Flow over dunes and its influence on fluid mud entrainment: A concept of the dune-mud transition in tide-controlled, coastal plain estuaries

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ABSTRACT: In tide-controlled estuaries, slack water settling leads to near-bed stratification and to the formation of ephemeral fluid mud layers. These layers exhibit low consolidation rates and are subject to entrainment by the tidal flow. Due to the tidal excursion and the associated displacement of the turbidity zone, fluid mud is also deposited in troughs of large dunes, upstream and downstream of the center of the turbidity zone. Previously, in-situ observations in the Weser estuary showed that fluid mud entrainment is strongly influenced by local morphology. Here, these results are discussed in view of long-term changes of estuarine conditions, and with respect to the formation of a distinct dune-mud transition in coastal plain estuaries.

1 INTRODUCTION

The geodiversity in tide-controlled estuaries is high, partly caused by changes in hydrodynamic conditions from the upper channel to the outer estuary. While tidal channels are naturally often covered by sand, estuarine processes cause accumulation of fine sediments in the turbidity zone (Dalrymple and Choi 2007).

The location of the turbidity zone is linked to the occurrence of fluid mud, frequently observed in tide-controlled estuaries. In addition, deposits of erosion-resistant mud of higher density are found close to the tidally averaged center of the turbidity zone. Further upstream and downstream, fields of large dunes coexist to these mud deposits, in estuarine channels with sandy bed sediments.

Research during the past years emphasized the role of sediment-induced stratification in estuarine mud formation. Settling during slack water leads to near-bed stratification, which effectively dampens turbulence and limits entrainment after slack water (e.g. Winterwerp 2006).

During the cycle of settling and entrainment, the turbidity zone is advected by tidal currents. Ephemeral fluid mud deposits may consequently formed (also) in troughs of large dunes, as observed in the Weser estuary (North Sea, Germany). In this case, the local distribution and intensity of turbulence in dune fields affects the entrainment of fluid mud, which occurs at some point in time after slack water (Becker et al. 2013).

These observations raised the question, if and how the impact of large dunes on fluid mud entrainment influences the along-channel distribution of sedimentary features, as different as dune fields and mud deposits, along an estuarine channel.

A brief summary of previous findings is given in the next chapter. Subsequently, the formation of estuarine mud is revisited, followed by ideas regarding the development of an along-channel transition between dunes and mud. This is discussed with respect to changes of estuaries on longer time scales.

2 FLUID MUD IN DUNE TROUGHS

Dynamics of near-bed stratification were analysed in the Weser, Southern North Sea, Germany, based on ADCP and sediment echo sounder data (Becker et al. 2013). Sediment cores were collected during slack water.

Near-bed sediment concentrations were between 25 g/l and 70 g/l, which is close to the gelling concentration of the suspension of mud flocs. The spatial distribution of these fluid mud layers coincided with the location of the estuarine turbidity zone.

Two types of fluid mud deposits were found. In the center of the tidally averaged location of the turbidity zone, fluid mud was deposited in form of contiguous layers on a predominantly flat river bed of fine grained bed sediments. Due to the tidal excursion, fluid mud formed also further upstream and downstream in troughs of large dunes. There, dune height (> 2 m) exceeded fluid mud layer thickness.

In dune troughs, the average residence time between formation and entrainment of fluid mud was 3.2 h. Entrainment occurred as velocities exceeded 0.45 m/s, measured 1 m above the fluid mud surface (Fig. 1). While these fluid mud deposits were entirely resuspended, less entrainment was observed over flat bed, where near-bed stratification persisted until the following slack water.

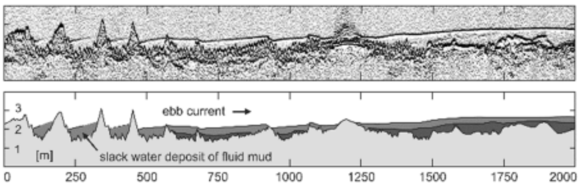

Figure 1. Sediment echo sounder profile of fluid mud during accelerating currents after flood slack water. Note the difference in stratification between dune troughs and the flat bed. In absence of dune crests, the interface between fluid mud and the upper layer appears undisturbed.

According to the local gradient Richardson number, based on mean shear, stratification in dune troughs was stable with respect to shear instabilities during entrainment. After slack water, entrainment is therefore considered to be induced by the development of dune specific turbulence, downstream of the dune crest. Such additional turbulent stress is absent in regions without large dunes, explaining the persistence of contiguous fluid mud layers over a flat river bed.

After fluid mud entrainment, a thin layer of higher concentrated mud was found to remain, adding to the heterogeneity of sediments in due troughs. These heterogeneous trough deposits are buried by sand during the following period of dune migration. They are seen in sediment echo sounder profiles as a reflector indicating the dune migration base.

