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Nutrient enrichment and N:P ratio decline in a coastal bay–river system in southeast China: The need for a dual nutrient (N and P) management strategy

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ABSTRACT

Eutrophication and harmful algal blooms (HAB) have become the primary water quality concerns in China. A comprehensive analysis was conducted using a dataset obtained from long-term monitoring of a coastal bay–river system in southeast China (Xiamen Bay–Jiulong River Basin), to examine the nutrient [nitrogen (N) and phosphorus (P)] dynamics and the management options. The analysis showed that increasing human stresses and external nutrient loads over the past 30 years were the main causes of water degradation and eutrophication. A significant decline of N:P ratio was observed in both river and estuarine waters since the 1990s due to relatively high P loadings as a consequence of waste discharges from the proliferating husbandry of livestocks and the application of excessive phosphate fertilizers to cash crops. Continued nutrient enrichment and the decline of N:P ratio have changed the nutrient stoichiometry and supply ratio in waters, which have increased the risk of nutrient-enhanced algal bloom. According to the findings and current knowledge concerning eutrophication and HAB processes, a dual nutrient (N and P) management strategy is necessary for management of water quality in the Xiamen Bay–Jiulong River Basin with a focus on animal wastes in the north Jiulong tributary and over-fertilization in the west Jiulong tributary.

1. Introduction

Eutrophication has become the primary water quality concerns for most freshwater, coastal marine and transitional waters (Smith and Schindler, 2009; Zaldivar et al., 2008). They threaten the use of the rivers, lakes, and reservoirs for provision of drinking water, fish farming, inland fisheries and ecotourism development. They also threaten estuaries, bays and seas resulting in fish kills, loss of biodiversity and other recreational services. Nutrient enrichment is the most common cause (not the only one) of eutrophication (Nixon, 2009) and subsequent harmful algal blooms (HAB) (Anderson et al., 2002; Heisler et al., 2008), hypoxic and anoxic conditions in bays and coastal seas (Scavia and Bricker, 2006). The increased nutrient loading from lands has led to the spread of so-called "dead zones", namely, hypoxic (low-oxygen) areas, in coastal seas (Diaz and Rosenberg, 2008), although dead zones can also be induced through physico-chemical changes due to heavy storm-water discharges, flooding, drought, and elevated temperature (Paerl, 2006; Russell and Connell, 2009).

Nitrogen (N) and phosphorus (P) are the key nutrients limiting eutrophication and HAB. The N:P ratio can serve as an index that represents the nutrient limitation for algal growth when compared with the average composition of nutrients assimilated in algae (C_{106}:N_{16}:P_1) as the so-called Redfield ratio (Fujimoto et al., 1997). Early experimental research established that a high concentration of P and a low N:P supply ratio ($<$29:1) are favorable for the production of cyanobacteria blooms (Smith, 1983). Cyanobacteria are able to compete for N better than other phytoplankton species when N is scarce. Therefore, when excessive P loading creates a surplus supply of P, N becomes relatively scarce, creating an opportunity for cyanobacteria to dominate the phytoplankton community. Hodgkiss and Ho (1997) suggested that nutrient ratios such as N:P and Si:P are far more important regulators of algal bloom, and the growth of most red tide causative organisms in

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Hong Kong coastal water is optimized at a low N:P (atomic) ratio of between 6 and 15. The N:P ratio in lentic systems has been used as a key indicator in predicting algal biomass and compositions and the seasonal succession (Kilham, 1990). Although the significance of N:P ratio as a trigger to HAB is remain debatable due to variability in other characteristics such as water residence times and relative light within a geographic region (Painting et al., 2007), the nutrients ratio presents a useful indicator for managing eutrophication in an aquatic environment.

