Analysis and numerical simulation of the limiting factors of algal blooms in Qiantang River estuary

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Abstract. Algal blooms generally occur in lakes and reservoirs rather than macro-tidal estuary. However, algal blooms repeated in the Qiantang River estuary, a typical macro-tidal estuary, which has seriously influenced the aquatic environment and water supply in Hangzhou. A coupled hydrodynamic-ecological model was established to explore controlling factors of algal blooms in Qiantang River estuary. Environmental variables were carried to study algal growth in which nutrients, water temperature and river runoff affect algal growth strongly in Qiantang River estuary according to the modeling. High nutrient concentration and temperature promote algal growth, and river runoff inversely. Substantially reducing on nutrient inputs is required to mitigate algal blooms due to high nutrient background concentration in the estuary, among which phosphorus reduce is more effective than nitrogen. In addition, more water should be discharged from the upstream reservoirs to suppress algal blooms in the drinking water source area of Hangzhou in summer.

1. Introduction
Algal blooms may give rise to a variety of adverse effects, such as decreasing water clarity, releasing noxious odours and toxins, and leading to hypoxia and fish kills, etc.[1][2] Therefore, it is of great significance to study the controlling mechanisms and mitigation techniques of algal blooms. Nitrogen (N) and phosphorus (P) are the key limiting nutrients in most aquatic ecosystems with P as the primary limiting nutrient to algal blooms in fresh waters generally[3][4]. However, estuaries and coastal marine ecosystems may display P limitation, N limitation, and co-limitation since much less N2 fixation by planktonic cyanobacterial in high salinity environment[5]. In addition to nutrients, temperature and irradiance are also important to algal blooms. Most phytoplankton cellular processes are temperature dependent, which are accelerating exponentially with increasing temperature, with maximal values occurring between 25 and 40°C [6].

Hydrodynamic is another important factor to impact algal blooms[7]. Algal blooms generally occur in waters with low velocity, e.g. lakes and reservoirs[4][8], and occasionally in some micro-tidal estuary[9][10], but rarely in macro-tidal estuary. Robson[9] speculated that tidal flushing was an important factor in decline of the blooms in the Swan River estuary. Algal blooms in Chesapeake Bay, a micro-tidal estuary, was likely occurred with the increasing of residence time[10]. However, in the Qiantang River estuary in China, a typical macro-tidal estuary, algal blooms (usually dominated by Cyanophyta) have occurred several times, especially in summer 2004[11]. These algal blooms seriously affect water supply and the aquatic environment of the estuary.

The Qiantang River estuary has been subject to increase anthropogenic nutrient loads and appears eutrophic[12][13]. To study the influencing factors of algal blooms in the Qiantang River estuary, a
coupled hydrodynamic-ecological model was established to simulate the reproduce of alga. Our goal is to simulate how the algal growth responds to water temperature, nutrients and river discharge, and then to acquire key limiting factors of algal blooms.

2. Study area

Figure 1. Sketching maps of the Qiantang River estuary, China.

Qiantang River, the largest river in Zhejiang Province, China, runs from west to east and flows into the East China Sea, with a watershed area of ~55558 km² (Figure 1). The downstream part of Qiantang River starting from Fuchunjiang Power Station (Figure 1) with 282 km in length is recognized as the tidal reach, that is, Qiantang River estuary, which is a macro tide estuary with maximum tide range of 9 m. Qiantang River estuary can be divided into three reaches according to hydrodynamic conditions, including runoff reach (from Fuchunjiang Power Station to Wenyan, 78 km), tidal current- and runoff-effected reach (Wenyan to Ganpu, 120 km), and tide-dominated reach (Ganpu to estuary mouth, i.e. the Hangzhou Bay, 84 km). 85% of the domestic water in Hangzhou city is taken from the freshwater end of the estuary, and the water intakes are densely distributed by the river bank of Wenyan to Zhakou is not affected by saltwater intrusion.

Figure 2. Perennial averaged monthly runoff of the Qiantang River estuary.

Width of Hangzhou Bay is about 100 km in mouth, and narrowing down upstream to 16.5 km at Ganpu. Tide range increases up to 75% from the bay mouth to Ganpu, with an average tide range of 5.60 m. Further upstream, width of river section continues to narrow down, while the tide range decreases, e.g., 1.6 km width and ~0.79 m average tide range of Qibao. The runoff varied seasonally with an average annual value of 950 m³/s, reaching to maximum in March to July and minimum in
October to February (Figure 2). Monthly mean water temperature is shown in Figure 3. High water temperature occurs from July to September, while the annual average value is 19°C with a range from 7°C to 33°C.

