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Simulating the gross primary production and ecosystem respiration of estuarine ecosystem in North China with AQUATOX

Jinxia Yan[a,b,*], Jingling Liu[b], Xiaoguang You[b], Xuan Shi[b], Lulu Zhang[b]

[a] Henan Key Laboratory of Water Environment Simulation and Treatment, Henan Engineering Research Center of Water Pollution and Soil Damage Remediation, School of Environmental and Municipal Engineering, North China University of Water Resources and Electric Power, Zhengzhou, China

[b] State Key Joint Laboratory of Environmental Simulation and Pollution Control, School of Environment, Beijing Normal University, Beijing, China

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ABSTRACT

AQUATOX, coupled water quality and estuarine hydrodynamic model based on food web, was implemented to simulate the temporal variations of gross primary production (GPP) and ecosystem respiration (R_e) in Haihe estuary of North China, also, the parameter sensitivity was calculated and the main factors of GPP and R_e were analyzed. Results showed that GPP ranged from 16 to 1789 mg $O_2\,m^{-2}\,d^{-1}$ and R_e from 56 to 1083 mg $O_2\,m^{-2}\,d^{-1}$, respectively. GPP and R_e exhibited significant temporal variation and both reached the highest level in June, however, GPP and R_e reduced in July and August, which could be explained by the increase of turbidity caused by high freshwater inflow discharge in rainy season. Maximum photosynthetic rate of blue-greens was the most sensitive parameter to GPP. Re was strongly related to temperature, the most sensitive parameter was average epilimnetic temperature. A significant negative correlation was found between GPP, R_e and freshwater inflow. Furthermore, significant direct and indirect effects of tidal height on GPP were observed by path analysis, increased turbidity induced by tidal action might explain the influence on GPP.

1. Introduction

Estuarine areas are at the interface between land and sea, in which many critical physical–chemical processes occur, such as dynamic mixing of fresh and oceanic waters, sediment deposition and pollutant retention (Dale et al., 2004; Engle et al., 2007; Fu et al., 2014; Cindrić et al., 2015; Shen et al., 2015). However, natural variability of river inputs to estuaries had been greatly modified by human activities, such as dam construction and flood protection (Burke et al., 2009; Mittal et al., 2014; Nidzieko et al., 2014). Freshwater inflow was likely to eliminate in most estuaries (Azevedo et al., 2010, 2014; Shen et al., 2015; Yan et al., 2016) and its tidal behaviour was changed (Vieira and Bordalo, 2000; Azevedo et al., 2008). These changes caused alterations of biological communities in species composition, diversity, abundance and distribution, then estuarine ecosystem metabolism (Chicharo et al., 2006; Greet et al., 2011; Rovira et al., 2012; Webb et al., 2012; Belmar et al., 2013; Tang et al., 2015).

As important indicators of ecosystem metabolism, gross primary production (GPP) and ecosystem respiration (R_e) played important roles in biogeochemical cycles of aquatic ecosystems. An analysis of 350 published studies of aquatic ecosystem metabolism revealed that this research had been done predominantly in North America (68%, USA and Canada), with fewer in Europe (27%), and very few in Asia and Africa (6%) (Staehr et al., 2012). Most of the past studies were on descriptive studies of annual, seasonal or daily changes of primary production and respiration, and the development of new techniques to measure net ecosystem production. Several approaches, such as bottle and chamber incubations (Kemp et al., 1997; Gazeau et al., 2005), the diel open-water technique Caffrey, 2003; Staehr and Sand-Jensen, 2007; Tang et al., 2015) and oxygen isotopes (Quay et al., 1995; Ostrom et al., 2005), had been applied to aquatic ecosystems to estimate GPP and R_e. In recent years, modeling has eventually become an important topic (Staehr et al., 2012).

Coupled hydrodynamic-biogeochemical models had been used to analysis the relationship between physical–chemical processes and ecosystem metabolism. For example, Trancoso et al. (2005) found that hydrodynamic conditions might be important for the productivity of phytoplankton and macroalgae, after the application of a 3D hydrodynamic-ecological model into Ria de Aveiro (Portugal) to simulate estuarine dynamics and productivity of these two primary producers. Azevedo et al. (2010, 2014) implemented a 3-dimensional hydrodynamic model to evaluate the influence of different freshwater

* Corresponding author at: School of Environmental and Municipal Engineering, North China University of Water Resources and Electric Power, No. 136 Jinshui East Road, Zhengdong New District, Zhengzhou 450046, China.

E-mail address: yanjinxia1122@163.com (J. Yan).

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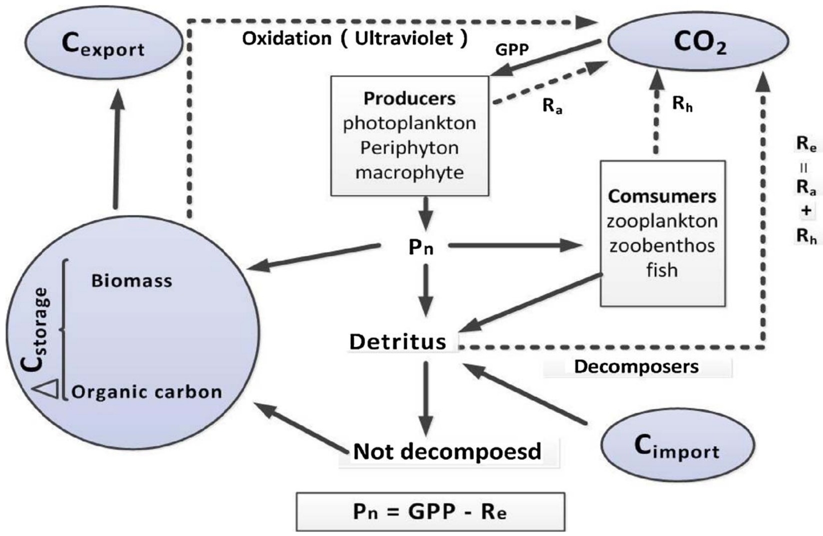