Numerous studies suggest that managing the level of P concentration in freshwater and N inputs in coastal water are critical to maintaining desirable water quality (Schindler, 2006; Smith, 2006). However, Paerl (2009) argued that dual nutrient (N and P) reductions are essential to control eutrophication along the freshwater–marine continuum. A central question facing water researchers and managers is how to control the level of nutrient concentration and stoichiometric ratio in an efficient way that will facilitate the recovery of degraded ecosystems. Therefore, scientific understanding and assessment of nutrient sources, fluxes and dynamic characteristics are fundamental to identifying suitable management interventions aimed at abating nutrient pollution and eutrophication problems in a specific coastal ecosystem. A number of overview analyses regarding eutrophication assessment and management options have been carried out in developed areas (Andersen et al., 2011; Bricker et al., 2008; Ferreira et al., 2011; McQuatters-Gollop et al., 2009). Niemi et al. (2004) emphasizes the need for improvements in understanding of stress–response relationships, contributions of multiple stressors, assessments over different spatial and temporal scales, and reference conditions in coastal waters. Less comprehensive analysis has been addressing coastal eutrophication in China due to a lack of long-term monitoring data (Xu et al., 2010). Since the 1990s, following China's open and reform policy initiative, the Xiamen Bay and Jiulong River Basin have experienced substantial water quality degradation and eutrophication problems as a consequence of increasing population growth, rapid agriculture development and urbanization (Hong et al., 1999; Li et al., 2011). Based on previous quantitative studies of N sources and exports in the Jiulong River Basin (Cao et al., 2005; Chen et al., 2008), the authors examined the impacts of economic development of the area on nutrient dynamics from river to bay. Specific objectives of the study were: (1) to investigate the nutrient dynamics in terms of concentrations and N:P ratio and associated economic activities over the past 30 years; (2) to clarify the relationship between nutrient dynamics and HAB proliferation; and (3) to propose management options based on the findings and current knowledge.

2. Materials and methods

2.1. Description of the study area

Jiulong River, the second largest river in Fujian Province, is located in southeast China (Fig. 1), with a drainage area of 14,740 km^2. The Jiulong River is mainly formed by the confluence of two major tributaries (North Jiulong tributary and West Jiulong tributary) and discharges about 12.4 billion m^3/yr of water into the Xiamen Bay through the estuary. The Jiulong River Basin has a population of 3.5 million residents in six counties and two cities (Longyan and Zhangzhou). Xiamen, one of the five special economic zones established in China in 1980, had an annual gross domestic product (GDP) growth rate of 18 percent for the last two decades and a population of 2.52 million in 2009. The Jiulong River Basin and Xiamen area cover only 13.4 percent of land area but contributes more than 25 percent of the GDP of Fujian Province. The hydrographical setting determines that Xiamen Bay receives wastewaters from both the Jiulong River Basin and its adjacent coastal areas (Fig. 1).

2.2. Data collection and analysis

A comprehensive database was developed from various sources (e.g., monitoring data, research reports, statistical yearbooks and publications). Time series data were gathered from eight counties/cities within the Jiulong River Basin and Xiamen City covering 1980–2009. Annual mean dissolved inorganic nitrogen (DIN) concentrations at stations N11 and W6 and flow rates at stations PN and ZD (Fig. 1) were used to calculate the watershed N export to estuary and Xiamen Bay. Anthropogenic nutrient (N and P) loadings originating from sewage, animal wastes and agricultural runoff were estimated on an annual basis using statistical data for population, livestocks, and fertilizers and relevant emission coefficients (Table 1). Data preparation, calculation and statistical analyses were performed using the software Microsoft Office Excel, Statistical Package for the Social Sciences (SPSS) and Trend/Change detection software.

3. Results

3.1. Nutrient (N and P) concentrations have increased over the past 30 years

In the Jiulong River Basin, economic activities (e.g., crops planting, animal husbandry, and associated land use changes and soil erosion) contribute to significant leaching and runoff of nutrients from land and their subsequent export downstream. Temporal data on population growth, GDP, fertilizers and animal husbandry (pig farming) showed that the aquatic environment is under increasing threat from human stresses (Fig. 2). The quantity of fertilizer consumption and the number of pig farms have increased three- to seven-fold over the last 30 years. Although industrial wastewater and animal manure were partly treated mainly for reduction of chemical oxygen demand (COD) in Zhangzhou, Longyan, and Xiamen City, the amount of nutrient discharged to water bodies continued to increase. Similarly, DIN concentration in both the North and West Jiulong tributaries increased significantly ($\alpha = 0.01$) since the 1980s (Fig. 3).

3.2. N:P ratio in the river has declined due to up-scaling of animal husbandry and over-fertilization of land crops

A significant decline of N/P values was observed recently in two tributaries of the Jiulong River although the overall nutrient concentrations were generally elevated (Fig. 4). Water quality measurements at stations N7 and W4 (Fig. 1) reflected the pollution load in the upper North tributary area covering Longyan City and Zhangping County and the upper West tributary area covering Pinghe County and Nanjing County. The total pollutant load from the three main sources (i.e., animal wastes, domestic wastes, and agricultural runoff) for the areas around the two tributaries has indeed increased (Fig. 5a and b). However, the N:P ratio in terms of load has in fact decreased over time (Fig. 5c). The observed decline of N:P ratio in stream waters is attributed to the relatively high P concentration in the excreta of piggery wastes (Table 1) generated from the proliferation of pig farming in the upper North tributary area since the 1990s, as well as the significant increase of phosphate fertilizers over nitrogenous fertilizers (Fig. 2) applied to cash crops in the upper West tributary area.

