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Trophic Assessment in Chinese Coastal Systems - Review of Methods and Application to the Changjiang (Yangtze) Estuary and Jiaozhou Bay

YONGJIN XIAO[1], JOÃO G. FERREIRA[1], SUZANNE B. BRICKER[2,*], JOÃO P. NUNES[1], MINGYUAN ZHU[3], and XUELEI ZHANG[3]

[1] *IMAR – Institute of Marine Research, Center for Ocean and Environment, Departmento Ciências e Eng. Ambiente, Fac. Ciências e Tecnologia, Qta Torre, 2829-516 Monte de Caparica, Portugal*
[2] *National Oceanic and Atmospheric Administration, National Ocean Service, National Center for Coastal Ocean Science, 1305 East West Highway, Silver Spring, Maryland 20910*
[3] *Research Center for Marine Ecology, First Institute of Oceanography, State Oceanic Administration, Qingdao 266061, China*

ABSTRACT: Coastal eutrophication has become one of the main threats to Chinese coastal areas during the last two decades. High nutrient loads from human activities have modified the natural background water quality in coastal water bodies, resulting in a range of undesirable effects. There is a need to assess the eutrophic level in coastal systems and to identify the extent of this impact to guide development of appropriate management efforts. Traditional Chinese assessment methods are discussed and compared with other currently-used methods, such as the Oslo-Paris Convention for the Protection of the North Sea (OSPAR) Comprehensive Procedure and Assessment of Estuarine Trophic Status (ASSETS). The ASSETS method and two Chinese methods were tested on two Chinese systems: the Changjiang (Yangtze) Estuary and Jiaozhou Bay. ASSETS is process based, and uses a pressure-state-response model based on three main indices: Influencing Factors, Overall Eutrophic Condition, and Future Outlook. The traditional methods are based on a nutrient index. ASSETS was successfully applied to both systems, classifying the Changjiang Estuary as Bad (high eutrophication) and Jiaozhou Bay as High (low eutrophication). The traditional methods led to ambiguous results, particularly for Jiaozhou Bay, due to the high spatial variability of data and a failure to assess the role of shellfish aquaculture in nutrient control. An overview of the Chinese coastal zone identifies 50 estuaries and bays that should form part of a national assessment. A comparison of methods and results suggests that ASSETS is a promising tool for evaluating the eutrophication status of these systems.

Introduction

Eutrophication of the coastal zone has received increasing scientific attention worldwide, resulting in the publication of about 5,000 journal articles over the last two decades (SCIRUS 2007). Although China is subject to a huge human-induced nutrient modification in coastal systems, only about 10% of these articles address this region, and very few (e.g., Wang 2006) deal with eutrophication assessment.

The strong development of the Chinese economy, centered mainly on manufacturing, together with the influx of rural populations to urban areas, many of which are located in the coastal zone or near major rivers, have resulted in a substantial increase in nutrient loads, leading to the proliferation of phytoplanktonic blooms (Guo et al. 1998; Hao et al. 2000; Shen 2001). Frequent occurrences of harmful algal blooms (HAB; Fig. 1) and other eutrophication symptoms have become serious issues in Chinese coastal systems (Harrison et al. 1990; Zhang et al. 1999a; Huang et al. 2003). In 2006, a total of 93 red tide events were observed in Chinese national marine waters, affecting an area of about 20,000 km^2 (P. R. C. State Oceanic Administration 2007). Although it can be argued that the increase in recorded HAB incidents is partly due to improvements in the national monitoring network, these figures clearly indicate the increasing development of serious eutrophication problems on a national scale.

The potential ecological consequences of nutrient enrichment, such as loss or degradation of seagrass beds, interdiction of shellfish aquaculture, and fish kills, are well established (Stevenson et al. 1993; Burkholder et al. 1999; Tomasko et al. 2001; Hauxwell et al. 2003; Wazniak and Glibert 2004) and strongly shape public concern and scientific research for better understanding of eutrophication (e.g., Cloern 2001; Tett et al. 2003, 2007).

In order to set priorities for managing and mitigating nutrient enrichment, there is a need for the nation to perform an assessment to

* Corresponding author; tele: 301/713-3020 ext. 139; fax: 301/713-4388; e-mail: suzanne.bricker@noaa.gov

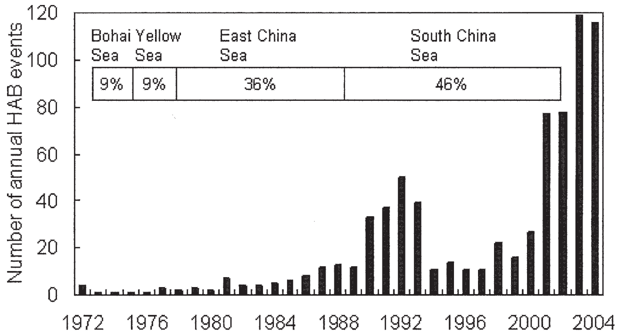

Fig. 1. Harmful algal bloom events in coastal China from 1972 to 2004 and regional proportion in the last decade (http://www.china-hab.cn).

determine the nature and scope of these problems. A range of eutrophication assessment procedures are currently applied in Chinese waters, such as Nutrient Index Methods. These approaches are derived from freshwater methods and are not necessarily appropriate to coastal systems, since it is commonly accepted that coastal eutrophication is a far more complex problem, as pointed out by May et al. (2003); Nunes et al. (2003), and Ferreira et al. (2005). These methods remain at the Phase I stage (sensu Cloern 2001) in the development of eutrophication assessment methods, focusing on nutrient concentrations rather than on complex direct and indirect ecosystem responses.

Although efforts have been made to improve reliability and precision, e.g. through the application of Principal Component Cluster Analysis (PCA; Lin et al. 2004) and Fuzzy Analysis (Xiong and Chen 1993), these mainly aim to optimize the application of Phase I methods, but fail to develop a new rationale for the assessment methodology. With the advances in our understanding of eutrophication, Phase II methods, defined as symptoms-based and multi-indicator, have the merit of taking into account system responses, and for some methods, pressures as well. Well known examples include the United States Environmental Protection Agency (USEPA) National Coastal Assessment (NCA) Water Quality Index method (USEPA 2005), the National Oceanic and Atmospheric Administration's National Estuarine Eutrophication Assessment (NEEA; Bricker et al. 1999) and Assessment of Estuarine Trophic Status (ASSETS; Bricker et al. 2003), and the Oslo-Paris Convention for the Protection of the North Sea Comprehensive Procedure (OSPAR COMPP; OSPAR Commission 2003).

These Phase II methods develop well-established scientific theory and have been successfully applied in America and Europe; none have been tested in Chinese coastal systems. This paper aims to provide an overview of Chinese coastal systems in order to define the spatial extent of the management issue, and to compare and contrast the Chinese Phase I methods with more recent approaches to help inform the choice of methods for integrated assessment.

Two Chinese systems, the Yangtze Kiang (Changjiang or Long River) Estuary, near Shanghai, and Jiaozhou Bay, near Qingdao, were chosen as test sites for this work. The contrasting nature of the two systems is appropriate for evaluating the wider application of these eutrophication assessment methods in China. As the Chinese coast encompasses a large area and about 20 degrees of latitude and longitude, this evaluation potentially contributes to improved coastal management in other southeast Asian nations.

