# Modeling net ecosystem metabolism influenced by artificial hydrological regulation: An application to the Yellow River Estuary, China

Shi Tang, Tao Sun *, XiaoMei Shen, Man Qi, MeiLi Feng

*State Key Laboratory of Water Environment Simulation, School of Environment, Beijing Normal University, No. 19, Xinjiekouwai Street, Haidian District, Beijing 100875, China*

## ABSTRACT

The present study examined the critical effects of artificial hydrological alterations to ecological processes in estuarine ecosystems. We integrated an open-water method of net ecosystem metabolism (NEM) with a system dynamics model of dissolved oxygen (DO) to understand responses of ecosystem function to variation in river flow. Turbidity pulse effects on NEM and temporal variation were emphasized following integration of a light attenuation coefficient–turbidity submodel into the system dynamics model. A logarithmic relationship between freshwater inflow and turbidity was derived from field data. Subsequently, the influence of discharge magnitude, rate of change, and flow timing to NEM variation were analyzed in a case study of the Yellow River Estuary, China. The model results indicated an ecosystem might transform from autotrophic to heterotrophic metabolism in April under the effects of artificial hydrological regulation and turbidity pulses. Furthermore, water temperature was identified as another critical factor influencing NEM, due to its relationship with biological processes. Therefore, the impact of artificial hydrological regulation, and consequent turbidity pulses on NEM would be more influential when water temperature increased during the hotter season.

© 2014 Elsevier B.V. All rights reserved.

## 1. Introduction

Natural flow regimes play a central role in maintaining the health of aquatic ecosystems, including rivers, wetlands, estuaries, and floodplains (Poff et al., 1997; Richter et al., 1997). However, the construction of reservoirs, weirs, and other hydraulic structures to sustain human activities has significantly altered the natural flow of rivers worldwide (Sun and Feng, 2013). Hydrological regulation activities and freshwater supplement have been conducted in many inner and coastal regions, *e.g.* Ebro River, Spain, Paraná River, Brazil, Green River Basin, USA (Merritt and Cooper, 2000; Agostinho et al., 2004; Wang, 2005; Cai et al., 2011; Gallardo et al., 2012). The flood pulse affects productivity and biodiversity of river ecosystem, plant species, connectivity and biocom-plexity of waterbodies (Amoros and Bornette, 2002; Leyer, 2005; Gallardo et al., 2012). Consequently, environmental flow assessment and

allocation have been conducted in different river basins to maintain and satisfy ecosystem water requirements. Furthermore, considerable efforts have been invested to improve our understanding of the relationships among flow events, and the resulting biotic and ecosystem responses (Poff and Zimmerman, 2010; Sun et al., 2012). It is essential to establish the relationship between estuarine ecosystem responses to anthropogenic interference, and improve our understanding and interpretation of dynamic systems. Until recently, ecosystem structure indicators, including environmental parameters (*e.g.*, salinity), aquatic macroinvertebrate populations, endangered species, and commercial fish resources have been applied to characterize ecosystem status, and to assess the effects of pulse events resulting from artificial hydrological ecosystem regulation (MacKay et al., 2010; Poff and Zimmerman, 2010). Odum (1956) first introduced Net Ecosystem Metabolism (NEM) as an informative index to represent a reliable characterization of ecosystem structure and function. As such, NEM is an equilibrium state between production and consumption in a specific ecosystem, and therefore widely used to indicate different ecosystem trophic states; and can be applied to many diversified estuaries (Kemp and Boynton, 1980; D'Avanzo et al., 1996; Swaney et al., 1999;

* Corresponding author at: Tao Sun, Beijing Normal University, Beijing 100875, China. Tel.: +86 10 58805053; fax: +86 10 58805053.
  *E-mail address:* suntao@bnu.edu.cn (T. Sun).

Russell et al., 2006; Russell and Montagna, 2007). Typically, a positive NEM suggests an autotrophic system that relies on internal nutrient sources, and a negative NEM indicates a heterotrophic system, where external organic matter is dominant (Caffrey, 2003). Furthermore, NEM can be used to evaluate ecosystem services or budgets (Dodds and Cole, 2007), and set threshold of system health. Establishing relationships between variation in NEM and distribution of environmental variables could be taken as a critical issue, which should be addressed in the assessment of ecosystem response to human activities and global climate change.

The open-water method is the most important and widely applied approach to estimate NEM using the diel oxygen curve (Odum, 1956). In general, it is necessary to conduct detailed field measurements to clearly elucidate temporal and spatial NEM variability due to the diversity in these detected data and its drivers, which have been derived from statistical analyses of different estuaries (Russell et al., 2006; Russell and Montagna, 2007). However, the limitations of monitoring conditions, and the complexity of biogeochemical processes can prevent the feasibility of NEM estimates. Furthermore, the interactions involved in aquatic system processes must be extracted from investigating the influences imposed on oxygen availability and NEM for aquatic organisms. To date, different effects have been proposed to predict NEM from traditional parametric analyses, which avoid the constraints of data acquisition. The dissolved oxygen (DO) dynamics in aquatic environments result from changes in physical, chemical, and biological processes caused by natural or anthropogenic activities. Swaney et al. (1999) described DO concentrations as a function of salinity and depth, and subsequently applied a regression analysis to estimate metabolic rates in the Hudson River. Vallino et al. (2005) employed a 1D advection–dispersion model and a nonlinear inverse technique to estimate gross primary production, community respiration, and net ecosystem production from DO estimates in the Parker River, Plum Island Sound estuarine system. Due to the complex ecosystem processes and uncertain relationships between different environmental factors, Young et al. (2011) simulated NEM with an artificial neural network and Bayesian belief network.

