that anthropogenic enrichment by nutrients has disturbed or may in the future disturb the marine ecosystem.

In OSPAR COMPP system e.g. the frequency and spatial coverage of all parameters depend on the classification of the areas (problem area, potential problem area, non-problem area).

To carry out the classification of eutrophication status of maritime areas, a number of steps should be undertaken which are described in the next section.

### 3.5.1. Step One: Assessment parameters for classification

In 2001 OSPAR adopted common harmonized assessment criteria and their respective (region-specific) assessment levels, which are presented in Table 8 (OSPAR, 2003).

The first step is to provide a score (+) for each of the harmonized assessment criteria being applied according to the commission-agreed guidance. For example, Category I is scored "+" in cases where one or more of its respective assessment parameters is showing an increased trend or elevated change.

### 3.5.2. Step Two: Integration of categorized assessment parameters for classification

The second step is to integrate those scores obtained from the first step together to provide a coherent classification of the area (Table 9). For each assessment parameter from four categories, it can be indicated whether its measured concentration relates to a problem area, a potential problem area or a non-problem area as defined.

Table 8 The agreed harmonized assessment parameters of the Comprehensive Procedure (adapted after OSPAR, 2003).

| **Categories** | | **Parameters** | **Criteria thresholds for elevated eutrophic status** |
|---|---|---|---|
| Category I | Degree of nutrient enrichment | Riverine TN and TP; direct discharge | Elevated inputs and/or increased trends |
| | | Winter DIN and DIP concentrations | Conc.>50% above background conc. |
| | | Winter N/P ratio | >25 |
| Category II | Direct effect of nutrient enrichment | Maximum and mean Chl. *a* concentration | Conc. >50% above background conc. |
| | | Region specific phytoplankton indicator species | Elevated levels and increased duration |
| | | Macrophytes | Shift from long-lived to short-lived nuisance species |
| Category III | Indirect effect of nutrient enrichment | Degree of oxygen deficiency | <2 mg $l^{-1}$: acute toxicity; 2-6 mg $l^{-1}$: deficiency |
| | | Changes/kills in zoobenthos and fish kills | Kills; long term changes in zoobenthos biomass and species composition |
| | | Organic carbon/matter | Elevated levels |

Table 8 (*continued*)

| Categories | | Parameters | Criteria thresholds for elevated eutrophic status |
|---|---|---|---|
| Category IV | Other possible effect of nutrient enrichment | Algal toxins | Incidence |

Table 9 Integration of categorized assessment parameter criteria.

| Category I | Category II | Category III | Initial Classification |
|---|---|---|---|
| + | + | + | A |
| + | + | - | A |
| + | - | + | A |
| - | + | + | B |
| - | + | - | B |
| - | - | + | B |
| + | - | - | C |
| + | ? | ? | C |
| + | ? | - | C |
| + | - | ? | C |
| - | - | - | D |

(+) = Increased trends, elevated levels, shifts or changes in the respective assessment parameters in Table 9.

(-) = Neither increased trends nor elevated levels nor shifts nor changes in the respective assessment parameters in Table 9.

(?) = Not enough data to perform an assessment or the data available is not fit for the purpose.

A=Problem area; B=Problem area or caused by transport from other parts of the maritime area; C=Potential problem area; D=Non-problem area.

### 3.5.3. Step Three: Overall classification

The third step is to make an appraisal of all relevant information (concerning the harmonized assessment criteria their respective assessment levels and the supporting environmental factors), to provide a transparent and sound account of the reasons for establishing a particular status for the area.

Supporting environmental factors and region specific characteristics should be taken into account, such as physical and hydrodynamic aspects, and weather/climate conditions. These region specific characteristics play a role in explaining the results of the area classification, and also, they are vital to identify a “final classification”.

## 3.6. EPA NCR Water Quality Index

To summarize the condition of ecological resources in the coastal waters of the United States, US Environmental Protection Agency (EPA) developed a Water Quality Index in National Coastal Condition Report II (NCCR II).

The water quality index is made up of five indicators: nitrogen, phosphorus, chlorophyll *a*, water clarity and dissolved oxygen.

### 3.6.1. Nutrients: nitrogen and phosphorus

Coastal monitoring sites were rated good, fair, or poor for DIN and DIP, using the criteria shown in Table 10 and table 11. These rating were then used to calculate an overall rating for each region.

Table 10 Criteria for assessing dissolved inorganic nitrogen (all values in mg $l^{-1}$).

| Area | Good | Fair | Poor |
|---|---|---|---|
| East/Gulf Coast sites | <0.1 | 0.1-0.5 | >0.5 |
| West Coast sites | <0.5 | 0.5-1.0 | >1 |
| Hawaii, Puerto Rico, and Florida Bay sites | <0.05 | 0.05-0.1 | >0.1 |
| Regional Scores | Less than 10% of the coastal area was in poor condition, and more than 50% of the coastal area was in good condition. | 10% to 25% of the coastal area was in poor condition, or more than 50% of the coastal area was in combined poor and fair condition. | More than 25% of the coastal area was in poor condition. |

Table 11 Criteria for assessing dissolved inorganic phosphorus (all values in mg $l^{-1}$).

| Area | Good | Fair | Poor |
|---|---|---|---|
| East/Gulf Coast sites | <0.01 | 0.01-0.05 | >0.05 |
| West Coast sites | <0.01 | 0.01-0.1 | >0.1 |
| Hawaii, Puerto Rico, and Florida Bay sites | <0.005 | 0.005-0.01 | >0.01 |
| Regional Scores | Less than 10% of the coastal area was in poor condition, and more than 50% of the coastal area was in good condition. | 10% to 25% of the coastal area was in poor condition, or more than 50% of the coastal area was in combined poor and fair condition. | More than 25% of the coastal area was in poor condition. |

### 3.6.2. Chlorophyll *a*

In NCCR II, surface concentrations of chlorophyll *a* were determined from a filtered portion of water collected at each site and were rated good, fair, or poor using the criteria shown in Table 12.

Table 12 Criteria for assessing chlorophyll *a* (all values in μg $l^{-1}$).

| Area | Good | Fair | Poor |
|---|---|---|---|
| East/Gulf Coast sites | <5 | 5-20 | >20 |
| West Coast sites | <0.5 | 0.5-1.0 | >1 |
| Hawaii, Puerto Rico, and Florida Bay sites | <1 | 1-5 | >5 |
| Regional Scores | Less than 10% of the coastal area was in poor condition, and more than 50% of the coastal area was in good condition. | 10% to 20% of the coastal area was in poor condition, or more than 50% of the coastal area was in combined poor and fair condition. | More than 20% of the coastal area was in poor condition. |

### 3.6.3. Water clarity

Water clarity was estimated by using specialized equipment that compares the amount and type of light reaching the water surface to the light at a depth of 1 meter, as well as by using a Secchi disk. Water clarity varies naturally among the various parts of American land; therefore, the water clarity indicator (WCI) is based on a ratio of observed clarity to regional reference conditions:

WCI = (observed clarity at 1 meter) / (regional reference clarity at 1 meter)

Table 13 summarizes the rating criteria for water clarity for the regions.

Table 13 Criteria for assessing water clarity.

| Area | Good | Fair | Poor |
|---|---|---|---|
| Individual sampling sites | WCI >2 | WCI=1-2 | WCI<1 |
| Regional Scores | Less than 10% of the coastal area was in poor condition, and more than 50% of the coastal area was in good condition. | 10% to 25% of the coastal area was in poor condition, or more than 50% of the coastal area was in combined poor and fair condition. | More than 25% of the coastal area was in poor condition. |

### 3.6.4. Dissolved oxygen

Dissolved oxygen was rated good, fair, or poor using the criteria shown in Table 14.

Table 14 Criteria for assessing dissolved oxygen.

| Area | Good | Fair | Poor |
|---|---|---|---|
| Individual sampling sites | >5 mg $l^{-1}$ | 2-5 mg $l^{-1}$ | <2 mg $l^{-1}$ |
| Regional Scores | Less than 10% of the coastal area was in poor condition, and more than 50% of the coastal area was in good condition. | 10% to 25% of the coastal area was in poor condition, or more than 50% of the coastal area was in combined poor and fair condition. | More than 25% of the coastal area was in poor condition. |

### 3.6.5. Calculating the water quality index

With the data on DIN, DIP, chlorophyll a, water clarity, and dissolved oxygen, the water quality index rating is able to be calculated using the criteria shown in Table 15.

Table 15 Criteria for determining the water quality.

| Rating | Criteria |
| --- | --- |
| Good | A maximum of one indicator is fair, and no indicators are poor. |
| Fair | One of the indicators is rated poor, or two or more indicators are rated fair. |
| Poor | Two or more of the five indicators are rated poor. |
| Missing | Two components of the indicators are missing, and the available indicators do not suggest a fair or poor rating. |

The water quality index was then calculated for each region using the criteria in Table 16.

Table 16 Criteria for determining the water quality index rating by region.

| Rating | Criteria |
| --- | --- |
| Good | Less than 10% of the coastal area was in poor condition, and more than 50% of the coastal area was in good condition. |
| Fair | 10% to 20% of the coastal area was in poor condition, or more than 50% of the coastal area was in combined poor and fair condition. |
| Poor | More than 20% of the coastal area was in poor condition. |

## 3.7. ASSETS

ASSETS (the Assessment of Estuarine Trophic Status) is developed by the United States National Estuarine Eutrophication Assessment (NEEA), which was applied to 138 estuaries in the US. ASSETS is a more sophisticated and integrated methodology for eutrophication assessment in coastal zones, which may be applied comparatively to rank the eutrophication status of estuaries and coastal areas.

The concepts underlying ASSETS approach includes quantitative and semi-quantitative components, and uses field data, models and expert knowledge to evaluate Pressure-State-Response (PSR) indicators (Fig. 3). The core methodology relies on three diagnostic tools: a heuristic index of pressure (Overall Human Influence), a symptoms-based evaluation of state (Overall Eutrophic Conditions) and an indicator of management response (Definition of Future Outlook). It combines primary and secondary symptoms to derive an OEC index, which is then associated with a measure of OHI and the DFO.

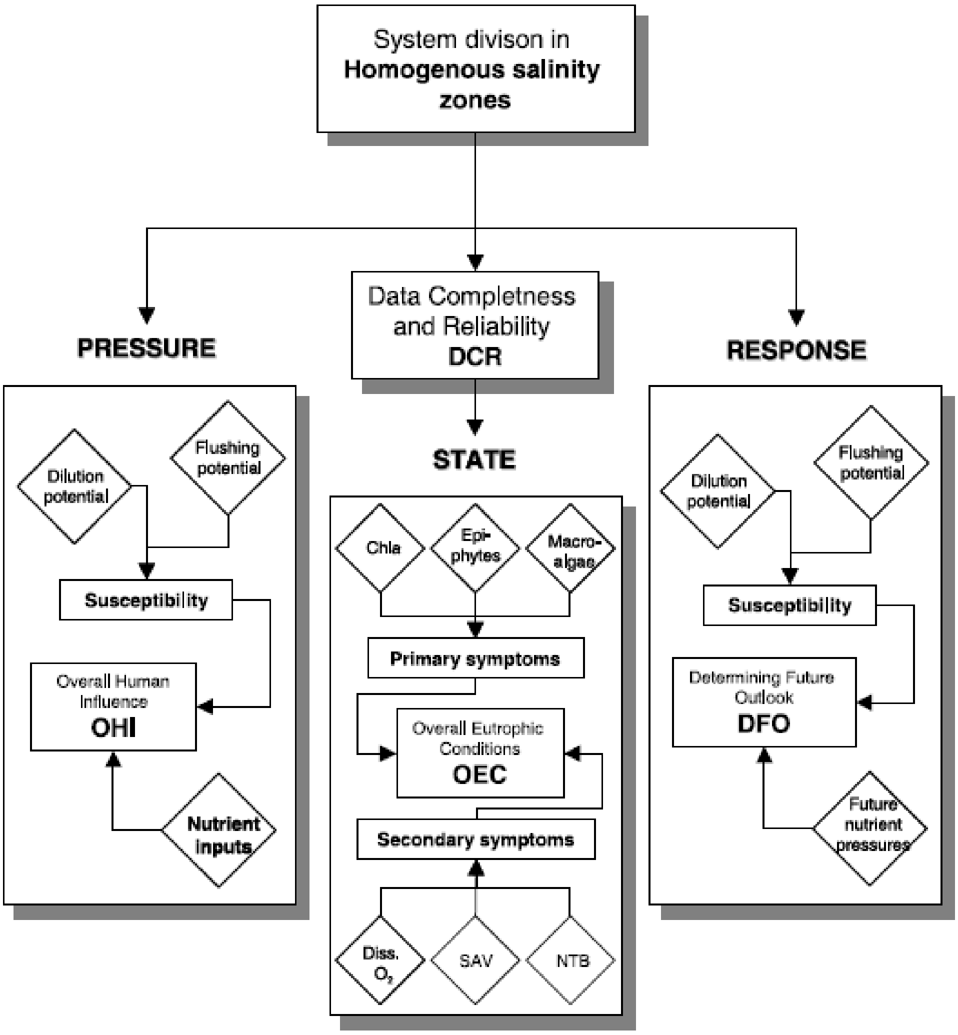


Fig.3. Flow chart of ASSETS methodology (adapted from Bricker, 2003).

ASSETS may be divided into two parts: data collection and compilation, and application of indices. The step-by-step methodology is briefly reviewed in the following sections.

### 3.7.1. Data collection and synthesis

The data collection framework could be divided into three parts: division of estuaries into homogeneous areas, data collection, and evaluation of data completeness and reliability.

#### 3.7.1.1. Physical division

The first step in applying the methodology is a physical classification of an estuarine system in terms of salinity. Each parameter was characterized for three salinity zones as defined in the NOAA's National Estuarine Inventory (NEI): tidal fresh (0-0.5 psu), mixing (0.5-25 psu), and seawater (> 25 psu).

#### 3.7.1.2. Data collection

Five variables from an original list of sixteen nutrient related water quality parameters are used for the assessment (Table 17; for a full description, see Bricker et al., 1999). According to Bricker et al. (2003), these eutrophication indicators were selected in order to:

a. be able to accurately characterize eutrophic conditions among highly varied systems; and to
b. allow a clear separation or comparison of estuaries.

Table 17 List of parameters considered in ASSETS.

| **Parameters** | **Existing conditions** |
| --- | --- |
| Chlorophyll *a* | a. Surface concentrations:<br>b. Limiting factors to algal biomass (N, P, Si, light, other)<br>c. Spatial coverage[1]; month of occurrence; frequency of occurrence[2] |
| Nuisance algae/toxic algae | a. Occurrence: problem (significant impact upon biological resources); no problem (no significant impact)<br>b. Dominant species<br>c. Event duration (hours, days, weeks, seasonal, other)<br>d. Months of occurrence; frequency of occurrence[2] |
| Macroalgae | a. Abundance: problem (significant impact upon biological resources); no problem (no significant impact)<br>b. Months of occurrence; frequency of occurrence[2] |
| a. Anoxia (0 mg $l^{-1}$)<br>b. Hypoxia (0-2 mg $l^{-1}$)<br>c. Biological stress (2-5 mg $l^{-1}$) | a. Dissolved oxygen condition: observed; no occurrence<br>b. Stratification (degree of influence): high; medium; low; not a factor<br>c. Water column depth: surface, bottom, throughout water column<br>d. Spatial coverage[1]; month of occurrence; frequency of occurrence[2] |
| Submerged aquatic vegetation/ intertidal wetlands | Spatial coverage |

Notes:

1) Spatial coverage (% of salinity zone): high (50-100%); medium (25-50%); low (10-25%); no SAV/wetland in system

2) Frequency of occurrence: episodic (conditions occur randomly); periodic (conditions occur annually or predictably); persistent (conditions occur continually throughout the year)

### 3.7.1.3. Analysis of data completeness and reliability

For each of these parameters, information on characteristics of timing, duration, spatial coverage, and frequency of occurrence are also collected as appropriate. Before compiling information for these parameters, there is a need to examine data gaps or speculative inferences. An analysis of data completeness and reliability (DCR) is carried out to inter-calibrate the spatial and temporal quality of the datasets and the confidence in the results. DCR is calculated by using the following combinations of parameter characteristics:

1) DCR (Chlorophyll *a*) = Concentration × Spatial Coverage × Frequency × Reliability;

   DCR (Macroalgae) = Concentration × Frequency × Reliability

   DCR (Diss. oxygen) = Concentration × Spatial Coverage × Frequency × Reliability

   DCR (SAV) =Direction of change × Magnitude × Reliability

   DCR (Nuisance algae) = Concentration × Frequency × Duration × Reliability

   DCR (Toxic algae) = Concentration × Frequency × Duration × Reliability

2) A rating based on the DCR score is assigned to each parameter and to the entire system as: high (75-100%); medium (50-74); low (0-49).

3) The entire system DCR value is then computed as the mean of the parameter DCRs.

### 3.7.2. State--Overall Eutrophic Condition (OEC)

The OEC index has a sequential approach based on two groups of symptoms, which bring together a subset of five parameters (Fig. 4).

The primary symptoms correspond to the early stage of water quality degradation, which are examined through the analysis of chlorophyll *a* concentrations and macroalgal blooms.

