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Extremely high sulfate reduction, sediment oxygen demand and benthic nutrient flux associated with a large-scale artificial dyke and its implication to benthic-pelagic coupling in the Yeongsan River estuary, Yellow Sea

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ABSTRACT

We investigated environmental impact of large-scale dyke on the sediment geochemistry, sulfate reduction rates (SRRs), sediment oxygen demand (SOD) and potential contribution of benthic nutrient flux (BNF) to primary production in the Yeongsan River estuary, Yellow Sea. The sediment near the dyke (YE1) with high organic carbon (C_{org}) content ($>$ 4%, dry wt.) was characterized by extremely high SOD (327 mmol m^{-2} d^{-1}) and SRRs (91–140 mmol m^{-2} d^{-1}). The sulfate reduction accounted for 73% of C_{org} oxidation, and was responsible for strikingly high concentrations of NH_4^+ (7.7 mM), PO_4^{3-} (67 μM) and HS^- (487 μM) in pore water. The BNF at YE1 accounted for approximately 200% of N and P required for primary production in the water column. The results present one of the most extreme cases that the construction of an artificial dyke may have profound impacts on the biogeochemical and ecological processes in coastal ecosystems.

1. Introduction

Effective management of natural water resources has been one of the incessant human endeavors in the 21st century (McCartney, 2002). At present, to resolve the shortage of water resources induced by a burgeoning population and increasing demand for agricultural and industrial activity, > 45,000 large dams and an estimated 800,000 small dams have been constructed in river systems worldwide (Manatunge et al., 2008; Rockström et al., 2009). However, in contrast to its positive effects, construction of a large dyke, especially in a macrotidal estuarine environment, may induce several serious issues associated with biogeochemical and ecological processes in coastal ecosystems. For example, a marked decrease of the current velocity near the dyke stimulates massive deposition of organic-rich fine particles, which greatly alter the physico-chemical properties of the water column and sediment (Portnoy and Giblin, 1997; Han and Park, 1999; Kang, 1999; Byun et al., 2004; Kim et al., 2006; Lee et al., 2012b; Min et al., 2012). The deposition of fine-grained sediment near the dyke resulting from a decreased tidal current also increases the depth of light penetration, which ultimately stimulates a phytoplankton bloom in the water column (Cole and Cloern, 1984, 1987; Moon, 1990). In addition, the discharge of freshwater, which presumably includes a tremendous amount of particulate and dissolved organic matter and inorganic nutrients, may induce eutrophication and a phytoplankton bloom (Cloern et al., 1983, 2014; Sin et al., 2013, 2015), which ultimately modifies trophic structures and biogeochemical processes in coastal ecosystems (O'Higgins and Wilson, 2005; Duan et al., 2008; Chai et al., 2009; Ylöstalo et al., 2016). Consequently, the combination of sediment settling and phytoplankton bloom results in an accumulation of a large amount of particulate organic carbon (POC) in the surface sediments near the dyke (Lee et al., 2012b).

In shallow coastal environments, organic materials that reach the sea floor are quickly mineralized by a variety of microorganisms using various electron acceptors, such as oxygen, nitrate, manganese oxide, iron oxide and sulfate (Canfield et al., 1993). In an organic-enriched coastal sediment, in which oxygen is rapidly depleted within the top few millimeters of the sediment, sulfate reduction becomes a dominant organic carbon (C_{org}) oxidation pathway, comprising 50–100% of the anaerobic C_{org} oxidation (Canfield et al., 2005; Jørgensen and Kasten, 2006; Hyun et al., 2007, 2009). Major environmental and ecological issues arising from enhanced sulfate reduction in a coastal ecosystem include the accumulation of toxic and highly reactive dissolved sulfide in the sediment (Bagarinao, 1992; Gray et al., 2002; Hargrave et al., 2008; Cottrell et al., 2016) and the release of nutrients, such as ammonium and phosphate, into the overlying water column (Grant et al., 1995; Richard et al., 2007; Hyun et al., 2013; Matos et al., 2016).

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The release of regenerated nutrients from the sediment to the overlying water may deepen the eutrophic conditions in the water column (Boynton and Kemp, 1985; Meyer-Reil and Köster, 2000; Giles et al., 2006; Percuoco et al., 2015; Lacoste and Gaertner-Mazouni, 2016). It has been shown that benthic nutrient release supplies 30–160% of the nutrients required for phytoplankton primary production in a shallow coastal ecosystem via benthic-pelagic coupling (Bulleid, 1984; Kemp and Boynton, 1984; Hopkinson et al., 2001; Lawrence et al., 2004; Lee et al., 2012a,b; Hyun et al., 2013).

In Korea, to ensure freshwater for agriculture and industry, over 18,000 dams, dykes and weirs have been constructed during the last four decades, and approximately 1200 of these dams are categorized as large, based on either their storage capacity of 3 million m^3 (with heights of 10 m to 15 m) or length > 2000 m (MIFAFF, 2002; Lee et al., 2009). However, little is understood regarding the impact of large-scale artificial dykes on the sediment geochemistry, sulfate reduction and its partitioning in total C_{org} oxidation, as well as the potential significance of benthic nutrient release resulting from C_{org} oxidation in stimulating high primary production in a coastal ecosystem (Lee et al., 2012b). Virtually, to our knowledge, any comprehensive studies on the benthic anaerobic metabolism by sulfate reduction and its potential impact on biogeochemical and ecological processes associated with the construction of a large-scale dyke have not been conducted worldwide in a macrotidal estuarine environment. The main objectives of this study were to: (1) elucidate the effect of an artificial dyke on the sediment geochemistry, sediment oxygen demand and anaerobic C_{org} oxidation by sulfate reduction, with a special emphasis on the massive deposition of organic matter near the dyke, and (2) evaluate the potential of the benthic nutrient flux to support primary production in the water column via benthic-pelagic coupling in the macrotidal Yeongsan River estuary, one of the four largest river systems in South Korea.

