ELSEVIER

Marine Geology 235 (2006) 177 – 192

MARINE GEOLOGY
INTERNATIONAL JOURNAL OF MARINE GEOLOGY, GEOCHEMISTRY AND GEOPHYSICS

www.elsevier.com/locate/margeo

Variability in cohesive sediment settling fluxes: Observations under different estuarine tidal conditions

Andrew J. Manning [a,b,*], Sarah J. Bass [b]

[a] HR Wallingford, Estuaries and Dredging Group, Howbery Park, Wallingford, OX10 8BA, UK
[b] Centre for Coastal Dynamics and Engineering (C-CoDE), Coastal Processes Research Group, School of Earth, Ocean and Environmental Sciences, University of Plymouth, Portland Square Building (A504), Drake Circus, Plymouth, Devon, PL4 8AA, UK

Accepted 3 October 2006

Abstract

The mass settling flux, which is defined as the product of the concentration and the settling velocity, is of prime importance with respect to both stratified and well mixed estuarine conditions. The determination of these fluxes (for applied modelling purposes) in high energy tidal estuarine environments, is very problematic. This is because the muddy sediments which dominate in estuaries, flocculate producing a variety of sizes and settling velocities, and this flocculation process is not understood well enough to be fully described theoretically. By drawing on examples of floc spectra acquired *in-situ* using the INSSEV system, this study explains how mass settling fluxes in the near-bed region can vary by three or four orders of magnitude in meso- and macro-tidal estuaries throughout a single tidal cycle. A floc population representative of dilute suspension conditions on a neap tide, indicated only 35% of the floc mass was macroflocs (>160 μm). However, the macrofloc settling velocity = 2.4 mm s^{-1}; three times faster than the microflocs, which meant the former fraction contributed 57% of the 205 mg $m^{-2}s^{-1}$ settling flux. Both highly concentrated (4–6 g l^{-1}) and very turbulent spring tide conditions ($\tau > 1.6$ N m^{-2}) produced a bi-modal distribution in terms of the floc size and dry mass. With the former, 54% of the mass was contained within the 240–480 μm size fraction, with a further 25% of the dry floc mass in the flocs over 480 μm in diameter. These large flocs had settling velocities between 4–8 mm s^{-1}, which meant 99.5% of the settling flux (33.5 g $m^{-2}s^{-1}$) was accredited to the macroflocs. The high turbulence environment saw the dry floc mass distribution shift 60:40 in favour of the microflocs. The microfloc settling velocity was 1.45 mm s^{-1}, 0.35 mm s^{-1} faster than the larger macrofloc fraction. In terms of the total mass settling flux, 0.9 g m^{-2} s^{-1}, this translates into the microflocs contributing 70% during high turbulence. At slack water the flux only reached 12 mg m^{-2} s^{-1} and macrofloc growth was mainly attributed to differential settling. Continuous floc observations made over a complete tidal cycle revealed that the asymmetrical distribution of the tidal energy generated throughout the spring conditions in the Tamar estuary demonstrated a distinct control on the flocculation process. The less turbulent ebb produced 86% of the total tidal cycle mass settling flux, of which only 8% of the settling flux was outside the turbidity maximum. An attempt to simulate these large settling fluxes by using a constant settling rate of 0.5 mm s^{-1}, under-estimated the tidal cycle settling flux by 78%, with less than 15% of the total flux being estimated during the advection of the turbidity maximum on the ebb. In contrast, using a faster constant settling velocity parameter of 5 mm s^{-1}, (representative of the macrofloc fraction), resulted in a mass flux over-estimate of 116% for the tidal cycle duration.

Keywords: mass settling flux; flocculation; turbulent shear stress; settling velocity; effective density; INSSEV instrument

* Corresponding author. Tel.: +44 1752 232407; fax: +44 1752 232406.
E-mail address: andymanning@yahoo.com (A.J. Manning).