Review of Chinese Coastal Systems

The Chinese coastal zone covers 23° of latitude (17°N to 40°N) and 16° of longitude (108°E to 124.5°E) and has an area of 2.85×10^5 km^2. These coastal areas are in general densely populated and subject to intense economic activity: the water bodies are often characterized by important anthropogenic nutrient loads.

As a result of these pressures, eutrophication is one of the most negative factors influencing ecosystem health of Chinese coastal systems. Coastal areas of all the major Chinese seas (Bohai, Huanghai, Donghai, and Nanhai) are a concern with respect to HAB (Fig. 1). HAB occurrence was first documented in the 1930s, and since then, the number and scale of HAB events appear to be increasing over time (Yan et al. 2002).

Physical and water quality data for Chinese bays and estuaries were collated based on Chinese reference material (Editorial Board of Bays in China 1993, 1998) in order to provide an overview of the spatial scope of the management issue. These data are largely from the 1980s, and have been condensed in Table 1 to provide a synthesis for 16 major coastal systems representing 95% of the overall area.

Although a national trophic assessment of Chinese coastal systems has not yet been conducted, it is known from various sources, both scientific and anecdotal, that most coastal areas and estuaries appear to exhibit nutrient-related eutrophication symptoms. The literature suggests that those systems undergoing most severe eutrophication include the Bohai Bay, Changjiang Estuary, Hangzhou Bay, and Pearl River Estuary (Zou et al. 1985; Peng and Wang 1991; Pei and Ma 2002; Chai et al. 2006).

Assessment Methods

Eutrophication assessment began with the classical freshwater approach (Vollenweider 1968, 1975;

TABLE 1. Overview of Chinese coastal systems condensed from a set of 50 major coastal systems, with size ranges that are considered medium (< 400 km^2), large (400–650 km^2), and extra large (> 650 km^2). Data from Jiaozhou Bay (excluding area) are median values of 150 water quality samples at seven stations, collected in 1999–2000 by the European Union International Cooperation for Developing Countries (INCO-DC) project: Carrying Capacity and Impact of Aquaculture on the Environment in Chinese Bays.

System	Area (km^2)	NH_4 ($\mu mol\ l^{-1}$)	NO_2 ($\mu mol\ l^{-1}$)	NO_3 ($\mu mol\ l^{-1}$)	PO_4 ($\mu mol\ l^{-1}$)	N:P	Chl *a* ($\mu g\ l^{-1}$)
Changjiang Estuary	51,000	1.40–20.0	0.10–2.50	68.0	20.7	3.40–3.50	1.13
Hangzhou Bay	5,000	9.86	1.71	112	1.13	110	NA
Leizhou Bay	1,690	NA	0.39	2.34	0.13	NA	NA
Wenzhou Bay	1,474	1.41	0.39	14.2	1.17	13.7	1.54
Honghai Bay	925	2.50	0.23	5.30	0.24	33.5	3.12
Taizhou Bay	912	NA	0.40	27.3	0.65	NA	2.15
Haizhou Bay	876	0.75	0.10	1.50	0.11	21.4	NA
Sanmen Bay	775	1.36	0.36	16.1	0.94	19.0	1.47
Sansha Bay	570	1.10	1.02	11.2	0.66	20.2	0.79
Pulandian Bay	530	NA	0.29	2.20	0.26	NA	5.68
Daya Bay	516	0.21	0.20	0.56	0.20	4.90	1.70
Zhanjiang Gang	490	NA	0.64	9.29	0.14	NA	NA
Yueqing Bay	464	0.80	0.27	31.1	0.72	44.7	1.40
Meizhou Bay	424	1.14	0.75	7.20	0.33	27.5	1.70
Aiwan-Xuanmen Bay	419	1.25	0.48	14.9	0.72	23.1	1.00
Jiaozhou Bay	397	4.62	0.64	3.77	0.26	33.5	1.67

Carlson 1977; Morihiro et al. 1981) and has developed through two phases as discussed earlier (Cloern 2001). Historically, a number of eutrophication assessment methods have been proposed in China, such as the Nutrient Index Method, PCA, and Fuzzy Analysis. These methods focus on the evaluation, using chemical tools, of effects of system loading by nutrients, and may be considered Phase I approaches (Wang 2005; Yao and Shen 2005). These methods are reviewed in this section, together with three Phase II methods: OSPAR-COMPP, NCA Water Quality Index, and ASSETS. These more current approaches will potentially help the evaluation of eutrophication in Chinese coastal waters.

Nutrient Index Method I

This method, proposed by the Chinese National Environmental Monitoring Center, is based on a nutrient index (N_I) in seawater (Lin 1996), calculated by using Eq. 1:

$$N_i = \frac{C_{COD}}{S_{COD}} + \frac{C_{TN}}{S_{TN}} + \frac{C_{TP}}{S_{TP}} + \frac{C_{Chla}}{S_{Chla}} \qquad (1)$$

where: C_{COD}, C_{TN}, C_{TP}, and C_{Chla} are measured concentrations of chemical oxygen demand (COD), total nitrogen, total phosphorus (all in mg l^{-1}), and chlorophyll *a* (in $\mu g\ l^{-1}$) in seawater, respectively. S_{COD}, S_{TN}, S_{TP}, and S_{Chla} are standard concentrations of COD (3.0 mg l^{-1}), total nitrogen (0.6 mg l^{-1}), total phosphorus (0.03 mg l^{-1}), and chl *a* (10 $\mu g\ l^{-1}$) in seawater, respectively (Lin 1996). If N_i is greater than four the seawater is considered eutrophic.

Nutrient Index Method II

Zou et al. (1985) proposed an alternative nutrient index method, adapted from Japanese assessment methods (Okaichi 2004):

$$N_i = \frac{C_{COD}\,C_{DIN}\,C_{DIP}}{S_c} \qquad (2)$$

where C_{COD}, C_{DIN}, and C_{DIP} are measured concentrations (in mg l^{-1}) of COD, dissolved inorganic nitrogen, and dissolved inorganic phosphorus in seawater, respectively. S_c in Eq. 2 is the mean product of standard concentrations of COD, DIN, and DIP, for which a constant value of 4.5×10^{-3} is used as it is believed that the critical value for COD is 1–3 mg l^{-1}, DIN is 0.2–0.3 mg l^{-1}, and DIP is 0.01–0.02 mg l^{-1} (Chen et al. 2002). If N_i, is greater than one the seawater is considered eutrophic.

These two limnology-originated methods are simple to apply and use indicators that are easy to determine. 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; Bricker et al. 2003; Ferreira et al. 2007a), and the adaptation of approaches used for freshwater has often met with limited success in coastal areas. This is partly because in coastal environments there is often no clear relationship between nutrient forcing and eutrophication symptoms—systems with similar pressures show widely varying responses. Nutrient concentrations have often been shown to be poor indicators of eutrophication symptoms (e.g., Tett et al. 2003), since ecosystem responses are modulated by typological factors, such as morphology, tidal range, natural turbidity, and water residence time.

Principal Component Cluster Analysis

PCA is applied to eutrophication assessment on the premise that traditionally sampled indicators are correlated to each other, enabling the principal components to be obtained from the set of indicators. Two main types of trophic indicators have been (and are still) used in eutrophication studies: physico-chemical and biological factors (Parinet et al. 2004). Although these factors are clearly related (Strain and Yeats 1999), the form of the relationship may vary considerably. Given the complexity of coastal systems, the aim of this method is to apply linear regression to provide a more reliable way to characterize the state of the aquatic system through an aggregation approach rather than through individual indicators.

