

Watersheds Nutrient Loss and Eutrophication of the Marine Recipients: A Case Study of the Jiaozhou Bay, China

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Abstract Industrialization and urbanization along the coastal population centers have brought great changes in the land cover and material fluxes from watersheds to receiving bays and estuaries. We have embarked a multiyear research project on “Watersheds Nutrient Loss and Eutrophication of Jiaozhou Bay” for the period of 2000 to 2004, funded by the Natural Science Foundation of China to examine human influence on the marine sector of ecosystem. Jiaozhou Bay, located in the southern part of Shandong Peninsula, was selected because of the existence of long-term hydrographic and meteorological records since the 1930s and recent observations on the marine ecological variables. We have made extensive and periodic measurements on the water movement, nutrients, phytoplankton, and microbe in water column and bottom sediments. Box and 3-dimensional hydrodynamic models were developed and utilized to understand the evolution of eutrophic status with

time. It was found that primary productivity has suffered from silica depletion followed by phosphate, and the dominance of large phytoplankton has been replaced by small-size communities. These ecosystem changes were brought by the changes in the relative contribution among major pathways and concentrations, owing to the human activities in the watershed. Eight articles in this volume reported various aspects of the linkage between watershed human activities and ecosystem for the Jiaozhou Bay as the initial outcome of this project.

Keywords Watersheds · Ecosystem · Nutrient loss · Marine community · Human perturbation · Eutrophication

1 Introduction

Important scientific issues for coastal water eutrophication are the increased terrestrial nutrient inputs, in particular, nitrogen and phosphorous forms, and nutrient accumulation within the coastal waters including bottom sediments (GEOHAB 2001). Hence, these artificially derived nutrients tend to be different from those in the natural watershed. Both accumulation and deviation of nutrient species ratios from the natural seawater in receiving environments resulted in changes in structure and function of phytoplankton community and adversary effects on fisheries through alteration of food-web. The wide

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scale ones are, for example, Danube River – Black Sea and Mississippi River – Gulf of Mexico systems (Turner and Rabalais 1994; Humborg et al. 1997), and even pose the concerns on human health and economic sustainability of coastal community (IMBER 2005).

The elemental composition of nutrients in the high nutrient-loading environment exhibits elevated nitrogen to silicon ratio than that of natural state. These water bodies forced phytoplankton community to adapt the new nutrients and results in lower biodiversity and higher biomass with frequent outbreaks of harmful algal blooms (Liu et al. 2005a). The bloom events, in turn, modify the nutrient environment (Conley and Johnstone 1995; Smayda 1997). In the eutrophic waters bacterial activity becomes higher than the natural waters because of the abundance of dissolved and particulate organic matter produced by phytoplankton. Bacteria facilitate the mineralization of organic matter and transform the dissolved organic matter to the particulate organic materials (Scaria 1988). In coastal waters, 40% of primary production may be consumed by the heterotrophic microbes, and 25–60% of photosynthetic carbon is believed to be transported to the main food web via micro-loop (Cho and Azam 1990).

Traditionally, pathways of nutrient influx to the coastal water bodies were considered mainly surface river runoff and waste water discharges (Henriksen and Henssen 1997; Henssen et al. 1997). However, more stringent control of surface water quality, pollutants from atmospheric and groundwater sources become more prominent in recent decades (Zhang 1994; Paerl 1997).

The internal processes within the receiving bay and estuaries are increasingly important once the nutrient level exceed the natural state. Notable ones are the interaction of phytoplankton community with changing nutrient dynamics and the interaction between bottom sediment and water; adaptation for nutrients and other trace elements are also important as the bottom sediment acts both sink and sources of nutrients and other pollutants (Cercio 1995a,b; Patsch and Radach 1997).

Hence, to understand the coastal eutrophication, the knowledge of nutrient loss from watersheds via a variety of pathways along the continuum of land – sea in coastal zone is of critical importance (Mulder et al. 1997; LOICZ 2005). An important issue of the coastal eutrophication is the interaction of phytoplankton

community with changing nutrient dynamics (Anderson et al. 1982). In the natural coastal water bodies, phytoplankton community thrives a high biodiversity as a result of the difference in organism-specific growth rate, while eutrophication causes change in nutrient concentration with skewed species ratio, inducing variation of community composition and structure, followed by a reduction of biodiversity, providing with opportunity for the blooming of harmful algal species, which in turn modifies the nutrient dynamics (Conley and Johnstone 1995), for example, competition between diatoms and dinoflagellates (Smayda 1997).

