Analysis and numerical simulation of natural and human-caused low dissolved oxygen in the Minjiang River Estuary
Peng Zhang, Yong Pang, Chengchun Shi, Yishu Wang, Lei Xu, Hongche Pan and Rongrong Xie

ABSTRACT

The Minjiang River, a typical tidal channel in Southeast China, plays an important role in the supply of drinking water, flood control and drought relief, farming and navigation, as well as shipping and other functions. Dissolved oxygen (DO), as a basic living condition for aquatic biota, has been deteriorating in the Minjiang River in recent years. In order to understand how the spatial distribution of DO responds to river discharge, nutrient loading and water temperature, a three-dimensional Environmental Fluid Dynamics Code model was used to simulate water age and the distribution of DO in the Minjiang River. The model presented in this paper was used for water resource and water quality simulations under various physical, chemical, and biological scenarios. Sensitivity simulation results indicated that the three factors had a significant impact on the spatial distribution variation of DO in the Minjiang River. Increased river discharge or split ratio of the North Channel resulted in decreased water age and increased DO. Increased nutrient loading and water temperature caused lower DO. In order to protect coastal environments in the Minjiang River, river discharge should be increased and pollutants of local cities should be reduced during the high temperature and drought period.

Key words | Environmental Fluid Dynamics Code (EFDC), low dissolved oxygen, Minjiang River Estuary, nutrient loading, river discharges, water temperature

INTRODUCTION

Dissolved oxygen (DO) is not only a fundamental parameter of coastal water quality, but also an indication of organics decomposed in water and the degree of eutrophication (Xia et al. 2010; Lanoux et al. 2013). Low DO is closely associated with declining shellfish productions and massive fish kills, deaths of phytoplankton and zooplankton, anaerobic decomposition of settled organic matter, deterioration of water quality and variation and loss of habitat (Holmer 1999; Diaz & Rosenberg 2008). Estuaries, as heterotrophic ecosystems where large quantities of organic material carried by rivers and imported from the sea are mineralized (Gattuso et al. 1998; Abril et al. 2002), have appeared hypoxic around the world (Diaz 2001; Scavia et al. 2004; Xia et al. 2010, 2011; Wang et al. 2012). The global dynamics governing the estuarine system are complex (Brochini et al. 2015). In an estuarine environment, fundamental for mixing is the interplay between various hydrodynamic forcing, like river current, wave forcing and tidal motion in a vertically stratified (haloclines and thermoclines subject to seasonal changes) environment. Several factors contribute to the temporal variability and spatial distribution of DO in estuaries. Physical influences include freshwater and groundwater inputs, water volume and tidal advection and dispersion. Biological and chemical factors include phytoplankton blooms, excess nitrification, high water temperature, sediment oxygen demand and transformation of nutrient and organic matter loading from drainage basins. (Justic et al. 2007; Xia et al. 2010, 2011; Lanoux et al. 2013).

Over the past three decades, there has been a large number of analytical and numerical studies that simulate DO dynamics for estuaries (Kazmi & Hansen 1997; Kamal et al. 1999; Hull et al. 2008; Rabalais et al. 2010; Paliwal & Patra 2011). With
increasing degradation of water quality and frequent occurrence of eutrophication, low DO in estuaries of China (the Yangtze River plume and the Pearl River estuary) have attracted more attention from scientists (Yang et al. 2004; Wang 2009; Wang et al. 2012; Lai et al. 2013; Zhang et al. 2014).

However, these previous extensive hydrodynamics and quality modeling studies, or large amounts of data analysis, only provided a solid foundation for understanding (physical) DO dynamics and there were only a few discussions on the relationship between variation of temporal and spatial DO with altered river discharge, nutrient loading and water temperature (Park et al. 1996; Zheng et al. 2004; Xia et al. 2010, 2011; Lanoux et al. 2013). From a management perspective, it is important to know the timescale for a pollutant discharged into a water body to be transported to another location or out of the system under different hydrological conditions, which can then be applied to determine biogeochemical processes and to elaborate mitigation strategies. The Minjiang River, a typical tidal channel, was selected to explore the distribution of DO and water age by using a three-dimensional hydrodynamic water quality model. Our goal is to understand how the spatial distribution of DO responds to river discharge, nutrient loading and temperature.

RESEARCH AREA

The Minjiang River is the longest river (2,959 km) in Fujian Province, Southeast China (Figure 1). In the Minjiang watershed, rainfall is the highest in summer and the lowest in autumn. The annual average discharge was 1,760 m$^3$/s, and the discharge varies seasonally, reaching a maximum in April to July (average 3,200 m$^3$/s) and a minimum in October to February (average 620 m$^3$/s). The annual average water temperature is 19.9°C with a range of 9.8 to 32.3°C. In order to guarantee the minimum demand of the water environment and ecology in the Minjiang River, the minimum ecological flow of Shuikou Dam is 308 m$^3$/s.

