



Aquatic metabolism response to the hydrologic alteration in the Yellow River estuary, China



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SUMMARY

Successful artificial hydrologic regulation and environmental flow assessments for the ecosystem protection require an accurate understanding of the linkages between flow events and biotic responses. To explore an ecosystem's functional responses to hydrologic alterations, we analysed spatial and temporal variations in aquatic metabolism and the main factors influenced by artificial hydrologic alterations based on the data collected from 2009 to 2012 in the Yellow River estuary, China. Gross primary production (GPP) ranged from 0.002 to 8.488 mg O₂ L⁻¹ d⁻¹. Ecosystem respiration (ER) ranged from 0.382 to 8.968 mg O₂ L⁻¹ d⁻¹. Net ecosystem production (NEP) ranged from -5.792 to 7.293 mg O₂ L⁻¹ d⁻¹ and the mean of NEP was -0.506 mg O₂ L⁻¹ d⁻¹, which means that the trophic status of entire estuary was near to balance. The results showed that seasonal variations in the aquatic metabolism are influenced by the hydrologic alteration in the estuary. High water temperature and solar radiation in summer are associated with low turbidity and consequently high rates of GPP and ER, making the estuary net autotrophic in summer, and that also occurred after water–sediment regulation in August. Turbidity and water temperature were identified as two particularly important factors that influenced the variation in the metabolic balance. As a result, metabolism rate did not decrease but increased after the regulation. ER increased significantly in summer and autumn and reached a maximum after the water–sediment regulation in September. GPP and NEP reached a maximum value after the water–sediment regulation in August, and then decreased in autumn. Estuarine ecosystem shifted from net heterotrophy in spring to net autotrophy in summer, and then to net heterotrophy in autumn. Our study indicated that estuarine metabolism may recover to a high level faster in summer than that in other seasons after the short-term water–sediment regulation due to higher water temperature and nutrients.

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1. Introduction

Estuarine ecosystems are complex and important ecosystems in which many critical environmental processes occur, such as sediment deposition, fresh water–salt water interaction, material–energy exchanges, delta accretion, and pollutant retention (Montagna et al., 2002; Bai et al., 2012). Meanwhile, estuarine ecosystems are subject to varied changes resulting from human activities and natural processes, which impair the health and fitness of resident biota, as well as the ability of the estuaries to deliver ecosystem functions and services for human well-being (Borja et al., 2010; Lotze et al., 2006). As one of the main effects caused by human activities in large estuarine ecosystems, the global regulation of rivers and streams by building reservoirs and dams, has

altered downstream hydrologic regime and significantly changed aquatic ecosystems during the twentieth century (Pyrn and Neumann, 2008; Ormerod et al., 2010). A variety of effects caused by hydrological regulation activities, the responses of basic physical and biogeochemical processes, e.g., the movement of sediment and benthic biota (Lake et al., 2000), nutrient cycling and decomposition rates (Liu, 2014), soil processes and pollutant accumulations (Bai et al., 2012), the alteration of landscape and riparian zone (New and Xie, 2008; Merritt et al., 2010), and the recruitment and survival of fish, macro-invertebrates, herbaceous community members associated with mycorrhizal fungi (Beauchamp et al., 2007; Humphries et al., 2013; Navarro-Llacer et al., 2010; Poff and Zimmerman, 2010) have been reported. However, the responses of basic function, aquatic metabolism and ecosystem balance, to the river discharges caused by hydrologic alteration, such as the flood pulse or the change of flood pulse time due to flow regulation, need to be further investigated, especially in estuaries compared to such responses in freshwater sections of river.

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Aquatic metabolism, a parameter first devised by Odum (1956), is an integrative measurement of aquatic ecosystem functioning and can be used to assess impairment (Aristegi et al., 2009). It represents a unique, convenient and integrative process that reflects system-level responses to external perturbations (Tuttle et al., 2008; Staehr et al., 2012). Aquatic metabolism, represented by the gross primary productivity (GPP), ecosystem respiration (ER), and net ecosystem production (NEP) of the water column, provides a useful composite indicator of ecosystem function in the aquatic ecosystem. GPP represents total autotrophic conversion of inorganic carbon to organic forms. ER represents total oxidation of organic C to inorganic C by both heterotrophic and autotrophic organisms. NEP represents the balance between system-level production and respiration. NEP also serves as a metric for the ecosystem's trophic state, carbon source or sink, and can transcend the range of spatial and temporal scales that are relevant for assessing ecological changes (Cole et al., 2000; Young et al., 2011). If $NEP > 0$, the ecosystem is autotrophic, suggesting that the internal production of organic matter dominates and the ecosystem will be a carbon sink. If $NEP < 0$, the system is heterotrophic and depends on external sources of organic matter the ecosystem will be a carbon source (Gu et al., 2011; Salisbury et al., 2008).

