Sediment Dynamics for a Changing Future (Proceedings of the ICCE symposium held at
Warsaw University of Life Sciences - SGGW, Poland, 14–18 June 2010). IAHS Publ. 337, 2010.

The influence of density fronts on sediment dynamics within river-to-sea estuarine transitional waters

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Abstract The interaction of river-borne suspended and bedload sediments with marine-derived sediments is complicated by the sharply defined lateral and transverse water density gradients of frontal systems that characterise many estuaries worldwide. These features, often recognised at the water surface as linear bands of foam or flotsam, develop principally due to tidal intrusion, axial convergence, longitudinal shearing and flow separation. However, knowledge of the relationships of such features with bathymetry is still poorly developed. Not only do frontal systems impact upon intra-water column fine particulate transport by entrapment and compartmentalisation, they also exert a control on the distribution of bedforms and bottom sediment grain size distributions, thereby delimiting often closely juxtaposed, but differing bottom current velocity fields on the ebb and flood tidal phases. In consequence, fronts are now considered as "sieves" within the transitional river-to-sea, estuarine sediment transfer system; this perception has been reinforced by numerical study of lateral grain size sorting.

Key words estuaries; density fronts; sediment compartmentalisation; sediment partitioning

INTRODUCTION

Whilst there have been innumerable studies of fluvial sediment dynamics and coastal sedimentary processes worldwide, there are still substantial gaps in our knowledge of the complex interactions between the two systems within transitional estuarine waters and the modes of interchange of both sediment particles and pollutants between these "end member" sources. It is typical for the fluvial sedimentologist to investigate sediment transport into the landward reaches of an estuary and the coastal sedimentologist to study transport at the seaward end. Similarly estuarine scientists often fail to fully integrate their studies with their coastal and fluvial counterparts into a holistic, catchment-based appraisal. However, the fate of suspended and bedload sediments delivered from river catchments into estuaries and the mixing therein with marine derived materials is not simple owing to the almost ubiquitous presence of frontal systems in such transitional waters. Largier (1993) provided a general description of a front as "a meeting of waters", with a fuller definition as "a region characterised by an anomalous local maximum in the horizontal gradient of some water property (e.g. temperature, salinity, nitrate concentration, chlorophyll concentration)". The aim of this contribution is to highlight and raise awareness of the importance of density fronts in influencing sediment and associated pollutant dynamics within river-to-sea estuarine transitional waters and to suggest avenues for future research. This is particularly significant at the present time as, around the world, land-use changes are influencing river sediment dynamics and climate change is, in many areas, forcing rising relative sea levels and hence both estuarine and fluvial evolution.

FORMATION OF FRONTAL SYSTEMS IN ESTUARIES

Frontal systems, or more simply fronts, are sharply defined water density and velocity gradients that occur both longitudinally and transversely in many estuaries. For example, an aerial survey of 26 estuaries in England and Wales revealed strong evidence for fronts in 15 cases, with a further six being identified during subsequent field observations (Brown *et al*., 1991). Indeed, except in fully mixed estuaries, fronts are almost ubiquitous, occurring in the water column as interfaces that are inclined or near to vertical (Bowman, 1988; El-Sabh, 1988; Reeves & Duck, 2001). At these interfaces, flowing water masses of differing densities converge, diverge or move laterally relative to one another much in the same way as plate tectonic movements of the Earth's lithosphere. Such systems form by several mechanisms in estuarine waters, including tidal intrusion of saline waters, axial convergence, advective flow or longitudinal shearing and flow separation (full accounts of the major forms recognised are given by, amongst others: Bowman (1988), O'Donnell (1993), Reeves & Duck (2001) and Duck (2005). They are often most readily identified at the water surface by remote observations (e.g. Anderson *et al.*, 1992; Brown *et al.*, 1991) of foam (the accumulation of dead algal cells such as diatoms, e.g. Fig. 1) and flotsam bands and water colour, transparency (e.g. Klemas, 1980) or surface roughness differences. Their occurrence has important consequences for estuarine mixing in that they compartmentalise the water mass, thereby inhibiting dispersion. Longitudinal fronts, for example, have been shown to offset transverse salinity contours due to shearing (McManus, 2005). Thus diffuse pollutants (e.g. adsorbed onto fine suspended sediment particles) and those discharged from point sources may not be transferred to the main body of the tidal prism and, therefore, dispersion is restricted (Ferrier & Anderson, 1996; Duck & McManus, 2003). In the Rio de la Plata, South America, Acha *et al.* (2003) have shown that a transverse "bottom salinity front" acts as a barrier causing the accumulation of litter debris on the landward side. Fronts may also act as a barrier to larval transport leading to along-frontal flows which, in turn, may serve as conduits directing larvae collected at a front to specific locations of settlement onto the estuary bed (Eggleston *et al.*, 1998). In this way the front is acting like a sieve in the water column (see below).

