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Estuarine, Coastal and Shelf Science 67 (2006) 653–663
ESTUARINE COASTAL AND SHELF SCIENCE
www.elsevier.com/locate/ecss

Tidal time-scale variation in nutrient flux across the sediment–water interface of an estuarine tidal flat

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Received 27 January 2005; accepted 3 January 2006
Available online 3 March 2006

Abstract

We determined the range of the tidal variations in nutrient flux across the sediment–water interface and elucidated mechanisms of the flux variation in two estuarine intertidal flats (one sand, one mud) in northeastern Japan. Nutrient flux was measured using in situ light and dark chambers, which were incubated for 2 h, 2–6 times per day. Results showed that nutrient concentration in overlying water varied by tide and was also affected by sewage-treated water inflow. The nutrient fluxes responded quickly to the tidal variation in overlying water chemistry and the range of the variation in flux was as large as the seasonal-scale variation reported in previous studies. In the sand flat, salinity increase likely enhanced benthos respiration and led to increases in both O_2 consumption and PO_4^{3-} regeneration under low illumination, while benthic microalgae were likely to actively generate O_2, uptake PO_4^{3-} and suppress PO_4^{3-} release under high illumination (>900 μmol photons $m^{-2}\,s^{-1}$). Also in the mud flat, PO_4^{3-} flux was related with O_2 flux, although the range of temporal variation in PO_4^{3-} flux was small. In both the flats, NH_4^+ flux was always governed by NH_4^+ concentration in the overlying water; either an increase in NH_4^+ uptake or a decrease in NH_4^+ release was observed as the NH_4^+ concentration rose due to inflow of river water or input of sewage-treated water. Although NO_3^- tended to be released in both tidal flats when low NO_3^- concentration seawater dominated, their relationship was likely to be weakened under conditions of low oxygen consumption and suppressed denitrification. It is likely that tidal variation in nutrient flux is governed more by the nutrient concentration than other factors, such as benthic biological processes, particularly in the case where nutrient concentration in the overlying water is relatively high and with wide amplitude.

Keywords: inorganic nitrogen and phosphorous; diffusive flux; tidal variation; intertidal flat; nutrient concentration; chamber; sand and mud; Nanakita estuary

1. Introduction

The nutrient exchange across the sediment–water interface of tidal flats is an important pathway for nutrient cycles in shallow coastal ecosystems. The evaluation of the exchange flux is indispensable to identifying the effects of tidal flats on the coastal environment and for effective planning and management of tidal flat ecosystems (Kurihara, 1988; Reay et al., 1995; Sanders et al., 1997; Yin and Harrison, 2000). However, there are a number of factors which influence the flux, and which vary spatially and temporally, making an accurate flux determination difficult. An accurate calculation of the flux is problematic, particularly in estuarine tidal flats, because of the dramatic temporal changes in environmental conditions due to the alternating replacement of overlying water with sea and river waters. Unless short-term fluctuations are taken into account in areas strongly affected by the tide, like estuaries, estimating a typical flux of nutrients is all but impossible.

Tidal variations in the flux are still a very obscure phenomenon, which is due to there having been insufficient observations focusing on tidal variations in the flux and environmental conditions. In most previous studies, nutrient flux measurement has been conducted only once, or once a month or season, using sediment core samples or in situ chambers (e.g. Reay et al., 1995; Rysgaard et al., 1995; Forja and Gómez-Parra, 1998). There is

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doi:10.1016/j.ecss.2006.01.005

a possibility that short-term fluctuations in the flux have been missed in those investigations. Hence, the range of flux variations and their sensitivity to short-term changes in environmental factors have yet to be clarified.

Various physical and chemical factors affect the nutrient exchange process at the sediment–water interface. The nutrient exchange flux and the vertical concentration profile in sediment have been shown to be influenced by changes in nutrient concentrations of overlying water (Asmus, 1986; Kristensen, 1993; Magalhães et al., 2002), water temperature (Klump and Martens, 1989; Forja et al., 1994; Rysgaard et al., 1995; Sundbäck et al., 2000), hydrodynamic condition (Rutgers van der Loeff, 1981; Vidal and Morguí, 1995; Oldham and Lavery, 1999), and sediment condition (Blackburn and Henriksen, 1983; Jensen et al., 1990; Enoksson, 1993; Sloth et al., 1995). Various biological processes, which can greatly modify the nutrient flux, have also been reported, including the mineralization of organic nutrients (Hopkinson, 1987; Reay et al., 1995; Yin and Harrison, 2000), oxygen production and nutrient uptake by benthic microalgae (Sundbäck and Graneli, 1988; Reay et al., 1995; Nishimura et al., 1996; Kuwae et al., 1998; Wilson and Brennan, 2004), nitrification and denitrification (Kemp et al., 1990; Risgaard-Petersen et al., 1994; Rysgaard et al., 1994, 1995; Sundbäck et al., 2000), and various macrofaunal activities, for example, irrigation, excretion, respiration, and physical disturbance of sediment (Clavero et al., 1991; Forja and Gómez-Parra, 1998; Mortimer et al., 1999; Webb and Eyre, 2004).

