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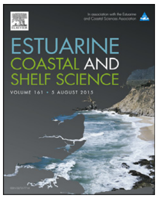

Field and laboratory observations of bed stress and associated nutrient release in a tidal estuary

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ABSTRACT

Nutrient release driven by sediment resuspension in a shallow coastal estuarine system is examined with field observations of bed stress and bed elevation, coupled with laboratory erosion experiments on sediment cores. Two field experiments were conducted over near-cohesive muddy-sand sediments in the Great Bay Estuary, New Hampshire. In the first deployment, boundary layer development during typical summer tidal forcing was observed, while the second deployment occurred under enhanced wind forcing of Tropical Storm Irene. *In situ* bed stress and erosion depths were estimated with a profiling acoustic Doppler velocimeter. Sediment cores were subjected to EROMES erosion chamber experiments to determine erosion depth and nutrient release as a function of applied shear stress. Results show erosion depths are consistent with *in situ* observations over shear stresses ranging from 0.10 N m^{-2} (incipient motion) to 0.35 N m^{-2} (resuspension events). Erosion chamber experiments showed that ammonium release (up to 2 mmol m^{-2}) increased with bed stress in both spring and summer. However, phosphate release was more variable, with no phosphate release during resuspension in spring and a variable phosphate flux (ranging −0.5–2 mmol m^{-2}) in summer. Increased hydrodynamic forcing during a storm event in the summer generated shear stresses (up to 0.58 N m^{-2}) during flood tides that exceeded the threshold for sediment motion, and resulted in erosion of the seabed. EROMES results predict there was concomitant release of nutrients into the water column from the muddy sediments of the Bay, and the release of dissolved inorganic nitrogen and phosphate was up to 10% and 65%, respectively, of the summer monthly riverine input of these nutrients. Results indicate qualitatively that in shallow, tidally dominated estuaries, fine-grained sediment beds may be a source of nutrients that are particularly important during storms that enhance near bed shear stresses.

1. Introduction

Excess nutrients in coastal waters can significantly impact the water quality and aquatic ecosystems by increasing primary productivity, and altering community structure (Cloern, 2001). Consequently, there is continued worldwide interest to mitigate these effects by reducing the input of nutrients to coastal waters (Boesch, 2002). In estuaries with large nutrient loads from rivers and/or high suspended sediment concentrations, the lateral advection component is generally assumed to be the dominant source of nutrient concentrations (Jay et al., 1997). However, in regions where there are fine grained sediments and intermittently large flows, the vertical flux of nutrients into and out of the sediment beds can significantly affect the nutrient budget (Jay et al., 1997; Kornman and de Deckere, 1998; Lorke et al., 2003). Organic matter that accumulates in fine-grained sediments can be remineralized, producing nutrients that can be returned to the water column (Giblin et al., 1997). In Chesapeake Bay, Maryland (Boynton and Kemp, 1985), and Mobile Bay, Alabama (Cowan et al., 1996), release from sediments has been estimated to supply over 25% of the dissolved nutrients for phytoplankton growth, and in Galveston

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Bay, Texas (Warnken et al., 2000) sediments were found to be the dominant source of nutrients to the Bay.

Despite sediments being a potentially large repository of nutrients, their influence upon the nutrient budget in coastal waters is often poorly quantified (Couceiro et al., 2013). The release of nutrients from sediments to the water column depends not only on sediment geochemistry, but also on local hydrodynamics (Lorke et al., 2003). Sediment geochemistry determines the reactions that produce nutrients from remineralization, as well as the reactions that remove nutrients, such as denitrification or phosphate mineral precipitation. Hydrodynamic stresses applied to the bed affect the suspension of sediments and rate of exchange of solutes across the sediment–water interface, which in turn influences the sediment geochemistry by controlling the supply of key reactants, and the release of dissolved products. At the bed interface, exchange can occur as a result of vertical diffusion as well as resuspension of sediment and accompanying pore water (Jorgensen and Revsbech, 1985; Hondzo, 1998). The rate of exchange or vertical flux is determined by the boundary layer dynamics, sediment erosion threshold, and the chemistry of the overlying water (Boudreau and Jorgensen, 2001; Lorke et al., 2003; Sanford and Maa 2001; Couceiro et al., 2013).

