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Spatial and temporal variability of a mixed sediment estuary

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Introduction

To accurately predict future and past coastal environments it is extremely important to understand sediment dynamics and variability. The process of bedform development is highly influenced by the sediment composition and biogenic matter present in a coastal environment. Most subaqueous sediment comprises of mixtures of cohesive clay and cohesion-less sand and silt. The sedimentary bedforms that develop are fundamental in controlling fluxes of particulate and dissolved matter in marine environments (Baas et al. 2012). However, very little field research has been undertaken in mixed sediment dynamics, particularly in modelling bedform development from laboratory and field collected data of mixed sediments. The lack of data on sedimentary bedform characteristics leads to great difficulty in producing accurate models of key processes in coastal areas. This project aims to address the lack of data by combining comprehensive data of sediment and bedform characteristics with bathymetry and biogenic matter to improve our understanding and prediction of bedform behaviour in a mixed cohesive and cohesion-less sediment environment.

Background

The United Kingdom, being a coastal nation, is bordered by rocky coastlines of high energy environments and lower energy environments consisting of mud and sand. The mud and sand environments are very important in the ecology and economy of the UK. They provide food for many species and protect the coastline from erosion and also allow for the capture of pollutants and eventual degradation of the molecules. Due to a combination of increasing sea level rise and storm events due to climate change, it has become of increasing concern how this will affect the behaviour and stability of these systems.

The flow of water over a sedimentary bed changes the topography and wave like structures form called bedforms. These topographic features influence the control of transport and erosion of mud, sand, nutrients and often pollutants. The ratio of mud, a cohesive particle, and sand, cohesion-less, has a high influence on the development and size, shape and wavelength of a bedform.

The most common sediment present in an estuary is cohesive mud made up of clay and silt. This sediment is composed of a combination of mineral grains from both fluvial and marine sources. Clay particles generally have a diameter less than 2µm, but tend not to act as individual particles, due to the electrostatic charging when passing through saline water and the biogenic coatings produced by organisms, and will instead form much larger aggregates (Manning et al. 2010, 2011, and 2013).

This cohesive nature influences the way bedforms develop as well as, sediment grain size distribution, tidal cycle, elevation in relation to mean low water, nutrient input, organism migration, erosion and deposition, currents, waves and episodic events such as storms all influence bedform development and stability (Tolhurst et al. 2006; Chu et al. 2011). These complex physical and biological processes can create considerable spatial and temporal variability (Tolhurst et al. 2006). The development of bedform structures is considered to be much more highly dependent on the sediment composition than other influences, as grain size is a primary control on equilibrium of bedform height and wavelength (Baas et al. 1994, 1999 and 2012). With water flow over a bed consisting of non-cohesive sediment, regular patterns of bedforms commonly form (Coleman et al. 1994). In these sand dominated areas, it is more common for regular shape and size bedforms to occur because of the reduced erosion threshold, whereas in a mixed sediment environment, where the presence of mud causes cohesive forces to occur between particles, bedforms will begin to form a more irregular shape. This is due to consolidation of particles on the stoss-side of the bedform from the erosion threshold increasing (Van Den Berg and Gelder. 1998). The presence of fine grain sediments, such as clay, greatly increase the critical bed shear stress (Baas et al. 2011), compared to primarily cohesion-less sediment which has much higher bed erosion rates.

The physics of these processes can be used in countless numbers of models to predict changes at local and regional scales. Models of sediment transport can be extensively used in dredging management and other important environmental management tools (Manning et al. 2006[a]). These models tend to only predict changes of sediment transport and development of bedforms in pure mud or sand environments or with steady uni-directional flow conditions. However, in reality, with estuarine sediments consisting of a mixture of cohesive and cohesion-less particles and the relatively high energy estuarine environment, in which sediment from transport of run off into rivers downstream and coastal sand is mixed, causes modelling to become problematic. Accurate representation of a coastal region will depend on the ratio of cohesive and non-cohesive particles and conditions of that particular area.

The mixture of sediments significantly changes the sediment transport regime of an environment from what is expected using a model with laboratory collected data due to the bed behaving differently to experiments conducted with component parts separately and/or under different flow conditions. Another problem with models based on laboratory data is that they do not account for the biogenic matter that affects bed properties.

As cohesive sediment transport is not only governed by hydrodynamic and electrochemical (ionic) forces, but by biological effects as well (Black et al. 2002), which significantly impact bed topography, transport and entrainment, it is important to consider this when using models. Certain biological organisms will secrete extra-cellular polymeric substances (EPS) (Underwood et al. 1995) as they move within the sediment and water column. This will enhance the cohesiveness of the sediment and reduce erosion and entrainment. In an intertidal area it is often found that a layer of biofilm is deposited as a thin layer at low tide just as the bed becomes exposed. This creates a cohesive matrix that will, to an extent, 'protect' the bed from erosion during the initial high flow velocity of the flood tide and throughout the tidal cycle. The critical erosion bed stress is affected by biological activity through, biostabilisation, biodestabilisation and bioturbation. The role an organism plays on bed cohesiveness can be significant. Biostabilisation through secretion of EPS, as mentioned above, is a common occurrence across most marine environments as well as the burrowing and reworking of sediment, biodestabilisation and bioturbation respectively, by larger marine species. This can potentially cause a dramatic change in bedform development and the entrainment of sediment into the water column.

Seasonal changes of biological populations can also substantially transform bed characteristics (Manning 2013). Widdows (1998) states that due to increases of around 1500%, from summer to winter of Microphytobenthos (biostabilisers) populations, will increase the erosion threshold and reduce the erosion rate ten-fold by enhancing the cohesiveness of the sediment through increased secretion of EPS. Whereas if a population of *Macoma balthica* (*M. balthica*)(bioturbators) increased in number, then there would be greater rates of bed erosion by loosening surface sediments and increasing bed roughness and water content. Thereby reducing the critical erosion threshold and increasing the erosion rate four-fold.