The application of PCA yields a subset of indicators that allow a simplified assessment of a system, while retaining the key information. After calibration, the selection of principal indicators may be extended to other systems, with the caveat that differences in typology may render the subset inapplicable.

Since most coastal systems have data gaps, PCA potentially allows scientists or managers to make better use of available information, due to the reduced subset of indicators required. In combination with Nutrient Index Methods, PCA is able to identify the most important indicators related to eutrophic conditions, providing more flexibility than the use of indicators from the Nutrient Index Methods themselves. Because PCA is based purely on statistical rationality, and since so few parameters are used in Nutrient Index Methods, it has not been commonly applied to Chinese systems.

Fuzzy Analysis

The main advantage of Fuzzy Analysis is the ability to deal with imprecise, uncertain, or ambiguous data or relationships, which clearly fits 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 indicators when evaluating the system status. 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 indicators.

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

Despite substantial efforts in development of Fuzzy Analysis based on ecological models (Kompare et al. 1994; Chen and Mynett 2003b), progress has been slow for two reasons: highly dimensional systems require a large and redundant ruleset, the size of which grows exponentially with the number of indicators; and membership functions and inference rules are difficult to define.

OSPAR COMPP

COMPP has been adopted by OSPAR for the identification of eutrophication status of the OSPAR Maritime Area (OSPAR 2003). OSPAR COMPP is a stepwise method that consists of two main procedures: the Screening Procedure and the Comprehensive Procedure. The Screening Procedure is a broad-brush approach, designed to identify obvious non-problem areas with respect to eutrophication. Areas that are not identified as obvious non-problem areas in the first procedure are subjected to the Comprehensive Procedure and classified into problem areas, potential problem areas, and non-problem areas. In OSPAR COMPP the required sampling frequency and spatial coverage of all indicators are dependent on the final classification of the areas.

The first step of OSPAR COMPP is the classification of assessment indicators to provide a score for each of the assessment criteria. Category I is scored + in cases where one or more of its respective assessment indicators show an increased trend, elevated change, or elevated concentration (i.e., greater than the reference value + 50%). The second step is to integrate the scores obtained from the first step so as to provide a coherent classification of the area. An evaluation is made for each assessment indicator from four categories (Influencing Factors, Direct Effects, Indirect Effects, Other Possible Effects) determining whether measured concentrations relate to a problem area, potential problem area, or non-problem area. The final step is to combine the results for the four categories, taking into account supporting environmental factors and region-specific characteristics, such as physical and hydrodynamic aspects and weather-climate conditions, to make a final rating of problem, potential problem, or non-problem area. The region-specific characteristics play a role in explaining the results of the area classification and are essential for the definition of a final classification.

NCA Water Quality Index

To summarize the condition of ecological resources in the coastal waters of the United States, the USEPA developed a Water Quality Index, outlined in the National Coastal Condition Report II (USEPA 2005). The Water Quality Index consists of five indicators: DIN, DIP, chl *a*, water clarity, and dissolved oxygen (DO). Each of the indicators is classified into one of three categories: good, fair, or poor. The overall water quality index uses the results for each of the five indicators to calculate an overall rating that also falls into one of these three categories, but unlike OSPAR COMPP and ASSETS, the Water Quality Index does not include an evaluation of influencing factors.

ASSETS

ASSETS was developed from the NEEA, which was applied to 141 estuaries in the U.S. ASSETS is a more sophisticated and integrated method for eutrophication assessment in coastal zones, which may be applied comparatively to rank the eutrophication status of estuaries and coastal areas. The ASSETS approach includes quantitative and semi-quantitative components, and uses a combination of field data, models, and expert knowledge to evaluate pressure-state-response indicators. The core methodology relies on three diagnostic tools: a simple model to estimate pressure (Influencing Factors), a symptoms-based evaluation of state (Overall Eutrophic Conditions), and an indicator of expected future conditions (Future Outlook). It combines primary (chl *a*, macroalgae) and secondary (DO, nuisance-toxic algal blooms, spatial changes of submerged aquatic vegetation [SAV] distribution) symptoms to derive an Overall Eutrophic Condition index, which is then associated with a measure of Influencing Factors and Future Outlook. ASSETS may be divided into three parts: data collection and compilation, application of indices (Table 2; for a full description see Bricker et al. 2003), and grouping and synthesis.

Pressure - Influencing Factors

The approach for Influencing Factors considers that systems exhibit varying symptoms or symptom levels as a consequence of a particular nutrient load, due to differential susceptibility to nutrient inputs (Bricker et al. 1999). System susceptibility is defined as the relative capacity of a system to dilute and flush nutrients, and is determined by system volume, tidal range, mixing, and river flow. Nutrient inputs describe the comparison of nutrients from watershed or land-based (human) loads with oceanic or natural loads. Susceptibility and nutrient inputs are combined in a matrix to determine the final Influencing Factors rating.

State - Overall Eutrophic Condition

The Overall Eutrophic Condition index uses a sequential approach based on two groups of symptoms, which bring together five indicators: chl *a* and macroalgae, which are indicators for primary symptoms, and loss of SAV, DO, and nuisance-toxic blooms, which indicate secondary symptoms. The primary symptoms correspond to the early stage of water quality degradation and potentially lead to well-developed eutrophic conditions, i.e., secondary (advanced) symptoms, such as SAV loss, nuisance-toxic algal blooms, and low DO (anoxia or hypoxia).

The level of expression of the primary symptoms is determined by calculating the average of two primary symptom expression values, with the chl *a* expression level determined as the 90th percentile of annual data values. The level of secondary symptoms is obtained in a precautionary manner by choosing the worst of three symptoms, with DO expression level determined from 10th percentile values of annual data. The primary and secondary symptoms are combined in a matrix to determine an overall level of eutrophic conditions for the estuary.

Response - Future Outlook

An analysis of Future Outlook is performed to determine whether conditions in an estuary or bay will worsen, improve, or stay the same in the medium term (e.g., over the next two decades). Assessment of expected changes in nutrient pressures is performed based on a variety of drivers, including demographic trends, wastewater treatment, and remediation plans, together with expected changes in agricultural practices and watershed uses. Projection of future nutrient inputs is combined with system susceptibility to predict future scenarios.

Synthesis - Overall Grade

The final 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

TABLE 2. List of indicators considered in ASSETS (adapted from Bricker et al. 2003).

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

[a] Spatial coverage (% of salinity zone): high (50–100%), medium (25–50%), low (10–25%), no SAV-wetland in system.
[b] Frequency of occurrence: episodic (conditions occur randomly), periodic (conditions occur annually or predictably), persistent (conditions occur continually throughout the year).

for pressure, state, and response is able to provide a grade falling into one of five categories: high (better), good, moderate, poor, or bad (worse). These grades match the quality classes of the European Union 2000/60/EC (Water Framework) Directive (European Community 2000).

Discussion of Methods

In terms of indicator variables, the four Chinese methods outlined above are quite similar although the underlying logic may vary. The indicators applied in the different methods are summarized in Table 3, and Table 4 presents a more detailed comparison among Chinese methods and Phase II methods.