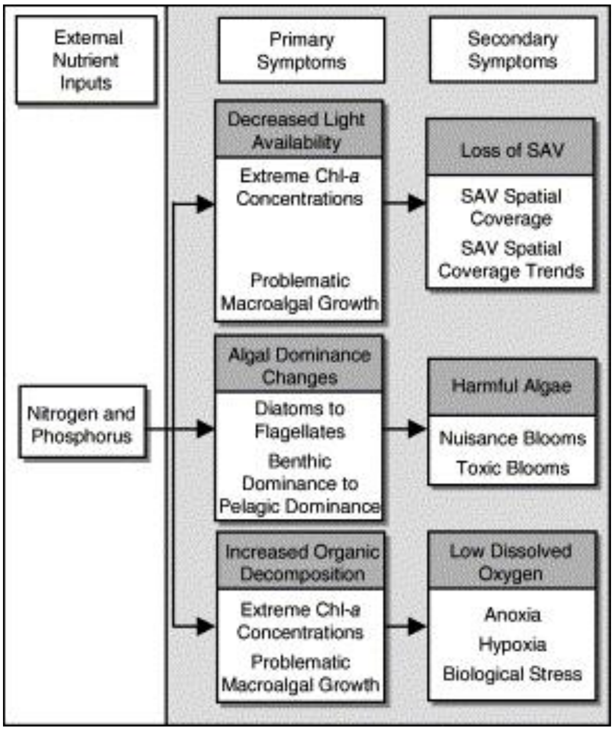


Fig.4. Conceptual model of OEC (adapted after Bricker et al., 2003).

In some systems, the primary symptoms lead to well developed eutrophic conditions, i.e., secondary (advanced) symptoms, such as submerged aquatic vegetation (SAV) loss, nuisance and toxic algal blooms and low dissolved oxygen (anoxia or hypoxia).

In the previous application of ASSETS, the epiphyte abundance was considered as one of the primary symptom. However, it would not be taken into account because of the lack of standard measure and conceptual overlapping with the SAV indicator, which reflects the level of epiphyte colonization in a large part.

To combine results for this subset of symptoms into an indicator of OEC, concentration, spatial coverage, frequency of occurrence of extreme or problem occurrences are considered for a logic stepwise decision method.

### 3.7.2.1. Primary symptoms method (PSM)

For each primary symptom, an area weighted expression value for each zone is determined, and the symptom level of expression $S_1$ was then obtained by summation.

$$S_1 = \sum_{1}^{n} \left( \frac{A_z}{A_e} E_1 \right) \quad \text{(Eq. 14)}$$

Where $A_z$ is the surface area of each zone; $A_e$ is the total estuarine surface area; $E_1$ is the expression value at each zone; $n$ is the number of estuarine zones.

The level of expression of the primary symptoms for the estuary $P_1$ is determined by calculating the average of two primary symptom expression values and estuary is then assigned a category for primary symptoms according to Table 18.

Table 18 Categories for primary and secondary symptoms.

| Estuary expression value | Level of expression category |
|---|---|
| 0-0.3 | Low |
| 0.3-0.6 | Moderate |
| 0.6-1 | High |

### 3.7.2.2. Secondary symptoms method (SSM)

For each secondary symptom (dissolved oxygen, submerged aquatic vegetation loss and nuisance and toxic blooms), an area weighted expression value for each zone is determined as described above. The level of expression of secondary symptoms for the estuary is determined by choosing the highest of the three estuary level symptom expression values. Secondary symptoms are considered to be a clear indicator of problems, and the application of the precautionary principle means that the highest (worst-case) value dictates the classification. The estuary is then assigned a category for secondary symptoms according to Table 17.

### 3.7.2.3. Overall ranking of eutrophic conditions

Finally, the primary and secondary symptoms are compared in a matrix to determine an overall level of eutrophic conditions for the estuary. As shown in Fig. 5, OEC is derived from a combination of Y-Axis (Primary symptoms) with X-Axis (Secondary symptoms).

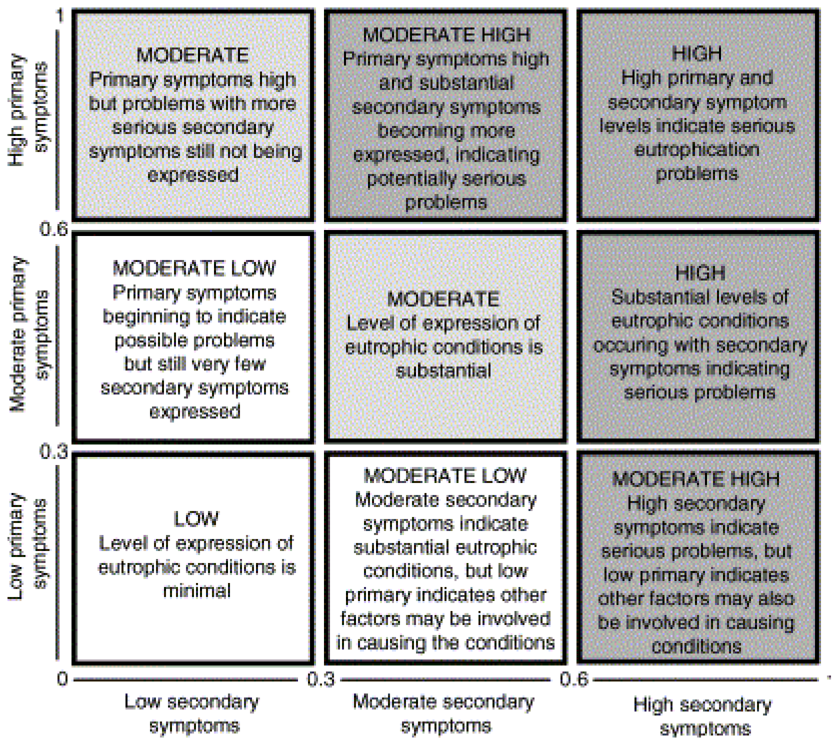


Fig.5. Determination of overall eutrophic condition based on primary and secondary symptoms

(adapted from Bricker et al., 2003).

### 3.7.3. Pressure--Overall Human Influence (OHI)

The basic assumption for OHI is that different systems vary in responding to any particular level of nutrient input, due to varying levels of susceptibility to nutrient inputs (Bricker et al., 1999). And thus, it is determined by combining system susceptibility and nutrient inputs.

#### 3.7.3.1. Nutrient load

This section is to determine the nutrient inputs being delivered to the water body from human activities. The watershed estimates are provided for five major nutrient source types: point sources, fertilizer, livestock, atmospheric deposition, and non-point/non-agricultural.

To simplify the complexity in coastal exchange, only conservative (mixing) processes are considered to derive the nutrient component of OHI. A simple "Vollenweider" mass balance model is used to describe the dispersive exchange between an estuarine black box and the ocean (Ferreira, 2000; Bricker et al., 2003).

$$\frac{dM_w}{dt} = M_{in} - M_{out} \qquad \text{(Eq. 15)}$$

where $M_w$ is the mass of nutrient in the estuary; $M_{in}$ is nutrient loading to the estuary (kg $s^{-1}$); $M_{out}$ is nutrient discharge from the estuary (kg $s^{-1}$).

Human-derived nutrient concentration $m_h$ is derived as following equation:

$$m_h = \frac{m_{in}}{1 + s_e / \Delta s} \qquad \text{(Eq. 16)}$$

where $m_{in}$ is the nitrogen concentration in the inflow (kg $m^{-3}$); $s_e$ is mean estuarine salinity (no unit); $\Delta s$ is the difference between offshore salinity and mean estuary salinity.

The calculation of background nutrient concentration $m_b$ is:

$$m_b = \frac{m_{sea} \cdot s_e}{s_o} \quad \text{(Eq. 17)}$$

where $m_{sea}$ is nitrogen concentration from the sea (kg $m^{-3}$); $s_o$ is offshore salinity.

The overall human influence (OHI) then may be obtained from Eq. 16 and 17:

$$OHI = \frac{m_h}{m_b + m_h} \quad \text{(Eq. 18)}$$

The ratio derived describes the comparison of nutrients from watershed or land based (human) loads with oceanic or natural loads. It determines the categorical response (Table 19), which is afterwards used to combine with the categorical response for susceptibility (Bricker et al., 2003).

Table 19 Thresholds set categories used to classify overall human influence (adapted from Bricker et al., 2003).

| **Class** | **Thresholds** | **Score** |
|---|---|---|
| Low | 0 to <0.2 | 5 |
| Moderate low | >0.2 to 0.4 | 4 |
| Moderate | >0.4 to 0.6 | 3 |
| Moderate high | >0.6 to 0.8 | 2 |
| High | >0.8 | 1 |

### 3.7.3.2. Susceptibility

Susceptibility is defined as the relative capacity of a system to dilute and/or flush nutrients.

Dilution potential is determined as a function of the system volume, weighted with a stratification term. Flushing potential is a relative to tidal range and river flow.

By combining dilution and flushing components, an export potential is determined (Fig. 6).

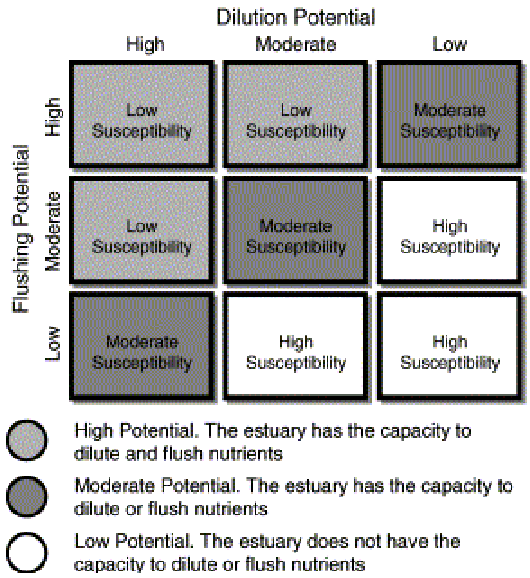


Fig.6. Combination of dilution and flushing for susceptibility (adapted from Bricker et al., 2003).

### 3.7.3.3. Determination of the overall level of human influence

OHI is determined by comparing susceptibility to retain nutrients with the level of nutrient input, as shown in following matrix (Fig. 7).

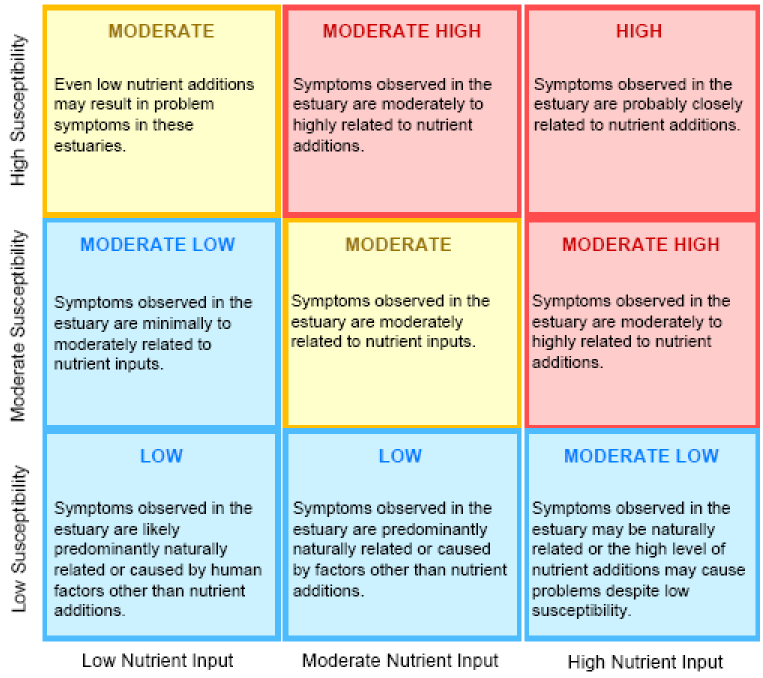


Fig.7. Combination of susceptibility and nutrient input for OHI (adapted from Bricker et al., 2003).

### 3.7.4. Response--Determination of Future Outlook (DFO)

DFO is performed to determine the likelihood of whether conditions in an estuary will worsen, improve, or stay the same over the next twenty years. Assessment of expected changes in nutrient pressures are carried out based on a variety of drivers, including demographic trends, wastewater treatment and remediation plans, and changes in watershed uses. Since the state of estuarine system is related not only to the nutrient pressures, but also to system carrying capacity, there is a need to include aforementioned susceptibility. Therefore, projection of future nutrient inputs is combined, in this section, with system susceptibility to obtain a foreseeable evolution (Fig. 8).

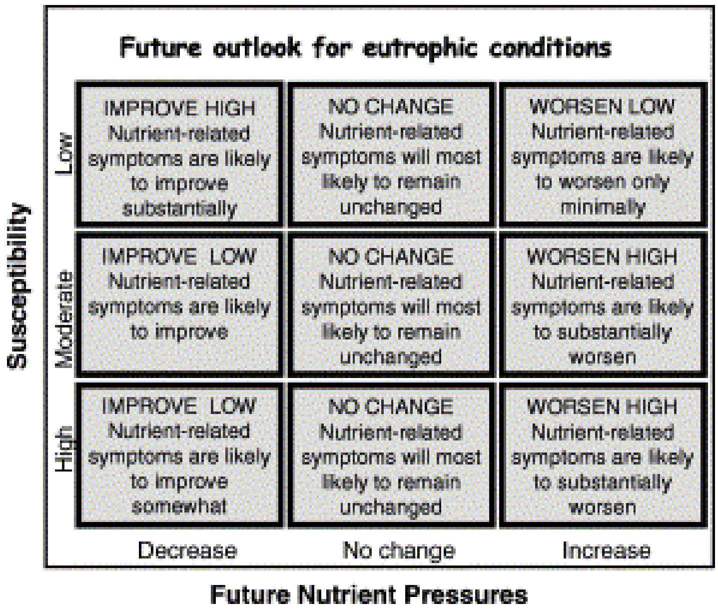


Fig.8. Combination of susceptibility and future nutrient pressure for DFO (adapted from Bricker et al., 2003).

### 3.7.5. Synthesis--Overall grade

The last stage of ASSETS is to synthesize the three indices mentioned above to provide an overall description of system status in terms of eutrophication. The combination of individual classifications for pressure, state and response is able to provide a grade falling into one of five categories: high, good, moderate, poor or bad (Table 20). Since there are five grades for each component, theoretically allows $5^3$ possibilities. However, clearly not every aggregation makes sense, and thus 31 highly improbable or unreasonable combinations were excluded.

Table 20 Combination of pressure (OHI), state (OEC) and response (DFO) components to provide an overall grade (adapted after Bricker et al., 2003).

| Grade | 5 | 4 | 3 | 2 | 1 |
|---|---|---|---|---|---|
| Pressure (OHI) | Low | Moderate low | Moderate | Moderate high | High |
| State (OEC) | Low | Moderate low | Moderate | Moderate high | High |
| Response (DFO) | Improve high | Improve low | No change | Worsen low | Worsen high |

| Metric | Combination matrix | Class |
|---|---|---|
| P | 5 5 5 4 4 4 | High |
| S | 5 5 5 5 5 5 | (5%) |
| R | 5 4 3 5 4 3 | |
| P | 5 5 5 5 5 5 5 4 4 4 4 4 3 3 3 3 3 3 | Good |
| S | 5 5 4 4 4 4 4 5 5 4 4 4 5 5 5 4 4 4 | (19%) |
| R | 2 1 5 4 3 2 1 2 1 5 4 3 5 4 3 5 4 3 | |
| P | 5 5 5 5 5 4 4 4 4 4 4 4 3 3 3 3 3 3 3 2 2 2 2 2 2 2 2 2 1 1 | Moderate |
| S | 3 3 3 3 3 4 4 3 3 3 3 3 5 5 4 4 3 3 3 4 4 4 4 4 3 3 3 2 3 3 | (32%) |
| R | 2 1 5 4 3 2 1 5 4 3 2 1 2 1 2 1 5 4 3 5 4 3 2 1 5 4 3 5 5 4 | |
| P | 4 4 4 4 4 3 3 3 3 3 3 3 2 2 2 2 2 2 1 1 1 1 1 | Poor |
| S | 2 2 2 2 2 3 3 2 2 2 2 2 3 3 2 2 2 2 3 3 3 2 2 | (24%) |
| R | 5 4 3 2 1 2 1 5 4 3 2 1 2 1 4 3 2 1 3 2 1 5 4 | |
| P | 3 3 3 3 3 2 2 2 2 2 1 1 1 1 1 1 1 1 | Bad |
| S | 1 1 1 1 1 1 1 1 1 1 2 2 2 1 1 1 1 1 | (19%) |
| R | 5 4 3 2 1 5 4 3 2 1 3 2 1 5 4 3 2 1 | |

These five categories are used by the EU Water Framework Directive (EUWFD, 2000/60/EC). Although the Directive is designed for EU members, the framework provides a useful scale for setting eutrophication-related reference conditions for different types of systems (Bricker et al., 2006).