The coastal water bodies are crucial component of economic entity for the marine community ranging from fishing, aquaculture, tourism and transportation, etc. Since the eutrophication processes of the receiving coastal water bodies are initiated by the loss of terrestrial nutrients in the watershed into sea, various management options have been exercised to curb the loss of nutrients in the watershed. However, these management options for reduction of nutrient loads from watersheds usually do not yield an immediate changes in the receiving water bodies because of the sustaining efflux from bottom sediments and hysteretic effect (Carpenter et al. 1999).

In 2001–2004, the Natural Science Foundation of China (NSFC) funded a research project: “Watersheds Nutrient Loss and Eutrophication of the Jiaozhou Bay” (Contract No. 40036010). The main objective of the project was to establish the qualitative and quantitative understanding of coastal ecosystem response to the nutrient and other pollutants from the watersheds, and to evaluate benefit and cost in measures of reduction of nutrient loss from the catchment areas on the sustainability of ecosystem health.

Concentrations of nutrients from surface and groundwaters in the watersheds, fluxes of nutrients from atmospheric depositions and across the sediment – water interface, nutrient uptake by dominant phytoplankton species in the water column using mesocosm experiment and laboratory incubations, nutrient dynamics in microbiol-loop together with suspended matter – were measured or determined, and sediment core samples were collected and analyzed to evaluate the history of pollution (e.g., nutrient load) in the Jiaozhou Bay; box and 3-D hybrid water circulation and nutrient transport and primary production models

utilizing field data were constructed to understand the processes of eutrophication (Fig. 1).

In addition to the field observations, data from archrivals and literature have also explored and compared. Particularly, the emphasis was placed on the processes that control the parameters characteristic of regional flux. The sea-based and land-based monitorings delivered data base for process studies and model validation.

2 The Jiaozhou Bay: An Area Under Intensive Human Perturbation Over the Watersheds and Marine Recipients

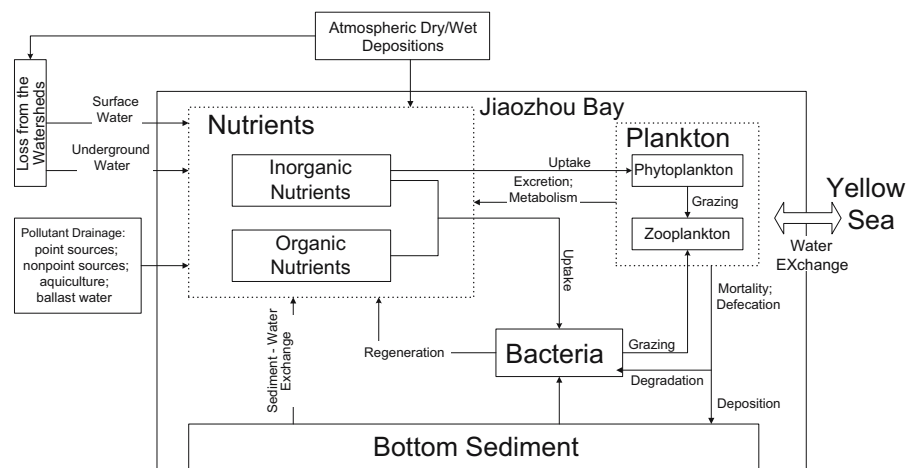
The Jiaozhou Bay is a shallow water body of the Yellow Sea extending 25 km from east to west and 32 km from south to north with surface area of ca. 400 km² (Fig. 2). The average water depth is <10 m, with maximum depth of up to 60–70 m in the eastern part of the Jiaozhou Bay. The watershed of the Jiaozhou Bay consists entirely of the Qingdao urban and suburb regions, with a surface area of ca. 7.5×10^3 km² and a total population of 7–8 million. The Jiaozhou Bay is connected to the Yellow Sea through a channel of 2.5 km in the southeast. The surface runoff in the watersheds of Jiaozhou Bay is composed mostly of seasonal rivers, notably the Baishahe, Daguhe, Moshuihe, Licunhe, and Yanghe, with total fresh water discharge of ca. $0.5\text{--}1.0 \times 10^9$ m³ yr⁻¹ (Fig. 2).