Even though Nutrient Index Methods are the approach recommended by the Chinese National Authorities, these methods have been criticized for their underlying limitations and simplicity (Yao and Shen 2005). There are two main reasons that the Phase I methods are considered inadequate for the assessment of Chinese coastal eutrophication. First, there has been an overemphasis on the significance of nutrient concentration as an indicator of eutrophication, which may not be a robust diagnostic indicator. 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 algae and loss of SAV. High nutrient concentrations are not necessarily indicative of eutrophication, and low concentrations do not unequivocally guarantee the absence of eutrophication (Cloern 2001; Dettmann 2001; Bricker et al. 2003). Second, there has been a failure in adaptation of a freshwater-based approach to coastal waters due to the differences between freshwater and coastal systems. For example, water exchange or top-down control by filter feeders (of great relevance in China due to the intensity of shellfish aquaculture) in estuaries and bays may greatly

TABLE 3. Summary of indicator variables used (adapted from Bricker et al. 2006).

Indicators	Nutrient Index I	Nutrient Index II	PCA	Fuzzy Analysis	OSPAR COMPP	EPA NCA	ASSETS
Nutrient (DIN, DIP) load or concentration	×	×	×	×	×	×	×
Chemical oxygen demand	×	×					
Chlorophyll *a*	×		×	×	×	×	×
Dissolved oxygen	×	×	×	×	×	×	×
Water clarity			×	×		×	
HABs/Nuisance					×		×
Phytoplankton indicator species					×		
Macroalgal abundance					×		×
Submerged aquatic vegetation loss					×		×
Zoobenthos-fish kills					×		

TABLE 4. Summary of comparison among Phase I and Phase II methods (adapted from 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 indicators 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	Individually/regionally determined reference condition	Integration of scores for four categories
EPA NCA	Summer index periods	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

mitigate the expression of eutrophication symptoms, even under high nutrient loading. Simple time-varying or statistical approaches established in freshwater, based on the clear relationships between pelagic algae and nutrient loading, contrast with ambiguous relationships that may occur in coastal waters (Ferreira et al. 2007a).

OSPAR COMPP and NCA differ from ASSETS in the following aspects: the concentrations of DIN and DIP are taken as indicators of eutrophication; and OSPAR COMPP fails to set thresholds for indicators concerned. This was initially intended to allow flexibility and discretion when applying it to a range of countries, but it also leads to ambiguity and uncertainty in the final results.

A general limitation of both the Chinese methods and OSPAR COMPP and NCA is that there is no differential weighting across indicators. Although the scientific community has been unable to agree upon a single, reliable trophic state index, it is commonly agreed that the relative importance of indicators differs (Lu and Lo 2002; Bricker et al. 2006). From the range of methods reviewed, only ASSETS (and its NEEA predecessor) provides weighting of the various components, both within components (Influencing Factors, Overall Eutrophic Condition, and Future Outlook) and in the overall aggregation procedure, where the Future Outlook component weighs less in the overall classification.

Selection of Study Sites and Methods

The Changjiang Estuary and Jiaozhou Bay were chosen to compare the Chinese Nutrient Index Methods and ASSETS, with respect to adequacy for a broad-scale assessment of Chinese coastal waters. The two systems have very different characteristics, as summarized in Table 5 (Editorial Board of Bays in China 1993, 1998). The Changjiang Estuary was selected because it is the largest estuary in China (of the longest river in Asia), with the largest watershed and highest population density, and consequently with high nutrient loads that frequently lead to eutrophication problems. The ASSETS method has been applied successfully to systems from different ecoregions representing all sizes in the U.S. and Europe (see http://www.eutro.org/syslist.aspx), from less than 1 km^2 to about 7,000 km^2, with variable population densities and watershed uses. This includes the Mississippi-Atchafalaya River Plume (Rabalais et al. 2002), which has an area greater than 12,000 km^2 whose similarity to the Changjiang Estuary makes it appealing for an international comparison.

The interest in Jiaozhou Bay is mainly due to the top-down control in the local ecosystem provided by shellfish aquaculture (Han and Wang 2001; Li et al. 2005), which might suggest broader options for the management of eutrophication. As a typical medium-sized system (Table 1), it is a perfect test

TABLE 5. Summary of two study sites.

	Changjiang Estuary	Jiaozhou Bay
Area (km^2)	51,000	397
Location	East China (31°14′N, 121°27′E)	East China (35°38′–36°18′N, 120°04′–120°23′E)
Discharge (m^3 yr^{-1})	9.3×10^{11}	8×10^8
Morphology	Tubular estuary	Bay
Pressure	Rural and industrial population 18 million (Shanghai City)	Rural and industrial population 8 million (Qingdao City)
Cultivated marine resources	Kelp, shellfish	Shellfish
Data availability	Low	High
Problems	HABs, hypoxia	HABs

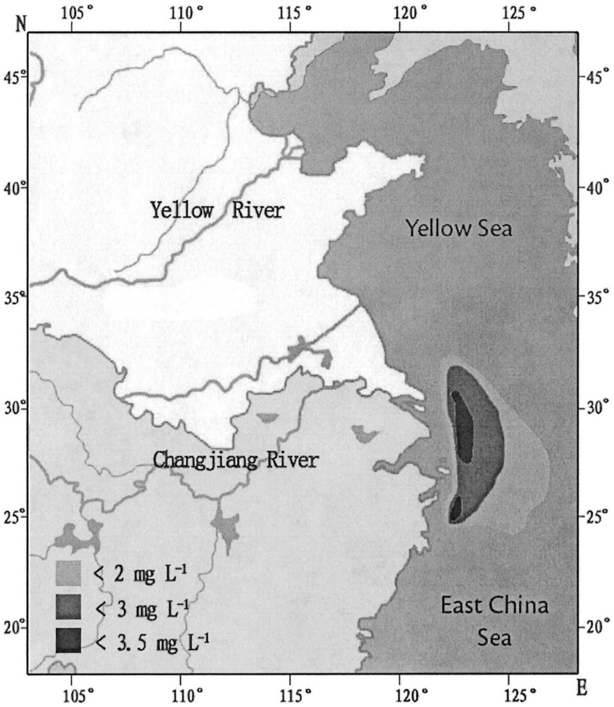

Fig. 2. Location map of Changjiang Estuary and estimated hypoxic areas (adapted after Chen and Zhong 1999; Li et al. 2002).

candidate prior to wider application in China. It is well studied and the data availability lends confidence to the reliability of the assessment.

Chinese Nutrient Index Methods I and II are the major assessment methods used in China and were used here to evaluate the eutrophication status of the Changjiang Estuary and Jiaozhou Bay. ASSETS was selected from the available Phase II approaches for comparison tests, based on the following features. It has been successfully applied and tested for 141 estuaries in the continental United States, 10 estuaries in Portugal, and a number of coastal systems in the U.K., Ireland, Italy, Germany, and Australia (Bricker et al. 1999; Ferreira et al. 2003, 2005; Bricker et al. 2007). It can accommodate diverse estuarine and coastal morphologies, river discharge, and tidal range conditions, together with a variety of system uses and environmental symptoms. It was consolidated through intense peer review within the scientific community, and has been extensively published in the open literature (e.g., Bricker et al. 2003; Ferreira et al. 2005; Scavia and Bricker 2006; Ferreira et al. 2007a; Whitall et al. 2007). It takes direct and indirect eutrophication symptoms into account, when compared to Nutrient Index Methods and provides a more accurate evaluation than OSPAR COMPP (a full discussion of comparisons among methods is given in the discussion section).