# Chapter 4. Discussion of methodology

In this section, the different methods are discussed and compared in terms of the rationale behind them. “Phase I” approaches usually establish nutrient-based classification systems through the measurement of variables such as transparency, nutrients and chlorophyll *a*, while “Phase II” approaches look at the symptoms. The details of comparisons are presented as follows.

## 4.1. Comparison among “Phase I” and “Phase II” methods

Even though the nutrient index methods aforementioned are the recommended approach by Chinese national authority, they have been criticized for their underlying simplicity and limitation (Yao & Shen, 2005). The main reasons that the “Phase I” methods are considered not appropriate in assessing Chinese coastal systems lie on:

a. They overemphasize the significance of nutrient concentration as an indicator of eutrophication, which instead may not be a robust diagnostic variable. Nutrients are the primary cause, but there are many factors causing or responding to the increase of eutrophic level, such as the presence of nuisance and loss of submerged vegetation. High concentrations are not necessarily indicative of eutrophication, and low concentrations do not inevitably guarantee the absence of eutrophication (Cloern, 2001; Dettmann, 2001; Bricker et al., 2003).

b. These freshwater-based methods fail to adapt themselves to coastal systems due to the unawareness of the difference between freshwater and coastal systems. It has been recognized in the last decades that estuarine and coastal eutrophication is potentially a far more subtle problem, with different sensitivity to nutrient enrichment (Cloern, 2001). For example, the water exchange in estuaries largely mitigates the pressures from eutrophication.

c. Simple time-varying or statistical approaches are established on the clear relationships between pelagic algae and nutrient loading. But in the case of coastal systems such as estuaries and bays, systems with similar pressures show widely varying responses as they are modulated by system attributes (Cloern, 2001; Ferreira et al., 2007). The ambiguous relationship between nutrient forcing and eutrophication symptoms poses a substantial obstacle to the success of applying the freshwater methods in coastal systems.
d. Unreasonable classification standards in statistic methods like nutrient index methods and PCA. Lu and Lo took Carlson index as an example to criticize, which gives Trophic State Index (TSI) = 49 and 50 different classifications but TSI=41 and 49 the same (Lu & Lo, 2002).
e. A further problem with Phase I methods is the failure in determining the weights to each parameter. Although the scientific community has been unable to agree upon a single, reliable trophic state index, it is commonly agree that the importance of variables should not be precisely equal to each other (Lu & Lo, 2002; Bricker et al., 2006).

## 4.2. Comparison among "Phase II" methods

Three main "Phase II" methods include OSPAR COMPP, EPA NCR Water Quality

Index, and ASSETS.

OSPAR and NCR distinguish themselves from ASSETS in the following aspects:

a. The concentrations of DIN and DIP are taken as indicators of eutrophication;
b. they give the same weight for each parameters, which is apparently not always the case;
c. OSPAR fails to set thresholds for parameters concerned. This was initially intended to allow flexibility and discretion while applying it to a range of countries. However, it also leads to ambiguity and vagueness in final results.

In terms of indicator variables, four Chinese methods mentioned above are quite similar although the underlying logic might vary. The indicator chosen in different methods are summarized in Table 21, while Table 22 presents a more detailed comparison among Chinese methods and “Phase II” methods.

Table 21 Summary of indicator variables used (adapted after Bricker et al., 2006).

| **Variables** | **Nutrient Index I** | **Nutrient Index II** | **PCA** | **Fuzzy Analysis** | **OSPAR COMPP** | **EPA NCR** | **ASSETS** |
|---|---|---|---|---|---|---|---|
| Nutrient (DIN, DIP) load or concentration | × | × | × | × | × | × | |
| Chlorophyll *a* | × | | × | × | × | × | × |
| Dissolved oxygen | × | × | × | × | × | × | × |
| Water clarity | | | × | × | | × | |
| HABs/Nuisance | | | | | × | | × |
| Phytoplankton indictor SPP | | | | | × | | |
| Macroalgal abundance | | | | | × | | × |
| Submerged aquatic vegetation loss | | | | | × | | × |
| Zoobenthos/fish kills | | | | | × | | |

Table 22 Summary of comparison among "Phase I/II" methods (adapted after Bricker et al., 2006).

| **Methods** | **Temporal focus** | **Indicator criteria/ thresholds** | **Combination method** |
|---|---|---|---|
| *Nutrient Index I* | Not specified | Modified after Japanese criteria | Sum of four ratios |
| *Nutrient Index II* | Not specified | Modified after Japanese criteria | Ratio of three parameters to their threshold values |
| *PCA* | Not specified | Modified after Japanese criteria | Comparisons among primary components and their threshold values |
| *Fuzzy Analysis* | Not specified | National standards | Probabilities comparison |
| *OSPAR COMPP* | Growing season, winter for nutrients | No | Integration of scores for four categories |
| *EPA NCR* | Summer | Determined from American national studies | Ratio of indicators: good/fair indicators to poor/missing data |
| *ASSETS* | Annual cycle | Determined from American national studies | Average of primary and highest secondary are combined by matrix |

# Chapter 5. Case studies

ASSETS was chosen to study two Chinese systems, Changjiang Estuary and Jiaozhou Bay. The reasons to choose ASSETS include:

- it was successfully applied and tested for 138 estuaries in continental United States, 10 estuaries in Portugal and a number of coastal systems in the U.K., Germany (Bricker et al., 1999; Ferreira et al., 2003; Brockmann, 2004);
- it reflects a diversity of environmental constitutions in estuarine use, morphology, river discharge and tidal ranges;
- it was consolidated through intense peer-review within the scientific community, and has been published in the open literature (Bricker et al., 2003; Ferreira et al., 2003);
- it takes biological components into account compared to Nutrient Index Methods, and provides a more accurate evaluation than OSPAR (a full discussion of comparisons among methodologies is given in the next chapter).

The reason to choose Changjiang Estuary to study is because it is the largest estuary in China with the largest watershed and densest population and therefore high level nutrient inputs which frequently lead to eutrophic problems. This is initial evidence that this is the case for the Changjiang because this area has recently had frequent report of the Harmful Algal Blooms and a detailed eutrophic study will allow the level of eutrophic condition. Additionally, its similarity to Mississippi River would make it appealing to compare them.

The interest in Jiaozhou Bay, on the other hand, is mainly due to the unique top-down control in the local ecosystem given by aquaculture (Han & Wang, 2001; Li et al., 2005), which might provide broader options for the management of eutrophication.

## 5.1. Changjiang Estuary

Changjiang River (Yangtze River) is the largest river in China and empties into the East China Sea at the city of Shanghai (Fig. 9).

The $1.94 \times 10^6$ $km^2$ Changjiang River Basin is characterized by intense industrial and urban activity, especially in the lower reaches and estuarine portion of the river. The temperate climate drainage basin is heavily populated with an estimated population of 400 million people.

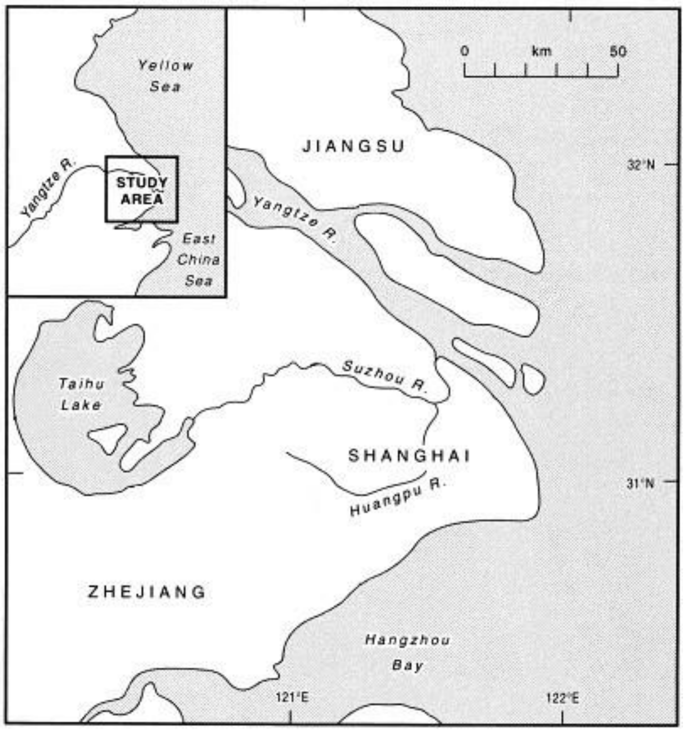


Fig.9. Location map of Changjiang Estuary (adapted after Chen & Zhong, 1999).

The river discharge of 29,000 $m^3$ $s^{-1}$ delivers about 480 million ton of sediment each year to the estuarine and coastal area. Changjiang River is a major source of nutrients to the coastal zone, acting as a conduit that transports anthropogenic nutrients from the catchment to the estuary and adjacent coastal waters (Chen & Chen, 2003).

It is commonly agreed that Changjiang estuary has its upstream limit at the Datong, Anhui Province. The huge suspended load aforementioned creates a bar system at the entrance into the East China Sea, with depth less than 10 meters extending over 40 km along each waterway (Chen et al., 1985, Wu et al., 2003). Located on a mesotidal coast, it is a wide, shallow and partially mixed estuary.

### 5.1.1. Issues of concern: HABs and Hypoxia

Harmful algal blooms are frequently observed in the Changjiang Estuary and extended coastal waters and are the primary issue of concern. The East China Sea is the area where the most severe HABs occur among the four Seas of China, accounting for 45% of the total recorded number of blooms. The frequency of HAB occurrences as well as the duration and spatial extent of affected areas have increased significantly and continually since the 1990s. In 2002, there were 51 individual HAB occurrences observed in Changjiang estuary and adjacent coastal areas (Guan & Zhan, 2003). Toxic species of HABs, such as *Alexandrium* and *Gymnodinium,* are often observed resulting in kills of fish and zoobenthos. These occurrences have damaged nearby fishing grounds such as the Zhoushan fishing area.

A secondary issue of concern in this area is hypoxic occurrences in near-bottom waters off the Changjiang River mouth, which have increased continuously since the first record in the 1950s (Li & Daler, 2004).

### 5.1.2. Homogeneous areas

Due to the large area of Changjiang Estuary, published results on salinity in the whole estuary are too limited to make a precise division of homogeneous areas. But the traditional way to divide the estuary based on tides and mixing process could be able to provide a snapshot of the homogeneity within the estuary (Fig. 10).

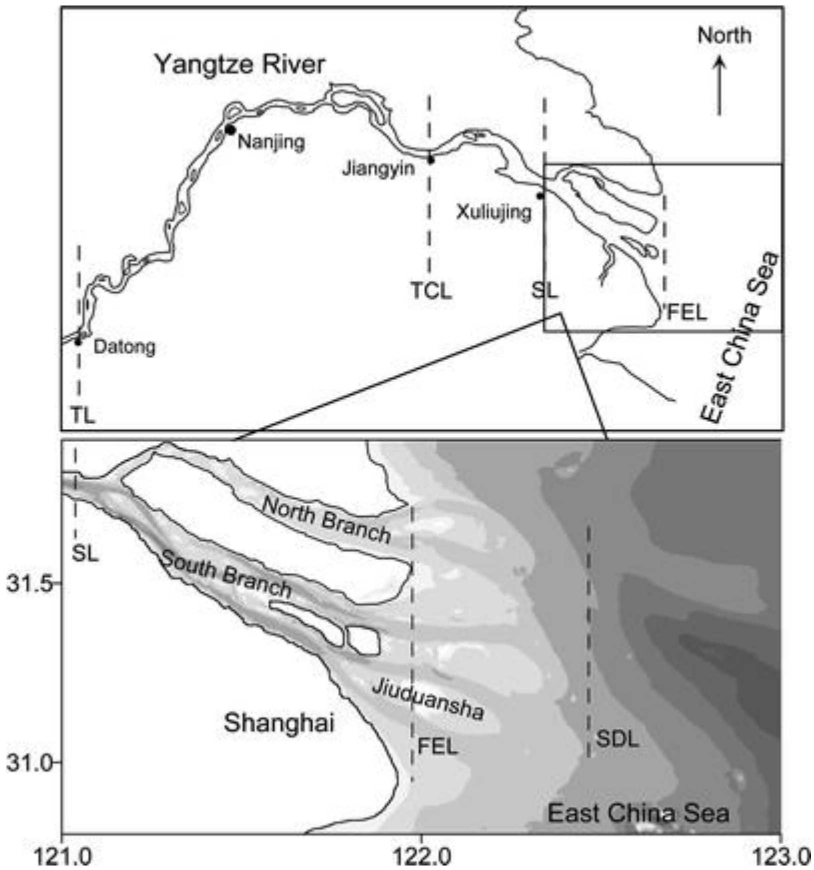


Fig.10. The sketch map of divisions of Changjiang Estuary (adapted after Huang et al., 2006).

It is widely agreed to divide the Changjiang Estuary into three zones (Editorial Board of Bays in China, 1998):

a. Lower estuary, from the mouth until Xuliujing (Jiangsu Province). The river mouth is also often cited as transitional limit of flood and ebb predominant currents (FEL), which is the boundary of the ocean. Xuliujing is where the saltwater intrusion limit (SL) is located.

b. Mid estuary, until Jiangyin (Jiangsu Province), the tidal current limit (TCL).

c. Higher estuary, until Datong, Anhui Province, the tidal limit (TL) of the river.

### 5.1.3. Data completeness and reliability

There is no raw data available from station gauges, but data on chlorophyll *a*, dissolved oxygen and harmful algal blooms are collected from the literature. Although data completeness is quite low, the reliability is adequate. Due to the lack of data the ASSETS methodology could only be partly applied to some of the primary and secondary symptoms.

### 5.1.4. Overall Eutrophic Condition (OEC)

#### 5.1.4.1. Primary symptoms method

Chlorophyll *a* is the only parameter with information indicating the primary symptoms. No information was reported in the literature concerning macroalgae, which were therefore classified as "Unknown".

##### *5.1.4.1.1. Chlorophyll a*

Concentration of chlorophyll *a* is commonly used as a parameter of phytoplankton biomass, and in ASSETS, the 90th percentile value of concentration of all annual data is more interested in indicating the eutrophic symptom.

In a large scale, the chlorophyll *a* concentration in summer has increased by a factor of four during the last two decades (Fig. 11).

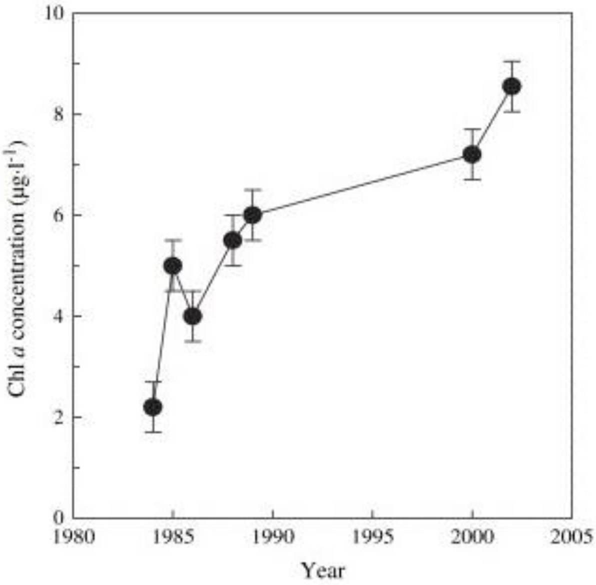


Fig.11. Variation of Chlorophyll *a* concentration in summer (August) in the surface water of the Changjiang Estuary during the last two decades (adapted after Wang, 2006).

Detailed station gauges on chlorophyll *a* concentration are hard to found, but for indicative purpose, the literature data are used to carry out a pilot test. Zhou and his colleagues reported one typical annual cycle variation of chlorophyll *a* in Changjiang Estuary from 2002 to 2003 (29.0-32.0 °N, 122.0-123.5 °E, with an area of 47712.5 $km^2$), where a *Prorocentrum donghaiense* bloom occurred in April (1076.04 $km^2$, from 29.5-30.0 °N, 122.3-122.5 °E), with higher concentrations in spring and summer (Zhou et al., 2004). Table 23 summarizes the yearly variation in the estuary.

Table 23 Variation of chlorophyll *a* concentration (μg $l^{-1}$) in an annual cycle (adapted after Zhou et al., 2004).

| | | **Spring** | **April (incurrence of HAB)** | **Summer** | **Autumn** | **Winter** |
|---|---|---|---|---|---|---|
| Surface | Mean value | 1.09 | 18.96 | 3.94 | 0.85 | 0.55 |
| | Data range | 0.25-9.08 | 6.13-39.88 | 0.10-24.21 | 0.38-1.66 | 0.27-1.39 |
| Middle | Mean value | 0.53 | 4.43 | 2.20 | 0.75 | 0.53 |
| | Data range | 0.12-1.56 | 0.32-17.27 | 0.11-10.56 | 0.20-1.37 | 0.19-1.29 |
| Bottom | Mean value | 0.49 | 2.11 | 1.89 | 0.73 | 0.53 |
| | Data range | 0.07-1.59 | 0.39-5.98 | 0.14-11.85 | 0.17-1.51 | 0.15-1.32 |

The mean values of maximum concentration fall into the medium category (5-20 μg $l^{-1}$). In addition to the huge area of bloom occurred, the symptom level of chlorophyll *a* concentration is considered as "*Moderate*".