Over the last half century, the Jiaozhou Bay has been affected by the ever increasing anthropogenic perturbations, and it has also been under the influence

of global and/or regional climate changes. For instance, the GDP per capita in Qingdao increased from ¥71 RMB (¥1 RMB=US 1/8\$) in 1949 to $\text{¥}28.2 \times 10^3$ RMB in 2004, and rapid GDP increase occurred after 1980 economic innovation in China (Qingdao Municipal Statistics Bureau 2005). In this period, the regional population increased from ca. 4.1 million in 1949 to 7.3 million in 2004 and the urban population increased from 25.6% in 1949 to 35.3% in 2004 (Fig. 3). Gross regional output increases from $\text{¥}0.38 \times 10^9$ RMB in 1949 to $\text{¥}425.6 \times 10^9$ RMB in 2004 and a rate of growth amounts to 20–40% per year since 1990s (Fig. 4). During the same period, the contribution of the agriculture sector to the total output dropped from 43.3% in 1949 to ca. 5% in 2004 (Fig. 4). The cultivation area was reduced by one-third over the last five decades, i.e. from 657×10^3 ha in 1949 to 423×10^3 ha in 2004, whereas the crop productions increased from 723×10^3 tons yr⁻¹ in 1949 to 2.32×10^6 tons yr⁻¹ in 2004 (Qingdao Municipal Statistics Bureau 2005). The application of chemical fertilizers has increased from 1.9×10^3 tons yr⁻¹ in early the 1950s to 325×10^3 tons yr⁻¹ in 2004, e.g., by 150–200 folds. The fertilizers used in agriculture were largely of composite (43.2%), nitrogen (38.4%), phosphorus (9.4%), and potassium (8.9%) (Fig. 5).

Over the last five decades, the marine sector has been gradually becoming a significant part of the regional economy. For example, the cargo handled in Qingdao was 0.73×10^6 tons in 1949, and reached to 163×10^6 tons in 2004, with the number of containers handled of 5.14×10^6 TEU in 2004 (Qingdao Municipal Statistics Bureau 2005). In 1949, the

Fig. 1 The concept model for the Jiaozhou Bay Project in 2000–2004, which shows the major sources and/or pathways and important pools for nutrients



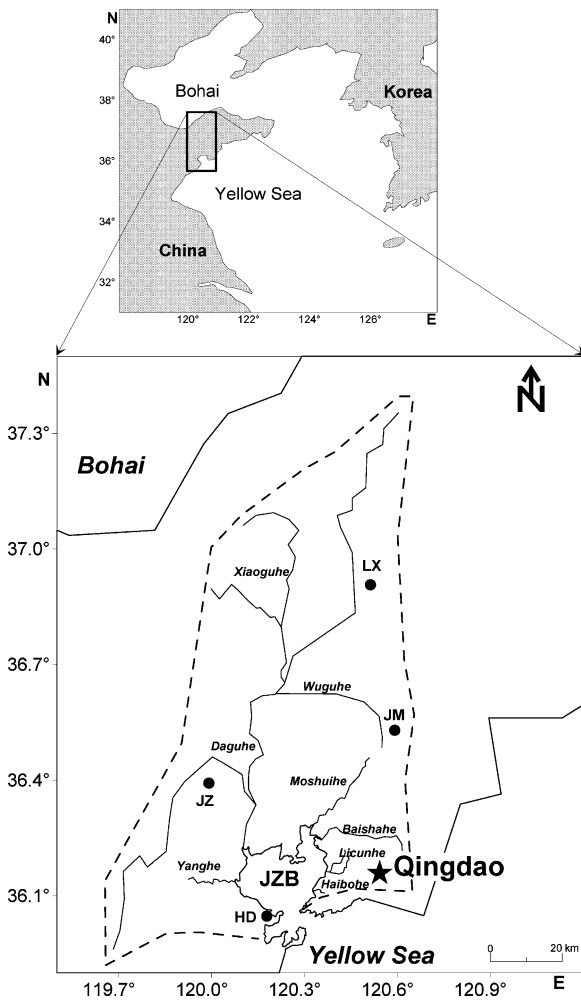


Fig. 2 The study area of the Jiaozhou Bay (JZB) Project shows the catchments for the major rivers, including Yanghe, Daguhe, Moshuihe, Baishahe, Licunhe, and Haibohe. The domestic centers, i.e., Qingdao, Jimo (JM), Laixi (LX), Jiaozhou (JZ), and Huangdao (HD) are also shown

output of farming in the region was $¥0.59 \times 10^9$ RMB and was almost two orders of magnitude that of fishery (i.e., $¥35.0 \times 10^6$ RMB). However, in 2004, the output of fishery from Qingdao was up to $¥5.73 \times 10^9$ RMB and could be comparable to that from farming (Fig. 6).