Previous studies have frequently reported on the seasonal variations in nutrient flux in response to variations in physical and chemical factors (e.g. water quality, temperature, sediment condition). With regard to time scales of less than a season, diurnal variations in nutrient flux have been attributed to the response of microphytobenthos to changes in illumination (Sundbäck and Graneli, 1988; Reay et al., 1995; Kuwae et al., 1998; Sundbäck et al., 2000). In estuaries, the water column chemistry and particularly the solute concentrations may change with the relative contribution of seawater and fresh water. These variations may modulate sediment–water fluxes on a tidal time scale. Tidal variations in the flux, however, have rarely been reported (Cabrita et al., 1999; Yin and Harrison, 2000).

The purposes of this study were to determine the range and sensitivity of nutrient flux responding to tidal variations in water column chemistry caused by tidal replacement of river water and seawater and to elucidate the mechanism of tidal flux variation in an estuarine tidal flat. This study presents several flux measurements per tidal cycle, obtained by repeated operations of the in situ chambers at sandy and muddy intertidal flats in a single estuary. An understanding of the short-term variations contributes to a determination of the typical flux of nutrients in the tidal flat.

2. Methods

2.1. Study site

We studied a sand and a mud intertidal flat on the east coast of Honshu Island, Japan (Fig. 1). Those tidal flats are located at the north and south banks of the Nanakita estuary, respectively. Each of the tidal flats has an area of about 20,000 m^2. The Nanakita River discharges to the Pacific Ocean ordinarily at 860,000–1,300,000 $m^3\ day^{-1}$. Sewage-treated water is discharged to the Pacific Ocean at a rate of 500,000 $m^3\ day^{-1}$ from 500 m south of the river mouth. The tidal amplitudes ranged from about 0.4 to 1.4 m in this estuary. In both the sand and mud flats, the bed elevation of the sampling point was 0.3 m below mean water level of this estuary. Investigations were conducted three times in the sand flat and five times in the mud flat in the summer of 1999. All investigations were carried out under similar fair weather conditions.

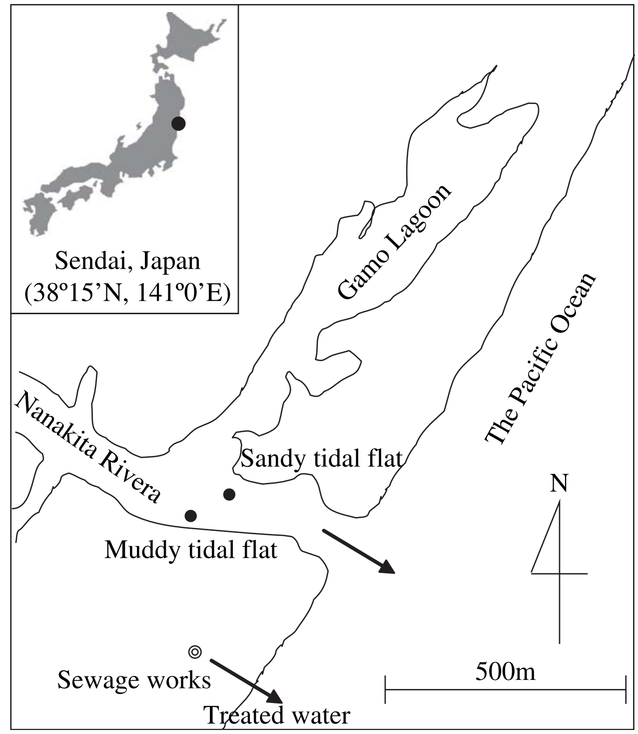

Fig. 1. Map of the study sites in the Nanakita estuary, Japan.

2.2. Repeating nutrient flux measurements

A transparent acrylic (light) chamber and an opaque vinyl chloride (dark) chamber were used to measure the short-term exchange flux across the sediment–water interface for dissolved oxygen (O_2) and inorganic nutrients. Each cylindrical chamber (33 cm inner diameter and 30 cm height) has two symmetrically facing side-ports of 10 cm diameter with rubber stoppers at the upper edge of the side-wall to allow for water exchange with the surroundings. The chambers were furnished with a sampling tube and an internal balloon for pressure compensation during sampling. Before the in situ measurements were taken, a salt tracer confirmed the water tightness of the chambers.

In the field, the chambers were inserted into the tidal flat sediment during low tide. The height and volume of the water column in the chamber were standardized to 10 cm and 8.5 l, respectively, maintaining the side-ports just above