#### 5.1.4.2. Secondary symptom method

Symptoms of dissolved oxygen and harmful algal blooms are analyzed in this section, while no information is found for loss of submerged aquatic vegetation.

##### *5.1.4.2.1. Dissolved oxygen*

Changjiang Estuary has been suffering from low dissolved oxygen for long (Li et al., 2002). During the last two decades, dissolved oxygen minimum values in the low oxygen region of the Changjiang Estuary have decreased from 2.85 mg $l^{-1}$ to 1 mg $l^{-1}$.

A 1999 survey of Changjiang Estuary revealed a 13,700 $km^2$ bottom water hypoxic zone (< 2 mg $l^{-1}$) with an average thickness of 20 m and a minimum value of 1 mg $l^{-1}$ (Li et al., 2002; Wei et al., in press). The plume of oxygen depleted water extended to the 100m isobath in a southeastward direction along the bottom of the continental shelf of the East China Sea (Fig. 12).


Fig.12. The estimated hypoxic areas in Changjiang Estuary (adapted after Li, et al., 2002)

These observations clearly indicate the system is under the condition of severe biological stress (<5 mg $l^{-1}$). In combination of the observed hypoxia and the large area (26.9%), the expression level of dissolved oxygen is considered as "Moderate".

### *5.1.4.2.2. Nuisance and toxic blooms*

The elevated phytoplankton biomass as indicated by the chlorophyll *a* concentration corresponds to an increase of toxic bloom events in the river plume. Incidents of harmful algal blooms in the Changjiang Estuary and adjacent coastal areas were rare before 1985, but have increased rapidly and continuously since then (Fig. 13).

Along with the frequent reports of HABs incidents, the duration of blooms could last for weeks to month. For example, a *Skeletonema costatum* bloom was registered to last from May 10th-23rd in 2001.

Considering the high frequency and long duration of occurrence of HABs in estuary, the level of “nuisance and toxic blooms” falls into the “High” category.

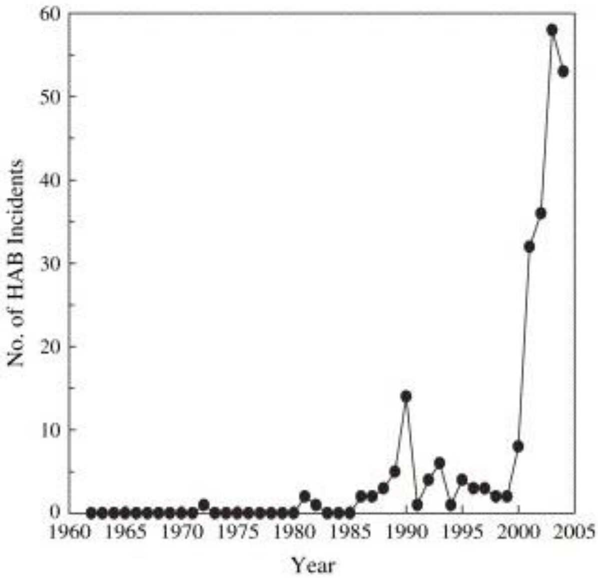


Fig.13. Variation of numbers of HAB incidents in the Changjiang Estuary and adjacent sea areas (29-32 °N, 122-124 °E) over the past 40 years (adapted after Wang, 2006).

Since the secondary symptom level is determined by the highest value of three symptoms in ASSETS, Changjiang Estuary is considered to fall into the “High” category, in spite of little information on loss of submerged aquatic vegetation.

The overall eutrophic condition in this system is considered “High” due to Moderate primary symptoms and High secondary symptoms.

### 5.1.5. Overall human influence (OHI)

#### 5.1.5.1. Nutrient input

As a result of increased fertilizer application and increased effluent from cities in the Changjiang River basin, nutrient concentrations (DIN and phosphate) in

Changjiang have increased by a factor of five from the 1960s to the 1990s (Duan and Zhang, 2001). By contrast, silicate concentrations decreased exponentially by two thirds during this same time period (Wang, 2006). Since 1985 the N/P ratio increased to 125 and has stayed nearly constant, while the Si/N ratio has decreased to 1.0 in the 1990s.

Trends in nutrients fluxes from 1968 to 1997 were calculated taking into account differences in sampling time, place, methods of analysis, as well as annual and seasonal variations of the nutrient fluxes. Results show that increased nutrients fluxes from Changjiang River have led to an increased concentration of DIN from 15 μmol $l^{-1}$ in 1968 to 118 μmol $l^{-1}$ in 1997 (Liu et al., 2002).

To estimate the nutrient load into the Changjiang Estuary, SWAT (Soil and Water Assessment Tool) was initially applied to simulate the nutrient load into the Estuary.

***5.1.5.1.1 Catchment delineation***

SWAT is a physically-based model with an objective to assess the impact of land management on water, sediment and agricultural pollution (Arnold et al., 1998). It simulates the water cycle and the nutrient transport, from a variety of data on climate, topography, soil properties, land use and management practices. SWAT divides the study area into watersheds, which is divided into Hydrological Response Units (HRUs). HRU is the basic unit in SWAT model, which homogeneously corresponds to a particular combination of one unique soil type and land use within the subbasin (Neitsch et al., 2002).

The forcing functions considered in SWAT are climate and human management, which accordingly are input as controlling factors, such as precipitation, mean temperature and land cover scenarios. Main results obtained by SWAT include vegetation growth, surface and subsurface runoff, soil erosion and nutrient export for the entire catchment (Santhi et al., 2005).

The model used in this thesis project is ArcView SWAT (AVSWAT), an integration of ArcView with SWAT. It provides a complete set of tools for watershed delineation, definition and editing of hydrological and agricultural management inputs, running and calibration of the model (available on http://www.brc.tamus.edu/swat/avswat/).

The topography map used is from Shuttle Radar Topography Mission (SRTM), USGS. Given the big area of Changjiang River Basin, the resolution was 1×1 km. Lambert Conformal Conic (WGS 1984) was chosen as the map projection. Applying SWAT automatic delineation tool, the Changjiang River Basin was divided into 87 subbasins. Fig. 14 presents the subbasins delineated by SWAT.

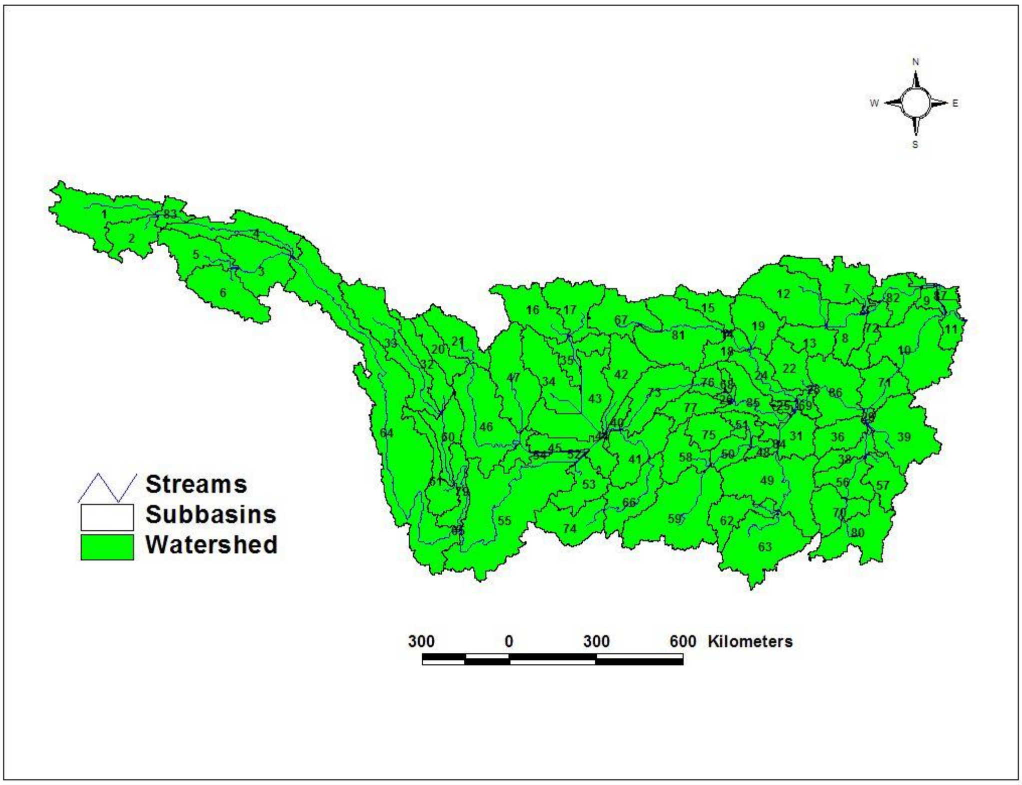


Fig.14. Subbasins map obtained from SWAT.

The original land cover map with 1 km resolution was obtained from the U.S. Geological Survey's (USGS) Global Land Cover Characteristics Data Base (http://edcsns17.cr.usgs.gov/glcc/). To be compatible with SWAT delineation, the land cover map was reclassified by SWAT land codes (Fig. 15). Table 24 summarized the land cover codes presented in Fig. 15.

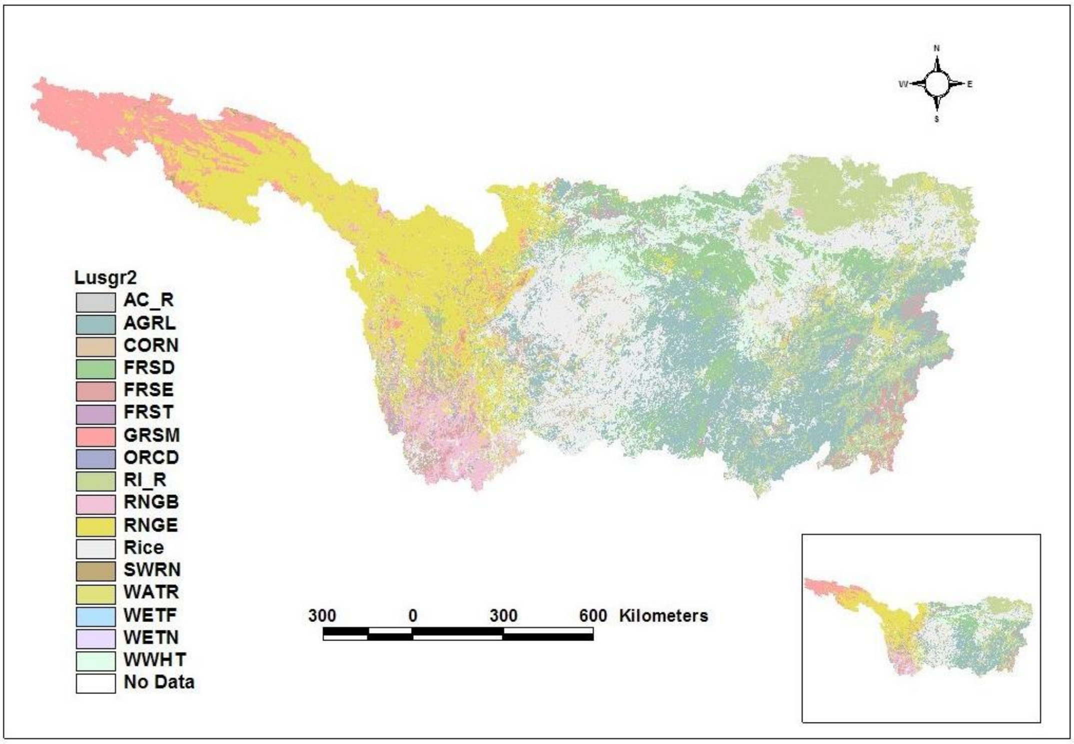


Fig.15. Land-cover map in Changjiang River Basin.

SWAT proved not to be an appropriate tool to simulate such a large area as Changjiang River Basin. The main reason for this is scale issues concerning the proper representation of the watershed's hydrological characteristics from thee available altimetry data. The resolution of altimetry map used is 1×1 km, which is too low for SWAT to run the model.

Alternatively, an Export Coefficient Model (ECM) was chosen to estimate nutrient loading to the estuary, based on watershed delineated by SWAT.

Table 24 Generic land covers included in Changjiang River Basin.

| **Land cover code** | **SWAT ID/Common name** |
| --- | --- |
| AC_R | Agricultural Land-Close-grown (Irrigated) |
| AGRL | Agricultural Land-Generic |
| CORN | Corn |
| FRSD | Forest-Deciduous |
| FRSE | Forest-Evergreen |
| FRST | Forest-Mixed |
| GRSM | Semi-arid Grassland |
| ORCD | Orchard |
| RI_R | Rice Irrigated |
| RNGB | Range-Brush |
| RNGE | Range-Grasses |
| Rice | Rice |
| SWRN | Southwestern US (Arid) Range |
| WATR | Water |
| WETF | Wetlands-Forested |
| WETN | Wetlands-Non-Forested |
| WWHT | Winter Wheat |
| No Data | No data available |

*5.1.5.1.2 Export Coefficient Model (ECM)*

The ECM uses land cover data maps to sum the total annual basin nutrient loads from the many unique watershed areas, and then add other nutrient sources such as septic systems, wastewater treatment plants, and precipitation (Reckhow & Simpson, 1980). The nutrient load in a river basin is obtained by the following equation:

$$L_N = \sum_{i=1}^{M} [E_i \cdot A_i] + S + W + P \qquad \text{(Eq. 19)}$$

where $L_N$ is the basin nutrient load (kg/y); $E_i$ the export coefficient (kg/h/y) for land class $i$; $A_i$ the area of the watershed in land class $i$; $S$ the septic load (kg/y); $W$ the wastewater load (kg/y); $P$ the precipitation load (kg/y).

As a scoping model for estimating lumped annual basin nutrient loads (Reckhow et al., 1980; Mattikllia & Richards, 1996; Johnes & Heathwaite, 1997; Endreny & Wood, 2003), ECM provides an applicable and robust method across many different watersheds (Beaulac & Reckhow, 1982; Clesceri et al., 1986; Frink, 1991; Line et al., 2002).

Unlike SWAT, The ECM does not use meteorological data or mechanistic pollutant-atmosphere-vegetation-soil equations, nor does it considering chemical process among nutrient compounds. But its modelling strength and adaptability have at least two advantages (Endreny & Wood, 2003):

a. it is functional within watersheds that meet the minimum data needs;

b. it remains as simple as possible to use (Worrall & Burt, 1999).

The areas used for ECM were obtained from SWAT subbasin delineation and area calculation, while the nutrient coefficients are collected from the literature (Table 25).

Table 25 Export coefficient (EC) summary for nitrogen and phosphorus (Reckhow et al., 1980; Johnes, 1996; Worrall & Burt, 1999; Bernald et al., 2003).

| **Crop code** | **SWAT_ID** | **Details** | **Nitrogen EC (kg/ha/y)** | **Phosphorus EC (kg/ha/y)** |
|---|---|---|---|---|
| FRSE | Forest-Evergreen | Forest | 1.8 | 0.11 |
| FRSD | Forest-Deciduous | Forest | 1.8 | 0.11 |
| FRST | Forest-Mixed | Forest | 1.8 | 0.11 |
| RNGB | Range-Brush | Forest | 1.8 | 0.11 |
| RNGE | Range-Grasses | Forest | 1.8 | 0.11 |
| ORCD | Orchard | Orchard | 4.8 | 3.6 |
| RI_R | Rice Irrigated | Rice_double | 33.6 | 10.8 |
| Rice | Rice | Rice | 16.8 | 5.4 |
| WWHT | Winter wheat | Wheat | 16.8 | 3.6 |
| CORN | Corn | Corn | 26.4 | 12.0 |
| AC_R | AGRC Irrigated | Wheat+Corn | 43.2 | 15.6 |
| AGRL | Agricultural Land-Generic | | 16.8 | 5.4 |
| WETF | Wetlands-Forested | Forest | 1.8 | 0.11 |
| WETN | Wetlands-Non-Forested | Forest | 0 | 0.11 |
| GRSM | Semi-arid Grassland | | 0.1 | 0.005 |
| SWRN | Southwestern US (Arid) Range | | 0.1 | 0.005 |

Table 25 (*continued*)

| Crop code | SWAT_ID | Details | Nitrogen EC (kg/ha/y) | Phosphorus EC (kg/ha/y) |
|---|---|---|---|---|
| SWRN | Southwestern US (Arid) Range | | 0.1 | 0.005 |
| WATR | Water | | 0 | 0 |

The combination of septic load and wastewater load are calculated by city populations, the water consumption per capital and the amount of nutrients per capital per day (for total nitrogen: 0.012 kg/d, phosphorus: 0.0025 kg/d), while the precipitation load is neglected. Wastewater generation rate is estimated as 85%, and wastewater treatment efficiency set as 90%. Fig. 16 is the summary of water consumption in different provinces (Ministry of Water Resources, 1999).