Economic development innovation, population increase with rapid urbanization and changes in land use have altered the nature and/or induced anthropogenic fluxes of materials from the watersheds to the Jiaozhou Bay. Thus freshwater, sediment, and nutrient inputs from rivers have undergone changes with adverse consequences for the regulatory, social, and economic functions of the adjacent coastal

ecosystems. Examples of anthropogenic impact on the coastal ecosystems include tourism, sewage disposal, illegal fisheries, and overexploitation for resources (e.g., wetlands). Thus, the land-based human activities over the watersheds of the Jiaozhou Bay in the past four to five decades have induced the deterioration of coastal water quality with damage to the ecosystem there. The projected global changes (e.g., change in surface water temperature) also affect many of the physical, biogeochemical, and ecological processes in coastal waters, which can be considered an added stress on an already overstressed environment and will further reduce the ability of coastal systems to provide goods and services. In the Jiaozhou Bay, the total wastewater drainage increased from 0.18×10^9 tons in 1993 to 0.24×10^9 tons in 2004, of which the emission from industrial sector amounted to 35–55% and only ca. 1/3 was processed by waste treatment facilities before being drained off (Fig. 7). The surface area of the Jiaozhou Bay has been reduced by 10–20% over the last 40 years (Yang et al. 2004). Concerning the marine recipients, it was indicated that the bay coastal surface areas used for

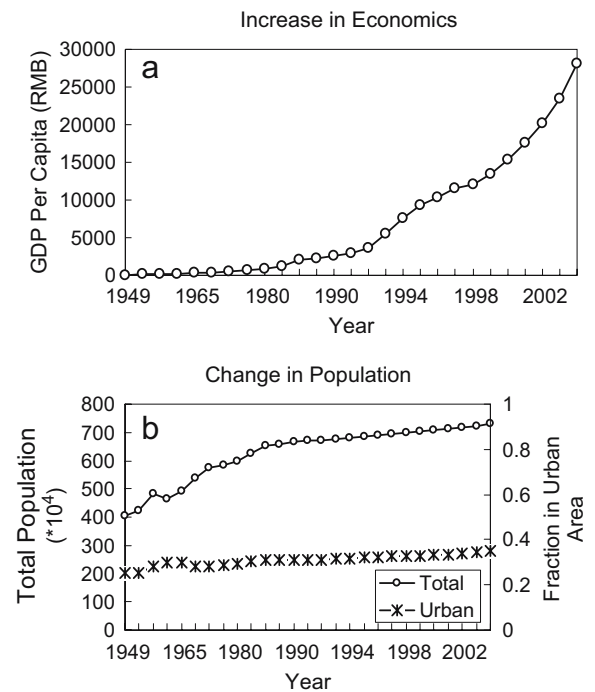


Fig. 3 Data of social reform and economics of Qingdao, which show the GDP per capita in RMB (a) and change in population (b) after 1949 (Data Source: Qingdao Municipal Statistics Bureau 2005)

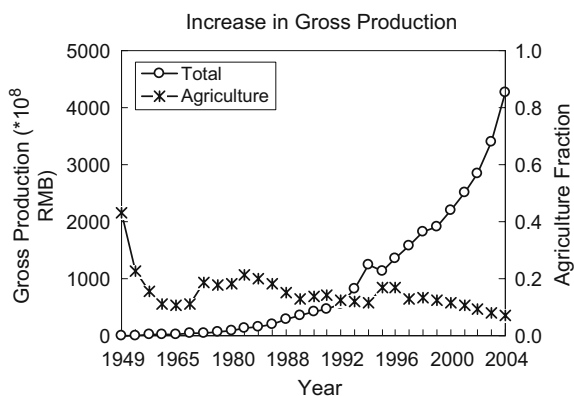


Fig. 4 Data of gross production for the watersheds of the Jiaozhou Bay, which show the rapid increase in gross production and decrease of agriculture after 1949 (data source: Qingdao Municipal Statistics Bureau 2005)

marine culture amounted to 17.5×10^3 ha in 1993 and increased to 44.8×10^3 ha in 2004. From 1994 to 2004, the outputs from marine culture (e.g., fish cage and shrimp pond) of the Jiaozhou Bay has shown a three-fold increase, accounting for 60–70% of total output of fishery in the region (Fig. 8). The