3. Methods

3.1. Model description

The study area is a shallow and wide estuary with no obvious phenomena of water stratification[13][14]. So the depth-averaged transport model can be used for this modeling purpose. The process-based model was set up using the Mike21 modeling system including HD, AD and Ecolab modules, which coupled descriptions of hydrodynamics, substances transport and biochemical reaction processes. Mike21, a two-dimensional numerical model, developed by Danish Hydraulic Institute, Water & Environment[15], has been successfully applied to a wide range of environmental studies simulating circulation, water quality and eutrophication process in coastal regions, estuaries, lakes, reservoirs, and rivers [16][17].

![Diagram of transformation interrelation of substances in the Ecolab module](image)

**Figure 4.** Transformation interrelation of substances in the Ecolab module

HD module is based on the horizontal 2D shallow water equations. AD module is based on the advection-diffusion equation. The HD module and AD module of Mike21 have been described by Xu[17]. Ecolab module is a numerical lab for ecological modeling. It is an open and generic tool for customizing aquatic ecosystem models to describe water quality, eutrophication, heavy metals, and ecology. Based on Ecolab we developed an ecological module, and the transformation interrelation of substances is shown in Figure 4. In the process, algal concentration is represented by chlorophyll-a concentration. Based on the principle of mass conservation, the variation in chlorophyll-a concentration is described in the following equation.

\[
\frac{dC_a}{dt} = \mu_a C_a - \rho_a C_a - \frac{\sigma_1}{h} C_a - \frac{\sigma_2}{h} C_a
\]  

(1a)

Where:

\[
\mu_a = K_{1e} \cdot (f(T) \cdot G(I) \cdot G(N))
\]  

(1b)

Where: 

\[
f(T) = \theta_{1e} \cdot \frac{(T - T_{\text{min}})}{(T_{\text{ref}} - T_{\text{min}})} \cdot G(I) = \frac{I}{k_I + I}, \quad G(N) = \min\left[\frac{N}{K_N + N}, \frac{P}{K_P + P}\right]
\]  

(1c)

Where: \(C_a\) is chlorophyll-a concentration, \(\mu_a\) is growth rate, \(\rho_a\) is respiratory rate, \(\sigma_1\) is setting rate, \(\sigma_2\) is death rate, \(K_{1e}\) is growth rate at 20°C, \(f(T)\) is temperature constraint function, \(G(I)\) is...
Illumination constraint function, \( f(N) \) is nutrients constraint function, \( K_N \) and \( K_P \) is half saturation concentration for nitrogen and phosphorus.

3.2. Model setup
Fuchun River Hydropower Station which cuts off the upstream and downstream of Qiantang River is the location of the tidal limit of Qiantang River estuary with more than 40 years’ daily runoff data, so upstream boundary of the model is set at Fuchun River Hydropower Station. As the Qiantang River estuary from Wenjiayan to Zhakou is the key research reach of this study, Cangqian is chosen as the downstream boundary to minimize the effects of the boundary condition. Puyang River is a key tributary of Qiantang River estuary, with ~6% drainage area of Qiantang River estuary, and its upstream boundary is located at Linpu. The upstream boundaries to control runoff are given daily discharge, and the downstream boundary to control tide is given hourly tidal level.

Unstructured triangular grids were generated with a high grid resolution to better fit land boundaries. The length of the test section of the river is 122 km, and the model area and grid distribution of the model are shown in Figure 5. The total number of elements is 14150, and the minimum mesh size is 40 m. The bottom topography data were obtained from the measured data of the Qiantang River estuary and interpolated into the model grids.

![Figure 5. Calculation range and grid distribution of the model.](image)

3.3. Model calibration
The observed data of flow and water quality measured during August 2010 were used for model validation. Flow data were collected from hydrological station (Tonglu, Fuyang, Wenyuan, Zhakou stations). Water quality measurements were taken on the main channel of six cross-sections (Tonglu, Zhongbu, Fuyang, Yushan, Wenyuan and Zhakou). The measurement stations were shown in Figure 5. In the model, manning coefficient, dispersion coefficient, half saturation concentration for nutrients, and maximum growth rate of phytoplankton were calibrated to fit the real data.

Part of validation results were shown in Figure 6. Simulated and observed results of tidal levels were in good agreement with each other at four stations. The average absolute error of the simulated and observed tidal levels was 0.08 m. Simulated and observed flow velocities were in good agreement with value and direction. Simulated and observed water quality including nitrate and ammonia, phosphorus and Chl-a et al. in monitoring points were in good agreement. So the model successfully simulated hydrodynamic and water quality of the Qiantang River estuary.
4. Sensitivity analyses on algal growth responding to environmental factors

Environmental factors including nutrients, water temperature and river runoff influencing on algal growth were simulated by the hydrodynamic-ecological model. Sensitivity analyses on algal growth were carried out with the parameters varying one by one in the model calculating process.