Many studies have examined effects of episodic events on metabolism in freshwater ecosystems (Acuña et al., 2004; Staehr et al., 2012; Tuttle et al., 2008; Uehlinger, 2000), less in marine systems (Guadayol et al., 2009; Sarma et al., 2005) and estuarine systems (Gutiérrez-Cánovas et al., 2009; Mead and Wiegner, 2010). Aquatic metabolism is influenced by various environmental parameters, including nutrient concentration (Delgadillo-Hinojosa et al., 2008; Smith and Hollibaugh, 1997), temperature and salinity (Caffrey, 2003, 2004), and freshwater discharge (Russell et al., 2006; Russell and Montagna, 2007; Mead and Wiegner, 2010). High flow events are often accompanied by pulsed inputs of inorganic nutrients, dissolved organic carbon and suspended sediments, which can induce both positive and negative effects on primary production and respiration, and subsequently the variation of metabolic balance in estuaries (Gregory et al., 1991; Kemp et al., 1997; Tang et al., 2014). Understanding the metabolic dynamic processes in estuaries due to hydrologic alteration is of importance to provide guidance in setting artificial hydrologic regulations.

The Yellow River is China's second longest river and the sixth longest river in the world. It once annually contributed approximate 6% of the world's terrestrial sediment supply to the global ocean. In recent years, dramatic changes have occurred, including an approximate 90% reduction in annual water and sediment flux, approximate 70% loss in suspended sediment concentration, and coarsening grain sizes (Sun and Feng, 2012; Yu et al., 2013). Water and sediment inflows into the Yellow River estuary have been decreasing for several decades. Drying occurred annually in the early 1990s, with an average of 100 days per year without water in the lower reaches. Simultaneously, heavy silting raised the riverbed in the main channel, as the flow of the river is not capable of washing down the silt into the sea (Miao et al., 2010; Yang, 2011). To prevent rise of the riverbed, relieve drought and alleviate water and sediment imbalances of the Yellow River, water–sediment regulation (WSR), also called water and sediment discharge regulation (Bi et al., 2014), water–sediment modulation (Yu et al., 2013), or flow–sediment regulation (Bai et al., 2012), has been carried out to transport the sediment deposited at reservoir and riverbed to the sea depending on the high discharge pulse by adopting some engineering activities or artificial regulations since 2002, such as releasing huge amount of freshwater from different reservoirs in a short time.

The overall aim of this study was to investigate the dynamic behaviour and environmental control of estuarine metabolism during the hydrologic alteration. We analysed the spatial and temporal variability of aquatic metabolism under the effects of WSR in the Yellow River estuary, China. González-Ortegón et al. (2010) pointed out that the resulting higher turbidity due to regulated freshwater inflow made the water column more heterotrophic. We hypothesized that (1) metabolism will be reduced and net heterotrophy will occur after WSR due to the high flood pulse over a short time. (2) Turbidity will be one of the main driving factors and negatively correlated with metabolism. (3) Variation in metabolism is significantly different between the freshwater dominated area and saltwater dominated area due to the alternative effects of tidal currents and river discharges. This study used statistical analysis of field monitoring data to infer the effects of hydrologic alteration on estuarine metabolism. The results may improve our understanding of the changes in aquatic metabolism caused by hydrologic alteration and will provide guidance in setting artificial hydrologic regulations.

2. Material and methods

2.1. Study area and experimental design

The Yellow River estuary is located in the eastern part of China's Shandong Province (Fig. 1). It has a warm-temperate continental monsoon climate with distinct seasons, including a rainy summer. The mean tidal range is 0.73–1.77 m. The estuary is shallow, with a water depth ranging from 1.3 to 5.5 m, and it is characterised by a high sediment concentration (mostly fine clay minerals) in the water column caused by the large sediment loads produced by erosion in the middle reaches of the Yellow River, as it flows through China's Loess Plateau (Ren and Shi, 1986). The average annual rainfall ranges from 530 to 630 mm, and rainfall tends to be higher in summer (70% of the annual total). Average monthly water temperatures range from -4.1°C in January to 26.7°C in July, and the average annual wind speed ranges from 3.1 to 4.6 m s^{-1} . Average annual runoff is $31.3 \times 10^9\text{ m}^3$; the highest and lowest annual runoffs were $97.3 \times 10^9\text{ m}^3$ and $1.9 \times 10^9\text{ m}^3$, which occurred in 1964 and 1997, respectively.

The WSR, carried out since 2002, resulted in high monthly average water discharge and sediment load occurring at least 2 months prior to the event (Fig. 2A and B). It was carried out six times and the maximum water discharge reached $3646\text{ m}^3\text{ s}^{-1}$ (on June 30, 2009) during the regulations from 2009 to 2012, which is 30 times the minimum flow and 3.7 times the typical low flow during the flood season based on data from the Lijin hydrologic station (Table 1; Fig. 2C). WSR caused a rapid increase in water discharge, which induced higher turbidity due to a high sediment load in the estuary.

Four sampling sites (A to D) were established in the Yellow River estuary at locations with open water and without canopy cover (Fig. 1). Sites A, B and C were located in the channel of the estuary and site D was located coastline. The distance between each two neighbouring sites was $\sim 10\text{ km}$. The salinity gradient of sampling sites was: site A low salinity (always $<1\text{‰}$), B and C variable salinity, D marine salinity (always $>18\text{‰}$). The mean water depth was approximately 2 m at all of our monitoring sites. The monitoring period in our study was from May 2009 to May 2012 which included samples pre-regulation (April, June and July) and post-regulation (August, September and October) each year (Fig. 2C, Table 1). Each site was continued monitoring one or three days during each sampling period (e.g., in May 2009) and these

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