The North Channel receives 80% of the domestic sewage and 90% of the industrial wastewater of the municipal district of Fuzhou (2,984,900 inhabitants) (Zhang et al. 2015). In particular, Baima River and Guangming River, two tributaries of the North Channel, are accompanied by water quality which is seriously substandard (chemical oxygen demand (COD) >40 mg·L$^{-1}$, ammonium >6 mg·L$^{-1}$). What is more serious is that the river discharge flowing into the North Channel has been significantly reduced due to riverbed entrenchment of the South Channel in recent years (Huang 2010). Several episodes of low DO content have been observed in the Minjiang River during the high temperature and the drought period.

MATERIALS AND METHODS

EFDC model

The Environmental Fluid Dynamics Code (EFDC), a general purpose and open-source three-dimensional hydrodynamic and water quality model, was applied in the Minjiang River including water levels, currents, water ages and water quality. The momentum and continuity equations, the governing mass-balance equation for each of the hydrodynamics state variables and other details of the EFDC model are documented by Hamrick (1992), Jeong et al. (2010) and Xia et al. (2011).

Figure 1 | Location of the study area: the Minjiang fluvial–estuarine system and its observational sample locations.
Water age is defined as ‘the time that has elapsed since the particle under consideration left the region in which its age is prescribed as being zero’ (Delhez et al. 1999). As defined in this study, age is the time elapsed since the water parcel under consideration exited the region in which its age is prescribed as zero, or, particularly, the time elapsed since a water particle is discharged from the headwater of an estuary (Shen & Wang 2007). The water age can be computed based on age concentrations by the EFDC model with specified initial and boundary conditions (Deleersnijder et al. 2001).

For the DO in the EFDC model, the sources and sinks in the water column included in the model are algal photosynthesis and respiration, nitrification, heterotrophic respiration of dissolved organic carbon, oxidation of COD, surface reaeration for the surface layer only, sediment oxygen demand for the bottom layer only, and external loads (Xia et al. 2011).

**Model setup**

**Configuration**

Rectangular grids were used with 5,241 active cells and a cell size 200 m in the x direction (from west to east) and 100 m in the y direction (from north to south), which was adequate to reproduce all fundamental dynamics (Stocchino & Brocchini 2010; Stocchino et al. 2011). The bottom topography data were obtained from the measured data of the Minjiang River and interpolated into the model grids. The time step was set to 5 s to satisfy the Courant–Friedrich–Levy criterion (Courant et al. 1928).

In order to set up and calibrate the model accurately, hydrology and water quality of the Minjiang River were simultaneously monitored over 1 or 3 hours by Fuzhou Research Academy of Environmental Sciences from 7 to 8 September 2013. The upstream and downstream boundaries of the model were provided by the measured results. The Dazhangxi is a major tributary of the Minjiang River, whose boundary was provided by Yongtai hydrological station. Atmospheric data was acquired from historical archives of the Fujian weather station except for incident solar radiation, which was computed with cloud cover data and theoretical maximum solar radiation based on a function of latitude shown in Xia et al. (2011).

**Calibration**

The measured results of the six simultaneous monitoring points (Zhuqi, Wenshanli, Kuiqi, Kegong, Wulongjiang and Baiyantan) were selected for EFDC model calibration. Hydrodynamic model results were compared to the observation data before running the water quality (WQ) model. The WQ model included more than 100 parameters, and the major calibrated values of the parameters of interest are shown in Table 1. The calibration process involved adjustments of these parameters within an acceptable range until the model results reproduced the observed data, and the model could reasonably represent the DO and other water quality dynamic processes of monitoring points (Zheng et al. 2004; Xia et al. 2010).

Simulated and observed water levels were in good agreement with amplitude and phase in five monitoring points (Zhuqi, Wenshanli, Kegong, Wulongjiang and Baiyantan). Three stations (Wenshanli, Kegong and Jingtangtui) were selected to calibrate the flow. Simulated and observed flow were in good agreement with value and direction. The temperature of monitoring points was nearly uniform at 20 °C with a little change. In addition, as salinity values of monitoring points upstream with freshwater have little change, only Kuiqi and Wulongjiang were selected to calibrate the salinity. Simulated and observed water quality were in good agreement with amplitude and phase at five monitoring points (Zhuqi, Wenshanli, Kuiqi, Kegong and Wulongjiang). Due to limited space, the calibration results of figures of water level, flow, salinity, DO, COD and ammonium are not listed. The mean absolute errors of water level and the mean absolute relative errors of flow, salinity and water quality parameters are shown in Table 2. So the model successfully simulated hydrodynamic and water quality in the Minjiang River.

