Estuarine, Coastal and Shelf Science 96 (2012) 151–158

Contents lists available at SciVerse ScienceDirect

Estuarine, Coastal and Shelf Science

journal homepage: www.elsevier.com/locate/ecss

Aggregation dynamics along a salinity gradient in the Bach Dang estuary, North Vietnam

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ARTICLE INFO

Article history:
Received 25 January 2011
Accepted 26 October 2011
Available online 11 November 2011

Keywords:
aggregation dynamics
Bach Dang estuary
transparent exopolymer particles
salinity
vertical export
Vietnam

ABSTRACT

Variations of the sticking properties of transparent exopolymeric particles (TEP) were investigated by studying the interactions between latex beads and TEP precursors collected along a salinity gradient in the Bach Dang estuary, North Vietnam. For each sampling station, a suspension of TEP and beads was prepared and the formation of mixed aggregates was monitored in the laboratory under controlled turbulence intensity. The number of beads attached to TEP per volume of TEP increased from $0.22 \times 10^{-3} \pm 0.15 \times 10^{-3}$ μm^{-3} to $5.33 \times 10^{-3} \pm 1.61 \times 10^{-3}$ μm^{-3}, from low (<1) to high (>28) salinities, respectively. The sudden increase in TEP sticking properties from salinity 10 to 15 suggests the occurrence of an "aggregation web" resulting from the stimulation of aggregation processes. For a given turbulence level, the formation of large aggregates should be enhanced seaward. The presence of a higher fraction of large aggregates seaward is supported by the increase of the slope of the particle size spectra measured *in situ*. The observed increase in TEP sticking properties toward high salinities may affect the vertical export pump in estuaries. This study suggests that the transition from a low to a high physico-chemical reactivity of TEP along estuaries may result in a succession from recycling for salinity <10 to enhanced aggregation/sedimentation processes and export dominated systems for salinity >10.

1. Introduction

The magnitude of vertical flux in aquatic systems, and thus their ability to export organic matter, is determined by the abundance and sinking characteristics of large organic aggregates (Shanks and Trend, 1980; Smetacek, 1985; Fowler and Knauer, 1986; Alldredge and Silver, 1988; Asper et al., 1992; Jackson and Burd, 1998). The abundance of large aggregates mostly depends on the balance between the rate at which particles collide, on the probability of adhesion upon collision (i.e., sticking coefficient; Kiørboe and Hansen, 1993; Passow and Alldredge, 1995), and on the turbulence-induced rupture of aggregates (Fugate and Friedrichs, 2003; Bache, 2004). The influence of turbulence intensity on particles has been largely documented (e.g. van Leussen, 1994; Uncles et al., 2006; Winterwerp, 2006). In the aggregation process, while particle concentration, size, and fluid dynamics control collision rate, adhesion depends upon the physico-chemical properties of the particles (Jackson, 1990).

The class of highly abundant transparent exopolymeric particles (TEP) (Alldredge et al., 1993) proved to play a critical role in mechanisms regulating aggregation and sedimentation in marine (Logan et al., 1995; Dam and Drapeau, 1995; Engel, 2000; Passow et al., 2001; Fabricius et al., 2003; Wolanski et al., 2003; Engel et al., 2004; Mari and Robert, 2008; Mari, 2008), fresh water (Grossart et al., 1997), and estuarine systems (Wolanski and Spagnol, 2003; Wurl and Holmes, 2008; Wetz et al., 2009). TEP are formed by coagulation of polysaccharidic fibrils, which represent the dominant part of the exopolymeric substances released by phytoplankton and other microorganisms (Bhaskar et al., 2005). Due to the stickiness properties of TEP, they present enhanced coagulation efficiency (Kiørboe and Hansen, 1993; Jackson, 1995) which tends to promote the appearance of larger aggregates. This latter, along with the altered density of the biologic/mineral blend, influence their sinking velocity (Azetsu-Scott and Passow, 2004).

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doi:10.1016/j.ecss.2011.10.028

The sticky nature and the structural integrity of TEP are linked to the presence of a high fraction of polysaccharides with sulfate ester groups (Zhou et al., 1998), which give them the ability to form cation bridges (Kloareg and Quatrano, 1988) and hydrogen bonds (Mopper et al., 1995; Chin et al., 1998).

In order to determine the role played by TEP in aggregation/sedimentation processes, one needs to examine their abundance and assess their sticking properties under different conditions. While most studies on TEP addressed their concentrations in various aquatic environments, only a few focused on their sticking properties and their potential variations. All the studies conducted so far concluded that TEP stickiness was much higher than that of other particles, but also quite variable (Kiørboe and Hansen, 1993; Kiørboe et al., 1994; Dam and Drapeau, 1995; Logan et al., 1995; Engel, 2000; Mari and Robert, 2008). Since TEP sticking properties depends upon their physico-chemical characteristics, they may vary according to environmental conditions. Estuaries are transition zones where physico-chemical processes of transformation of dissolved and particulate matter are particularly dynamic due to the presence of strong gradients (e.g., salinity, pH, metals, cations, turbulence) that alter the structure of exopolysaccharides (Baalousha et al., 2006). Therefore, TEP may exhibit wide temporal and spatial variations of their sticking properties within an estuarine domain, which in turn could affect the biogeochemical functioning of the system. TEP-induced aggregation process is one of the key factors to investigate in estuaries as it affects the fate of suspended aggregates (Wetz et al., 2009). Several studies focused on the influence of the concentration of suspended particles, turbulence (e.g. Uncles et al., 2006), and salinity (e.g. Thill et al., 2001) on aggregation processes. Although studies on the influence of the physico-chemical characteristics of the suspended organic matter are scarce, they have showed that organic matter characteristics modified aggregation processes (Ayukai and Wolanski, 1997; van der Lee, 2000; Mikes et al., 2004).

