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The river–estuarine continuum of nutrients and phytoplankton communities in an estuary physically divided by a sea dike

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ABSTRACT

Spatial and temporal variation in nutrients, physical variables, primary productivity and the size and taxonomic composition of phytoplankton was investigated over an annual cycle in a macrotidal estuary transected by a sea dike in a temperate region. Our aim was to evaluate whether the river continuum approximation was valid in the highly altered estuary. Ambient nutrient concentrations were generally much higher in the freshwater than in the seawater zone, but decreased downstream. The chlorophyll *a* concentrations were also much higher in freshwater and decreased downstream along the river–estuary continuum. Primary productivity displayed a similar pattern, except in February and August, when it increased rapidly in seawater following freshwater discharge. This suggests that nutrient availability could have been important in determining the spatial variation in phytoplankton biomass and production. Winter and summer blooms of nano-sized phytoplankton developed in freshwater dominated by *Stephanodiscus* sp. and *Eudorina elegans*, which favour low and high temperatures, respectively. The nutrient increase following eutrophic freshwater discharge may have supported phytoplankton blooms dominated by *Thalassiosira rotula* (micro-sized) and *Heterocapsa* sp. (nano-sized) in the late winter and monsoon season, respectively, in the upper regions of the seawater zone. However, blooms and primary productivity decreased downstream and the taxonomic composition also varied, corresponding to significant spatial changes of nutrients, salinity and water transparency that were validated by statistical analyses. This suggests that the river continuum was sustained between the fresh and seawater zones, as well as within individual zones, although they were physically transected by the sea dike. The river continuum in highly altered estuaries that can extend seaward during monsoons may be important to the primary production and food web of the Yellow Sea.

1. Introduction

Estuaries where freshwater and seawater interact are complicated marine systems. However, they are excellent ecological study sites because biotic and abiotic mechanisms that vary spatially and temporally control the dynamics of organisms in the entire system. Estuaries are also productive (Ryther, 1969) and play a major role in supporting the commercial fisheries of coastal areas because they provide habitat and food resources for juvenile commercial fish and shellfish (Smith, 1966; EPA, 1982; Levinton, 1982). The concept of the river continuum was proposed to interpret a linkage between a continuum in physical parameters, including geomorphology, and biotic communities along the channel of pristine river systems (Vannote et al., 1980; Minshall et al., 1985). The concept theorises that rivers are linked horizontally, so that the processes occurring in downstream ecosystems are influenced by those in upstream ecosystems from a holistic perspective. This concept was introduced to explain the sources and sinks of organic carbon and its metabolism along the river–estuary continuum in estuaries (Howarth et al., 1996; Prahl et al., 1997). The linkage between nutrients and biotic communities in relation to river–estuary functioning must also be addressed because nutrients delivered along the continuum, especially during high-flow periods, contribute to primary and fishery production increases in estuaries and along the coast (Robins et al., 2005; Billen and Garnier, 2007; Saeck et al., 2013). Therefore, the temporal and spatial linkage between the biotic and abiotic continuum is important for understanding the various coastal estuarine systems, and for improving the biological

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integrity of estuaries. Human activities, such as estuary damming, may cause perturbations in the river–estuary continuum, but anthropogenic effects on river–estuary continua are not fully understood. Few holistic studies exploring freshwater systems formed by the damming of marine (seawater) systems have been reported.

Changes in the sizes and species composition of phytoplankton, major primary producers in coastal systems, affect the biogeochemistry and structure of the food web in these systems; thus it is important to understand them (Rousseau et al., 2000; Jouenne et al., 2005; Finkel et al., 2009). Phytoplankton size and species structure are sensitive to perturbation (Lassen et al., 2004; Totti et al., 2005; Spatharis et al., 2007), so they may also be used to identify changes in the chemical and physical attributes of the water column generated by environmental perturbations.

The Youngsan River estuary (Fig. 1), one of the five major river estuaries in South Korea, is located in the temperate south-western part of the country (34°N, 126°E). The estuary is influenced by Asian monsoons, with a high rainfall in summer but low rainfall in the other seasons. It has also experienced anthropogenic pressure since a sea dike was constructed 7 km from its mouth, which physically partitioned the water body into freshwater and seawater zones (Fig. 1). The degradation of water quality, such as the development of hypoxia in the bottom water, has been reported for the freshwater zone (Park et al., 2008) and seawater ecosystems (Lim et al., 2006). Seasonal variation in water quality and the size structure of phytoplankton in the seawater ecosystem are influenced mainly by freshwater discharge rather than by climate (Sin et al., 2013). However, the seawater zone behaves as a "semi-enclosed coastal body of water that receives essentially no inflow of fresh water" (Pinet, 2012) when the waterway gates of the dike are closed. The phytoplankton and nutrient dynamics of the estuary have been studied mostly in the seawater zones (e.g. Byun et al., 2005, 2007; Sin et al., 2013). Information on the taxonomic composition of phytoplankton is not available for the estuary, including the freshwater zone. In this context, the validity of the concept of a river continuum within and between the freshwater and seawater zones must be addressed. Thus, we investigated the spatio-temporal variation in nutrients, physical properties, primary productivity and phytoplankton size and taxonomic structures along the river–estuary continuum. Many estuarine systems on the west coast of South Korea have experienced similar perturbations due to the construction of sea dikes (e.g. Sin et al., 2012). Estuarine systems on the west coast, including the Youngsan River estuary, exchange water masses with the Yellow Sea (mean depth 44 m), and a shallow water body is located between the east coast of China and the west coast of Korea. Elucidating estuarine phytoplankton, nutrient dynamics and physical properties within the river continuum concept is important to promoting better management and an understanding of Yellow Sea ecosystems.