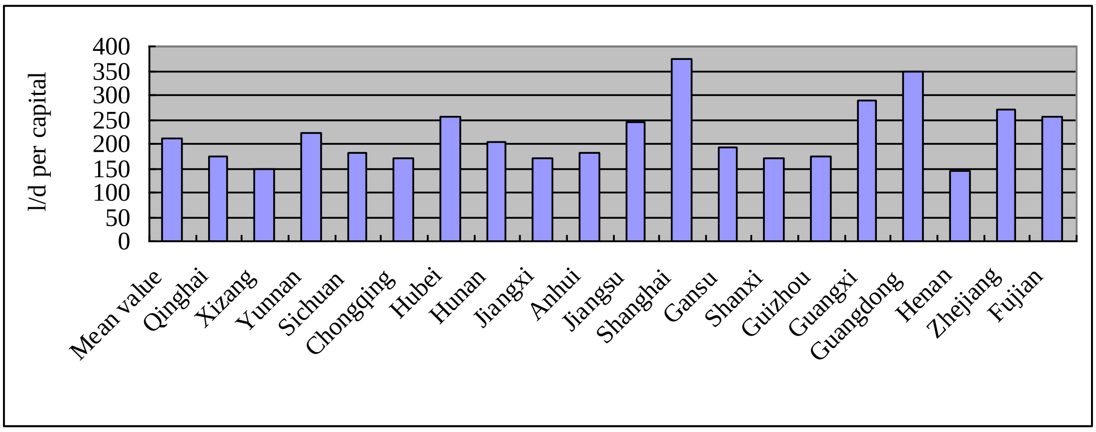


Fig.16. Summary of daily water consumption (liter per capital per day).

The nutrient loads are then calculated by the product of urban population, water consumption per year, and wastewater treatment ratio, i.e.:

$$S + W = P_u = W_c \times 365 \times R_w \times N_h \times R_t \qquad \text{(Eq. 20)}$$

where $P_u$ is urban pollution (kg/y); $W_c$ is the water consumption per capital (l/d); $N_h$ is the average amount of nutrient produced by human being per capital per day; $R_t$ is the wastewater generation rate, equal to 0.85 (no unit); $R_t$ is the wastewater treatment ratio, with a value of 0.9 (no unit). Accordingly, urban pollution outputs were obtained based on the aforementioned formula (for full results see Annexes, Table 2).

The results from ECM indicate that the total nitrogen input into Changjiang Estuary is 2208653 tons/y while phosphorus input 686721 tons/y. Fig. 17 and 18 present the details in nutrient distribution in Changjiang River Basin.

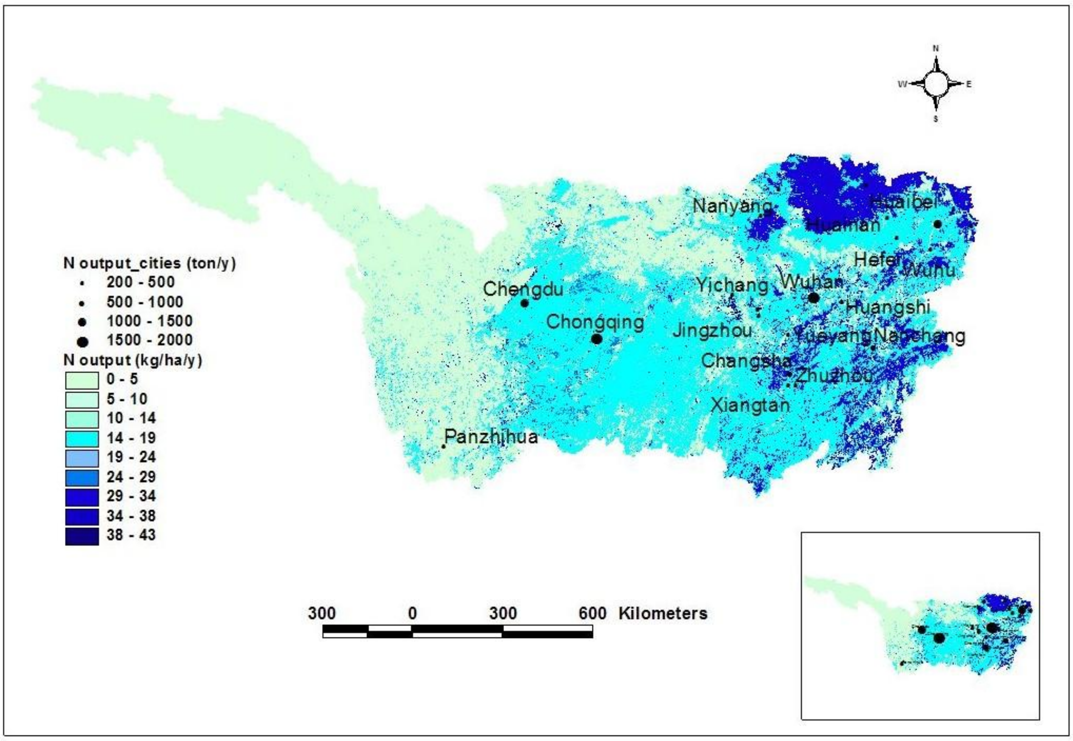


Fig.17. Annual nitrogen load in Changjiang River Basin.

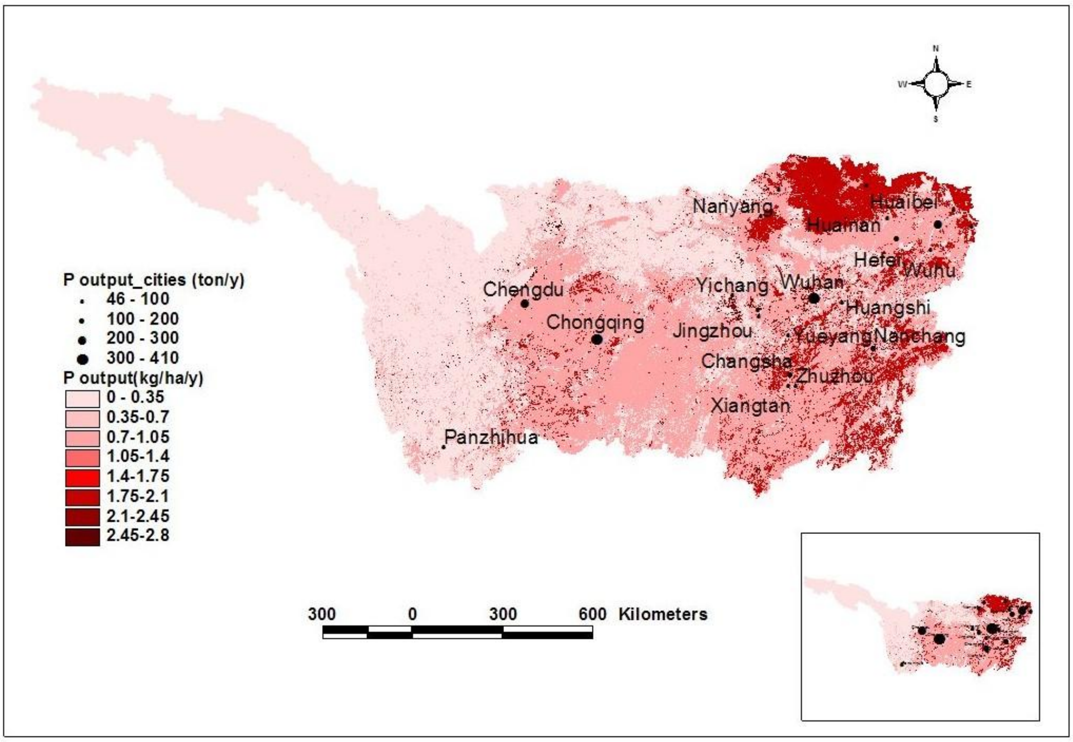


Fig.18. Annual phosphorus load in Changjiang River Basin.

Fig. 19 and 20 present the nutrient details within each subbasin in Changjiang River Basin (for a detailed results for each subbasin, see Annexes, Table 3).

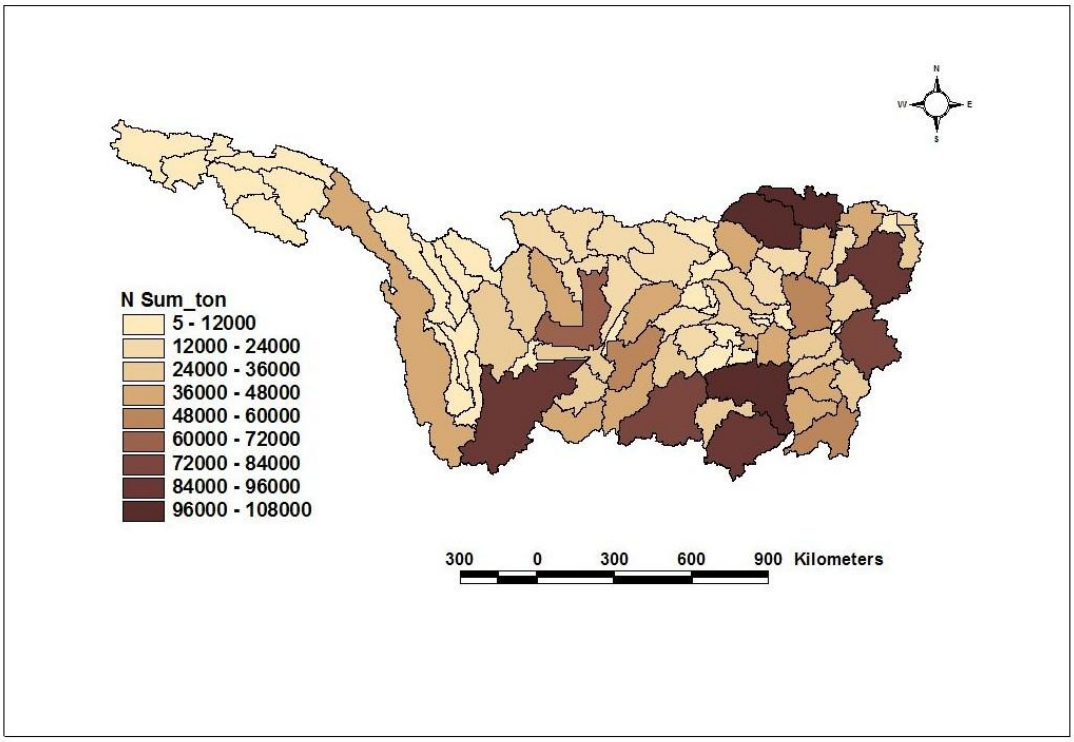


Fig.19. Annual nitrogen load per subbasin in Changjiang River Basin.

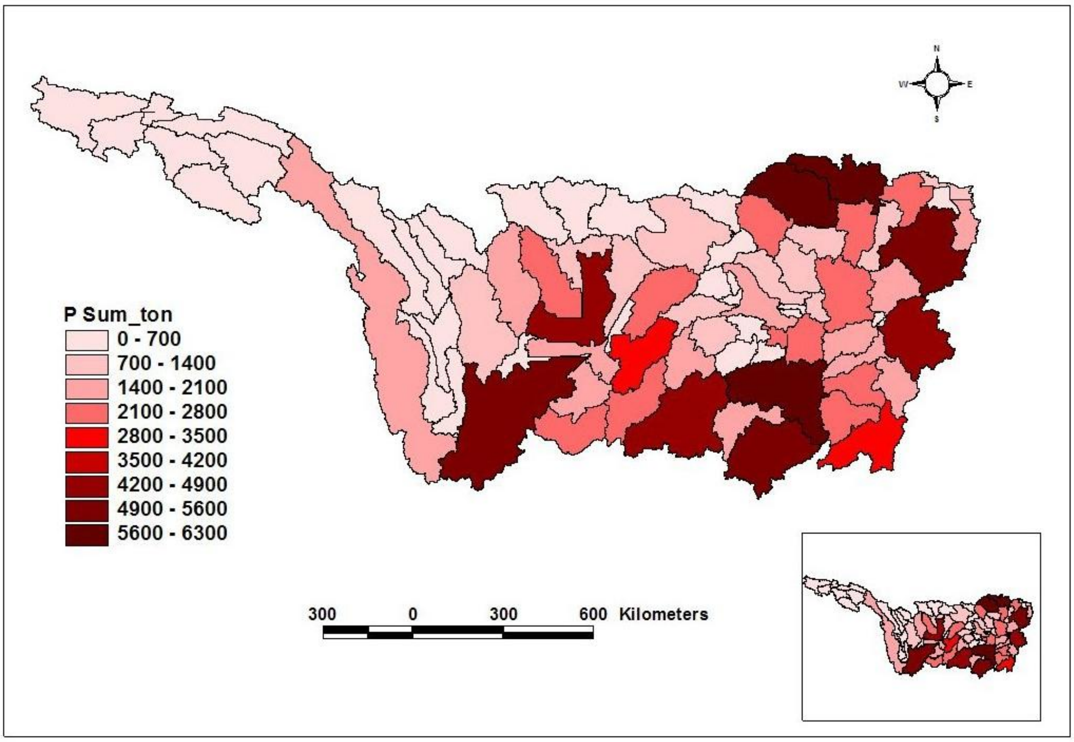


Fig.20. Annual phosphorus load per subbasin in Changjiang River Basin.

The aforementioned "Vollenweider" mass balance model was run to calculate the load component of OHI, based on three key parameters, the system volume, mean salinity in estuary and nitrogen load (Table 26).

Table 26 Parameters to calculate load component of OHI.

| **System volume** | **Mean salinity** | **Nitrogen load** | **OHI** |
|---|---|---|---|
| **$10^6 m^3$** | **psu** | **ton $d^{-1}$** | |
| 408000 | 25 | 6000 | 99.98% |

As a result, the load component of OHI score falls into a category of "*High*" (>0.8)

### 5.1.5.2. Susceptibility

The susceptibility of the Changjiang is considered *Moderate* based on dilution and flushing capabilities. The dilution volume in Changjiang Estuary was estimated as $6.375\times10^{11}$ $m^3$, with a mean thickness of 12.5 m upper stratified layer. Mean salinities in this layer and offshore are 25 and 30 psu respectively giving a dilution potential of *Moderate*. The flushing potential is considered *Moderate*, given a tidal range of 2.7 m and discharge of 925 $\times10^{11}$ $m^3/y$ from Changjiang River (Che et al., 2003).

The combination of High load and Moderate susceptibility gives an OHI final rating of "*Moderate High*".

### 5.1.6. Future outlook

Based on China's strategic planning for development, the Changjiang drainage basin is expected to provide an estimated $10^7$-$10^8$ t/y additional food in order to feed the increasing population within the next 50 years. This will likely result in a further increase in fertilizer application in a dense population that is already characterized by intensive agriculture (Zhang et al., 1999). If the DIN concentrations continue to increase at the same rate as that in the last two decades, the DIN load would be an estimated $290 \times 10^9$ mol/y, twice as much as that in 1998. One additional concern is that with the construction of the Three Gorges Dam, upstream silicate discharge is expected to decrease drastically leading to further decreases in the Si/N ratio. In short, the eutrophic status in Changjiang Estuary is expected to become even worse in the near future.

#### 5.1.7. Summary of the ASSETS indices

Table 27 summarizes the results obtained for the application of ASSETS to Changjiang estuary. The OHI index is considered as high due to the huge amount of nutrient load into the estuary, in spite of moderate system susceptibility. The frequent reports of toxic blooms indicate a well-developed eutrophic condition. The construction of Three Gorges Dam, in addition to population projection, suggests a high possibility that the eutrophic level will be getting higher in the future.

The main issues identified for the Changjiang Estuary are: (i) stress from the huge population living in the Changjiang River basin; (ii) HABs, which has increased a factor of ten times during the last two decades; (iii) the construction of the Three Gorges Dam, which is expected to reduce flow and to modify hydrological scenarios leading to worsening eutrophic conditions.

Table 27 ASSETS application to the Changjiang Estuary.

| Index | Method | Parameter | Level of expression | Index result | ASSETS score |
|---|---|---|---|---|---|
| OHI[a] | Susceptibility | Dilution potential | Moderate | ***Moderate High*** | ***Bad*** |
| | | Flushing potential | Moderate | | |
| | Nutrient inputs | | High | | |
| OEC[b] | PSM[c] | Chlorophyll *a* | Moderate | ***High*** | |
| | | Macroalgae | Unknown | | |
| | SSM[d] | Dissolved Oxygen | Moderate | | |
| | | SAV loss | Unknown | | |
| | | Nuisance and toxic blooms | High | | |
| FO[e] | Future nutrient pressure | | Increase | ***Worsen High*** | |

[a]OHI – Overall Human Influence index; [b]OEC – Overall Eutrophic Condition index; [c]PSM – Primary Symptoms Method; [d]SSM – Secondary Symptoms Method; [e]FO – Future Outlook index

## 5.2. Jiaozhou Bay

Jiaozhou Bay (Fig. 21) is located at the west coast of Yellow Sea (35°57′-36°18′N, 120°06′-120°21′E) with a surface area of 397 $km^2$ and average depth of 7m (Editorial Board of Bays in China, 1993). As a typical semi-enclosed water body, Jiaozhou Bay connects with the Yellow Sea through a channel as narrow as 2.5 km. In general, the tidal range is 2.5-3.0 m, but in spring tide, it can reach 3.8-4.2 m. The tides induce strong turbulent mixing, resulting in nearly homogeneous vertical profiles of temperature and salinity (Liu et al., 2004).