Changjiang Estuary

The 1.94×10^6 km^2 Changjiang river basin is characterized by intense industrial and urban activity, especially in the lower reaches and estuarine portion of the river (Editorial Board of Bays in China 1998). It has a temperate climate and is heavily populated with an estimated population of 400 million. The river discharge of 29,000 m^3 s^{-1} delivers about 480 million tons of sediment each year to the estuarine and coastal area. The Changjiang River is a major source of nutrients to the coastal zone and acts as a conduit that transports anthropogenic loading from the catchment to the estuary and adjacent coastal waters (Chen and Chen 2003a). Located on a mesotidal coast, the estuary is a wide, shallow, and partially mixed system (Fig. 2).

The main issues of concern are HABs and hypoxia. HABs are frequently observed in the Changjiang estuary and extended coastal waters and are the primary environmental issue. The East China Sea is the area where the most severe HABs occur among the four seas of China, accounting for 36% 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 the Changjiang estuary and adjacent coastal areas (Guan and Zhan 2003). Toxic HAB genera, such as *Alexandrium* and *Gymnodrium*, are often observed, resulting in kills of fish and zoobenthos, and have damaged nearby fishing grounds such as the Zhoushan fishing area.

A secondary issue of concern in this area is the occurrence of hypoxia in near-bottom waters off the Changjiang estuary and adjacent coastal waters, which has increased continuously since first recorded in the 1950s (Li and Daler 2004; Fig. 2). The conditions in the Changjiang and adjacent waters are very similar in scale to the low DO zone in the Mississippi-Atchafalaya River Plume, which has increased in size since 1985, reaching the largest area ever recorded in 2002 (Rabalais et al. 2002; Bricker et al. 2007).

Estimation of Nutrient Input to the Changjiang

Although ASSETS usually determines nutrient loading based on river discharge and concentrations of relevant nitrogen and phosphorus species, the Changjiang basin was treated differently, because of uncertainties with respect to measured data and to permit evaluation of catchment management scenarios. Different watershed modeling approaches were tested, as detailed below.

The first step was the collection of relevant hydrological and agricultural data on the Changjiang catchment, including: a topographic map, built using the GTOPO30 (Global Digital Elevation Model with a horizontal grid spacing of 30 arc seconds) data set with a resolution of 1 km^2; and a land cover map with 1-km^2 resolution, based on the U.S. Geological Survey's Global Land Cover Characteristics Data Base. The topographic data set was used to divide the Changjiang river basin into 87 subbasins using an automatic watershed delineation method (the D8 method; Grayson and Blöschl 2001), in order to further detail the spatial sources of nutrients within the catchment.

The Soil and Water Assessment Tool (SWAT) was initially applied to simulate the nutrient load into the Estuary. SWAT is a physically-based model with the objective of assessing the effect of land management on water, sediment, and agricultural pollution (for a full description see Neitsch et al. 2002). SWAT proved to be an inappropriate tool to simulate such a large area as the Changjiang river basin. Several authors have shown that the results of hydrological models are significantly affected by problems related to coarse-scale representation of indicators and small-scale processes over large areas (e.g., Fisher et al. 1997; Bashford et al. 2002; Muttiah and Wurbs 2002; Venohr et al. 2005). Booij (2003) determined that the calculation of hydrological indicators related to topography should use data sets with a minimum resolution of 100 × 100 m, so the digital elevation map used in this study (1,000 × 1,000 m) is inappropriate for this purpose. Booij (2003) also determined that a basin should be subdivided into modeling units of 100 km^2 or less, while the huge size of the Changjiang basin led to modeling units averaging 11,600 km^2. It appears that issues of scale prevent the application of a dynamic modeling tool to the Changjiang catchment; in spite of this, SWAT is recognized as a useful tool for water quality management in smaller catchments (e.g., Arheimer and Olsson 2003; Santhi et al. 2006; Chaplot 2007) and can potentially be applied to the smaller catchments of other Chinese systems.

In the light of these results, an Export Coefficient Model (ECM) was chosen to estimate nutrient loading from the Changjiang catchment to the estuary, based on the watershed delineation detailed previously. The ECM is not dependent on hydrological process modeling, using instead land cover data maps to integrate the total annual basin nutrient loads from the many unique watershed areas, and then adding other nutrient sources such as septic systems, wastewater treatment plants, and precipitation (Reckhow and Simpson 1980). The nutrient load in a river basin is obtained through the following equation:

$$L_N = \sum_{i=1}^{M} [E_i \times A_i] + S + W + P \qquad (3)$$

where L_N is the basin nutrient load (kg yr^{-1}); E_i is the export coefficient (kg ha^{-1} yr^{-1}) for land class i, A_i is the area of the watershed in land class i (ha), S is the septic load (kg yr^{-1}), W is the wastewater load (kg yr^{-1}), and P is the precipitation load (kg yr^{-1}).

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

Unlike SWAT, ECM does not use meteorological data or mechanistic pollutant-atmosphere-vegetation-soil equations, nor does it consider chemical processes among nutrient species. Its modeling strength and adaptability have at least two advantages (Endreny and Wood 2003): it is functional within watersheds that meet the minimum data needs, and it remains simple to use (Worrall and Burt 1999).

The areas used for ECM were obtained from the subbasin delineation, while the nutrient coefficients were collected from the literature (Reckhow et al. 1980; Johnes 1996; Worrall and Burt 1999; Bernal et al. 2003). The annual average nutrient loads have been estimated as 11.4 ton N ha^{-1} and 3.5 ton P ha^{-1}, with the highest specific export rates from areas with intensive agriculture (double crop ricelands and wheat + corn croplands). ECM coefficients can be difficult to transfer among catchments (Wade et al. 2005), but they have been shown to be consistent across broad land-use types (e.g., cropland, pasture) for different watersheds (Harmel et al. 2006); Wade et al. (2005) report a broad dependency of river N concentration on catchment land-use typology, rather than on specific agricultural practices, which supports the usefulness of ECM in determining the magnitude of N and P exports from a given catchment (Wade et al. 2004).

JIAOZHOU BAY

Jiaozhou Bay (Fig. 4) is located on the west coast of the Yellow Sea (35°57′–36°18′N, 120°06′–120°21′E) with a surface area of 397 km^2 and average depth of 7 m (Editorial Board of Bays in China 1993). Jiaozhou Bay is a semi-enclosed water body, connected to the Yellow Sea through a 2.5-km channel, and has a mean tidal range of 2.5–3.0 m. The tides, which at spring tide can reach 4.2 m, induce strong turbulent mixing, resulting in nearly

TABLE 6. Summary of ASSETS application to the Changjiang Estuary.

Index	Method	Indicator	Level of Expression	Index Result	ASSETS Score
Influencing Factors	Susceptibility	Dilution potential	Moderate	Moderate High	Bad
		Flushing potential	Moderate		
	Nutrient inputs		High		
Overall Eutrophic Condition	Primary Symptoms Method	Chlorophyll *a*	Moderate	High	
		Macroalgae	Unknown		
	Secondary Symptoms Method	Dissolved oxygen	Moderate		
		SAV loss	Unknown		
		Nuisance and toxic blooms	High		
Future Outlook	Future nutrient pressure	Increase		Worsen High	

homogeneous vertical profiles of temperature and salinity (Liu et al. 2004).

The bottom of Jiaozhou Bay contains spawning, nursery, and feeding grounds for fish. Over the last two decades, intensive mariculture has been developed. Historically, this has focused on the bay scallop (*Argopecten irradians*) and Pacific oyster (*Crassostrea gigas*), cultivated on longlines. More recently, the longlines have been removed and the system is currently used for cultivation of Manila clam (*Tapes philippinarum*), with an estimated production of 200,000 tons (total fresh weight) per year. Shellfish biomasses of this scale will filter the entire bay in under one week, considering an average clearance rate of 1 l ind^{-1} h^{-1} for *T. philippinarum* (Hawkins personal communication). Top-down control from aquaculture has a potentially significant effect in reducing the expression of eutrophication symptoms (Zhou et al. 2006).