**RESULTS AND DISCUSSION**

**Sensitivity experiments of DO to factors**

The water quality model was configured for the ideal sensitivity experiments to explore DO dynamics within the estuary under different conditions. Below are presented selected case studies to understand how the Minjiang River responded to the different river discharge, nutrient loading and temperature.

**Response to altered river discharges or the split ratio of the North Channel**

The first case study changed the river discharge to the minimum ecological flow (308 m³·s⁻¹) and a high flow (1,000 m³·s⁻¹) of the calibration model setting (370 m³·s⁻¹) while maintaining the same nutrient concentration. Another
set of the numerical experiment changed the split ratio of the North Channel (SRNC) to be 50% (the calibration model was 20%) by building spur-dikes at the inlet of the South Channel, while maintaining the other condition. The results were all compared with those predicted from the standard run.

Based on these experiments, it was clear that DO increased due to increasing river discharge in the downstream region of the Minjiang River, especially in the North Channel (Figure 2). As river discharge was from the outlet in the bottom of Shuikou Dam, average DO was low at the upper region of the Minjiang River. DO increased

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Major model parameters</th>
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<tbody>
<tr>
<td><strong>Parameter</strong></td>
<td><strong>Value</strong></td>
</tr>
<tr>
<td>Oxygen half-saturation constant for algal respiration</td>
<td>0.10</td>
</tr>
<tr>
<td>Half-saturation constant for denitrification</td>
<td>0.10</td>
</tr>
<tr>
<td>Ratio of denitrification rate to oxic dissolved organic carbon respiration rate</td>
<td>0.50</td>
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<tr>
<td>Maximum nitrification rate per day</td>
<td>0.07</td>
</tr>
<tr>
<td>Oxygen half-saturation constant for nitrification</td>
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<tr>
<td>NH$_4$ half-saturation constant for nitrification</td>
<td>1.00</td>
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<tr>
<td>Suboptimal temperature effect coefficient for green algae growth</td>
<td>0.01</td>
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<tr>
<td>Super-optimal temperature effect coefficient for green algae growth</td>
<td>0.02</td>
</tr>
<tr>
<td>Temperature effect coefficient for basal metabolism of green algae</td>
<td>0.069</td>
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<tr>
<td>Oxic respiration half-saturation constant for DO</td>
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</tr>
<tr>
<td>Background light extinction coefficient</td>
<td>0.50</td>
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<tr>
<td>Light extinction due to total suspended solids</td>
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<tr>
<td>Light extinction due to chlorophyll</td>
<td>0.031</td>
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<tr>
<td>Light extinction due to particulate organic matter</td>
<td>0.08</td>
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<tr>
<td>Maximum phytoplankton growth rate</td>
<td>2.00</td>
</tr>
<tr>
<td>Algal basal metabolism rate at 20 °C</td>
<td>0.01</td>
</tr>
<tr>
<td>Algal predation rate</td>
<td>0.20</td>
</tr>
<tr>
<td>Minimum organic phosphorus hydrolysis rate</td>
<td>0.005</td>
</tr>
<tr>
<td>Minimum organic nitrogen hydrolysis rate</td>
<td>0.005</td>
</tr>
<tr>
<td>Mass of DO consumed per unit mass of ammonium nitrogen nitrified</td>
<td>4.33</td>
</tr>
<tr>
<td>DO-to-carbon ratio in respiration</td>
<td>2.67</td>
</tr>
<tr>
<td>Temperature rate constant for reaeration</td>
<td>1.024</td>
</tr>
<tr>
<td>Oxygen half-saturation constant for COD decay</td>
<td>1.50</td>
</tr>
<tr>
<td>COD decay rate</td>
<td>0.10 ~ 0.15</td>
</tr>
<tr>
<td>Temperature rate constant for COD decay</td>
<td>0.041</td>
</tr>
<tr>
<td>Carbon/chlorophyll a</td>
<td>0.065</td>
</tr>
</tbody>
</table>