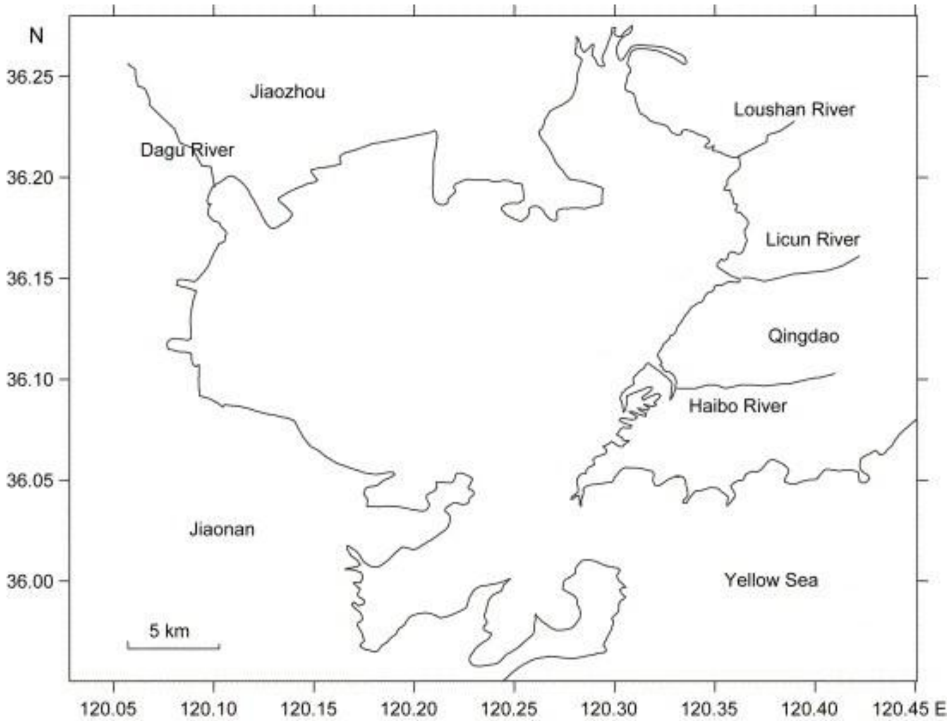


Fig.21. Location map of Jiaozhou Bay (adapted after Shen et al., 2006).

There are more than ten rivers flowing to Jiaozhou Bay, but the Dagu River, Baisha River and Yang River contribute over ninety-eight percent of river discharge ($8\times10^8$ $m^3$/y). Most of these rivers, however, have become canals of industrial and domestic waste discharge with the advance of economic activity and increase of population in the region (Liu et al., 2005; Li et al., 2006), and thus the major sources of external nutrients entering the bay (Shen et al., 2006).

Since the last two decades, intensive mariculture has been developed in Jiaozhou Bay. In the bottom of the bay, there is spawning, nursery and feeding ground for fishes. The bay provides a site for aquaculture and growth of Manila Clam and the production reaches 300,000 tons per year. The potential top-down control from aquaculture is appealing, which potentially aids in mitigating eutrophication pressures. Zhou and his colleagues conducted experiments in Jiaozhou Bay and suggested that macroalga *Gracilaria lemaneiformis* (Rhodophyta) should be a good candidate for seaweed/fish integrated mariculture for bioremediation and economic diversification (Zhou et al., 2006).

### 5.2.1. Issues of concern

The main issue in Jiaozhou Bay is the increase of harmful algal blooms (HABs). Both the frequency and scale of the HABs incidents have increased since 1990s, although most events are non-toxic (Han et al., 2004). The main causative species include *Biddulphia aurita, Eucampia zoodiacus, Mesodinium rubrum, Noctiluca scintillans* and *Skeletonema costatum* (Wang et al., 2006). For example, there were a *Skeletonema costatum* and *Biddulphia aurita* bloom reported in July 1998 (Hao et al., 2000; Huo et al., 2001), and a *Mesodinium rubrum* (Lohmann) bloom in July 2003.

### 5.2.2. Homogeneous areas

The average of salinity in Jiaozhou Bay ranges from 24.88 to 32 psu (Editorial Board of Bays in China, 1993; Yang & Wu, 1999), and the isohaline sketch in 2001 indicates mostly salinity in this bay is not less than 25 psu (Fig. 22). Due to the high salinity throughout the bay area, only one zone is considered, i.e., seawater zone, with a surface area of 390 $km^2$.

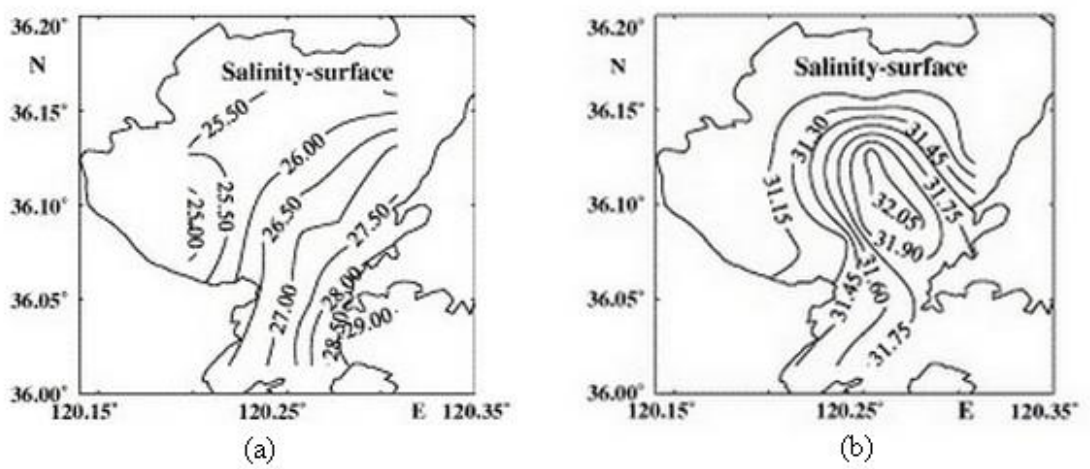


Fig.22. Isohaline map for Jiaozhou Bay in 2001. (a). in August; (b) in October (adapted after Su et al., 2005).

### 5.2.3. Data completeness and reliability

Data used in this study were taken from the BarcaWin2000™ database which groups the results of campaigns made in Jiaozhou Bay. The number of campaigns, dates and water quality parameters for Jiaozhou Bay are shown in Table 28. The HABs record was retrieved from Chinese HABs website (http://www.china-hab.cn), as summarized in Table 28. The analysis of the data completeness and reliability

(DCR) is presented in Table 30.

Table 28 Datasets for Jiaozhou Bay.

| Number of campaigns | Date | Site | Parameters |
|---|---|---|---|
| 15 | Sep 1992 - Jul 2000 | Seawater | Salinity<br>Dissolved oxygen<br>Chlorophyll *a* |

Table 29 Harmful algal blooms reported in Jiaozhou Bay (adapted after http://www.china-hab.cn/chinese/ccls/ccls2001.htm).

| Date | Location | Type of bloom |
|---|---|---|
| June, 1990 | N/A | Blue-green algal bloom with an area of 90,000 $m^2$. |
| August, 1997 | Center | *Skeletonema costatum* bloom |
| July, 1998 | Northeast | *Skeletonemaceae* bloom |
| June, 1999 | Northeast | *Eucampia zodiacus* bloom |

Table 30 Data completeness and reliability calculation for Jiaozhou Bay.

| Chl *a* | Macroalgae | DO | SAV | Nuisance algae | Toxic algae | Total DCR |
|---|---|---|---|---|---|---|
| 100% | 0 | 100% | 0 | 100% | 100% | 57.1% |

### 5.2.4. Overall Eutrophic Condition (OEC)

#### 5.2.4.1. Primary symptoms method

Chlorophyll *a* is the only parameter with information for the primary symptoms. No information was found for macroalgae, which was therefore classified as "Unknown".

##### *5.2.4.1.1. Chlorophyll a*

Maximum chlorophyll *a* values in the Jiaozhou Bay did not exceed the threshold indicated in the ASSETS for "Medium" eutrophic conditions (Fig. 23).

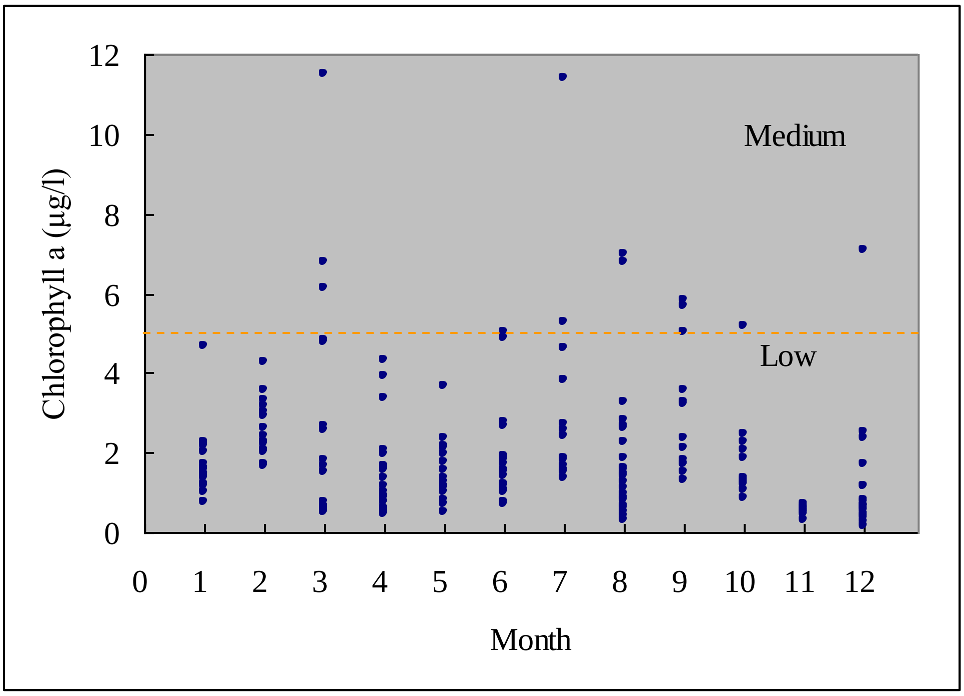


Fig.23. Distribution of chlorophyll *a* concentration during annual cycle.

ASSETS uses the percentile 90 value to alleviate the extreme value problem in order to provide a more robust maximum concentration for chlorophyll *a*. The percentile 90 value falls within the 4-5 µg $l^{-1}$ class, below the threshold defined for the "Low" category (Fig. 24).

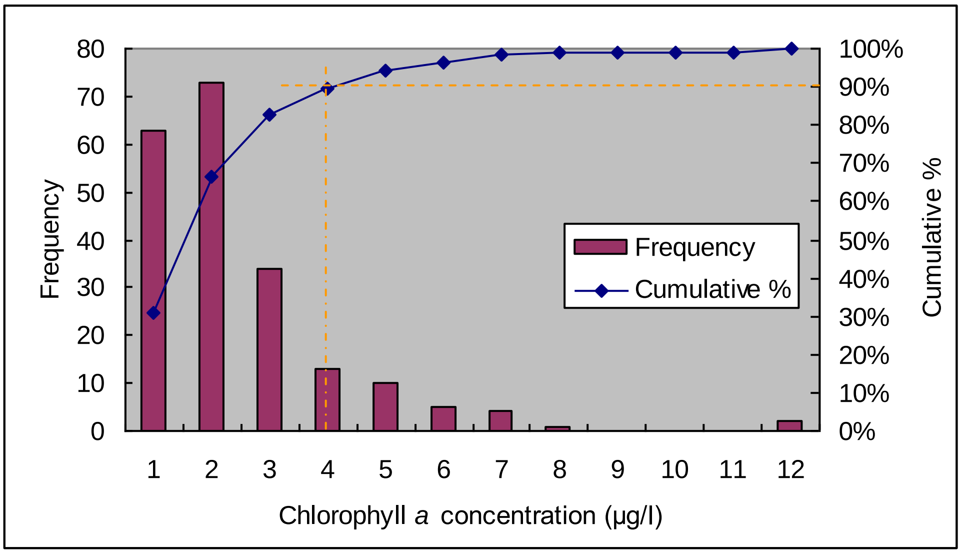


Fig.24. Frequency distribution for chlorophyll *a* concentration.

Therefore, the rating for primary symptoms is Low based on chlorophyll *a*.

### 5.2.4.2. Secondary symptoms method

Discrete data for dissolved oxygen were collected from various sites to cover one annual cycle. No information was found for submerged aquatic vegetation, but considering the large scale of kelp aquaculture in the bay, the level of symptom of "Loss of SAV" can be "Low" as the worse of the worst.

#### *5.2.4.2.1. Dissolved oxygen*

Very few values below the ASSETS threshold for the biological stress condition (5 mg $l^{-1}$) were registered for Jiaozhou Bay (Fig. 25). Similar to the way to interpret chlorophyll *a* concentration, the percentile 10 value is applied to provide a more solid minimum value for dissolved oxygen. The percentile 10 is within the 6-7 mg $l^{-1}$ class indicating no problems with this parameter (Fig. 26).

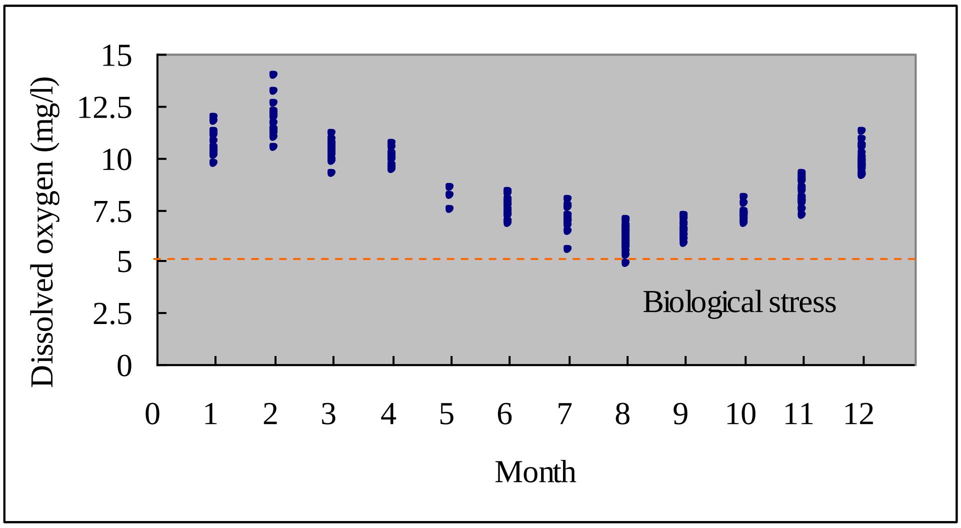


Fig. 25. Distribution of dissolved oxygen concentration during annual cycle.

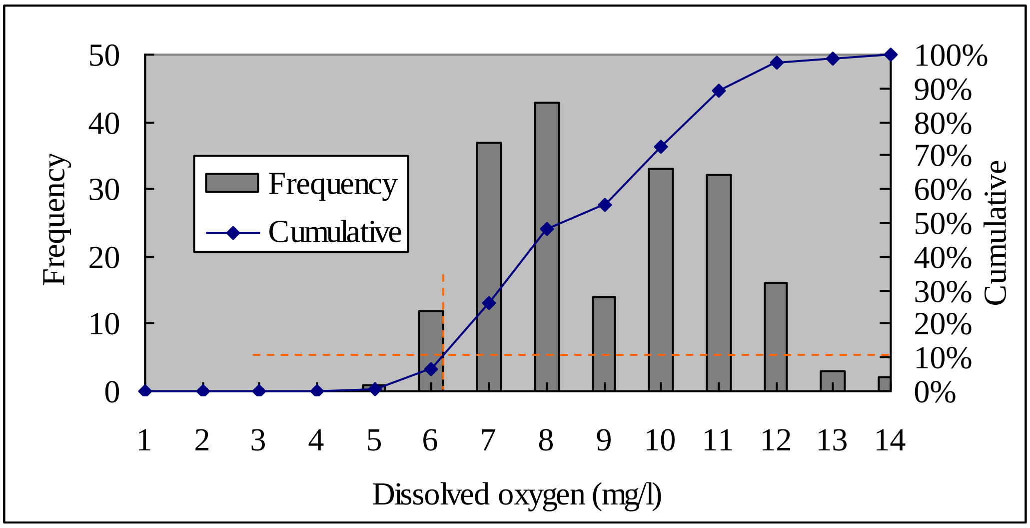


Fig. 26. Frequency distribution for dissolved oxygen concentration.

### *5.2.4.2.2. Nuisance and toxic blooms*

Although it is not rare to have reports of harmful algal blooms, most of them are non-toxic (Han et al., 2004). According to Han and his colleagues, there were up to 69 harmful algal species observed in Jiaozhou Bay (Han et al., 2004). Table 31 presents dominant algal species in different seasons from historical records and the literature.