The main issue in Jiaozhou Bay is the increase of HABs, as both the frequency and magnitude of the HAB incidents have increased since 1990s, although most events are non-toxic (Han et al. 2004). The main HAB species include *Biddulphia aurita*, *Eucampia zoodiacus*, *Mesodinium rubrum*, *Noctiluca scintillans*, and *Skeletonema costatum* (Wang et al. 2006).

Results and Discussion

Tables 6 and 7 present the results from the application of different eutrophication assessment methods for the Changjiang Estuary and for Jiaozhou Bay.

Changjiang Estuary

Influencing Factors

Nutrient Input. The results from the application of ECM indicate that the total N input into the Changjiang Estuary is 2.21×10^6 ton yr^{-1} and the P input is 0.69×10^6 ton yr^{-1}. Figure 3 presents the details of nutrient distribution in the Changjiang river basin. This N load, combined with system volume and mean salinity, indicates a High category for the nutrient component of the Influencing Factor score (0.9998).

Susceptibility. The susceptibility of the Changjiang is considered Moderate based on dilution and flushing capabilities. The dilution volume in the Changjiang Estuary was estimated as 6.4×10^{11} m^3, with a mean thickness of 12.5 m in the upper 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 925×10^{11} m^3 yr^{-1} from the Changjiang River (Che et al. 2003). The combination of High load and Moderate susceptibility gives a final Influencing Factor rating of Moderate High.

Overall Eutrophic Condition

Primary Symptoms Method. Chl *a* is the only indicator with available data for evaluating primary symptoms. No information on macroalgae was reported in the literature, which was classified as

TABLE 7. ASSETS application to Jiaozhou Bay.

Index	Method	Indicator	Level of Expression	Index Result	ASSETS Score
Influencing Factors	Susceptibility	Dilution potential	Moderate	Low (due to intense shellfish aquaculture)	High
		Flushing potential	Moderate		
	Nutrient inputs		High		
Overall Eutrophic Condition	Primary Symptoms Method	Chlorophyll *a*	Low	Low	
		Macroalgae	No problem		
	Secondary Symptoms Method	Dissolved oxygen	Low		
		SAV loss	Low		
		Nuisance and toxic blooms	Low		
Future Outlook	Future nutrient pressure	Decrease		Improve low	

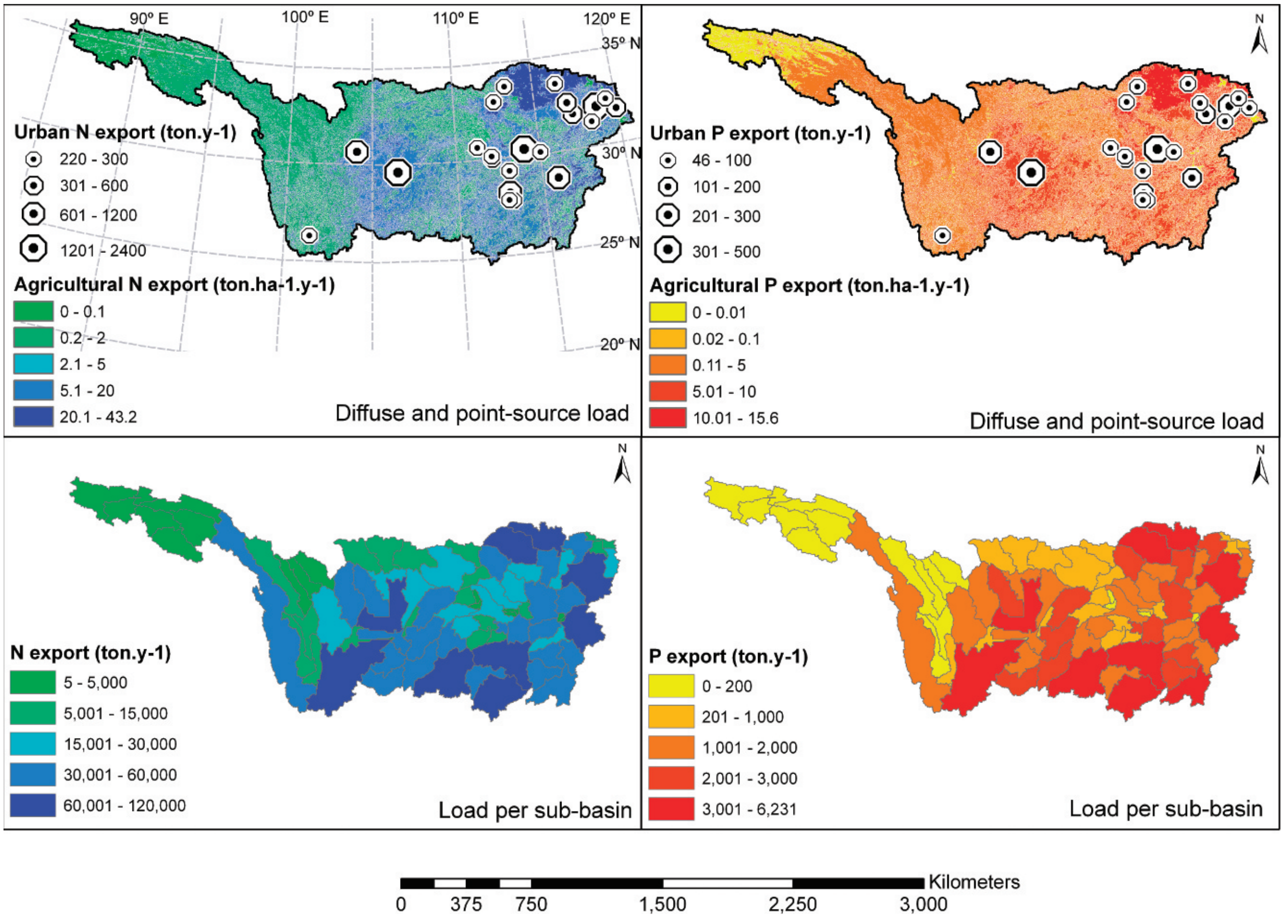

Fig. 3. Nutrient load in Changjiang river basin.

Unknown. Detailed chl *a* data are difficult to find, but for indicative purposes, the literature data are used to carry out a pilot test (Zhou et al. 2004). The mean values of maximum concentration fall into the ASSETS medium category (5–20 μg l^{-1}), but blooms occur over a huge area. The symptom level of chl *a* concentration is considered to be Moderate.

Secondary Symptoms Method. DO and HABs are analyzed as secondary symptoms, but no information was found for loss or change of SAV. The Changjiang Estuary has long exhibited problems with low DO (Li et al. 2002). Over the last two decades, minimum values of DO in the low oxygen region of the Changjiang Estuary have decreased from 2.85 to 1 mg l^{-1}. A 1999 survey of the 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). The plume of oxygen-depleted water extended in a southeasterly direction to the 100-m isobath, along the bottom of the continental shelf of the East China Sea (Fig. 2). These observations clearly indicate that the system is under severe biological stress (< 5 mg l^{-1}). The combination of observed hypoxia that occurs on an annual basis and the large area over which it occurs (26.9% of the system area) results in an expression level of DO of Moderate.