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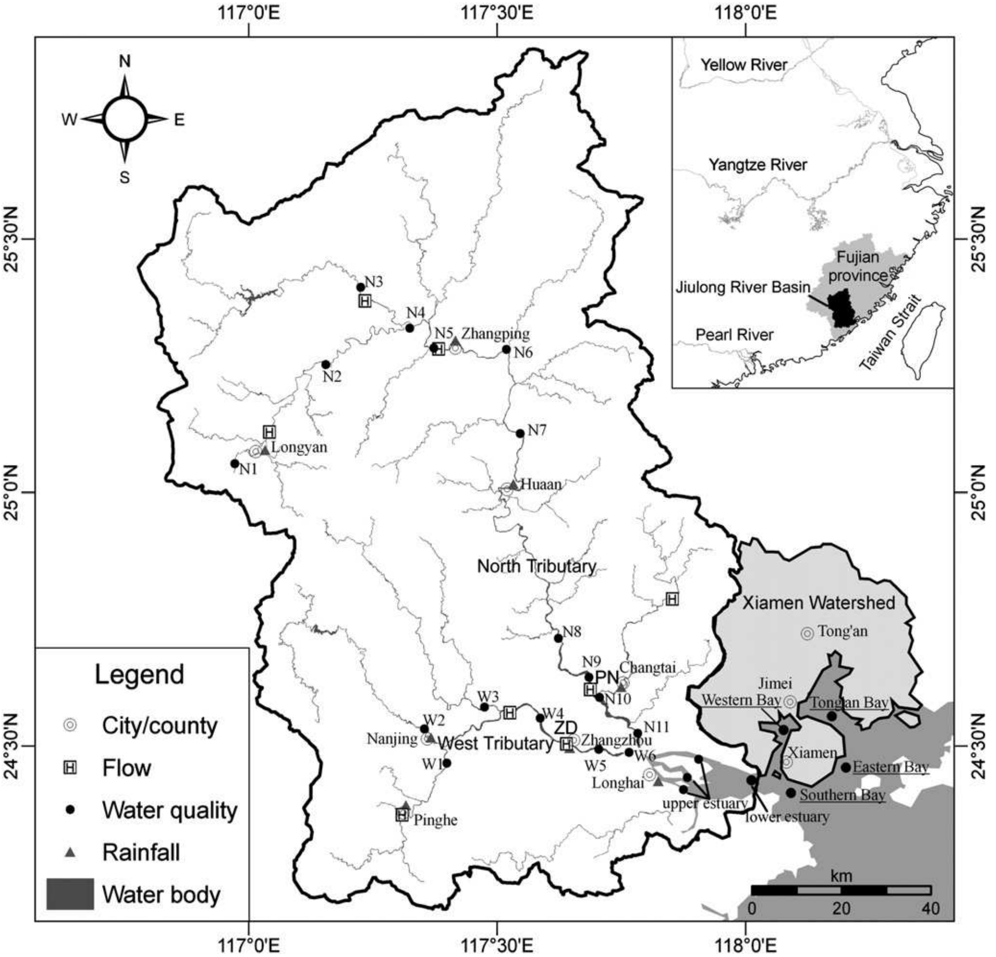

Fig. 1. Map of the Jiulong River Basin and Xiamen Bay area (N and W are sampling stations in two main tributaries, with stations located in Xiamen estuary and Bay shown as black dot; PN and ZD are national gauge stations set up for discharge measurement).