0025-3227/$ - see front matter
doi:10.1016/j.margeo.2006.10.013

1. Introduction

Models of sediment transport are widely used as dredging management tools in estuarine locations. However an accurate representation of the vertical sediment settling fluxes is very problematic. This is due to the cohesive nature of the muddy sediments which dominate estuarial locations. Observations of fine sediment suspensions suggest that, except for extremely high energetic conditions, most of the sediment mass occurs as flocs (Kranck and Milligan, 1992). These cohesive sediments can flocculate to form a spectra of aggregates known as flocs. Flocs are less dense, but faster settling than their constituent particles. As flocs grow their effective density generally decrease, but their settling rates rise. Flocculation is a dynamically active process which readily reacts to changes in turbulent hydrodynamic conditions (Manning, 2001, 2004a). The flocculation of particles is a function of the mechanisms which bring the particles into contact, e.g. differential settling or turbulence (Manning and Dyer, 1999) and the mechanisms that make them stick together, e.g. salinity related electro-static charging or organic matter content (van Leussen, 1988). In addition to increasing particle collisions, turbulent shear may also break up aggregates (McCave, 1985), and this is further complicated by concentration gradients which can form in the near-bed region throughout a tidal cycle (Dyer et al., 2004).

The processes of aggregation and disaggregation are still not understood well enough to be fully described theoretically, and at the moment predictions tend to rely on empirical generalisations. Until recently, a lack of reliable floc measurements together with those of hydrodynamic turbulence, limited studies of the complex interactions between the factors affecting flocculation (e.g. shear, salinity, organic content and concentration) and floc characteristics. Laboratory experiments do not reliably represent field situations because of the difficulty of reproducing the chemical, physical and biological processes involved, and *in-situ* measurements have historically been unreliable because of floc disruption when sampling (van Leussen, 1988). However, the advent of video floc devices (e.g. van Leussen and Cornelisse, 1994; Hill et al., 1998; Mikkelsen et al., 2004), in particular the unique INSSEV instrument (Fennessy et al., 1994; Manning and Dyer, 2002) which was developed at the University of Plymouth (UK), and when combined with an array of miniature high frequency velocimeters, INSSEV has provided a means of accurately determining time series of both the spectral distribution of the floc dry mass and settling velocities, directly from within a turbulent estuarine water column. INSSEV has observed low density (~30 kg m^{-3}) macroflocs over 1.5 mm in diameter which have displayed settling velocities of 3–25 mm s^{-1} (Manning and Bass, 2004).

In contrast to floc particle sizers, the additional measurement of individual floc settling rates means that INSSEV can provide reliable estimates of floc effective density by using a modified Stokes' Law relationship. A knowledge of floc effective density is very important in the calculation of vertical settling fluxes (Manning, 2004b). As flocs increase in diameter they become more porous (>90–95%); since their voids are filled with interstitial water; the higher order flocs are less dense than the lower order microflocs. Very few direct quantitative studies have been conducted on floc effective density variations. Floc fragility has precluded the direct measurement of floc density. Also the rheological properties of suspended particulate matter are governed by volume concentrations, as opposed to mass concentrations (Dyer, 1989).

A flux which is of prime importance with respect to both stratified and well mixed estuarine conditions, is the mass settling flux (MSF), which is defined as the product of the suspended particulate matter (SPM) concentration and the settling velocity (Manning, 2004b). By drawing on examples of floc spectra acquired *in-situ* using the INSSEV system, this paper will illustrate in a semi-quantitative manner how these settling fluxes in the near-bed region can vary by three or four orders of magnitude in meso-/macro-tidal estuaries under different tidal conditions (Bass et al., 2006; Manning et al., 2006). The examples presented were obtained from experiments conducted in the Gironde Estuary, France and the Tamar Estuary, England, and cover a variety of conditions including: spring and neap tides, slack water and times when concentrations and turbulent shear stresses were high.

2. Method

2.1. Data acquisition

Near-bed flocculation dynamics during neap tides were studied in the lower reaches of the Gironde estuary during June 1999 as part of the European Commission (EC) funded SWAMIEE project international field experiment, referred to as *SWAMGIR1* (Manning et al., 2004). The sampling location was located 1 km from the shore at Le Verdon (3 km from the mouth) and this was within the vicinity of one of the localised mud deposits situated between Bordeaux and Talais (Jouanneau and Latouche, 1981). These 2–3 m deep patches of