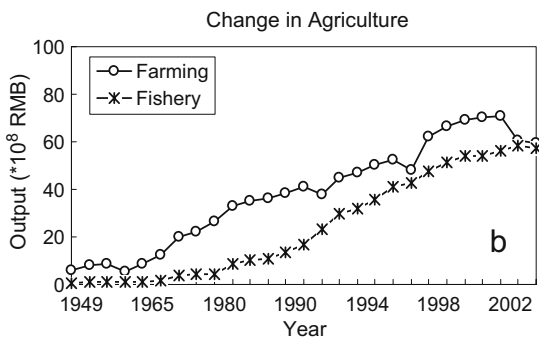
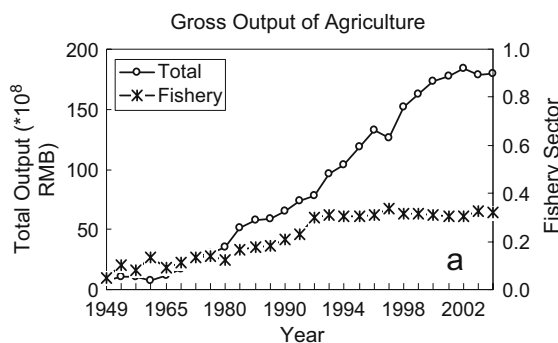


Fig. 6 Change in land use and agricultural practice over the watersheds of the Jiaozhou Bay, which shows the total output from agriculture (a) and comparison between farming and fishery sectors (b)

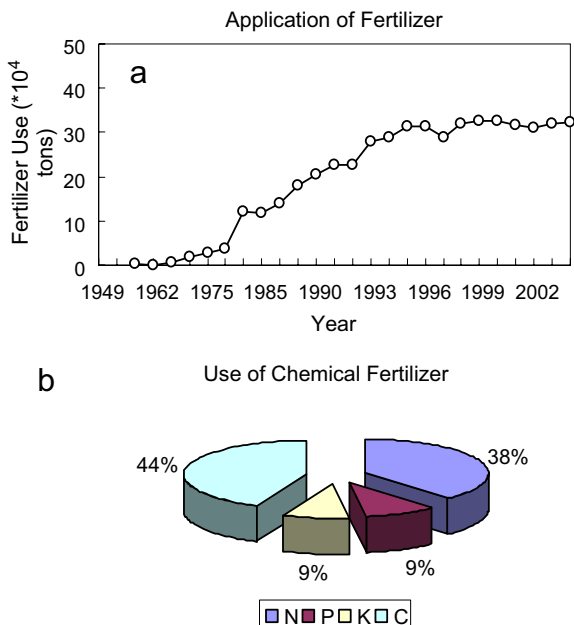


Fig. 5 Application of synthesized fertilizers over the watersheds of the Jiaozhou Bay, which shows an increase in the amount of chemical fertilizer use (a) and proportions (b) by different kinds of fertilizer applications (data source: Qingdao Municipal Statistics Bureau 2005)

production of marine culture of the Jiaozhou Bay comprises breeding of fish (25.7%), crustaceans (9.8%), shell-fish (63.7%), and algae (0.9%), respectively (Fig. 8).

In the recent three decades from 1960s to 1990s, the concentration of phosphate increased by two- to three-folds, whereas concentrations of NO_3^- and NH_4^+

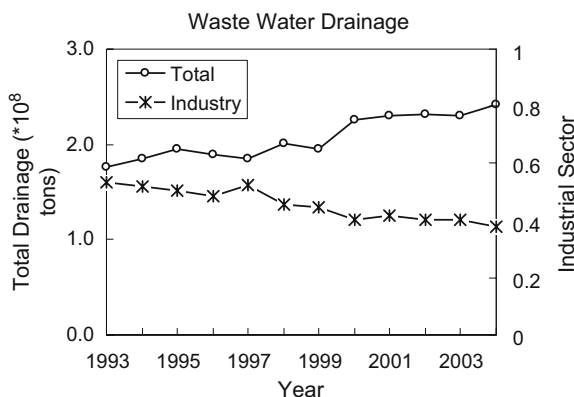


Fig. 7 Change in waste water drainage into the Jiaozhou Bay and proportion by industrial sector since the mid-1990s (data source: Qingdao Municipal Statistics Bureau 2005)