| Table 2 | The mean absolute errors of water level and the mean absolute relative errors of flow and water qualities in different monitoring stations |
|---------|-------------------|----------|----------|----------|----------|----------|
| Monitoring points | Water level (m) | Zhuqi | Wenshanli | Kuiqi | Kegong | Wulongjiang | Baiyantan | Jingangtui |
| The mean absolute errors | / | 0.12 | 0.11 | / | 0.14 | 0.14 | 0.11 | / |
| The mean absolute relative errors | / | 21% | / | 21% | / | / | 14% |
| Salinity | / | / | 19% | / | 16% | / | / |
| DO | 4% | 7% | 8% | 6% | 6% | / | / |
| COD | 14% | 17% | 15% | 25% | 14% | / | / |
| NH$_4$ | 17% | 17% | 14% | 13% | 23% | / | / |
Figure 2 | Average DO (mg·L$^{-1}$) distribution response with: (a) the calibrated model setting (570 m$^3$·s$^{-1}$); (b) river discharge being 308 m$^3$·s$^{-1}$; (c) river discharge being 1,000 m$^3$·s$^{-1}$; (d) the SRNC being 50%.
along the river because of high reaeration and relatively low biochemical reaction due to good water quality until the water body reached Zhuqi. But these experiments had some differences: average DO with low flow increased faster than that with high flow, possibly because reaeration at the water surface was faster with low flow when the depth was shallower (3–5 m) at the same meteorological condition (wind and temperature). On the other hand, the water column at low flow had more time for reaeration when discharge was transported from Shuikou Reservoir to the same location (Figure 3). For example, it took about 9 days for the discharge from Shuikou Dam to reach the bifurcation under the minimum ecological flow (Figure 5(b)), which was 3 days under river discharge of 1,000 m$^3$·s$^{-1}$ (Figure 3(c)). So average DO with low flow had a higher reaeration than that with high flow which was validated by these experiments. But DO increased more with high flow in the downstream where there was more pollutant input. The North Channel, receiving 80% of domestic sewage and 90% of industrial wastewater of the municipal district of Fuzhou (2,984,900 inhabitants), had the lowest DO. In the upper part of the municipal district of Fuzhou, the flow of the North Channel depended on river discharge or split ratio. Increased flow caused freshwater to reach the North Channel where oxygenated water was transported. In the lower region of the Minjiang River, DO was high when dilution with estuarine oxygenated saltier water occurred. Average DO at Kuiqi increased 0.5 mg·L$^{-1}$ with increased river discharge (50 m$^3$·s$^{-1}$) of North Channel based on the calibrated model setting; average DO at Kuiqi decreased 1.0 mg·L$^{-1}$ with decreased river discharge (50 m$^3$·s$^{-1}$) of North Channel based on the calibrated model setting. This indicated: (1) relative influence of river discharge on DO was higher at low flow than that at high flow; and (2) relative influence of river discharge on DO would be decreased with increasing river discharge.

Increased river discharge had an important effect on DO by renewing water in the hypoxia section (the section of the North Channel) with more oxygenated upstream freshwater (Rabalais et al. 2010; Xia et al. 2010, 2011; Lanoux et al. 2013), decreasing the residence time of waters and diluting nutrient concentration (Shen & Wang 2007; Shen et al. 2013). In order to better understand the relationship between the transport timescales of dissolved pollutant substances and spatial DO distribution, the mean water age (day) distribution of the Minjiang River was simulated under different hydrological conditions (Figure 3). At very low discharges, residence time of water bodies was longer, water renewal was lower and water environmental capacity for nutrients in water reduced (Xie et al. 2014). Oxygen consumption increased due to degradation of the organic carbon and ammonium by continuous input from local urban sources. When the river discharge was 308 m$^3$·s$^{-1}$ (Figure 3(b)), contour plots of age distribution were relatively denser and average DO decreased to 4.2 mg·L$^{-1}$ in the North Channel near Guangming River (Figure 2(b)). Residence time decreased and average DO increased with increased river discharge for the estuary, which could be better explained by the experiment of the SRNC increasing to 50% (Figures 2(d) and 3(d)). When river discharge of the South Channel decreased, the residence time increased and average DO decreased. The decreased water age meant the contamination could be discharged quickly, then resulting in an increasing trend of DO in the North Channel (Hong & Shen 2012, 2013). It just took about 5 days for domestic sewage and industrial wastewater of the municipal district of Fuzhou to discharge into the sea under river discharge of 1,000 m$^3$·s$^{-1}$ (Figure 3(c)), which was 8 days less than the experiment with the minimum ecological flow. It was clear that the minimum ecological flow (308 m$^3$·s$^{-1}$) could not meet the demand of the water environment and ecology in the Minjiang River (Figure 2(b)).