2. Materials and methods

2.1. Study area

The Yeongsan River estuary (YRE) is located in the southwestern part of the Korean Peninsula (Fig. 1). The Yeongsan River dyke is 4.3 km in length and 19.5 m in height and was constructed in February 1981 to enlarge the reclaimed land space and provide freshwater for agriculture and industry. However, the construction of the dyke and the consequent reclamation of the coastal area led to a marked increase in the tidal amplitude and a decrease in the current velocity. For example, the tidal range measured at Mokpo Harbor increased from 246 cm to 283 cm before and after the construction of dyke, respectively (Kang, 1999). The tidal current decreased from 81 cm s^{-1} before the dyke construction to 15 cm s^{-1} after the dyke construction (Kang, 1999). The inner part of the dyke, Yeongsan Lake, has an area of 34.6 km^2 and a 235 million m^3 storage capacity of freshwater. The annual average hydraulic retention time and discharge of Yeongsan Lake are 33.21 d^{-1} and 28×10^8 m^3 yr^{-1}, respectively (Lee and Kim, 2003; Park et al., 2008). Therefore, the discharge of high-nutrient freshwater also exerts a large impact on the coastal ecosystems by replacing plankton species and inducing phytoplankton blooms (Sin et al., 2013, 2015).

2.2. Sampling and handling

In the YRE, approximately 80% of the annual discharge of freshwater occurs during the summer monsoon, from July to September (Cho et al., 2004). To avoid disturbance by freshwater discharge, sea water and sediment samples were collected twice in springtime in 2008 and 2011, when freshwater discharge had not been executed for > 15 days before sampling. The first sampling campaign was performed in May 2008 to investigate the sediment geochemistry and benthic microbial metabolic activities by sulfate reduction. Samples were taken at three sites (YE1, YE2 and YE3) according to the sediment color, velocity of the tidal current and sedimentation rate at different distances from the dyke (Table 1, Fig. 1). Based on the results obtained from the first sampling, we performed an additional experiment to determine the sediment oxygen demand (SOD) and benthic nutrient flux (BNF) at two sites (YE1 and YE3) in April 2011. This experiment was conducted to evaluate the potential impact of the dyke on the total C_{org} oxidation and benthic nutrient release and its contribution to primary production in the water column via benthic-pelagic coupling.

The sea water temperature and salinity were measured using a salinity-temperature probe (YSI model-85). The light penetration depth was estimated using a Secchi disk. Water samples were collected with a 5 L Niskin sampler at the surface and bottom layer of the water column. Water samples for measuring concentrations of suspended particulate material (SPM), chlorophyll-a (Chl-a) and inorganic nutrients were collected in duplicate. Water samples taken for an analysis of inorganic

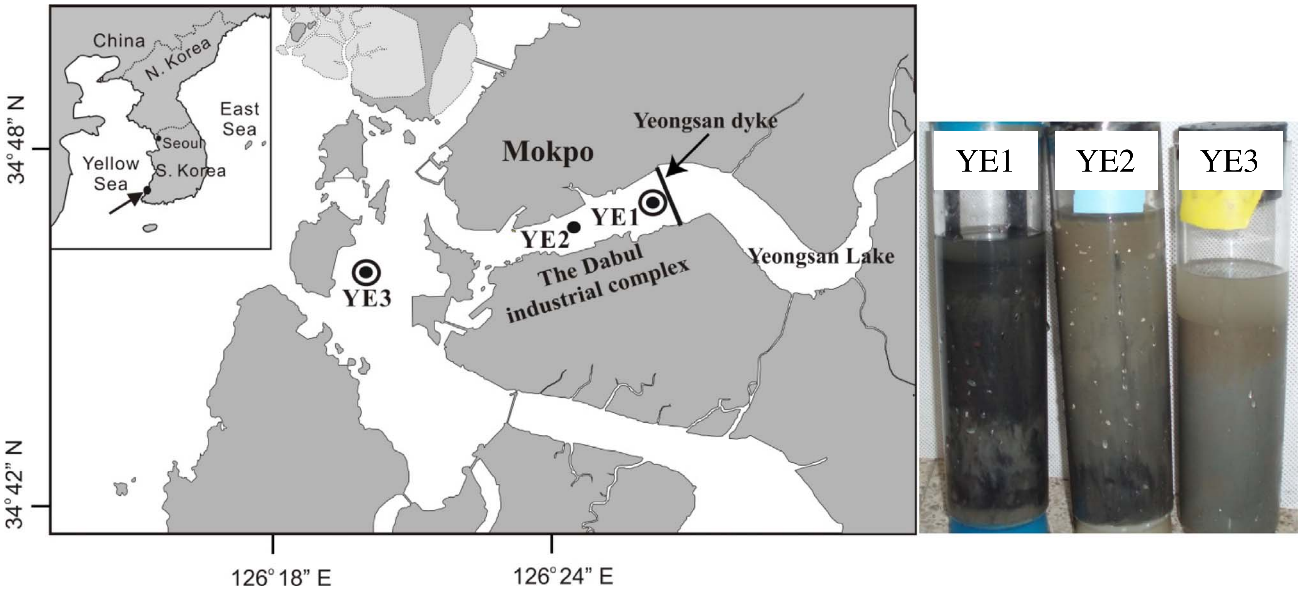

Fig. 1. Sampling stations in the Yeongsan River estuary and pictures showing the sediment color at each station. Sediment oxygen demand and benthic nutrient flux were measured once in 2011 at YE1 and YE3 (double circles).