3.3. Changing nutrient stoichiometry could trigger HAB proliferation

Xiamen Bay has experienced nutrient-enhanced eutrophication and HAB since the mid-1990s (Fig. 6a). The synchronous pattern between HAB occurrences and water DIN levels at various sites of Xiamen Bay indicated that nutrient enrichment was the important basis of algal blooms events. Furthermore, the findings showed that the declining N/P value in the river has resulted in a significant shift in nutrient supply ratios [DIN:DRP (dissolved reactive phosphorus)] in estuarine water (Fig. 6b), which demonstrated close correlation with the frequent widespread occurrence of algal blooms in Xiamen Bay in recent years. Another analysis shows that the DIN:DRP ratio in the western Xiamen Bay decreased from 64 in the late 1980s to 45 in the 1990s and 24 in the 2000s (Zhang and Lin, 2008). Those river-dominated coastal ecosystems are likely to favor phytoplankton blooms, which may be associated with stoichiometric nutrient balance (close to Redfield ratio), due to decreasing potential for nitrogen and phosphorus limitation (Justic et al., 1995). Nutrient balance changes (increased N, P but decreased Si) in Changjiang River Estuary have been linked to the increase in frequency of HAB caused by dinoflagellates (Li et al., 2010; Wang et al., 2008). Yan et al. (2012) compared recent observations with historical data sets from 1980s to 1990s and suggested that concentrations of nitrate and phosphate increased 2–3 times in upper/middle areas of the Jiulong River Estuary, while dissolved Si remained at the same level. Although it is not possible to simply link the increase in red tides in Xiamen Bay to the nutrient variation (change in concentration and ratio) since other factors might be involved (Paerl, 2006; Smayda, 2008). According to current knowledge, as discussed in the introductory section, the shift in nutrient supply ratio would add risk of HAB proliferation in aquatic systems.

4. Discussion and conclusion

4.1. Key pollution source

The results showed that DIN levels in Xiamen Bay are closely correlated with watershed N export (Fig. 7), as the Jiulong River

Table 1
Emission coefficients for estimating nutrient load.

Items	TN (kg/capita/yr)	TP (kg/capita/yr)	TN:TP (mass)	Reference
Pig manure	2.34	1.36	1.7	SEPA, 2002
Pig urine	2.17	0.34	6.4	SEPA, 2002
Cattle manure	31.9	8.61	3.7	SEPA, 2002
Cattle urine	29.2	1.46	20.0	SEPA, 2002
Sheep excreta	2.28	0.45	5.1	SEPA, 2002
Poultry excreta	0.275	0.115	2.4	SEPA, 2002
Human sewage	11.6	0.95	12.2	OCPSC, 2008

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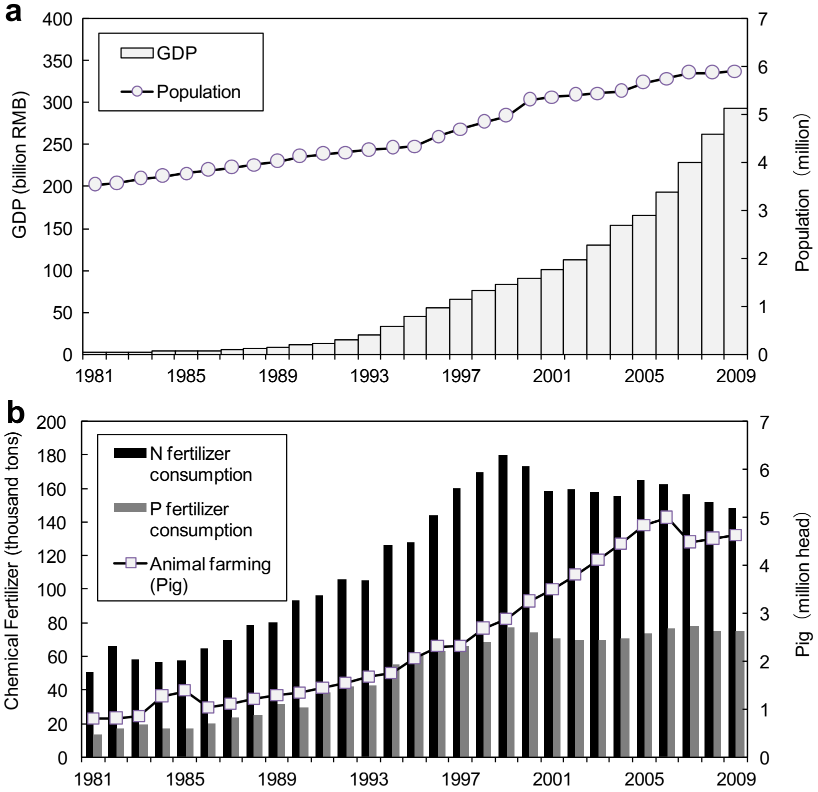

Fig. 2. Human stresses on the Jiulong River Basin and Xiamen Bay area (1981–2009). (a) Population and GDP growth; (b) N and P fertilizer consumption and animal farming.

input contributed to more than 70% of total nutrient loading in Xiamen Bay (Fig. 8). Management of water quality in Xiamen Bay will not be effective without addressing the pollutant loadings from the adjacent Jiulong River Basin.