3 FORMATION OF ESTUARINE MUD

In the subsequent description, the influence of several processes, relevant to fine sediment transport, are taken into account, e.g. flocculation, hindered settling, and entrainment (Winterwerp 2002). On longer time scales, the influence of these processes on the along-channel distribution of sediments depends on subtle balances, between specific processes.

3.1 Entrainment and turbulence damping

The formation of estuarine mud strongly depends on the balance of turbulence damping and entrainment. This is due to the specific vertical density distribution, which results from the settling behaviour of flocculated fine sediments.

Fine sediments reach the bed in form of large mud flocs. Their settling velocity determines the mass settling flux in estuaries (Manning and Dyer 2007, Soulsby et al. 2013). Unlike sand grains, mud flocs are not immediately part of the bed surface once they reach the bed. If the settling flux is high, e.g. at the location of the turbidity zone during slack water, hindered settling causes a reduction of settling velocities near the river bed. A concentrated near-bed suspension is formed, which acts as a buffer layer for fine sediments (Uncles et al. 2006). At its surface, hindered settling leads to a distinct vertical density gradient, the lutocline (e.g. Wolanski et al. 1989).

As concentrations increase near the bed, flocs form a dense network, usually called fluid mud (Winterwerp 2002). Consolidation rates of fluid mud are small, preventing the formation of an erosion-resistant layer of significant thickness and density, at least during slack water.

Due to damping of turbulence at the lutocline, fluid mud may be dynamically decoupled from the turbulent flow in the upper part of the water column (Becker et al.

2018). This decoupling must be effective for a sufficient time during the tidal cycle, to facilitate consolidation despite high current velocities. In most engineering models, this scenario is not explicitly modelled but parameterized by critical shear stresses for deposition and erosion of the respective grain size classes.

3.2 Influence of tidal excursion

The region of fluid mud deposition is linked to the location of the turbidity zone during slack water. In case that fluid mud deposition occurs at the end of the flood phase, settling during the following ebb slack water would occur further downstream, due to the tidal excursion and the associated displacement of the turbidity zone.

If the along-channel extent of the turbidity zone exceeds the tidal excursion, two settling periods occur at the tidally averaged location of the turbidity zone (Fig. 2). Note that in this simplified scenario, intratidal variations in the vertical velocity profile, in shear dispersion, and therefore in suspended sediment transport, are neglected.

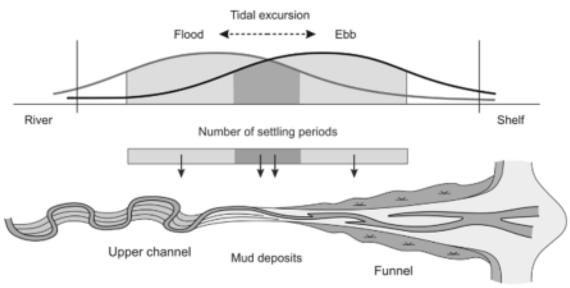

Figure 2. Number of settling periods in relation to tidal excursion and the extent of the turbidity zone.

As already mentioned, freshly deposited fluid mud was observed to persist entrainment during one tidal phase, if fluid mud is deposited over a flat river bed. Taking into account this persistence of fluid mud, slack water settling potentially leads to an increase of sediment concentration in the (remaining) fluid mud layer. Higher concentrations then induce higher stratification, and increase the effect of turbulence damping at the lutocline.

This quasi-continuous supply of sediments by slack water settling is considered to introduce a positive feedback regarding the persistence of fluid mud to entrainment. As a result, the probability of the formation of erosion-resistant estuarine mud is increased in the tidally averaged location of the turbidity zone.

4 DUNE-MUD TRANSITION

Both cohesive and non-cohesive transport processes are relevant to the overall distribution and development of estuarine sedimentary features. In case of fluid mud in dune troughs, cohesive (fluid mud deposition) and non-cohesive (dune migration) transport processes are distinctly separated in time, due to the change of current velocities during the tidal cycle.

One aspect of this interaction of processes is their influence on the shape of the transition between a dune field and adjacent deposits of estuarine mud. The transition is expected to be located close to the tidally averaged location of the turbidity zone.

A scenario is considered, in which estuarine mud is already deposited somewhere in the fluvial-marine transition zone, and in which fields of large dunes coexist up and downstream of the mud deposits.

It is assumed that fine sediments settle in form of large mud flocs, such that deposition of mud occurs only according to the mechanism outlined in the previous chapter. Changes in hydrodynamic conditions and sediment supply on time scales longer than a tidal cycle are neglected. Dune height is assumed to exceed the thickness of fluid mud layers, which results from slack water settling. Dune are considered to be oriented in direction of the tidal current after slack water.

For this situation it is hypothesized that the observed differences in fluid mud entrainment lead to a sharp transition of dunes and mud. For the Weser estuary, this transition is shown in Fig. 1, upstream of the center of the turbidity zone. The transition is sketched in Fig. 3. It is further suggested that the dune-mud transition is relatively resistant to changes in environmental conditions.