Along with the frequent reports of HAB incidents, the duration of blooms can last for weeks to months; a *S. costatum* bloom was reported from May 10 to 23, 2001. Considering the high frequency and long duration of occurrence of HABs in the estuary, the level of nuisance and toxic blooms falls into the High category.

Since the secondary symptom level is determined by the highest value of three symptoms in ASSETS, the Changjiang Estuary is considered to fall into the High category. The overall eutrophic condition in this system is considered to be High due to Moderate primary symptoms and High secondary symptoms.

Future Outlook

Based on China's strategic planning for development, the Changjiang drainage basin is expected to provide an estimated 10^7–10^8 ton yr^{-1} of additional food in order to feed the increasing population within the next 50 yr. This will probably result in an expansion of croplands, coupled with a further increase in fertilizer application in a densely populated area that is already characterized by intensive agriculture. If DIN concentrations continue to increase at the same rate as in the last two decades, the DIN load will be an estimated 4.1×10^6 ton yr^{-1}, twice as much as in 1998 (Zhang et al. 1999b). One additional concern is that with the construction of the Three Gorges Dam, upstream silicate (Si) discharge is expected to decrease drastically, leading to further decreases in the Si:N ratio and potentially introducing substantial changes in phytoplankton composition. In short, the eutrophic status in Changjiang Estuary is expected to worsen over the next few years. Table 6 summarizes the results obtained for the application of ASSETS to Changjiang estuary, with an overall score of Bad, indicating a high level of eutrophication.

Jiaozhou Bay

Influencing Factors

The volume of Jiaozhou Bay is $1,900 \times 10^6$ m^3 and the N load into the bay is 30 ton d^{-1} (Wang et al. 2006), which result in a High rating for the nutrient component of Influencing Factor (0.933).

Strong tidal mixing and high river discharge (8×10^8 m^3 yr^{-1}) contribute to moderate flushing and dilution potential (Editorial Board of Bays in China 1993). The intensive top-down control of the foodweb has a significant effect on mitigating eutrophic symptoms. In the 1960s, there was some kelp culture along the east coast of Jiaozhou. Since the 1980s, shrimp and shellfish culture have been developing in the bay. In the 1990s, shellfish culture has become more dominant (Fig. 4).

The susceptibility component of the Influencing Factor based on only natural circumstances is considered Moderate but when shellfish aquaculture is taken into account, the overall susceptibility is considered to be Low. This is one example of the difficulty in universal application of this kind of method, since ASSETS must be potentially adapted to incorporate local societal factors. Another is the human consumption of *Enteromorpha* sp. in China, often produced in areas highly affected by sewage discharge. The excessive growth of opportunistic macroalgae, considered a primary eutrophication symptom in ASSETS, is not seen as a liability in many parts of China.

The combination of High nutrient load and Low susceptibility gives an overall Influencing Factor rating of Moderate Low.

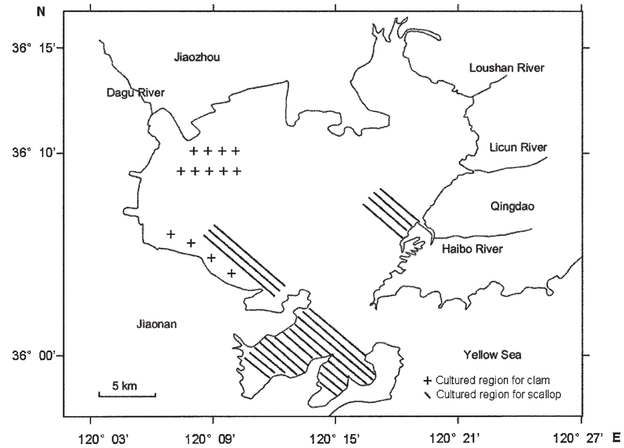

Fig. 4. Location map of Jiaozhou Bay and the shellfish culture distribution in late 1990s (adapted from Shen et al. 2006).

Overall Eutrophic Conditions

Primary Symptoms Method. Chl *a* is the only indicator with information for the primary symptoms. No information was found for macroalgae, which was therefore classified as Unknown. Maximum chl *a* values in Jiaozhou Bay did not exceed the threshold indicated in ASSETS for Medium eutrophic conditions. ASSETS uses the 90th percentile value to alleviate the extreme value problem, in order to provide a more robust maximum concentration for chl *a*. In the bay this value is between 4–5 μg l^{-1}, i.e., in the Low category (Fig. 5). The rating for primary symptoms is Low based on chl *a*.

Secondary Symptoms Method. Discrete data for DO were collected from various sites to cover one annual cycle. No information was found for SAV, but considering the large scale of kelp aquaculture in the bay, the level for this symptom would be at worst Low.

Very few values below the ASSETS threshold for biologically stressful DO conditions (5 mg l^{-1}) were detected in Jiaozhou Bay. As described earlier, the 10th percentile value is applied to provide a more consistent minimum value for DO. In this system, the 10th percentile for annual DO data is between 6–7 mg l^{-1}, indicating no problems for this indicator (Fig. 5).

Although HAB reports are not unusual, most of these are non-toxic (Han et al. 2004). According to Han et al., there were up to 69 harmful algal species observed in Jiaozhou Bay. Toxic blooms are registered episodically, and usually last only a few days; a *S. costatum* bloom was reported to last for five days in July 1998 (Huo et al. 2001). The symptom of nuisance and toxic blooms is rated as Low.

In synthesis, the highest level of the three secondary symptoms falls into the Low category, and the Overall Eutrophic Condition resulting from

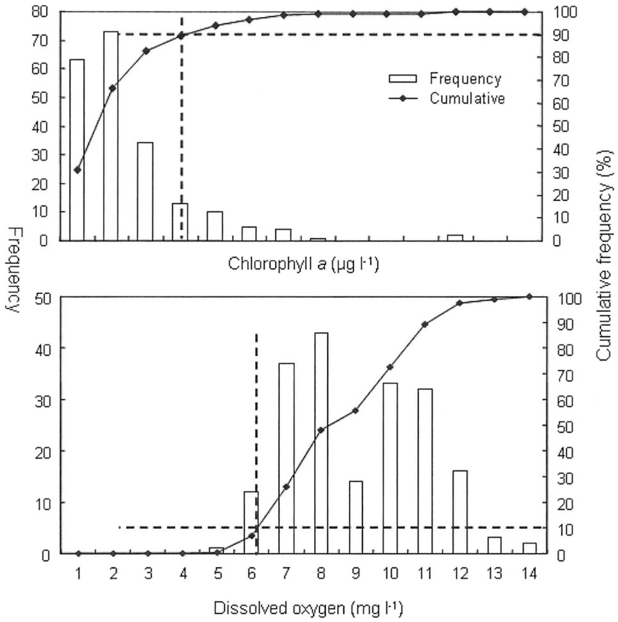

Fig. 5. Frequency distributions for chlorophyll *a* and dissolved oxygen in Jiaozhou Bay.

the combination of primary and secondary symptoms for this system is Low.

Future Outlook

The estimate based on the current development scenario gives a 9.3% population increase over 20 yr (P.R.C. National Bureau of Statistics 2001). Qingdao (the main land nutrient source, population of 8 million) is strongly promoting its tourism industry and less space is available for mariculture in Jiaozhou Bay. The reduced top-down control on primary production could lead to increased eutrophic symptoms.

Qingdao also prepares to host the Olympic Sailing Regattas in 2008, which has focused attention on water quality issues and mitigation of eutrophic symptoms. The government has pledged to build more wastewater treatment plants in the near future and more restrictive pollutant emission regulations are coming into effect (Wang et al. 2006).