Most previous research efforts have quantified release of nutrients under quiescent conditions. Calculation of the vertical flux from porewater profiles often assumes molecular diffusion is the dominant mixing mechanism. Direct flux measurement techniques such as benthic chambers (Warnken et al., 2000; Berelson et al., 2003) and core incubations (Fulweiler et al., 2010; Tucker et al., 2014) provide valuable measurements of nutrient flux but generally isolate the overlying fluid, thereby altering the boundary layer dynamics. Chambers and incubations typically use a single stirring speed to circulate the overlying fluid, providing flux observations for a single flow condition that is usually selected to ensure no sediment is resuspended. Interpretation of these results is therefore limited due to highly dynamic and variable flow conditions present in coastal waters. When the flow field exceeds the threshold for rough turbulent flow, the diffusion due to turbulence significantly exceeds viscous contributions and the diffusive flux can be increased by more than an order of magnitude (Hondzo, 1998; Lorke et al., 2003; Wengrove and Foster, 2014). Moreover, nutrient exchange across the sediment–water interface may be further enhanced when the shear stress exceeds the erosion threshold and sediment is mobilized into the water column (Tengberg et al., 2003; Kalnejais et al., 2010; Kleeburg and Herzog, 2014). Nutrient release during resuspension can be due to entrainment of sediment and porewaters into the water column and also due to reactions of freshly suspended particles (Kalnejais et al., 2010; Couceiro et al., 2013).

Owing to challenges involved in making measurements of nutrient release under strong flow conditions, erosion devices designed to simulate sediment resuspension have been simultaneously used to investigate nutrient release (Sloth et al., 1996; Tengberg et al., 2003; Almroth et al., 2009; Kalnejais et al., 2010; Couceiro et al., 2013; Kleeburg and Herzog, 2014). These devices impose a known shear stress at the sediment–water interface, and sampling of the overlying fluid allows for evaluation of both erosion and local chemical transformations associated with a range of shear stresses. In situ determination of sediment erodibility prevents sediment disturbance associated with coring, and there are a number of *in situ* erosion devices (e.g. Amos et al., 1992; Widdows et al., 2007; Thompson et al., 2011, 2013). However, *in situ* determinations of nutrient release in the marine environment are limited (Tengberg et al., 2003; Almroth et al., 2009) and typically have been restricted to a single level of resuspension. Erosion chamber experiments performed in the laboratory on freshly collected cores (Koschinsky et al., 2001; Kalnejais et al., 2010; Couceiro et al., 2013) have provided information on nutrient release across a wider range of shear stresses. With climate change predicted to increase the number of extreme events in many regions the use of erosion devices to determine erosion response and associated chemical release is becoming increasingly important (Statham, 2012). Unfortunately, interpretation of erosion chamber results are hampered by poor comparisons between devices (Tolhurst et al., 2000b; Widdows et al., 2007) and lack of direct comparison between erosion chamber results and field observations (Andersen et al., 2007). Robust validation of the chambers requires high resolution observations of the velocity field, as a proxy for *in situ* shear stress, in the lowest few centimeters of the water column, with concomitant observation of sediment erosion.

In this work, field observations of near bottom fluid velocities and seabed elevation changes are used to assess the accuracy of the erosion threshold and depth determined by an EROMES erosion chamber. The field observations are coupled with erosion chamber measurements of nutrient release from muddy sites within the Great Bay estuary, New Hampshire, USA to provide information on nutrient mixing across the sediment–water interface in a shallow, temperate estuary. Field observations were obtained under typical non-storm (low winds) conditions where there was no evidence of sediment resuspension, and during a storm (high winds) when there was a fully rough turbulent boundary layer and active resuspension. The objectives of this paper are to 1) observe the fine-scale velocity structure near the seabed and concurrent bed elevation changes in estuarine field experiments, 2) verify theoretical critical shear stress values for sediment mobilization, 3) verify the accuracy of the EROMES erosion chamber and 4) relate the field-estimated shear stresses to nutrient release through coupled laboratory erosion chamber experiments. This study provides a significant step towards the validation of the erosion characteristics simulated by an erosion chamber with in-situ measured erosion rates and estimated shear stress. Additionally, the pairing of *in situ* hydrodynamic and erosion observations during a moderate storm and estimates of the magnitude of benthic nutrient release at increasing erosion thresholds show that resuspension events may be important terms in the nutrient budget of shallow estuarine systems.

2. Materials and methods

2.1. Field site

Field observations were obtained in the Great Bay Estuary (Fig. 1), a shallow well-mixed estuary with a (generally) sub-critical flow regime (Swift and Brown, 1983; Bilgili et al., 2005). Bottom sediment type is roughly correlated to water depths with grain sizes ranging from fine grained cohesive muds to coarse grained sands (Fig. 2). Spatial variability of sediment type is evaluated with both a depth model and with historic grab samples. In the first method, surficial mud fraction is estimated with a logarithmic model based on water depth and calibrated with observed sediment size fractions in the Little Bay portion of the Great Bay (Fig. 2b). The model has a correlation of 0.67, accounting for 44% of the variance (Lippmann, 2013). In the second method, historical sediment data (Poppe et al., 2003) is qualitatively discretized into regions of similar sediment type within the Bay (Fig. 2c). Sediment type is classified into four categories based on sediment size: mud, muddy-sand, sandy-mud, and sand following Shepard (1954) in Table 1.

The Great Bay is showing several symptoms of eutrophication, including substantial loss of eelgrass beds and macroalgae growth (Short and Wyllie-Echeverria, 1996; PREP, 2013), and there is