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The fate of phosphorus in the Yangtze (Changjiang) Estuary, China, under multi-stressors: Hindsight and forecast

Hao Xu [a, b], Alice Newton [c, d], Eric Wolanski [e, f], Zhongyuan Chen [a, *]

[a] State Key Laboratory of Estuarine and Coastal Research, Shanghai 200062, China
[b] Department of Urbanscience, Ningbo University, Ningbo 315211, China
[c] NILU-IMPEC, Box 100, 2027 Kjeller, Norway
[d] CIMA, Gambelas Campus, University of Algarve, Faro 8005-136, Portugal
[e] School of Marine and Tropical Biology, James Cook University, Townsville, Queensland 4811, Australia
[f] Australian Institute of Marine Science, PMB No. 3, Townsville MC, Queensland 4810, Australia

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ABSTRACT

The present study provides evidence that large dams that trap riverine sediment, decrease significantly SPM within estuaries, making them less turbid and less of a particulate trap for phosphorus adsorption. The study gives science-based insights for a future integrated estuarine water management in the Yangtze (Changjiang) Estuary. The hindsight focuses on the evolution and fate of riverine dissolved inorganic phosphorus (DIP) in the Yangtze Estuary from 1999 to 2010. A significant correlation between phosphorus and suspended particulate matter (SPM) was established. This shows that, in the past decade, the estuary has changed from being a source of DIP to being a sink, and from a heterotrophic system to an autotrophic system. The ecosystem shift may be explained by the combined impact of the construction of dams that retain SPM but not nutrients, and to increasing nutrient fluxes to the estuary due to increasing usage of fertilizer and sewage. The foresight study is based on likely future scenarios for 2050. These are estimated using historical data and the stratified and a muddy-LOICZ model, which takes stratification and adsorption–desorption of phosphorus into account. We forecast that in 2050 the effective DIP inflow into the Yangtze Estuary will increase by a factor of 1.5 if the SPM remains at the current annual average of 700 mg L^{-1}, and by a factor of 3.3 if the SPM decreases to 200 mg L^{-1} as a result of the dams, which will further degrade the estuary.

1. Introduction

The supply of nutrients is an especially important factor for healthy estuarine ecosystems (Anderson et al., 2002). The molar proportions of N:P:Si has often been used for an assessment of estuarine health (Glibert et al., 2012). Overloading of nutrients, primarily nitrogen and phosphorus, has caused eutrophication worldwide in estuaries (Bricker et al., 1999; Cloern, 2001). In the past 100 years, anthropogenic inputs of nitrogen and phosphorus have increased dramatically in many mega-estuaries, such as the Yangtze, the Mississippi and the Nile (Goolsby et al., 1999; Ludwig et al., 2009; Xu et al., 2013a, b). The high nutrient pressures combined with the physical structure of the water column (high freshwater discharge, wind mixing, regional circulation, and summer warming controls, etc.), enhance primary production (Howarth, 1988) and can lead to HABs (harmful algal blooms) in the estuarine waters.

The Yangtze Estuary (Fig. 1A) is one of the most urbanized coastal regions of China. In 2014, there were approx. 80 million residents on the coast, including the 24 million official residents of Shanghai. The estuarine environment has significantly deteriorated in recent decades (Wang, 2006). The frequency of occurrence of algal blooms has increased with each decade since 1970. There were 2 HABs in the 1970s, 9 in the 1980s, 33 in the 1990s and 126 from 2000 to 2010 (Liu et al., 2013). The increase of N and P comes from fertilizer, sewage (domestic and industrial), and manure from livestock in the river basin (Xu et al., 2013a). The silicon cycle is much slower than the nitrogen and phosphorus cycles, due to its geo-bio-weathering processes (Turner et al., 2003). Damming in the basin and blooms of freshwater diatoms results in silicon retention in the reservoirs (Triplett et al., 2012), thus decreasing the silicon flux to the estuary (Li et al., 2007). The ratio of N: P: Si in the Yangtze Estuary was about 43:1:50 in 2006 (Chai et al., 2009). A

* Corresponding author.
E-mail address: z.chen@sklec.ecnu.edu.cn (Z. Chen).

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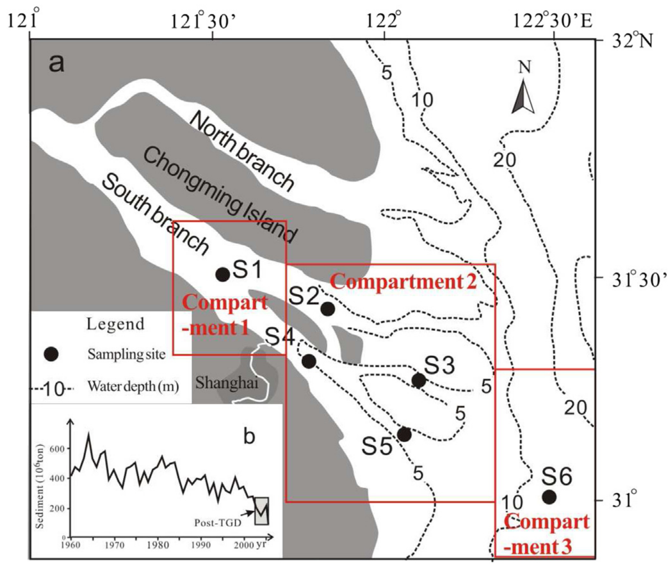

Fig. 1. a) The Yangtze Estuary, showing the survey sites and water boxes for LOICZ model. Three compartments were also defined for the model requirement. b) Lowering sediment flux into the river mouth since 1960's due to dam construction, including the TGD (complete in 2003).

comparison with the Redfield ratio (Redfield et al., 1963) indicates that there is an excess of N with respect to P and Si. Phosphorus bioavailability is the likely limiting nutrient determining the ecosystem productivity.