China's economic boom in recent decades has stimulated consumer demand for animal products and consequently, a vast expansion in animal production and environmental challenge (Wang et al., 2010). Manure discharges from the growing animal husbandry industry in the Jiulong River Basin are a serious pollution concern because of the absence of efficient treatment systems for animal wastes. Raising livestock is currently a major income generation for local residents. Although animal manure was traditionally used as fertilizer for crop production, high transportation costs and the availability of relatively inexpensive synthetic fertilizers have rendered the use of manure as a fertilizer as uneconomical. More effective and less pollutive methods for treating animal wastes have become an urgent need (NRC, 2000), such as biogas approach through manure decomposition (Bond and Templeton, 2011). There is also a need to develop market-based policies to provide incentives to encourage farmers to use animal manure as a fertilizer. The pollution risk of land application of animal manure could be acceptable if it were properly distributed and applied (Qian et al., 2012).

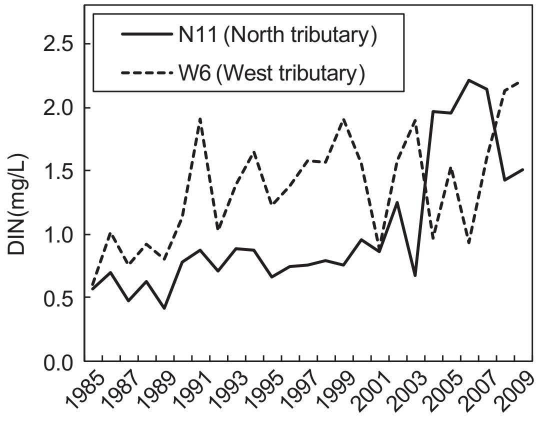

Fig. 3. Temporal change in DIN concentration from 1985 to 2009 at stations N11 and W6, the outlet of North tributary and West tributary, respectively where water enter the Jiulong River estuary.

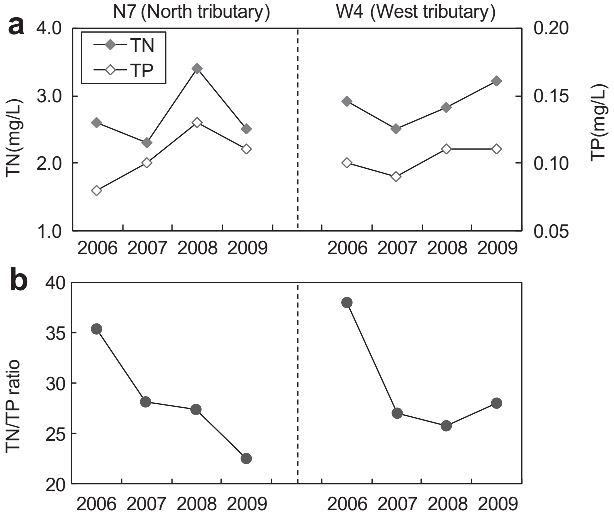

Fig. 4. Nutrient enrichment (a) and TN:TP ratio decline (b) in recent years (2006–2009) in the two main tributaries of Jiulong River.

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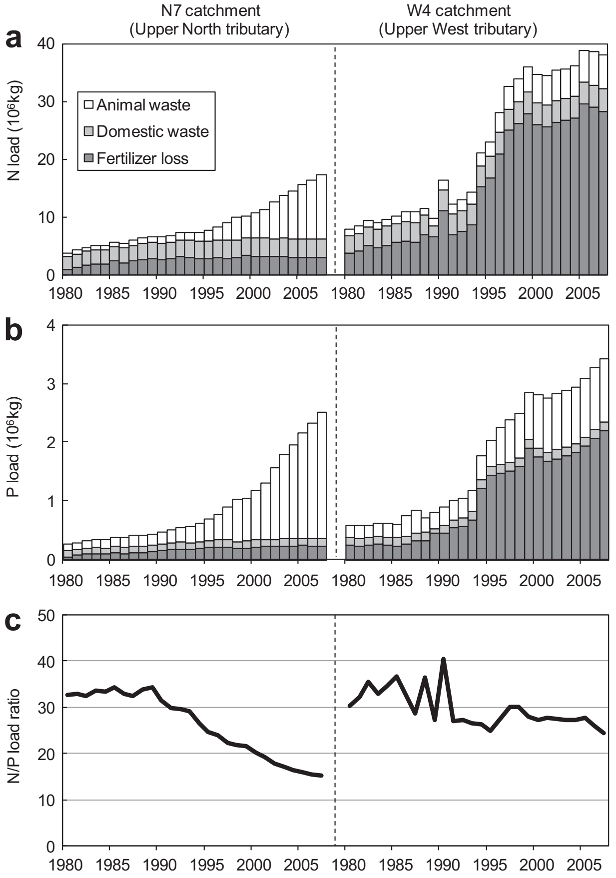