The aim of the present study was to describe changes in TEP sticking properties along salinity gradients, and to discuss the implications of such variations for the cycling of elements in the tropical estuary of the Bach Dang River via control over the balance between retention and export.

2. Materials and methods

2.1. Study area

Located at the North-eastern part of the Red River delta, Haiphong is the third largest city and second largest harbor of Vietnam. The Haiphong Bay receives water from the Cam and Bach Dang Rivers whose confluence is located in the estuary, 10 km from the mouth, and from the Lach Tray River (Fig. 1). The Bach Dang River flows in northern Vietnam through the Yen Hung district of the Quang Ninh province and the Thuy Nguyen district of Haiphong. The Cam and Lach Tray Rivers are tributaries of the Van Uc River, the further Eastern main tributary of the Red River.

Haiphong Bay is characterized by a funnel-shaped estuary and an intricate tidal flat and creek system. The tide is a dominant dynamic factor and regulates its morphology and sedimentology (Tran et al., 2000). The tide is diurnal and its range in Haiphong is about 4 m in spring tide.

The hydrological regime strongly depends on the monsoon regime, with the northeast monsoon from November to May in the dry season and the southwest monsoon from May to November in the wet season. The rainfall is $\sim$1500 mm yr^{-1}. The average wind speed is 3–4 m s^{-1}, and reaches up to 45 m s^{-1} during typhoons. The average wave height is 0.5–1.0 m and the prevalent directions (East, Southeast and South) follow the wind climate which depends on the monsoon regime. The average yearly temperature is 23.5 °C.

The average yearly river discharge into the Haiphong Bay lies in the range 350–440 m^3 s^{-1} and the average suspended sediment concentration between 290 and 360 mg L^{-1} (Tran, 1993). For comparison, the average discharge of the Red River at the Son Tay gauging station (upstream of the bifurcation into a number of distributaries creating the Red River delta) is 4300 m^3 s^{-1} (1200 m^3 s^{-1} in the dry season and 14 000 m^3 s^{-1} in the flood season, values based on the years 1956–1998) and the average suspended sediment concentration is close to 1000 mg L^{-1}, varying between 200 and 1400 mg L^{-1} in the dry and wet seasons, respectively (van Maren and Hoekstra, 2004; van Maren, 2007). The interface between saline and fresh water depends on the river flow, the tidal cycle and the river morphology. The saline intrusion

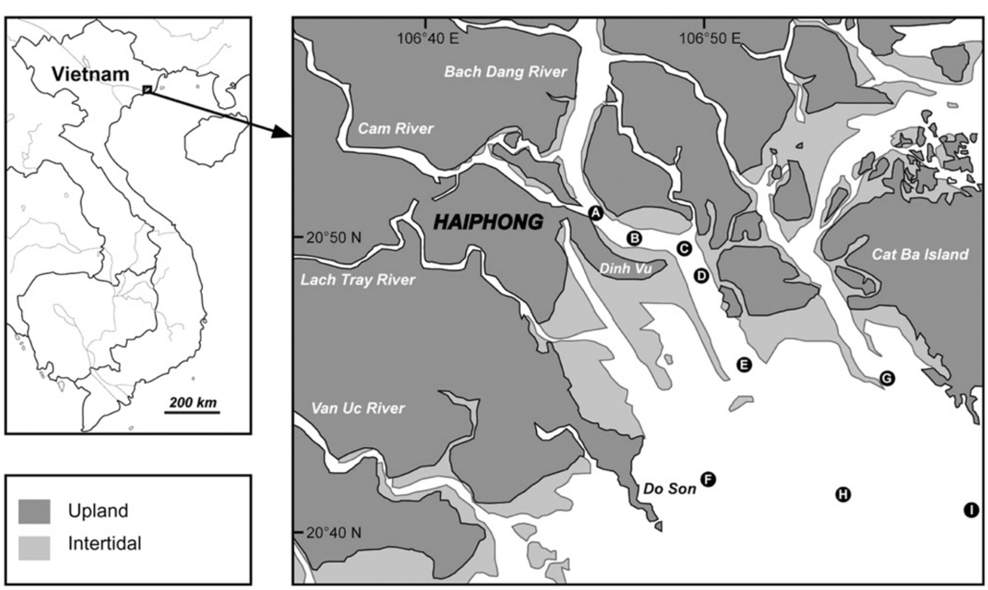

Fig. 1. Map of the study area with position of the sampling stations.