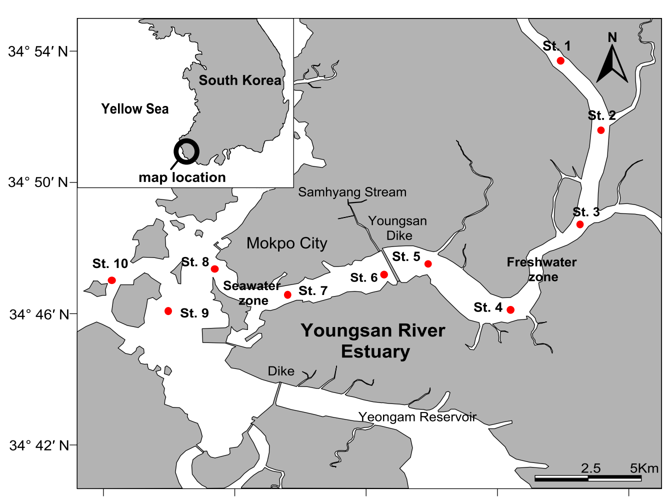

Fig. 1. The location of the sampling stations along the axis of the Youngsan River estuary on the west coast of South Korea, in an area that interacts with the Yellow Sea.

2. Materials and methods

2.1. Study site and sampling design

The Youngsan River has a watershed area of 3468 km^2 and flows along a length of 137 km. In 1981, a sea dike 4.4 km in length and 20 m in height was constructed in its estuary (Fig. 1). The tidal flats in the river were land-filled to reclaim paddy fields and to control floods; freshwater from the river is supplied to an extensive area of paddy fields in the river basin. Freshwater is also introduced into the seawater zone of the estuary at low tide from the sluice gates in the dike when the gates are opened at peak water level in the freshwater zone. The gates were opened 76 times during the study period from September 2008 to November 2009 and the volume of freshwater discharge ranged from 0.354 to 127.6 $\times$ 10^6 m^3 (Fig. 2). The tides in the estuary are primarily semidiurnal and dominated by ebb tides with a macrotidal range of 3–6 m (Kang and Jun, 2003; Byun et al., 2004).

Ten stations along the estuary channel (Fig. 1) were sampled monthly from September 2008 to November 2009 (except in December 2008 and September and October 2009) to include four seasons: winter (January–February), spring (March–May), summer or monsoon season (June–August) and autumn (September–November). Five stations (Sts. 1–5) were located in the freshwater zone inside the sea dike, and five stations (Sts. 6–10) were located in the seawater outside the sea dike. Inside and outside zones of the sea dike were defined as "freshwater" and "seawater", respectively, in this study. The sluice gates of the dike were closed, and no freshwater was discharged during sampling. Water samples were collected using a Niskin water sampler during a low neap tide at 0.5 m below the surface and above the bottom. The water depth at the sampling stations ranged from 3.2 to 17.5 m and from 8.0 to 25.3 m in the freshwater and seawater zones, respectively (Table 1), and the tidal range was 1.2–4.4 m during sampling.

2.2. Measurement of water properties

Water temperature (°C), salinity, turbidity (NTUs) and dissolved oxygen (DO, mg l^{-1}) were measured with a YSI® Model 6600 multiparameter probe (YSI Inc., Yellow Springs, OH, USA). Salinity was measured based on the Practical Salinity Scale. Water density (kg m^{-3}, ρ) was calculated from the salinity and temperature data using the EOS-80 equation of state by assuming that pressure does not change with depth for the study sites. The density difference between surface and bottom water ($\triangle\rho$) was used to estimate the extent of stratification in the water column. Water clarity was estimated using a Secchi disk and water depth was measured using a Hondex™ PS-7 digital sounder (Honda Electronics, Aichi, Japan). Underwater light intensity was measured with an LI-COR® photosynthetically active radiation (PAR) quantum sensor (Li-Cor, Lincoln, NE, USA).

Water samples (100 ml) for nutrient analysis were filtered through 25-mm GF/F glass microfibre filters (0.7 μm; Whatman, Maidstone, Kent, UK) shortly after sampling to minimise microbial transformation. Samples for ammonium (NH_4^+), nitrite + nitrate ($NO_2^- + NO_3^-$), dissolved silica (DSi) and orthophosphate (PO_4^{3-}) analyses were preserved frozen (<−20 °C). Nutrient concentrations