This temporal change is inherently more difficult to predict, but once evidence was obtained that could show these changes, a sediment transport model including empirical biogenic data could provide a much more accurate model showing bed load transport and deposition rates. This advance would provide great benefit to the dredging industry and potentially reduce costs by knowing more precisely when to dredge an estuary.

Previous work

Research by Baas et al. (2011), on the depositional processes and bedform development in rapidly decelerated cohesive sediment flows, found that bed development is highly dependent on the cohesive and turbulent forces within the flow and the textural and rheological properties of the bed. They also proposed that cohesive forces increase at greater suspended clay concentrations due to the electrostatic bonding of the clay particles. At low concentrations the turbulent forces generated by shear at the bed-flow interface are capable of breaking these bonds, but as the concentration increases the bonds will become sufficiently strong and spatially widespread to decrease the effect of turbulence.

Mitchener et al. (1996) states that the input of cohesive clay into a bed consisting of cohesion-less sediments, increased the critical shear stress for sedimentary entrainment to increase by a factor up to five. Research by Baas et al. (2011) similarly states that this dramatic increase in sediment shear strength is important in the change of flow dynamics in present experiments. Changes will not only occur from one experimental run to another, but also within individual runs using identical variables. Consideration of changes in feedback mechanisms between the flow and sediment bed were essential, as a result of the changing surface drag and form roughness when bedforms begin to develop on the bed.

Further research by Baas et al. (2012) focuses on the role of cohesive forces in flow and bed on the development of bedforms. Experimentation with sand: kaolin (kaolin being a well characterised clay material) ratios of 98.2-82 sand:1.8-18 clay is much more common at the mouth of an estuary. A flume is used to measure the development of bedforms and their time to reach equilibrium height and wavelength. The bedform growth rates, in height and wavelength, were shown to remain similar throughout each sand:kaolin ratio investigated, however, the initial appearance of bedform structures took progressively longer with increasing clay content. The shape and size of the bedform was also seen to change significantly and become more irregular with increasing percentage clay. The results provide a better understanding of development and could be easily placed in a model. However, the research, whilst incredibly beneficial to our understanding, does not account for the role biological organisms and matter plays within this development. It is unlikely that, in situ, this would occur without biological influence and requires field research to further knowledge of these processes.

Focus on the biological side is seen in work by Widdows (2002) in two estuarine/river locations. This showed that a well-developed Microphytobenthos population and low *M. balthica* during the spring lead to an increase in sediment stability with a critical erosion velocity of 0.35m s^{-1}. Whereas during the spring and autumn the following year a contrasting situation occurred whereby there was a significantly higher density of *M. balthica* and a less dominant microphytobenthos population lead to a decrease in the critical erosion velocity (<0.15 m s^{-1}). This meant the sediment was much more easily eroded than the previous year. The temporal change of this magnitude shows that biogenic factors not only change seasonally, but annually as well. As mentioned previously, regarding the use of this data to better predict dredging of an estuary or river channel, the input of biogenic data can also benefit countless other uses for models of marine dynamics. Consideration of this change has to be taken and research understanding the causes of these events to occur should be undertaken for accurate predictions and more effective management.

Required work

Research into cohesive and cohesion-less sediments contained within the bed and dynamic surface layer, is shown to be vitally important to our coastal and estuarine regions for understanding of past and future depositional environments. Improved knowledge will allow for much more accurate modelling of bedform development and sediment transport. The understanding of sediment dynamics also leads to a better comprehension of pollution dispersal and control to help forward integrated coastal management systems (Wang and Andutta 2013). Mitchener (1995) stated that there are currently no empirical models that predict aggregation of mixed sediment or mixed sediment environments in general. Models used for coastline prediction, sediment dynamics and, in particular, bedform development is entirely based on phase diagrams produced from experiment using only sand in unidirectional flows. The influence of biology is also a key factor in erosion of sediment, but is often overlooked. In the majority of research mentioned, biology of the environment is stated as a key factor, but not recorded in order to account for its contribution to bed cohesive properties. The undertaking of multi-disciplinary studies will lead to a more realistic understanding of natural marine systems and their inherent biological and physical complexity (Black et al. 2002).

Data obtained in the field is also vital. Research has generated a greater understanding in the development of bedforms, however, lab investigations that have been conducted with mixed sediment still only recreates these processes under steady, uni-directional flow conditions without the influence of biogenic material. Past in situ work only seems to give a brief insight into the complexity of marine dynamics as often many variables are not quantified. Mitchener (1995) stated the need for empirical models, but yet it still continues to be the case that only scientific information on pure sand environments under uni-direction flow is used in predicting bedform development.

Research Project: Dee Estuary, UK

This review is the preliminary stage of a research project that aims to address the influence of cohesive mud and biogenic content on bedform development. 3D measurements of changes in sediment (i.e. grain size) and the organic content of the bed will be analysed spatially across a defined area to cover a wide range of bed features along with temporal analysis over a spring tidal cycle to assess changes in bed characteristics due to current velocities and wave conditions. Values for bed shear stress will also be taken for spatial and temporal analysis in relation to sediment composition and current velocities.

The data collected from the Dee Estuary shall be positioned using RTK GPS in order to better visualise and present the data and for spatial analysis to be as accurate as possible.

The project will provide scientific data to benefit our understanding of the development of bedforms and help in the derivation of models predicting growth, movement and stability of bedforms that contain cohesive sediments.

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