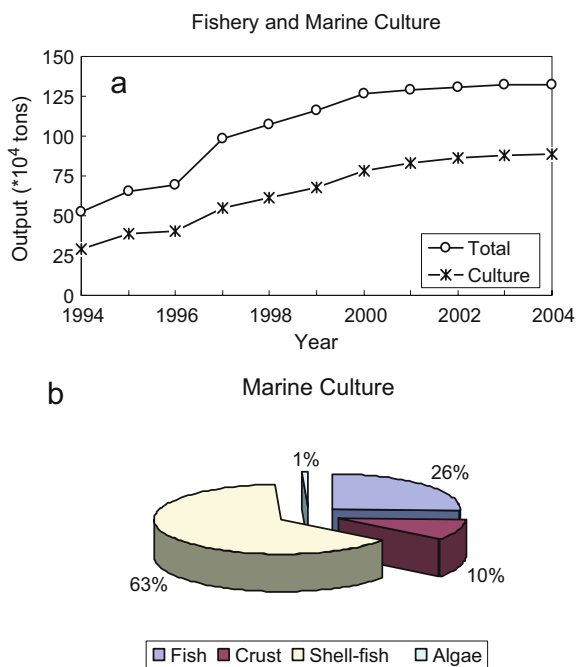


Fig. 8 Comparison of outputs between fishery and marine culture since the mid-1990s (a) and production of different kinds of species in marine culture (b) of the Jiaozhou Bay (data source: Qingdao Municipal Statistics Bureau 2005)

increased by a factor of 7–8 (Shen 2001), i.e., five- to 10-folds higher than the central part of the Yellow Sea. The atomic ratio of DIN/PO_4^{3-} (i.e., $DIN = NO_3^- + NO_2^- + NH_4^+$) increased from 10 to 20 in 1960s to 30 to 40 in the 1990s after extensive nutrient remobilization from watersheds, whereas the Si/DIN ratio drops to ≤ 1.0 after the 1980s, for most of the time Si/DIN of 0.1–0.3 was found in 2001–2004 (Liu et al. 2005b). Moreover, the nutrient flux from rivers into Jiaozhou Bay amounts to $65 \times 10^6 \text{ mol yr}^{-1}$ for DIN, $2.5 \times 10^6 \text{ mol yr}^{-1}$ for PO_4^{3-} , and $60 \times 10^6 \text{ mol yr}^{-1}$ for SiO_3^{2-} , respectively, with higher DIN/PO_4^{3-} and lower DIN/Si ratios in comparison with those natural marine environment (Liu et al. 2005a). Concentration of phosphate increased by two-fold after the 1960s and then remained stable after 1990s; dissolved silicate concentrations varied considerably by a factor of 2–4 and is much lower than that in the Yellow Sea (ca. $10 \mu\text{M}$), although measurements of dissolved silica had been limited (Fig. 9). In the Jiaozhou Bay both NO_3^- and NH_4^+ tend to increase after 1960s, particularly the reduced nitrogen form (e.g., NH_4^+). And concentrations of NH_4^+ and NO_3^- in

2001–2004 can be five to 10-folds higher than those found in 1960s ($\gamma^2 > 0.5 - 0.6$). It was estimated that some 60% of total nitrogen input into the Jiaozhou Bay was accounted for by the erosion from the catchment areas and some 70% of total phosphorus input into the bay could be accounted for by waste water discharge from the land source (Shen 2001; Liu et al. 2005b). The areal yields of nutrients over the watersheds amount to $60\text{--}70 \times 10^3 \text{ mol km}^{-2} \text{ yr}^{-1}$ for DIN, $5\text{--}10 \times 10^3 \text{ mol km}^{-2} \text{ yr}^{-1}$ for phosphorus, and $30\text{--}40 \times 10^3 \text{ mol km}^{-2} \text{ yr}^{-1}$ for dissolved silicates, respectively (Liu et al. 2005b). It should be noted that catastrophic events (e.g., typhoon) can dramatically change the nutrient regimes in the Jiaozhou Bay by bring a huge amount of fresh water as well as nutrients and other pollutants from the watersheds within a rather short period, resulting in algal blooms (Liu et al. 2004). Over last four to five decades, the