Fig. 5. Temporal variation of nutrient loads in two upstream areas of the Jiulong River Basin (1980–2007). The N7 catchment area covers Longyan City and Zhangping County, and the W4 catchment area covers Pinghe County and Nanjing County. N:P ratio of nutrient load (c) was further calculated based on the total magnitude obtained in (a) and (b).

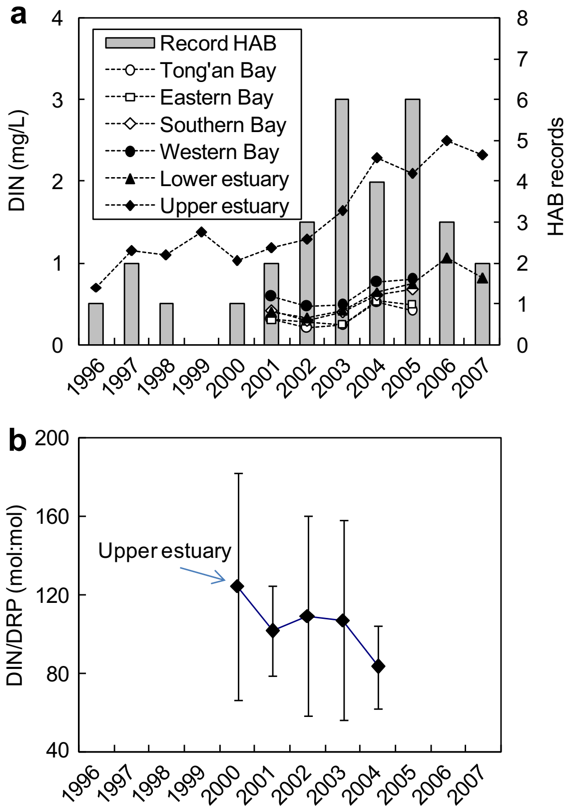

Fig. 6. Past records of HAB in Xiamen Bay and related increase of DIN concentrations at various sites in Xiamen Bay and estuary (a); declined DIN/DRP value in estuarine water (b). HAB records were extracted from the annual report of the Ocean and Fisheries Bureau of Xiamen. Nutrient concentrations in (a) indicate mean value of monthly measurement at three stations in the upper estuary during high and low tidal periods. The error bar in (b) indicates one standard deviation.

China has witnessed a tremendous increase in the use of synthetic fertilizers over the past half century (Vitousek et al., 2009). However, the nutrient-use efficiencies of the principal crops in China (e.g., rice and wheat) are lesser than those in European countries and are descending as a result of over-fertilization (e.g., 30–35% for N, 15–20% for P_2O_5 in 1990s; 27.5% for N, 11.6% for P_2O_5 in 2000s, data cited from Zhu (1997) and Zhang et al. (2008)). Over-fertilization has resulted in increased N and P losses due to soil leaching and land runoff and has accelerated eutrophication in receiving water bodies. For the Jiulong River Basin, cash crops were fairly low in N-use efficiency with less than 15%, even if all crop harvests (e.g., seeds, stocks and consumable portions) were included in the budget (Chen et al., 2008). The large amount of surplus nutrients in the budget implies increasing non-sustainable agriculture practices within the Jiulong River Basin. Ju et al. (2009) advocated for improvements in the management of intensive Chinese agricultural systems to reduce nutrient loss and environmental risk. In addition, more cost-effective management practices (e.g., vegetative strip, riparian buffer zone, stormwater pond) were suggested to implement in the upland area so as to successfully trap nutrients before entering adjacent water bodies.