Table 31 The seasonal and yearly variation of dominant species in Jiaozhou Bay (adapted after Han et al., 2004).

| | **1980** | **1992** | **1995** | **1999** |
|---|---|---|---|---|
| **Spring** | *Skeletonema costatum* | *Rhizosolenia latal f. indica* | *Ditylum brightwellii* | *Chaetoceros curvisetus* |
| | *Rhizosolenia stolterfothii* | *A. glacialis* | *Coscinodiscus spp* | *Actinocyclus ehrenbergii* |
| | *Chaetoceros curvisetus* | *Chaetoceros compressus* | | *Eucampia zoodiacus* |
| | *Asterionellopsis glacialis* | | | |
| **Summer** | *S. costatum* | *Coscinodiscus spp* | *S. costatum* | *S. costatum* |
| | *Rhizosolenia delicatula* | *Guinardia flaccida* | *C. curvisetus* | *E. zoodiacus* |
| | *Chaetoceros affinis* | *Rhizosolenia frgissima* | *P. pungens* | *C. curvisetus* |
| | *C. lorenzianus* | | | |
| | *Pseudonitzschia Pungens* | | | |
| | *Ceratium macroceros* | | | |

Table 31 (*continued*)

| | **1980** | **1992** | **1995** | **1999** |
|---|---|---|---|---|
| **Autumn** | *Lptocylindrus danicus* | *Chaetoceros debilis* | *Rhizosolenia styliformis* | *R. styliformis* |
| | *C. affinis* | *C. compressus* | *A. glacialis* | *S. costatum* |
| | *E. zoodiacus* | | *C. compressus* | *C. lorenzianus* |
| | *C. macroceros* | | | |
| **Winter** | *S. costatum* | *S. costatum* | *S. costatum* | *A. kariana* |
| | *Rhizosolenia setigera* | *R. alata. f. indica* | *A. glacialis* | *P. pungens* |
| | *C. affinis* | *P. pungens* | *A. kariana* | *S. costatum* |
| | *A. glaciaslis* | | | |
| | *P. pungens* | | | |

Toxic blooms are registered episodically, and the durations, if occurred, usually last for only few days. For example, a *Skeletonemacostatum* bloom was reported to last for five days in July, 1998 (Huo et al., 2001). Therefore, the symptom of "nuisance and toxic blooms" is considered as "Low".

Therefore, the highest level of three secondary symptoms falls into the "Low" category.

The Overall Eutrophic Condition for this system is "*Low*" given the Low ratings for both primary and secondary symptoms.

### 5.2.5. Overall human influence (OHI)

#### 5.2.5.1. Nutrient input

Concentrations of nutrients increased for nitrogen and phosphorus from the 1960s to the 1990s, while concentrations of $SiO_3^{2-}$ decreased from the 1980s to the 1990s (Shen, 2001). The atomic ratio of dissolved inorganic N to $PO_4^{3-}$-P increased, but the atomic ratio of $SiO_3^{2-}$-Si to dissolved inorganic N remained at a very low level. The possibility that $PO_4^{3-}$ and dissolved inorganic N are limiting elements for phytoplankton growth in this region is less likely, while silica limitation may have increased (Shen, 2001 and Zhang and Shen, 1997). The changes of nutrient regime and phytoplankton structure are attributed to increased human activity in this region, changed water circulation (Chen, Sun, & Wang, 1982) and increased aquaculture (Sun, Chen, & Zhang, 1993). Fig. 27-31 summarize the historical variations of nutrient conditions in Jiaozhou Bay.

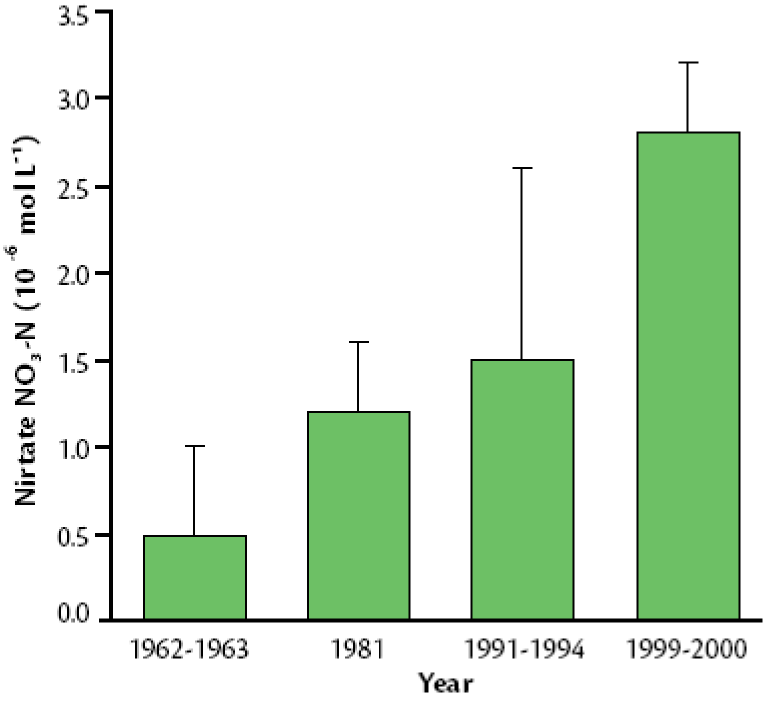


Fig.27. Nitrate concentrations in Jiaozhou Bay (adapted after Bricker et al., 2007)

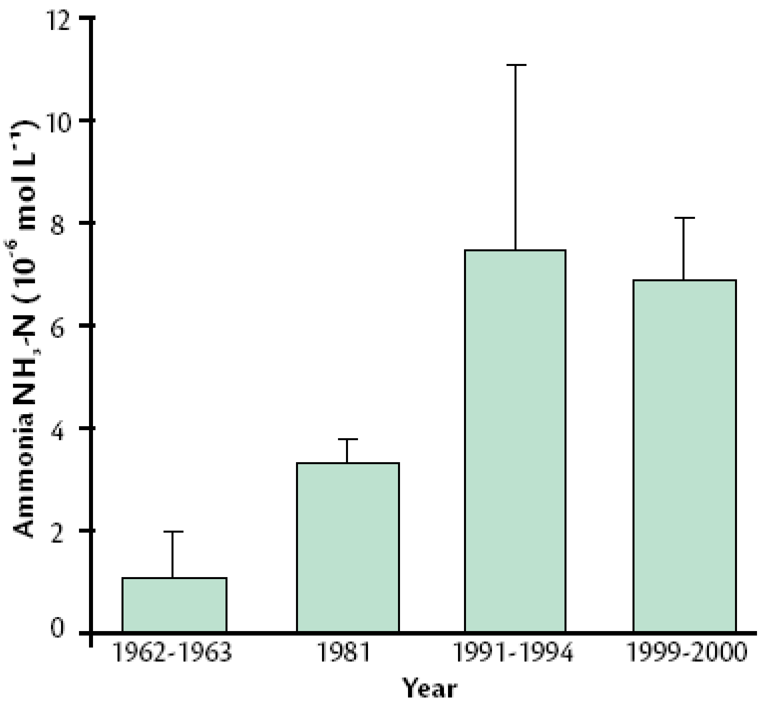


Fig.28. Amonia concentrations in Jiaozhou Bay (adapted after Bricker et al., 2007).

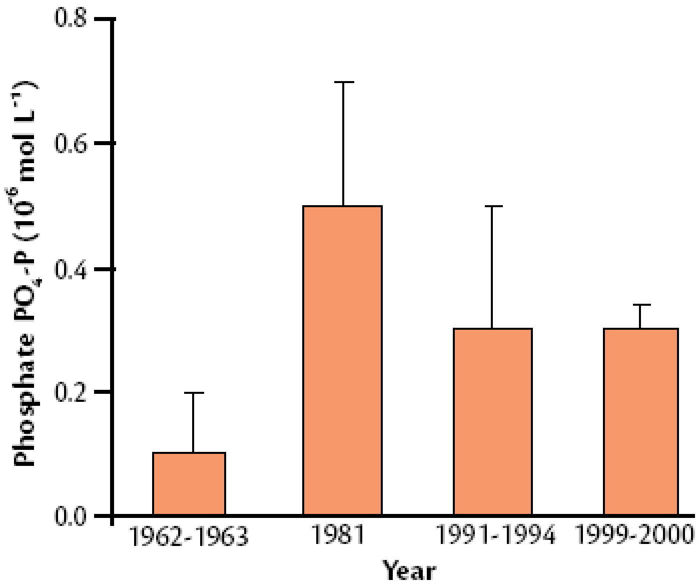


Fig.29. Phosphate concentrations in Jiaozhou Bay (adapted after Bricker et al., 2007).

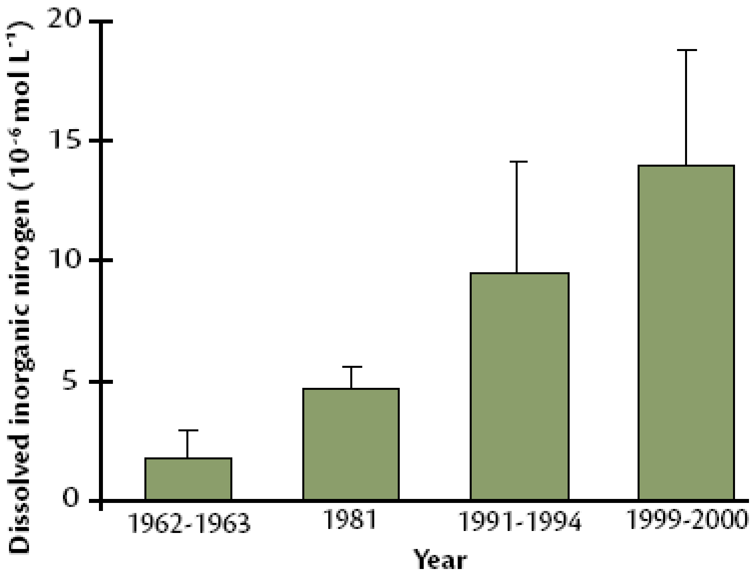


Fig.30. Dissolved inorganic nitrogen concentrations in Jiaozhou Bay (adapted after Bricker et al., 2007).

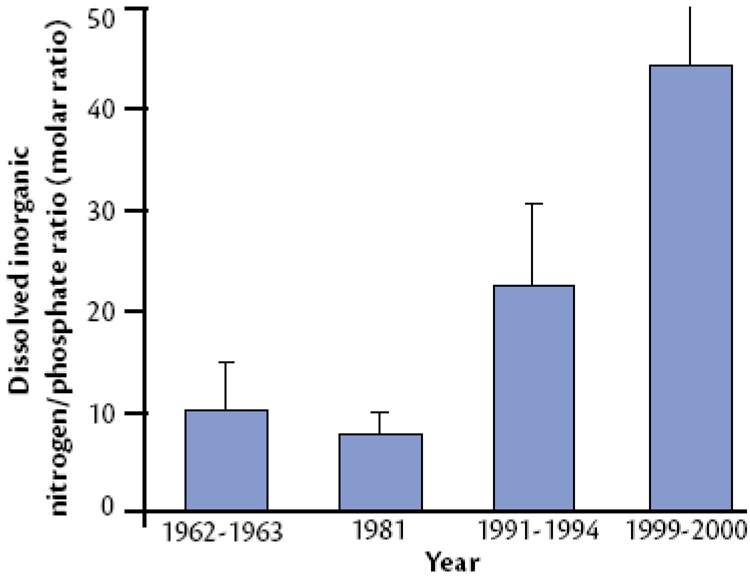


Fig.31. Dissolved inorganic nitrogen/phosphate ratios in Jiaozhou Bay (adapted after Bricker et al., 2007).

Table 32 summarizes key parameters used to run ASSETS model to calculate load component of OHI.

Table 32 Parameters to calculate load component of OHI.

| **System volume** | **Mean salinity** | **Nitrogen load** | **OHI** |
|---|---|---|---|
| **$10^6 m^3$** | **psu** | **ton $d^{-1}$** | |
| 1900 | 29.7 | 38.3 | 94.64% |

Therefore, the nutrient component score of OHI falls into a category of "*High*" (>0.8).

### 5.2.5.2. Susceptibility

Strong tidal mixing and large river discharge ($8 \times 10^8$ $m^3$/y) contribute to a moderate flushing and dilution potentials. However, the intensive top-down control of food web has a more significant impact on mitigating eutrophic symptoms.

Since 1980s, kelp, shrimp and shellfish culture have been developing in the bay. In the 1990s, shellfish culture became more dominant (Fig. 32).

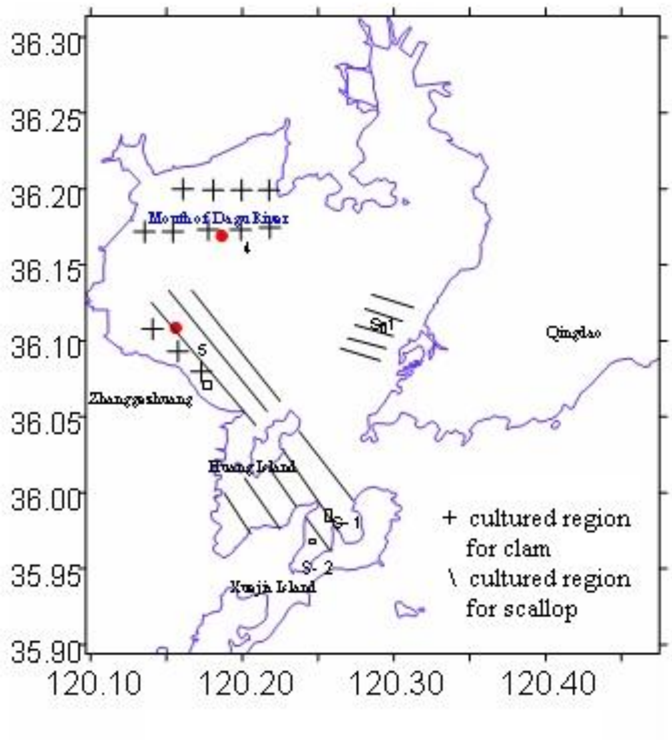


Fig.32. The shellfish culture distribution in Jiaozhou Bay in late 1990s (Zhu M., personal communication).

The main species include the Manila clam (*Ruditapes philipinnarum*), blue mussel (*Mytilus edulis*), Chinese scallop (*Chlamys farreri*), and bay scallop (*Argopecten irradians*). Table 33 synthesizes the areas and productions for these four dominant species.

Table 33 Areas and productions of shellfish culture in Jiaozhou Bay in the late 1990s.

| | **Manila clam** | **Mussel** | **Chenese scallop** | **Bay scallop** |
|---|---|---|---|---|
| Area (ha) | 8,180 | 313 | 233 | 1,180 |
| Production (t $y^{-1}$) | 197,900 | 74,500 | 2,100 | 42,200 |

The susceptibility component of the OHI based on only natural circumstances is considered moderate but when the aquaculture is taken into account, the overall susceptibility is considered low.

The combination of High nutrient load and Low susceptibility gives an overall OHI rating of "*Moderate Low*".

### 5.2.6. Determination of Future Outlook (FO)

The population change around the Jiaozhou Bay is hard to predict due to complex in simulating the immigration and the change of population reproduction pattern. However, according to National Bureau of Statistics, China, the natural increase rate in Shangdong Province (where Jiaozhou Bay is located) was 4.46 per 1,000 in 2000 (National Bureau of Statistics P.R.C., 2001). The rough estimate based on the current scenario gives an about 9.3% population increase rate after 20 years, compared to nowadays population. In addition, Qingdao is highly promoting its tourism industry and less space is available for mariculture in Jiaozhou Bay. Accordingly, the decrease top-down control on food web could lead to increased eutrophic symptoms.

On the other hand, as the main land nutrient resource--Qingdao city prepares itself to host the Olympic Sailing Regattas in 2008, more attention has been focused on the water quality issues and mitigating eutrophic symptoms. The government promised to build up more wastewater treatment plants in the short future, and more restrictive pollutant emission regulations are coming into effect (Wang et al., 2006).

As a whole, the nutrient loads are expected to decrease in spite of increase of city population, and the water quality in Jiaozhou Bay is likely to improve. Therefore, it can be considered that the Future Outlook is "*Improve low*".

### 5.2.7. Summary of the ASSETS indices

Table 34 summarizes the results obtained from the application of ASSETS to Jiaozhou Bay. The nutrient load into the bay is not small, but the strong tidal mix reduces the system susceptibility. The top-down control from shellfish aquaculture, along with seawater exchange, contributes to the system's low eutrophic conditions. The future outlook is believed to improve low based on a rough estimate. Overall, the final ASSET rating for Jiaozhou Bay is "*Low*".

Table 34 ASSETS application to Jiaozhou Bay.

| Index | Method | Parameter | Level of expression | Index result | ASSETS score |
|---|---|---|---|---|---|
| OHI[a] | Susceptibility | Dilution potential | Moderate | ***Low*** *(due to intense aquaculture)* | ***Low*** |
| | | Flushing potential | Moderate | | |
| | Nutrient inputs | | High | | |
| OEC[b] | PSM[c] | Chlorophyll *a* | Low | ***Low*** | |
| | | Macroalgae | No problem | | |
| | SSM[d] | Dissolved Oxygen | Low | | |
| | | SAV loss | Low | | |
| | | Nuisance and toxic blooms | Low | | |
| FO[e] | Future nutrient pressure | | Decrease | ***Improve low*** | |

[a]OHI – Overall Human Influence index; [b]OEC – Overall Eutrophic Condition index; [c]PSM – Primary Symptoms Method; [d]SSM – Secondary Symptoms Method; [e]FO – Future Outlook index

## 5.3. Results

In this section, the results from different assessment methods are compared, including nutrient index methods.