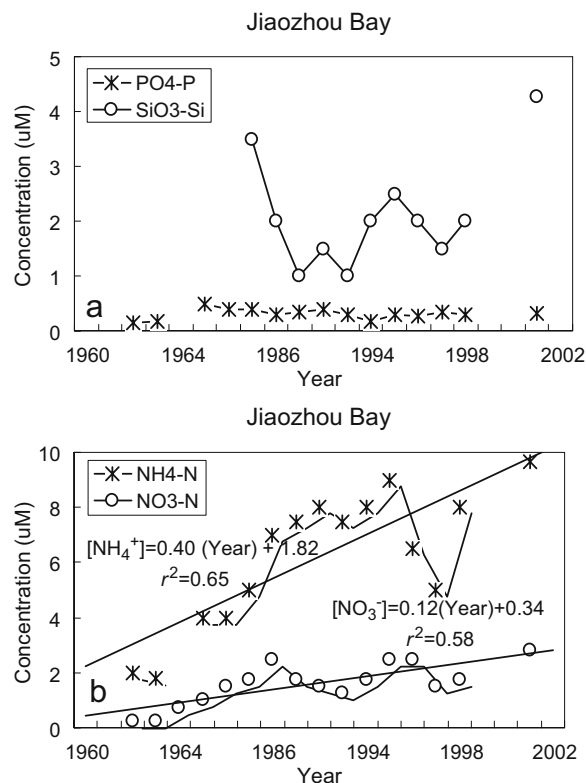


Fig. 9 Historical assessment of the nutrient concentrations in the Jiaozhou Bay after 1960s, which shows the low but varying concentrations for phosphate and dissolved silicate (a), concentrations of nitrate and ammonia increase after 1960s (b), although the data are scattered. Data are from Shen (2001), Liu et al. (2005b), and unpublished measurements

primary producers have been gradually shifted to the non-Si demanding species because of limited availability of silicate in the surface waters of the Jiaozhou Bay (cf. Yang et al. 2002). Diatoms were traditionally the major component of net phytoplankton (e.g., $>50\ \mu\text{m}$), but the dominance of diatoms has dramatically decreased in the last 40–50 years (Shen 2001), while the nano- and pico-phytoplankton become dominant. Moreover, primary productivity and net phytoplankton biomass have been reduced in recent decades, with an increase of ratio between net and nano- and pico-phytoplankton.

3 Major Findings of the Jiaozhou Bay Project

Through the Jiaozhou Bay Project the watershed and marine recipients were characterized comprehensively in terms of watershed climatology including hydrology, bay water biology, and nutrient dynamics. These data sets served to develop box and numerical models for hydrographic and nutrient dynamics (e.g., eutrophication) coupled with phytoplankton ecology for the bay. Further, these models were used to assess the health of the bay ecosystem against the anthropogenic perturbations from both land and coastal-based activities. Some of major findings are compiled here.

3.1 Circulation and Nutrient Budgets

The Jiaozhou Bay is of semi-diurnal tide with an average tidal range of 2.7–3.0 m with a maximum of 5.1 m. The tidal current at spring tide can be $2\text{--}3\ \text{m s}^{-1}$ at the bay mouth and the residual current is $\leq 20\ \text{cm s}^{-1}$ in the Jiaozhou Bay. The water residence time varies from $<5\text{--}10$ days in the mouth to ~ 100 days at the head of the Jiaozhou Bay (Liu et al. 2004). The different residence time of water leads to the strong spatial gradient in nutrient concentration in the bay with high and low in the head and mouth, respectively. Stratification of water column is generally weak owing to a strong tidal current.

Seasonal variation in nutrient concentrations in the Jiaozhou Bay is forced by fluvial influx and exchange with Yellow Sea, and to less extent by phytoplankton uptake. Nutrients are depleted in the spring due to phytoplankton uptake and enriched throughout the rest of the year (Liu et al. 2007e). However, advective transport of tidal current regulates the nutrient

concentration in the bay on time scales from hours to days. The input from the river has decreased over recent decades owing to exhaustive consumption of water resources and damming over the watersheds. Atmospheric nutrients deposition has gained an increasing importance against riverine input. Overall primary production in the Jiaozhou Bay shows a character of silicate limitation, followed by phosphorus, whereas nitrogen in the water column has been increased over the last several decades (Liu et al. 2007d). The budgetary calculation of nutrients reveals that Jiaozhou Bay is an autotrophic system.

3.2 Trace Elements (As and Al) and Gas Species (CH_4 and N_2O)

Relative low concentrations of trace elements (e.g., As) occur in the Jiaozhou Bay as compared to other urban coastal waters in the world. Dissolved trace elements appeared to be controlled by the exchange with the Yellow Sea, followed by the riverine input and atmospheric deposition, whereas contributions from groundwater and sewage drainage are of minor importance (Ren et al. 2007).

As for the trace gas species (e.g., CH_4), their profiles in the water column show the signature of tidal rhythm with significant seasonal variations. Among the various land-source inputs, riverine influx is dominant over the groundwater discharge. Jiaozhou Bay acts as a source of CH_4 and other gas species to the atmosphere (Zhang et al. 2007).

3.3 Biomass of Phytoplankton and Microbes

The community structure of macro-algae reflects the nutrient gradients across the Jiaozhou Bay. The slow-growing macro-algae are dominant in low nutrient concentrations toward the mouth and fast-growing opportunistic species in high-nutrient waters toward the head of the Jiaozhou Bay. Short-lived, opportunistic, and filamentous algae have rather high nutrient uptake rates, which is related to their thin morphology and higher relative surface areas (Liu et al. 2007a).