Any sediment-induced near-bed stratification, formed during slack water, is rapidly destroyed by turbulence in fields of large dunes (Fig. 3 b), at some point in time during the following tidal phase. In other words, dune specific turbulence prevents mud deposition.

By contrast, the same stratification can function as a buffer layer for fine sediments over a flat, muddy river bed, promoting consolidation and mud deposition (Fig. 3 c, d).

Obviously, both bed configurations are associated with mechanisms, which act to sustain the respective state of the river bed. The flat bed in presence of mud supports the persistence of near-bed stratification during the tidal cycle. Dune crests, acting as roughness elements, prevent or at least reduce deposition of mud in dune fields.

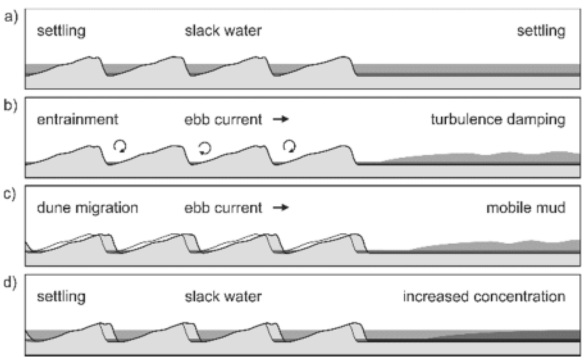

Figure 3. Settling and entrainment of fluid mud upstream and downstream of the dune-mud transition, sketched for the situation upstream of the center of the turbidity zone. Fluid mud is entrained in dune troughs (b). Relatively persistent stratification over the flat bed leads to an increase of near-bed concentration (d).

The dune-mud transition is therefore considered to resist certain changes in environmental conditions, e.g. in the supply of suspended sediments, or in the tidal current regime, which may be caused by variations in river discharge.

5 DISCUSSION

The aim to document this concept on the dune-mud transition is to draw attention to the interaction of cohesive and non-cohesive transport processes, in view of recent changes in estuaries.

In response to channel deepening and extended maintenance work, the transport regime in many estuarine systems changed towards flood-dominant conditions (Burchard et al. 2017, Winterwerp and Wang 2013). The trapping efficiency and suspended sediment concentrations increased, promoting the deposition of estuarine mud. In addition, the turbidity zone is shifted further upstream.

Studies demonstrate that the varying content of mud and the associated cohesive properties of bed sediments change size and dynamics of smaller bedforms, e.g. current ripples (Malarkey et al. 2015). By contrast, almost no information exists on the fate of dune fields for the specific case considered in this study. Recent progress in physical modeling of tide-controlled estuaries shows the effect of mud on large scale morphological features (Leuven et al. 2018). Still, the small scale interaction of dunes and mud is hardly implemented in a physical model, and, at this stage, also not in common numerical models. The response of a field of large dunes to an “invasion” by mud is essentially unknown.

In general, the response of the river bed to a local change in the transport regime depends on the time scale. Neglecting anthropogenic effects, e.g. dredging activities, and assuming a continuous upstream migration of the turbidity zone, the (spatial) transition between dunes and mud may be governed by the processes described in the previous chapters. Accordingly, an abrupt transition is expected between the mud deposit and the dune field, where mud deposition is prevented by dune specific turbulence.

During the upstream shift of the turbidity zone, the locally increased supply of cohesive sediments presumably leads to pronounced stratification in dune fields. To deposit erosion-resistant estuarine mud, this stratification must persist dune related turbulence, in case that the dune height exceeds the thickness of the fluid mud layer. If instead fluid mud thickness exceeds dune height, dunes are decoupled from the flow in the upper layer and cannot act as roughness elements, potentially leading to a faster infill of dune troughs with fine sediments.

6 OUTLOOK

Ideas presented in this contribution are rather speculative. In view of the complexity of the subject, the concept described here is only a starting point, in order to define a model set-up for an appropriate analysis.

The concept of the dune-mud transition stresses the aspect of self-organization, neglecting large-scale boundary conditions. One goal of the analysis would therefore be to show the effectiveness of internal processes, such as the influence of dunes on fluid mud entrainment, in contrast to external processes, e.g. the overall sediment supply.

Sediment supply to the near-bed region depends on the settling flux during slack water. In the turbidity zone, the settling flux probably varies in along-channel direction, with the maximum settling flux expected to occur in the center of the turbidity zone, which is neglected in the conceptual model.

Also neglected is the possibility that dunes are oriented not as assumed but, e.g. in ebb direction downstream of the turbidity zone. This is the case in the Weser estuary. The flood current is directed against these dunes. The structure of turbulence is different (Lefebvre et al. 2016), compared to the situation upstream of the turbidity zone. Fluid mud entrainment might occur later, increasing the time for consolidation around ebb slack water. This may have an impact on the dune-mud transition downstream of the turbidity zone.

However, these aspects can only be investigated with an appropriate model setup. This should be the next step, in view of this and similar questions regarding the interaction of near-bed transport processes in estuaries.

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