4.1. Algal growth vs. nutrients

The Qiantang River is highly impacted by anthropogenic inputs, resulting in high nutrients concentration[18]. The quality of water in the Qiantang River estuary and the Hangzhou Bay was very poor in recent years, ascribed to nitrogen and phosphorus inputs basically according to "Zhejiang Marine Environment Quality Bulletin". Inorganic nitrogen concentration (including nitrate and ammonia) was ~2.7mg/L, while phosphorus concentration was among 0.1-0.2mg/L with primary component of phosphate in 2010. Algal growth influenced by nitrogen and phosphorus was simulated to explore of the impact on algal growth of nutrients (Figure 7 and Figure 8).

Figure 6. Calculated (line) and observed (dot) tidal level, nitrogen, phosphorus and Chl-a.

Figure 7. Algal growth vs. nitrogen.

Figure 8. Algal growth vs. phosphorus.
Model validation results showed that the half-saturation constants for nitrogen and phosphorus limitation for algal growth were 0.40 mg/L and 0.03 mg/L, respectively, which are far less than actual nitrogen and phosphorus concentration in the estuary. Chlorophyll-a concentration showed a decline of 0.63 μg/L when nitrogen concentration was decreased from 2.5 mg/L to 1.0 mg/L (Figure 7), and a reduction of 1.90 μg/L for phosphorus concentration decreasing from 0.2 mg/L to 0.1 mg/L (Figure 8). Thus, in order to control algal blooms, nutrient inputs must be significantly reduced, with better effect of reduction on phosphorus than nitrogen input under the existing nitrogen and phosphorus loads in Qiantang River estuary.

4.2. Algal growth vs. water temperature

Water temperature is an important factor of phytoplankton growth, and the optimal water temperature for algal growth is among 20~30°C[6]. Algal growth was simulated under water temperature of 20°C, 23°C, 26°C and 30°C, respectively. The growth rates of the chlorophyll-a were 0.33 μg/L, 0.48 μg/L and 0.62 μg/L per temperature rise of 1°C among 20°C~23°C, 23°C~26°C and 26~30°C, respectively, i.e. the higher the water temperature is, the more rapidly the alga grows (Figure 9).

4.3. Algal growth vs. river runoff

As discharge distributes mainly in summer in the Qiantang River, runoff were set as 200, 350, 500 and 1000 m³/s based on the scheme with the water temperature of 30°C. The results indicated that chlorophyll-a concentration was increased by 0.22 μg/L, 0.46 μg/L and 0.60 μg/L per discharge decreasing of 50 m³/s among 1000~500 m³/s, 500~350 m³/s and 350~200 m³/s, respectively, which demonstrated that alga grows faster under smaller river runoff (Figure 10). Chlorophyll-a concentration exceeded 10 μg/L when the river discharge went down to 350 m³/s at Zhakou station.

Small river runoff with low current velocity results in long residence time, benefiting algal growth. The transport time of different river runoff discharged from Fuchun River Power Station to Zhakou station was shown in Figure 11. The transport time was increased by 0.4 d, 1.3 d and 2.0 d per decreasing of 50 m³/s among 1000~500 m³/s, 500~350 m³/s and 350~200 m³/s, respectively, which pronounced transport time growth rate increased with river discharge decline, consisting with algal growth vs. river discharge(Figure 11).
Generally, current shows bi-directional and swings back and forth gradually within certain distance due to invasive tide in the estuary, leading to longer residence time to promote algal growth. Wu[19] indicated that the oscillation periods within the reach from Wenyan to Zhakou were about 2 d and 5 d while the river discharges were 1000 m$^3$/s and 500 m$^3$/s, respectively. Our results was consistent with Wu[19], with ~10 d oscillation under discharge of 200 m$^3$/s. Gao[20] claimed that water exchange was slower in the downstream due to tide influence, which agreed with higher growth rate of chlorophyll-a concentration in the downstream in our results (Figure 6).

Water temperature can reach above 30$^\circ$C in Qiantang River estuary in summer, which is favorable to growth of algal plants. Based on our analysis, increasing river runoff has a good effect on algal growth inhibition, which means river runoff could be an important limiting factor of algal bloom during high-temperature season.

5. Conclusions
Based on a coupled hydrodynamic-ecological numerical model, the sensitivity of algal growth responding to nutrients, water temperature and river runoff is analyzed in the Qiantang River estuary. The following conclusions can be drawn:

1) The Qiantang River estuary is highly eutrophic. In order to control algal blooms, nutrient input must be significantly reduced, and reduce of phosphorus input is more effective than nitrogen.

2) Residence time of water which increases significantly with runoff decreasing promotes algal growth in Qiantang estuary.

3) During high-temperature season, substantial nutrient inputs reduce are required to control algal blooms, as well as river runoff increase from the upstream reservoir regulation.

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