Phosphorus in estuarine waters mainly participates in two processes. The first is the adsorption–desorption processes with suspended particulate matter (SPM) (Froelich, 1988; Stumm, 1992; Tessier and Turner, 1995). Dissolved inorganic phosphorus (DIP) is available for uptake by microorganisms (Taft et al., 1975) both heterotrophic and autotrophic. A decrease in SPM therefore increases the proportion of bioavailable DIP; it also decreases turbidity and thus light-limitation of photosynthesis (Jones and Wills, 1956).

The construction of dams in the Yangtze basin, especially the Three Gorges dam completed in 2003, decreased the SPM load to the estuary from nearly 480 Mt a^{-1} in the 1950s to <150 Mt a^{-1} presently (Fig. 1b) (Chen et al., 2010). This represents a SPM decrease in the estuary of about 20–30% from 2000 to 2010 (Li, 2012). The construction of dams will continue during the next few decades (Chen et al., 2010). On the other hand, nutrients fluxes into the estuary have increased 5–7 folds with respect to previous decades (Xu et al., 2013a) because of the increased application of fertilizers and increased fluxes of sewage.

The forecast is therefore for an increase of nutrients fluxes from the catchment simultaneous with a decrease in SPM in the estuary. To predict the resulting impact, the present study investigates: (i) phosphorus bioavailability from field studies; (ii) the relationship between phosphorus bioavailability and the trophic status of the estuary, using the stratified muddy-LOICZ model modified after Swaney et al. (2011), and (iii) the effect over the last 10 years and for the next 40 years of dams and increased nutrient discharge.

2. Methods and database

2.1. Field studies

A survey of the estuary in December, 2012 included six sites (S1–S6 in Fig. 1) selected to fulfill the nutrient budget requirements of the muddy-LOICZ model (Swaney et al., 2011; Xu et al., 2013b). The sites belonged to three compartments: S1 representing the riverine system, S2–S5 representing the estuarine system, and S6 representing the marine system. Water samples were taken about every 4 h during 26 h (a tidal cycle). Samples at three depths (surface, mid-water column and bottom), were collected at stations S1–S5. The water depth of station S6 was deeper, therefore samples were taken at 6 depths, at the surface, at fractions (0.2, 0.4, 0.6, 0.8) of the water column depth, and at the bottom. A total of 150 samples were collected.

Water samples (500 ml) were fixed with 1 ml mercury chloride (1 mol L^{-1}) and transported to the laboratory in dark glass bottles, below 10 °C. The DIP samples were filtered into individual bottles through a 0.45 μm filter (25 mm Whatman GFF). The samples were analysed in triplicate for SPM, salinity, DIP (dissolved inorganic phosphorus), DIN (dissolved inorganic nitrogen), and TIP (total inorganic phosphorus) following the methods in the Chinese National Standards for Marine Surveys (GB12763.4–2007). The ratio DIP/TIP was correlated to SPM.

2.2. Other data sources

Daily river discharge data were collected from the Datong gauging station (http://yu-zhu.vicp.net/). Two week average discharges were calculated prior to the date of the on-site survey, since a discharge takes about 7 days to reach the estuary. The sewage data came from the National Bureau of Statistics of China, (http://www.stats.gov.cn/tjsj/ndsj/). DIP and DIN data from 1999 to 2007 in the estuary were obtained from past studies (Shen, 2001; Meng et al., 2004; Yang and Wang, 2008; Wang, 2012; Zhang, 2012). DIP and DIN concentrations for 2050 were predicted by the method of Xu et al. (2013a).

2.3. Stratified muddy-LOICZ model

The stratified muddy-LOICZ model was used because a saltwater wedge occurs in the estuary and because the estuary is highly turbid (Shen, 2001). This model considers the two layers of the salt wedge, which enables the calculation of DIP and DIN fluxes (Xu et al., 2013b) between the different compartments of the estuary, the freshwater reach, the saline reach, and the coastal sea (Fig. 1). Both the estuary and coastal sea compartments were divided into a surface layer and a deep layer (Fig. 2a), and these were called the Surface Estuary (SE), the Deep Estuary (DE), the Surface Sea (SS) and the Deep Sea (DS).

The water and salinity balances can be determined in both SE and DE in order to calculate the fluxes between the compartments. These are V_r (river flow rate), V_{se} (sewage inflow into Surface Estuary), V_Z (turbulent mixing flux between SE and DE), V_{ent} (water inflow from DE to SE), V_{deep} (inflow from DS to DE), V_s (outflow from SE to SS),V_e and V_p (water fluxes due to evaporation from and precipitation in the estuary, respectively).

The equations governing the system are:

(a) water balance in the surface layer (left = inflow; right = outflow);

$$V_q + V_{deep} = V_s \tag{1}$$

where V_q is the sum of V_r, V_e, V_p and V_{se},

(b) water balance in the deep layer (left = inflow; right = outflow);