### 5.3.1. Changjiang Estuary

*a). Result from ASSETS*

The overall ASSETS grade obtained was "*High*" (Table 35), based on the "*High*" conditions obtained for pressure and state, given by OHI and by OEC respectively, and on the expected increase of nutrient pressure given by FO.

Table 35 ASSETS application to the Changjiang Estuary.

| Index | Index result | ASSETS score |
|---|---|---|
| OHI | High | |
| OEC | High | Bad |
| FO | Worsen high | |

*b). Result from Nutrient Index Method I*

Nutrient Index is obtained using Eq. 1:

$$N_I = C_{COD}/S_{COD} + C_{TN}/S_{TN} + C_{TP}/S_{TP} + C_{Chla}/S_{Chla} \qquad \text{(Eq. 1)}$$

where the historical average value for $C_{COD}$ is 0.3-55.5 mg $l^{-1}$; $C_{TN}$ is 69.5-90.5 μmol $l^{-1}$, or 1.0-1.3 mg $l^{-1}$; $C_{TP}$ is recorded as 0.24-1.2 μmol $l^{-1}$, equal to 0.007- 0.037 mg $l^{-1}$; $C_{Chla}$ is 1.13 μg $l^{-1}$ (Editorial Board of Bays in China, 1998; Yang et al., 2006).

Then the result for $N_I$ ranges from 2.61 to 22.61, which clearly indicates the estuary is in “Eutrophic” condition (>1).

*c). Result from Nutrient Index Method II*

Nutrient Index is obtained using Eq. 2:

$$N_I = (C_{COD} \times C_{DIN} \times C_{DIP} \times 10^6) / 4500 \quad \text{(Eq. 2)}$$

The result ranges from 0.47 to 593, which envelops the threshold value (=1). Although data available is not able to determine the eutrophic level by this, it is highly possible that the estuary is under the state of “Eutrophic”.

### 5.3.2. Jiaozhou Bay

*a). Result from ASSETS*

The overall ASSETS grade obtained was “*Moderate*” (Table 36), based on the “*Moderate*” and “*Low*” conditions obtained for pressure and state, given by OHI and by OEC respectively, and on the expected low increase of nutrient pressure given by FO.

Table 36 ASSETS application to Jiaozhou Bay.

| **Index** | **Index result** | **ASSETS score** |
|---|---|---|
| OHI | Low | |
| OEC | Low | Low |
| FO | Improve low | |

*b). Result from Nutrient Index Method I*

Nutrient Index is obtained using Eq. 1:

$$N_I = C_{COD}/S_{COD} + C_{TN}/S_{TN} + C_{TP}/S_{TP} + C_{Chla}/S_{Chla} \qquad \text{(Eq. 1)}$$

where value for $C_{COD}$ is 1.15-2.0 mg $l^{-1}$ (Yao & Shen, 2004); $C_{TN}$ is 7.4-14.2 μmol $l^{-1}$, or 0.10-0.20 mg $l^{-1}$; $C_{TP}$ is 0.22-0.44 μmol $l^{-1}$, equal to 0.007- 0.014 mg $l^{-1}$ (Shen, 2001); mean value for $C_{Chla}$ is 1.97 μg $l^{-1}$.

Then the result for $N_I$ ranges from 0.98 to 1.66, which indicates a high likelihood of the estuary to be in "Eutrophic" condition (>1).

*c). Result from Nutrient Index Method II*

Nutrient Index is obtained using Eq. 2:

$$N_I = (C_{COD} \times C_{DIN} \times C_{DIP} \times 10^6) / 4500 \qquad \text{(Eq. 2)}$$

The result ranges from 0.18 to 1.24, which envelops the threshold limit value (=1), and thus being difficult to determine the real situation.

# Chapter 6. Conclusions

a) Most Chinese assessment methods, evolved from freshwater methods, are mainly based on chemical indices, such as nutrient concentration and chlorophyll *a*, regardless of the carrying capacity or susceptibility in the coastal system. On the other hand, ASSETS and other symptom-based methods realize coastal eutrophication is a more subtle issue, and take into account of both the pressure and response.

b) The system classifications from applying ASSETS to Changjiang Estuary and Jiaozhou Bay are “Bad” and “Low”. The success in testing these two case studies suggests that ASSETS could be a potential method to assess the eutrophic conditions in more Chinese systems. To apply ASSETS to a national survey on eutrophic assessment on Chinese coast is a potentially useful way to better understand the current status, and to highlight the areas where priority should be set.

c) As Bricker pointed out that Future Outlook is an area where more effort is clearly needed in ASSETS (Bricker et al., 2003), FO is not well-studied yet in either of these two Chinese systems.

d) Acquiring data was the most difficult part of this study, and it could be expected that inadequate data will be a limiting factor to apply ASSETS to more Chinese cases. There is a need to collect more data on eutrophic symptoms in both areas to better represent the real condition.

e) In Changjiang River Basin, agriculture contributes 99% of nitrogen load into the estuary and 98% of phosphorus load. The east part of the River Basin supplies more nutrients given intensive agricultural activities. So more attention should be paid to agriculture in the eastern areas if the government wishes to improve the eutrophic condition in the estuary.

f) The top-down control of food web in Jiaozhou Bay suggests a feasible way to manage the eutrophication in a coastal system. While Chinese government and scientists mainly focus on a bottom-up scenario in improving water quality, there is still a large space to promote top-down control in food chain. Along with economical benefits, a reasonable scale of introducing filter-feeders is able to remove the nutrients and to mitigate the eutrophic conditions, which is more environmentally-friendly and sustainable for a coastal system (Shastri & Diwekar, 2006). On the other hand, environmental managers should be cautious while reducing mariculture since that could lead to a worse eutrophic condition. For example, there is a proposal in Qingdao city to limit aquaculture in Jiaozhou Bay so as to leave more space for Olympic Sailing Regattas in 2008. But as it is mentioned in previous sections, aquaculture is the major reason why this bay is not severely eutrophic given a large amount of nutrient load. Any decrease of culture intensity may be results in more severe eutrophic symptoms in Jiaozhou

Bay.

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# Annexes

Table 1 Background data for small Chinese coastal systems.

| Categories | System | Area | Tidal height | Average salinity | Rainfall | Air temperature | Water temperature |
|---|---|---|---|---|---|---|---|
| | | $km^2$ | m | psu | mm | ℃ | ℃ |
| **Small (area: 100-150 $km^2$)** | Quanzhou bay | 128.2 | 4.27 | 28.92 | 1095.4 | 20.4 | 25.8 |
| **Extra small (area<100 $km^2$)** | Tong-an bay | 91.7 | 3.95 | 28.61 | 1432.2 | 21.0 | N/A |
| | Shidao bay | 35.3 | 1.70 | 31.02 | 826.1 | 11.4 | 11.8 |
| | Dayao bay | 33.0 | 2.37 | 30.36 | 497.4 | 10.4 | 11.2 |
| | Shantou Gang | 30.5 | 1.00 | 15.86 | 1559.0 | 21.3 | 26.3 |
| | Rongcheng bay | 22.7 | 1.00 | 30.94 | 768.0 | 11.1 | 11.5 |
| | Xiaoyao bay | 19.0 | 2.37 | 30.43 | 497.4 | 10.4 | 11.2 |
| | Anpu Gang | 19.0 | 3.30 | 30.33 | 1753.0 | 22.5 | 23.1 |
| **Others** | Dongshan bay | N/A | 2.30 | 31.48 | 1583.7 | 20.8 | 22.5 |
| | Guanhe mouth | N/A | 3.07 | 30.89 | 925.0 | 13.5 | 12.5 |
| | Hai He estuary | N/A | 2.48 | N/A | 394.0 | 12.0 | 12.0 |
| | Huang He estuary | N/A | 0.63 | 27.40 | 545.0 | 12.3 | 23.5 |
| | Laoshan bay | N/A | N/A | N/A | N/A | N/A | N/A |
| | Liao He estuary | N/A | 2.71 | N/A | 667.4 | 8.9 | 11.3 |
| | Lingshan bay | N/A | N/A | N/A | N/A | N/A | N/A |
| | Luan He estuary | N/A | 1.00 | N/A | 608.7 | 10.1 | 28.0 |
| | Majia He estuary | N/A | N/A | N/A | N/A | N/A | N/A |
| | Minjiang estuary | N/A | 4.11 | N/A | 1343.6 | 19.6 | N/A |
| | Pearl River estuary | N/A | 1.55 | N/A | 1945.0 | 22.1 | 23.6 |
| | Tuhai He estuary | N/A | N/A | N/A | N/A | N/A | N/A |
| | Wuleidao bay | N/A | N/A | N/A | N/A | N/A | N/A |
| | Xiaoqing / Zi He estuary | N/A | N/A | N/A | N/A | N/A | N/A |

Table 2 Nutrient outputs from main cities.

| NAME | LONG_E | LATI_N | Population | TN (t/y) | TP (t/y) |
|---|---|---|---|---|---|
| Huaibei | 116.47 | 33.57 | 612400 | 268.2 | 55.9 |
| Yangzhou | 119.42 | 32.39 | 531200 | 232.7 | 48.5 |
| Hefei | 117.27 | 31.85 | 1107100 | 484.9 | 101.0 |
| Wuhu | 118.35 | 31.33 | 551100 | 241.4 | 50.3 |
| Nanjing | 118.78 | 32.04 | 2822100 | 1236.1 | 257.5 |
| Changzhou | 119.95 | 31.79 | 827100 | 362.3 | 75.5 |
| Pingdingshan | 113.29 | 33.75 | 663400 | 290.6 | 60.5 |
| Nanyang | 112.53 | 33.01 | 524000 | 229.5 | 47.8 |
| Yueyang | 113.09 | 29.37 | 511000 | 223.8 | 46.6 |
| Nanchang | 115.89 | 28.68 | 1386500 | 607.3 | 126.5 |
| Chongqing | 106.50 | 29.60 | 3934200 | 1723.2 | 359.0 |
| Chengdu | 104.06 | 30.67 | 2341100 | 1025.4 | 213.6 |
| Changsha | 113.00 | 28.21 | 1489300 | 652.3 | 135.9 |
| Xiangtan | 112.91 | 27.87 | 550600 | 241.2 | 50.2 |
| Zhuzhou | 113.16 | 27.83 | 567700 | 248.7 | 51.8 |
| Panzhihua | 101.43 | 26.34 | 502500 | 220.1 | 45.9 |
| Yichang | 111.30 | 30.70 | 639600 | 280.1 | 58.4 |
| Wuhan | 114.08 | 30.37 | 4488900 | 1966.1 | 409.6 |
| Huainan | 117.02 | 32.48 | 863100 | 378.0 | 78.8 |
| Jingzhou | 112.11 | 30.20 | 605400 | 265.2 | 55.2 |
| Xiangfan | 112.14 | 30.02 | 633200 | 277.3 | 57.8 |
| Huangshi | 115.03 | 30.15 | 593200 | 259.8 | 54.1 |

Table 3 Nutrient summary for each subbasin.

| SUBBASIN | Area ($km^2$) | Nitrogen input (t) | Phosphorus input (t) |
|---|---|---|---|
| 1 | 41670.36 | 456.11 | 4.09 |
| 2 | 19483.83 | 343.27 | 3.32 |
| 3 | 34167.19 | 4881.97 | 52.75 |
| 4 | 29327.73 | 1572.39 | 16.48 |
| 5 | 24141.31 | 2117.40 | 22.40 |
| 6 | 30181.64 | 4558.54 | 48.81 |
| 7 | 31612.48 | 99543.94 | 5649.34 |
| 8 | 20405.73 | 43474.43 | 2435.10 |
| 9 | 5347.40 | 10660.31 | 635.87 |
| 10 | 51723.24 | 92593.35 | 5488.33 |
| 11 | 10879.79 | 25819.66 | 1507.62 |
| 12 | 41648.36 | 106411.32 | 6029.31 |
| 13 | 16023.21 | 22530.13 | 1252.98 |
| 14 | 59.99 | 74.53 | 4.24 |
| 15 | 15621.26 | 11107.19 | 585.36 |
| 16 | 27587.93 | 12613.93 | 561.73 |
| 17 | 26935.00 | 13319.44 | 654.32 |
| 18 | 11298.74 | 9429.25 | 487.45 |
| 19 | 23232.41 | 47405.81 | 2695.00 |
| 20 | 15783.24 | 3292.64 | 60.17 |
| 21 | 22073.54 | 4609.11 | 83.46 |
| 22 | 19011.88 | 20384.62 | 1153.17 |
| 23 | 169.98 | 90.92 | 4.82 |
| 24 | 18315.96 | 24648.08 | 1399.23 |
| 25 | 1843.79 | 3515.79 | 205.46 |
| 26 | 2148.76 | 3383.30 | 199.05 |
| 27 | 108.99 | 245.06 | 15.37 |
| 28 | 17.00 | 8.40 | 0.47 |
| 29 | 1389.85 | 2240.48 | 125.85 |
| 30 | 1669.81 | 2694.15 | 152.98 |
| 31 | 20854.68 | 41832.98 | 2396.01 |
| 32 | 18493.94 | 3876.24 | 73.08 |
| 33 | 44846.00 | 8853.18 | 153.31 |
| 34 | 32155.42 | 43441.10 | 2439.90 |
| 35 | 17181.09 | 18428.89 | 1052.55 |
| 36 | 16589.15 | 30151.06 | 1685.53 |
| 37 | 569.94 | 1024.58 | 57.54 |
| 38 | 11935.67 | 24100.16 | 1451.86 |
| 39 | 40883.45 | 75372.52 | 4208.37 |

Table 3 (*continued*)

| SUBBASIN | Area ($km^2$) | Nitrogen input (t) | Phosphorus input (t) |
|---|---|---|---|
| 40 | 5177.42 | 8428.86 | 488.18 |
| 41 | 30510.60 | 49966.27 | 2860.99 |
| 42 | 27007.99 | 20538.48 | 1130.27 |
| 43 | 42896.22 | 68103.52 | 4262.58 |
| 44 | 3.00 | 5.04 | 0.28 |
| 45 | 19114.87 | 32244.44 | 1895.45 |
| 46 | 51215.29 | 26765.52 | 1260.48 |
| 47 | 39891.55 | 31527.09 | 1777.58 |
| 48 | 5559.38 | 9156.51 | 523.35 |
| 49 | 56514.70 | 107145.53 | 6230.83 |
| 50 | 11492.72 | 11925.26 | 651.15 |
| 51 | 8370.07 | 8770.28 | 509.03 |
| 52 | 621.93 | 980.10 | 55.29 |
| 53 | 20032.77 | 32758.48 | 1968.31 |
| 54 | 8540.05 | 11304.81 | 666.54 |
| 55 | 103290.49 | 93895.47 | 5071.28 |
| 56 | 18436.95 | 39499.34 | 2223.71 |
| 57 | 17439.06 | 33786.24 | 1865.00 |
| 58 | 20263.74 | 31693.28 | 1773.54 |
| 59 | 61916.10 | 80530.93 | 4422.50 |
| 60 | 19344.84 | 5121.67 | 146.45 |
| 61 | 19410.84 | 5713.18 | 179.02 |
| 62 | 19714.80 | 33572.61 | 1891.17 |
| 63 | 46841.78 | 89213.48 | 5107.47 |
| 64 | 150674.21 | 45954.55 | 1590.91 |
| 65 | 206.98 | 65.40 | 2.37 |
| 66 | 28614.81 | 41006.99 | 2290.65 |
| 67 | 26253.07 | 12047.73 | 562.17 |
| 68 | 2088.77 | 1983.84 | 145.13 |
| 69 | 5440.39 | 11114.06 | 945.55 |
| 70 | 20389.73 | 39978.00 | 2242.72 |
| 71 | 20307.74 | 32237.85 | 1795.77 |
| 72 | 14132.42 | 21818.30 | 1265.11 |
| 73 | 31794.46 | 43323.19 | 2419.27 |
| 74 | 25624.14 | 40820.24 | 2373.54 |
| 75 | 15035.32 | 22620.10 | 1262.38 |
| 76 | 9600.93 | 8731.08 | 458.44 |
| 77 | 15024.33 | 17868.67 | 973.97 |
| 78 | 101.99 | 125.92 | 7.40 |

Table 3 (continued)

| SUBBASIN | Area ($km^2$) | Nitrogen input (t) | Phosphorus input (t) |
|---|---|---|---|
| 79 | 15169.31 | 5185.01 | 200.23 |
| 80 | 31348.51 | 57209.08 | 3137.83 |
| 81 | 49602.47 | 19770.05 | 913.67 |
| 82 | 17496.05 | 40318.13 | 2269.35 |
| 83 | 8046.10 | 151.96 | 1.49 |
| 84 | 117.99 | 205.05 | 13.06 |
| 85 | 22046.54 | 27944.56 | 1672.53 |
| 86 | 35131.08 | 49529.80 | 2794.09 |
| 87 | 5935.34 | 14890.96 | 838.81 |