In the present study, we simulated NEM variation under the effects of artificial hydrological regulation by integrating an open-water method of net ecosystem metabolism, and a system dynamics DO model. Turbidity pulse effects on NEM and temporal variation effects were emphasized following integration of a light attenuation coefficient–turbidity submodel into the system dynamics model. NEM responses to variation in discharge magnitude, rate of change, and flow timing were analyzed in the Yellow River Estuary case study. Distinguishing NEM response to altered conditions have potentially important implications in the decision-making process regarding sustainable and comprehensive control of water resources and ecosystem health.

## 2. Materials and methods

### 2.1. Model configuration

A dynamic model was developed for the middle water body in a spatially homogenous environment to simulate diel DO variability, and sequentially, net ecosystem metabolism. Odum (1956) first applied the approach to calculate Net Ecosystem Metabolism (NEM) from the diel oxygen curve. The open-water method was used to estimate NEM (Caffrey, 2003) as follows:

$$NEM(dt) = (DO_{t1} - DO_{t2}) \cdot Z - R_{aer} \tag{1}$$

where $DO_{t1}$ and $DO_{t2}$ are instant oxygen concentrations at $t_1$ and $t_2$, respectively; $Z$ represents the water depth; $R_{aer}$ is oxygen exchange

across the air–water interface, which increases or decreases DO concentrations in the water column. The method to calculate $R_{aer}$ will be introduced in the submodel Re-aeration below.

Multiple physical, chemical, and biological processes regulate the range in temporal and spatial variance of oxygen concentration in estuaries. Well-established data shows that time–variable interactions between photosynthetic production, community respiration, and re-aeration processes produce sinusoidal oscillations characteristic of diel DO profiles (O'Connor and Di Toro, 1970; Odum, 1956). In aquatic communities, DO is produced by plant photosynthesis, and consumed by community respiration, organic matter decomposition, nitrogen compound degradation (including ammonia and nitrite), and oxygen demand from streambed sediments. Another critical physical process affecting oxygen concentrations in the stream is re-aeration across the air–water interface. The DO model integrates phytoplankton oxygen production and consumption as a real component of the ecosystem. The re-oxygenation submodel consists of two components: re-aeration ($R_{aer}$) by wind and photosynthesis ($P_h$) by phytoplankton. The de-oxygenation term indicates how DO is consumed in the water body, including the biochemical oxygen demand (BOD), nitrogenous oxygen demand (NOD), and respiration ($R$) of aquatic phytoplankton. DO concentration in water can be described by the following rate equation:

$$\frac{dDO}{dt} = R_{aer} + P_h - R - BOD - NOD \tag{2}$$

#### 2.1.1. Re-aeration

$R_{aer}$ is the atmospheric and water body gas exchange flux governed by wind regimes and physical processes. Gas transfer from atmosphere to stream will occur when the water column is undersaturated; oxygen concentration in the water body will decrease when supersaturated (Caffrey, 2003). Re-aeration is dependent on flow hydraulic properties (Moog and Jirka, 1998; Rathbun, 1977), and is dominated by wind surface turbulence regimes (Chu and Jirka, 2003; Wanninkhof, 1992). Re-aeration is proportional to the difference between the instant oxygen concentration (DO), and the saturated dissolved oxygen concentration (DO$_{sat}$). Furthermore, estimates of $R_{aer}$ also depend on the following re-aeration coefficient ($K_r$) (Bott, 1996; Gelda et al., 1996):

$$R_{aer} = K_r(DO_{sat} - DO) \tag{3}$$

where $K_r$ is dependent on water temperature ($T$) and wind velocity ($W$). Eq. (4) proposed by Antonopoulos and Gianniou (2003) is used in the model.

$$K_r = 0.2W \cdot T_{cf} \cdot \exp(T - 20) \tag{4}$$

where $T_{cf}$ is a temperature correction factor. DO$_{sat}$ in Eq. (3) is a landmark value that has the potential to change if a change occurs in temperature or salinity. Elmore and Hayes (1960) provide many available formulas to calculate oxygen concentration at saturation. However, estuarine zones are under the influence of tidal invasion, and salinity ($S$) is an essential factor affecting the oxygen concentration. Therefore, DO$_{sat}$ is quantified following the polynomial Eq. (5) reported by Weiss (1970):

$$DO_{sat} = 14.6244 - 0.367134T + 0.0044972T^2$$
$$- 0.966S + 0.00205ST + 0.0002739S^2 \tag{5}$$

#### 2.1.2. Photosynthesis

$P_h$ is the amount of oxygen produced from carbohydrates through photosynthesis. Stefan and Fang (1994) deduced that gross photosynthetic oxygen production depends on several factors,