4.2. *Dual nutrient management strategy*

Traditionally, nutrient management efforts to control eutrophication focused on reducing P inputs. However, controlling the eutrophication of river basins, estuaries and the adjacent coastal waters requires basin-wide nutrient abatement of both N and P (Smith, 2006). The overall increase in nutrient concentrations accompanied by a declining N:P ratio in the Jiulong River and estuarine waters calls for an optimal design of N and P loading control at a basin-wide scale. Based on the linkage between historical changes in in-channel nutrient concentrations and loads,

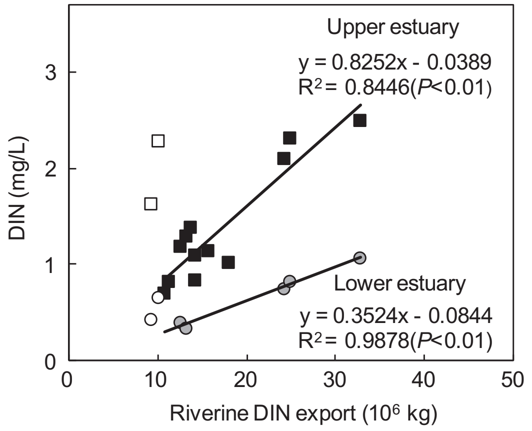

Fig. 7. Relationship between Riverine DIN export from watershed and DIN concentration in the Jiulong River estuary. DIN concentrations are available only in 1994–2004 for the upper estuary and 2001–2007 for the lower estuary. Dry years (2003 and 2004) data indicates as blank squares and circles are excluded in regression analysis.

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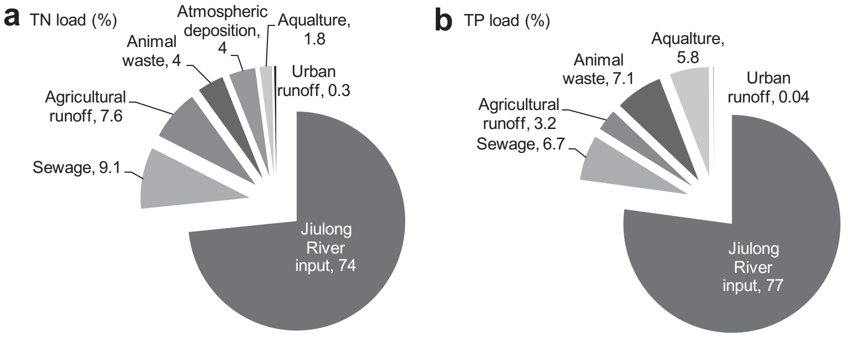

Fig. 8. Nutrient loads to Xiamen Bay. Numbers in pies indicate the percentage of various sources of TN load (a) and TP load (b) to Xiamen Bay. Data source: Chen et al. (2007, 2008, 2011).

as well as the requirement of national water quality standard (Class three), at least a 20 percent reduction of N load and 50 percent reduction of P load basin-wide were suggested in order to improve the water quality to the previous status of no-HAB periods in this region. To achieve the abovementioned objectives, a dual nutrient management strategy is proposed by implementing preferential practices that focus on controlling the scale of animal husbandry and manure treatment in the North Jiulong tributary area, and fertilizer management within the agriculture system in the West Jiulong tributary area. However, as this suggestion was concluded with respect to the present condition of the Jiulong River, we emphasized that it should be prudent to retain flexibility and can be adapted to future changes in land use, wastes treatment levels, damming, urbanization, and climate change, which all influence estuarine conditions.

Water quality management should therefore involve the identification of nutrient sources, pathways and fluxes, especially in view of the impacts of climate change (e.g., precipitation) and associated shift of hydrological regime. In addition, adequate monitoring of water quality needs to be established especially for the detection of changes in N:P ratios over time and space, which may enhance early warning for algal blooms. Nutrient management is an essential part of water management because of the importance of water as a medium for the transport of nutrients and other pollutants from land to coast. Long-term goals for water or nutrient management should be clarified with consensus among concerned agencies, planners from all cities (Longyan, Zhangzou and Xiamen) and relevant stakeholders (Departments of Agriculture, Forest, and Water resource, industry units, communities, etc.). A coordinating mechanism will be needed for coordination of the multiple jurisdictions and usage of water by various economic sectors at different levels of governance. In addition, a holistic but adaptive plan of action is required with agreed management targets and time schedule.

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