As well as inhibiting mixing within the water column, where fronts meet the bed they often delimit juxtaposing bedform fields of differing geometries, as identified using side-scan sonar (McManus *et al.*, 2003; Bates & Oakley, 2004). Thus they exert a control on the partitioning and persistence of bedload transport pathways along which coarse sediments and any associated pollutants migrate (Duck & Wewetzer, 2001). This has important implications for estuarine sediment transport modelling. Adjacent pairs of fronts in an estuary (e.g. Fig. 1) delimit areas on the bed in which the bedforms are of closely similar geometries, in terms of amplitudes and wavelengths. The contrast with the bedforms developed in the sediments of neighbouring areas indicates that differing energy levels from the overlying water column are interacting with the bed

Fig. 1 Parallel longitudinal fronts delimited at the water surface by foam lines in the Ría de Ribadeo of NW Spain. This estuary, ~900 m in width along much of its length, forms the mouth of the River Eo at the border between Galicia and Asturias; the Bay of Biscay is to the left of the field of view (north). The photograph was taken during the early phase of the ebb tide.

(Duck & Wewetzer, 2001). Moreover, sediment transport rates need to be calculated separately for each “field”, as a single value for bedload (and suspended sediment) transport calculated across an entire estuarine reach could be spurious. Furthermore, since the differing bedform geometries developed have varying resistance to flow, dynamic modelling strictly requires the application of differing values of Manning’s roughness coefficient (*n*) appropriate for each bedform “field”. Contrasting bedform geometries, from which bottom current velocities can be estimated (see Stow *et al*., 2009), suggest that sediment transport rates are likely to differ in neighbouring fields. Moreover, it is the presence of foam and flotsam bands at the water surface that typically provides the first indication of the presence of fronts and thus the potential occurrence of multiple bedform and bottom sediment transport fields on the estuary bed. Furthermore, in certain situations, fronts appear to stimulate sediment trapping and subsequent accumulation to such an extent that they are believed to exercise an important degree of control on both the location and distribution of longitudinal estuarine sandbanks (McManus, 2000).

Fronts as “sieves”

Reeves & Duck (2001) suggested that the role fronts play in estuarine circulation, productivity, sediment dynamics and water quality may be likened to that of a series of transient “sieves” which migrate and change location with time, according to variations in tidal flow, river flow and local bathymetry. These authors further asserted that, where characterised by many fronts, an estuary should most appropriately be considered as a “complex of sieves”, which collectively create a “dynamic sieve regime”. Numerical validation of the “sieves concept” has recently been undertaken by Neill (2009), by means of a model of an estuarine cross-section, parameterised on the axial convergent front that characterises the Conwy Estuary of north Wales (Nunes & Simpson, 1985). The simulations have shown that considerable lateral grain size sorting of bottom sediments can take place due to secondary frontal flows across the recirculation zone, analogous to the lateral grain size sorting which occurs in river meanders. Model sensitivity tests revealed that the contribution of the convergent front to lateral grain size sorting was influenced strongly by the gradients of the lateral slopes of the estuarine channel and the magnitude of the lateral density gradient (Neill, 2009). In close agreement with the direct observations of Reeves & Duck (2001), made in the Tay Estuary of eastern Scotland, the model of Neill (2009) similarly predicted an order of magnitude change in near surface suspended sediment concentrations across the frontal interface.

DISCUSSION AND CONCLUSIONS

The fate of suspended and bedload sediments delivered from river catchments into estuaries is not simple. The interaction and mixing of river-borne materials with marine-derived sediments is complicated by the almost ubiquitous persistence of the sharply defined lateral and transverse water density gradients of frontal systems that characterise many estuaries worldwide. The mechanisms by which these features are formed are now well established. However, knowledge of the relationships of such features with estuarine bathymetry is still not well developed. Not only do frontal systems impact upon intra-water column fine particulate transport by entrapment and compartmentalisation, they exert a control on the distribution of bedforms and bottom sediment grain size distributions, thereby delimiting often closely juxtaposed but differing bottom current velocity fields on both the ebb and flood tidal phases. Our understanding of the *persistence* of bottom sediment transport pathways in estuaries is limited. However the concept of preferred “highways” along which sediment migration takes place, albeit limited by tidal flow conditions, as propounded by McManus *et al*. (2003), requires further investigation.

The perception that fronts are now considered to act like “sieves” within the transitional river-to-sea, estuarine sediment transfer system has been reinforced by the numerical study of lateral grain size sorting by Neill (2009). However, this model validation related specifically to an axially convergent front and, in consequence, Neill (2009) has noted the important point, reiterated herein, that further research is required into the role of the differing categories of front (i.e. modes of origin) on the sieving process. For example, the extent to which fronts control the distribution and location of longitudinal estuarine sandbanks, as described from several sites in Scotland by McManus (2000), is a specific topic in need of further research within the topical framework of land use and climate changes acting as drivers for changes in the morphodynamic evolution of estuaries.

Direct measurements of flow velocities obtained using, for example, acoustic Doppler current profilers, require integration with airborne remote sensing and underwater geophysical techniques to improve understanding of how frontal density gradients control not only sediment transport and dynamics but also pollutant partitioning and the persistence of flow pathways. Fronts are seldom considered within the context of estuarine management, yet their influence on mixing and morphodynamics can be of significance to the sustainable use and development of estuaries. As a pertinent example, it has been suggested that frontal partitioning plays a contributory role in the non-compliance of coastal and estuarine bathing waters with statutory directives (Duck, 2003; Duck & McManus, 2003). This is particularly significant at the present time, as land-use changes are influencing river sediment dynamics and climate change is, in many areas, forcing rising relative sea levels and hence both estuarine and fluvial evolution.

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