In the Jiaozhou Bay, heterotrophic bacterio-plankton competes with phytoplankton for available nutrients, particularly in summer. The turnover time of DIN is longer than that of DIP by heterotrophic bacterio-plankton in the Jiaozhou Bay, which leads to phosphate limitation (Bai et al. 2007).

3.4 Submarine Groundwater Discharge

The Baishahe represents the largest source of groundwater among the sub-aquifers from the watersheds of the Jiaozhou Bay, e.g., the Baisha Aquifer discharges 8–15 times as much water and 35–400 times as much NO_3^- compared to the Yang Aquifer.

The regime of groundwater discharge into the Jiaozhou Bay has dramatically changed over last three to four decades, owing to the hydrographic engineering and overexploration of water resources over the drainage basin (Liu et al. 2007b). Although the concentration of nutrients in the groundwaters has been shown to increase after 1970s, the nutrient input into the Jiaozhou Bay becomes less owing to reduction of water flow.

3.5 Sediment Records

Sediment core samples revealed that sediment deposition rate was of 0.6–0.7 cm yr⁻¹ in the Jiaozhou Bay. Based on the profiles of radio nuclides of ²³⁸U, ²³⁴Th, ²²⁸Th, ²²⁶Ra, ²²⁸Ra, ¹³⁷Cs, ²¹⁰Pb, and ⁴⁰K, it is indicated that bioturbation and storm-induced resuspension affect surface of a few centimeters of sediments with apparent mixing coefficient of 35–55 cm² yr⁻¹. And ¹³⁷Cs reveals the records of pollution by nuclear tests with the maximum in the mid-1960s (i.e., 1963–1964) and later in the 1980s (i.e., 1986) for Chernobyl Nuclear Power Plant Accident in the former Soviet Union (Liu et al. 2007c).

4 Summary and Prospective

The NSFC Jiaozhou Bay Project is, albeit all its remaining deficits, a new approach toward a holistic analysis of the Jiaozhou Bay Ecosystem. For the first time, investigations have been carried out simultaneously for physics, chemistry, biology, and sedimentary dynamics for understanding eutrophication in the Jiaozhou Bay. Furthermore, model simulations of the water circulation, nutrient transport, and primary production has been incorporated in the design of field work and evolved in parallel to the observations. The water circulation and corresponding transport of dissolved and particulate materials (e.g., total

suspended matter) are mainly tidal-driven, contribution by density gradients caused by heat and salt fluxes is negligible. The hydrographic and chemical properties are dominated by the seasonal changes under monsoon climate, but there are also strong inter-annual and decadal signatures corresponding to El-Nino and PDO. Hence, the field experiments should be taken as the realization of stochastic processes.

The model simulation and output are generally in agreement with observational data from Jiaozhou Bay, the effect on the ecosystem of the Yellow Sea Proper through water exchange can be evaluated. Since tidal residuals are rather small despite strong tidal currents, the export of nutrients and other dissolved and particulate materials from Jiaozhou Bay to the Yellow Sea is relatively limited compared to other coastal areas of China. Eutrophication of Jiaozhou Bay is characterized by silicate and phosphate limitations in terms of primary production owing to extensive nitrogen species input from land-sources (i.e., biogeochemical domain) and relative low bio-mass compared to other eutrophic coastal areas of China (i.e., water exchange domain). And eutrophic, polluted waters and sediments remain for the extended period of time within the bay. The substances released from land via river and sewage facility are retained close to the coast.

In summary, the project was initiated with hope to bridge the outcome of scientific research to the environmental protection measures. The circulation model allows reliable scenario calculation and diagnostic analysis to understand the response of ecosystem in the Jiaozhou Bay to the external forcing (e.g., change in land-source input). However, from the prospective of understanding biogeochemical processes, more field data are necessary if the simulation will be undertaken on temporal scales up to decades, particularly when the food web structure and function in the pelagic and benthic domains are concerned, because the water is rather shallow in the Jiaozhou Bay. Aside from long-term monitoring that is often difficult in China, carefully designed experiments to examine relationships of multi-parameters are needed for the identification of major processes related to eutrophication that allows quantification of anthropogenic perturbation entangled within changing climate, which is challenge in coastal oceanography. Hence, the future campaigns require to be accompanied by high-resolution remote sensing in spatial and temporal

scales and modeling of coastal environment with incorporation of atmosphere in a nested frame.

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