**Response to altered nutrient loading effects**

The second case study changed nutrient loading rate by 0.3 and 0.5 times reduction of the model calibration rates while maintaining the same river discharge (Figure 4). This case showed that nutrients had a significant impact on spatial distribution of DO in the Minjiang River, especially in the North Channel. Compared with the calibrated model (Figure 2(a)), the average DO of water in the North Channel increased by 0.2–0.8 mg·L$^{-1}$ and 0.4–1.2 mg·L$^{-1}$, respectively, after removing pollutants by 0.3 and 0.5 times of the model calibration rates. So we could draw the conclusion that average DO at Kuiqi in the North Channel increased about 0.3 mg·L$^{-1}$ with decreased 10% of nutrient loading rate based on the calibrated model setting (Figures 2 and 4).

**Response to water temperature effects**

The third case study changed the water temperature to 15, 25 and 30 °C. Water temperature of the current calibration model setting influences DO by changing oxygen solubility in water (Benson & Krause 1984) and oxygen consumption rate due to degradation of the organic carbon and ammonium. DO decreased with increasing water temperature (Figure 5). DO in the North Channel was predicted to be less than 4 mg·L$^{-1}$ during high water temperature
Figure 3 | Average water age (day) distribution response with: (a) the calibrated model setting (570 m$^3$.s$^{-1}$); (b) river discharge being 308 m$^3$.s$^{-1}$; (c) river discharge being 1,000 m$^3$.s$^{-1}$; (d) the SRNC being 50%.
(Figure 5(c)), which indicated a serious potential negative impact on phytoplankton and zooplankton in water. In winter, DO concentration was high because of low water temperature. Average DO at Kuiqi increased or decreased about 0.2 mg·L⁻¹ with increased or decreased water temperature (1 °C) based on the calibrated model setting (20 °C).

CONCLUSIONS

The purpose of this study was to investigate the response of DO to river discharge, nutrient loading and water temperature by integrating a hydrodynamics and WQ model in the Minjiang River, which was a typical tidal channel seriously affected by human activities. The model presented in this paper was used for water resource and water quality simulations under numerous physical, chemical, and biological scenarios. The main conclusions are as follows:

1. The spatially variable DO and water age simulated under various river discharges and the SRNC provided useful information for understanding the relationship between DO and water exchange and dissolved substance transport in the Minjiang River. Increasing river discharge or the SRNC resulted in increased DO and decreased water age. Increased river discharge had an important effect on DO by renewing water in the hypoxia section with more oxygenated upstream freshwater, decreasing the residence time of waters and diluting nutrient concentration.

2. Nutrient loading had a significant impact on the spatial distribution of DO in the Minjiang River, especially in the North Channel which received wastewater from the
Figure 5  |  Average DO (mg·L⁻¹) distribution response with: (a) water temperature of 15 °C; (b) water temperature of 25 °C; (c) water temperature of 30 °C.
municipal district of Fuzhou. Water temperature influenced seasonal trends of DO by changing oxygen solubility in water and oxygen consumption rate, which was related to degradation of the organic carbon and ammonium.

3. A complete understanding of these factors will help to predict the evolution of oxygen content of estuarine waters and to elaborate mitigation strategies, when necessary. The minimum ecological flow (308 m³·s⁻¹) cannot meet the minimum protection of the water environment and ecology in the Minjiang River due to hypoxia leading to deterioration of water quality and variation and loss of the habitats. In order to protect the ecological environment, river discharge must be increased and pollutants of local urban source must be reduced during the high temperature and drought period. This paper presents the model application with emphasis on the sensitivity analysis to study low DO.

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REFERENCES


Hong, B. & Shen, J. 2012 Responses of estuarine salinity and transport processes to potential future sea-level rise in the Chesapeake Bay. *Estuarine Coastal and Shelf Science* 104, 35–45.


a highly turbid, macrotidal estuary (the Gironde, France).


Shen, J. & Wang, H. V. 2007 Determining the age of water and long-term transport timescale of the Chesapeake Bay. Estuarine Coastal and Shelf Science 74 (4), 585–598.

Shen, J., Hong, B. & Kuo, A. Y. 2015 Using timescales to interpret dissolved oxygen distributions in the bottom waters of Chesapeake Bay. Limnology and Oceanography 58 (6), 2237–2248.


Wang, B. D. 2009 Hydromorphological mechanisms leading to hypoxia off the Changjiang estuary. Marine Environmental Research 67 (1), 53–58.


Xie, R. R., Pang, Y. & Bao, K. 2014 Spatiotemporal distribution of water environmental capacity – a case study on the western areas of Taihu Lake in Jiangsu Province, China. Environmental Science and Pollution Research 21, 5465–5473.