Fig. 1. Conceptual model of different trophic biological communities of aquatic ecosystem with GPP, R_e and P_n. Dashed lines represent degradation of C, solid lines production or transfer of C.

discharge regimes on phytoplankton biomass and production of the Douro estuary. Tang et al. (2015) developed a system dynamics model for the middle water body to simulate diel DO variability, and sequentially net ecosystem metabolism, the results showed the critical effects of artificial hydrological alterations to ecological processes in estuarine ecosystems. However, the focus of most studies was on phytoplankton community, other biological communities such as macrophyte, periphyton, zooplankton and zoobenthos communities, were ignored. Moreover, GPP and R_e were driven by a series of environmental factors, such as temperature, salinity, wind, light, nutrients, hydrodynamics, even biological feeding in estuarine ecosystem (Caffrey, 2003; Caffrey et al., 2014; Testa and Kemp, 2008; Azevedo et al., 2008; Rochelle-Newall et al., 2011; Parker et al., 2012; Tang et al., 2015), the effects of a single stressor were difficult to separate from that of other stressors (*e.g.* predation). Therefore, it was significant to take into account combined pressure such as water quantity, water quality, and biological feeding.

AQUATOX model is a general water ecological model that represents the combined environmental fate and effects of conventional pollutants, such as nutrients and sediments, and toxic chemicals in aquatic ecosystems (Park and Clough, 2014), which was described extensively in the literatures. Park et al. (2008) applied the AQUATOX model to simulate ecosystem environmental fate and ecological effects of pollutants in lakes and other aquatic ecosystems, and obtained direct or indirect influence of various factors on the lakes. Niu et al. (2016) predicted the variations of nutrient with the changes of plant and animal species in a landscape lake using AQUATOX model. Clough et al. (2017) estimated natural resource injuries for the Deepwater Horizon Oil release using AQUATOX Release 3.1. AQUATOX model was also applied in determining the ecological risk assessment of organic chemicals in aquatic ecosystems (Zhang et al., 2013; Zhang and Liu, 2014; Lombardo et al. 2015). However, the studies of AQUATOX model application mainly focused on the variances of ecosystem structural metrics, measured by biomass, when affected by light, nutrient or chemical stressors; the functional metrics, such as GPP and R_e, were reported less.

The aim of the study was to develop an AQUATOX model for estuarine ecosystem, and simulate the temporal change of GPP and R_e in estuarine ecosystem; analyze the main factors of GPP and R_e by stepwise multiple regression analysis and path analysis based on the model output. It perhaps is the first application of AQUATOX in GPP and R_e simulation of estuarine ecosystem. The study is helpful for us to understand correlation between physical–chemical processes and ecosystem metabolism, and gives information for estuarine ecosystem management.

2. Model and materials

2.1. Model description

AQUATOX, developed by US EPA in 2002 for Release 1, is updated in 2014 for Release 3.1 plus. The model includes five parameter libraries and contains a large number of model parameters. The model parameters provide relevant coefficients for the process functions. Users can use the default input parameters of the model itself, and also specify values in terms of the specific circumstances of simulated objects. AQUATOX considers several trophic levels, including producer populations, consumer populations and detritus. It can be implemented as a truly complex food-web model, and provides a means for simulations of aquatic ecosystem metabolism, even in estuarine environment.

GPP is defined as the total autotrophic conversion of inorganic carbon to organic forms, R_e is the total oxidation of organic C to inorganic C by both heterotrophic and autotrophic organisms, where, R_e is the sum of the respiration of the autotrophs (R_a) and that of the heterotrophic organisms (R_h) (Lovett et al., 2006; Dodds and Cole, 2007). Net ecosystem production (P_n) is the difference between GPP and R_e ($P_n = GPP - R_e$), and reflects the balance between all anabolic ($P_n > 0$) and catabolic processes($P_n < 0$). Fig. 1 provides conceptual model of different trophic biological communities of aquatic ecosystem with GPP, R_e and P_n.

Dominant species found in Haihe estuary had been modeled with AQUATOX (Release 3.1 plus) in the study. These are three phytoplankton, one periphyton, one macrophyte, two zooplankton, three benthic macroinvertebrate and two fish populations. Basic equations used in the model were listed in Table 1. Detailed descriptions of the equations used could be found at the following web link: http://water.epa.gov/scitech/datait/models/aquatox/upload/Technical-Documentatio-3-1.pdf.

2.2. Study area and sampling

The study area is in Haihe estuary, at 38°58′N and 117°42′E, the west of Bohai Sea, locating in Binhai New Area of Tianjin city. The average temperature was 12.3 ℃, and the water depth 5–10 m. This is a shallow water area with a mild slope (0.001–0.008) and fine silt bottom (< 0.02 mm). Now, river runoff decreased to less than $9 \times 10^8\ m^3/y$ due to water extraction or dam construction in the upstream of Haihe