As a whole, nutrient loads are expected to decrease in spite of the increase in the urban population, and the water quality in Jiaozhou Bay is likely to improve. The Future Outlook can be considered to be Improve Low. Table 7 summarizes the results obtained from the application of ASSETS to Jiaozhou Bay, which resulted in an overall score of High, indicative of a system without eutrophication problems.

Conclusions

Comparison of Results

The system classifications from the application of the ASSETS assessment method to Changjiang Estuary and Jiaozhou Bay are Bad and High, respectively (Tables 6 and 7). While the assessment for the Changjiang is expected, the result for Jiaozhou is better than expected as a result of top-down control related to intensive mariculture in this system. This has important implications for successful management of nutrient-related problems (see the next section).

Comparison of the ASSETS classifications to those from the application of the Chinese methods shows differences among the results (Table 8). While the Chinese Nutrient Index Phase I methods may discriminate between problem and non-problem areas, they are unable to indicate the degree of severity. ASSETS provides a more detailed classification of system eutrophication status. This becomes more important when required management measures are implemented and the success of the measures must be examined. In the case of ASSETS, it is possible to measure incremental changes as a system evolves, and management measures may be modified as necessary. Smaller changes would not be detected by the Chinese Nutrient Index Methods and timely adaptive management would not be possible.

The Nutrient Index Methods cannot by definition be clear indicators for a large system, because there is no accommodation in the methods for spatial differences in level of effect within a water body. Nutrient Index Method II could not be successfully applied in Jiaozhou Bay because the large variability in results from different sampling sites made it impossible to calculate an overall value. The evaluation of systems by salinity zone, as in ASSETS, contributes to a more accurate evaluation of the system and subsystems, which is necessary to target management efforts.

Comparison of results for the Changjiang to results from the application of ASSETS to the

TABLE 8. Comparisons of results from different assessment methods.

	Nutrient Index Method I	Nutrient Index Method II	ASSETS
Changjiang Estuary	Eutrophic	Eutrophic	Bad
Jiaozhou Bay	Eutrophic	Could not be applied	High

Mississippi-Atchafalaya River Plume show similar results. The Mississippi-Atchafalaya River watershed drains about 40% of the continental United States, a catchment area characterized by intensive agriculture. The overall eutrophic condition is High as a result of high levels of chl *a* and of its most characteristic problem, persistent hypoxia (Bricker et al. 2007). The Future Outlook is for worsening conditions due to expected population growth and increased fertilizer use to grow food to support increased dietary needs (Turner et al. 2006). In 2001, an action plan for reducing, mitigating, and controlling hypoxia in the Mississippi-Atchafalaya River Plume (Mississippi River/Gulf of Mexico Watershed Nutrient Task Force 2001) was endorsed by federal agencies, states, and tribal governments. The goal of reducing the hypoxic zone to an area $< 5{,}000\ km^2$ by the year 2015 requires a N load reduction of 30–45%. Implementation will be based on a series of voluntary and incentive-based activities, including proper timing and amount of fertilizer applications, best management practices on agricultural lands, wetland restoration and creation, river hydrology remediation, riparian buffer strips, and nutrient removal from storm water and wastewater. Comparison of the results of the success of the Mississippi-Atchafalaya River management plan with plans for reduction of the Changjiang hypoxic zone may help to promote more successful management in both systems.

Future Developments and Wider Application

The ECM results show that most of the N and P loads from the Changjiang river basin come from the eastern part of the catchment as a result of intensive agricultural activity. This information should be used to provide the basis for targeted management. As an example, focusing more intensive management efforts on agriculture in the eastern areas of the basin will provide greater success in reducing nutrient-related problems than if management efforts were applied with equal intensity across the basin.

The top-down control of the foodweb in Jiaozhou Bay suggests a feasible way to manage the eutrophication in a coastal system. These strategies for eutrophication control, which have traditionally been used in China for many years, are being discussed with respect to practical implementation in the EU and the U.S. (e.g., Lindahl et al. 2005; Ferreira et al. 2007b). Paradoxically, the Chinese, U.S., and other governments and scientists currently focus mainly on a bottom-up approach in improving water quality, though there is still plenty of scope to promote top-down control in the food chain. Water quality data from an annual program with monthly measurements at seven stations in Jiaozhou Bay during 1999–2000 were used to estimate the gross removal of algae by Manila clams. On the basis of reported bivalve stocks, these organisms annually remove about 627 ton yr^{-1} of chl *a*, which (considering a carbon:chlorophyll ratio of 50 and the standard Redfield C:N ratio of 45:7 in mass) corresponds to the removal of almost 4,900 ton yr^{-1} of N. This equates to the annual discharge of about 1.5 million people, or 17% of the population of Qingdao, and to about 45% of the estimated 11,000 ton yr^{-1} N load. Along with economic benefits, the introduction of filter feeders on a reasonable scale allows for cost-effective removal of nutrients and mitigation of eutrophic conditions, which is more environmentally friendly and sustainable for a coastal system (Shastri and Diwekar 2006).

Environmental managers should be cautious when reducing mariculture, since doing so could lead to worsening eutrophic conditions. There is a proposal in Qingdao city to limit aquaculture in Jiaozhou Bay as part of future management plans, partly driven by the Olympic sailing regattas in 2008. As mentioned previously, shellfish aquaculture appears to be the major reason why this bay is not severely eutrophic given the high nutrient load. Decrease of shellfish culture may result in more severe eutrophic symptoms in Jiaozhou Bay.

Compared to Chinese assessment methods, ASSETS proved to be a more feasible method to apply to coastal systems based on these two case studies. Data acquisition proved to be the most difficult part of this study, and it is expected that data limitations will be a challenge in a more comprehensive assessment of Chinese coastal systems. It is recommended that additional data be collected for the two study sites and that monitoring of other sites should also be a priority, to provide the basis for a national coastal eutrophication assessment. In some cases, particularly for subtropical systems, it may be necessary to make adjustments to thresholds for indicators such as chl *a*. In the application of ASSETS in the U.S., the ranges and thresholds determined by the group of eutrophication experts accurately reflected conditions in all 141 systems, with the exception of Florida Bay, a sensitive system in the Gulf of Mexico region. For this system, a lower threshold was established heuristically.

There is a clear need to better understand the current eutrophication status of Chinese coastal water bodies, given concerns about eutrophication-related degradation during the past two decades and perspectives for an increase in nutrient-related pressures on the coastal zone over the coming years. The successful assessment of these test systems, despite the differences in size, physical characteristics, and uses, suggests that the ASSETS method may potentially be recommended for a Chinese national eutrophication assessment. Such an assessment will provide the necessary support to coastal managers, by providing an overview of the scale of the problems, highlighting the areas where priority management plans should be developed, and informing integrated coastal zone management, bearing in mind the critical effects that changes in bivalve mariculture may have on eutrophication symptoms.

Many of the aspects discussed herein are of potential interest in other parts of southeast Asia, which share with China the challenges of balancing rapid economic growth with improvement of environmental quality in the coastal zone. In this context, rural and peri-urban activities such as integrated multitrophic aquaculture have over thousands of years provided natural remediation for the excessive discharge of nutrients to bays and estuaries.

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HAWKINS, A. J. S. personal communication. Plymouth Marine Laboratory, The Hoe, Plymouth PL1 3DH, Devon, U.K.

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