The influence of tides and wind speed on fine-sediment transport in a semi-enclosed natural harbour (Pagham Harbour, UK)

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Abstract

Preliminary analysis of results from a study of fine sediment transport in a macrotidai harbour (Pagham Harbour, West Sussex, U.K.), has revealed patterns of fine sediment transport which may be related to the tidal range and the wind speed. This paper will present preliminary analysis of regular and frequent monitoring of turbidity, salinity, water level, wind speed and wind direction over a continuous 70 days period. Analysis of sediment transport over individual tidal cycles has also been carried out, in order to ascertain a possible mechanism for the flux of fine sediment to and from the intertidal mud areas. Shorter, faster flood-tide currents lead to concentrations of suspended sediment that are normally highest during the first 90 minutes of the flood tide. These concentrations decrease rapidly due to settling, during the relatively low velocities at, and immediately following, high slack water. Peak flood-tide suspended sediment concentrations appear to be correlated more with tidal range, than with wind speed, suggesting that there is a greater sediment mobility during spring tides.

Introduction

The management of semi-enclosed natural harbours around the UK coastline relies on a quantitative understanding of the processes of fine sediment transport within these systems. Several such systems, generally characterised by a narrow harbour entrance and relatively low fresh water input, exist along the heavily
populated areas of the Southern and East Anglian coastlines. At present, there is concern that changing environmental factors, coupled with a general ever-increasing demand for land development at some coastal sites, has implications for the balance of fine sediment transport processes occurring in and around these harbours. Several issues have arisen in recent years that particularly highlight the need for further study of these systems, including:

- the possibility of managed realignment schemes as a ‘soft’ coastal defence strategy, and the influence of these on sediment transport processes;
- the importance of fine sediment deposits as a food source for primary producers, thus sustaining the population of both migratory and resident bird life in these environments;
- the effect on natural harbour processes of high discharge from extreme rainfall events, such as those experienced in Southern England during October, 2000.

In order to investigate these issues, high resolution, good quality field data describing existing sediment budgets and transport mechanisms within natural harbours are required. Field data are also essential for the design and calibration of numerical models used to predict the effects of any changes imposed on the system. These data and models may then be used to produce effective management tools.

This study presents the preliminary analysis of an initial continuous monitoring data set obtained from Pagham Harbour, a semi-enclosed harbour on the Southern English coast, over a 70-day monitoring period between 11 October and 18 December, 2001.

**Previous knowledge**

Hydraulic and meteorological conditions are well known to influence sediment erosion / deposition rates within estuarine systems (Dyer, [1]). The transport of material under the action of tides, river flow, wind and wave action and thus the distribution of suspended material throughout the estuarine system is governed by the interaction of tides, river flow and wind-induced wave action.

Field studies of estuary systems of this type have focused mainly on larger estuaries where fluvial influence from a single major point source is important (e.g. Mitchell et al., [2]). Relatively few investigations have been made focusing on cohesive sediment transport in natural harbours. Given the influence of fluvial flow on the formation and maintenance of turbidity maxima in estuaries, there is a need to identify sediment cycling mechanisms of systems with less fresh water input.

Asymmetry of the tidal wave can result in higher velocity during the flood tide, leading to greater erosion than during the subsequent ebb tide. As the floodwaters rise out of the creeks to cover the mudflats the velocities slow as the relative cross-sectional area increases, resulting in a settling out of the sediment
on the mudflats. On a larger time scale, ‘tidal pumping’ (Dyer, [1]) has been proved to be a major contributor to sediment movement in estuaries.

Although the influence of waves is limited, their influence may be very significant in shallow water, and the wave-dominated zone will be advected across the mudflats as the tide rises and falls (Whitehouse et al., [3]). The importance of erosion and re-distribution of cohesive sediment due to the influence of locally induced wind waves has been observed by various authors (e.g. Kirby and Parker, [4]). Furthermore, analysis of field data collected in the East Frisian Sea (Santamarina Cuneo and Flemming, [5]), a site with certain similarities to Pagham Harbour, has shown that higher wind speeds do indeed lead to greater concentrations of suspended matter.

Dyer [1] highlighted that short-term field measurements were of little use in solving significant problems related to estuaries, as the data collected are likely to be unrepresentative due to the influence of weather effects and the fact that estuaries are seldom in a steady state. Furthermore, in common with other sites of this type (e.g. Ke and Collins, [6]), it is known that Pagham Harbour is accreting at its landward limits (Cundy et al., [7]). While suggestions have been made as to the overall accretion rates in response to local sea level rise, only limited progress has thus far been made in identifying and quantifying the mechanisms by which this accretion takes place. By the deployment of a moored, self-recording Conductivity-Temperature-Depth (CTD) probe, with an on-site automatic weather station nearby, good quality medium-term data has been collected.

Study site and methods

Pagham Harbour (0° 45’ W, 50° 48’ N), with an area 2.8 km² (measured at high water level on spring tides, Geodata Institute, [8]), is one of a series of semi-enclosed natural harbours situated on the central south coast of England (Figure 1). Fresh water input is low and occurs via a small network of rifes which drain the surrounding agricultural land (the principal locations of these are indicated as Q1-Q4 on Figure 1). A system of inner sea walls protects the surrounding low lying reclaimed land, with tidal flaps preventing saline intrusion upstream. The harbour is connected to the English Channel via a 100 metre wide entrance, and protected by an artificially replenished shingle spit (Figure 1). Local tides are semi-diurnal with a tidal range of between 3 m (Neaps) and 6.5 m (Springs), but owing to its relatively high elevation, the tidal cycle within the harbour is asymmetrical, with inundation occurring only during the upper parts of the tide.

The sheltered nature of the harbour makes it very susceptible to problem growths of Enteromorpha and/or Ulva green seaweeds (Geodata Institute, [8]), which are symptomatic of eutrophication problems worldwide. Thus under certain conditions, levels of chlorophyll could be significant. This could also affect optically measured turbidity (Black et al., [9]). For the purposes of this analysis, however, this affect has been ignored due to the fact that all readings were taken in late Autumn/early winter when such growth is limited.
The water of the harbour was sampled remotely by the deployment of a moored SBE-19 CTD with internal data logger and an additional Optical Backscatter (OBS) sensor attached for monitoring turbidity. The CTD was situated at site FC (Figure 1) in a side channel near a freshwater input, sampling every 10 minutes. The instrument was suspended so that its sensors were 0.25 m from the bed of the creek, by attaching it to a scaffold tube mounted onto the concrete apron surrounding the tidal flap gate. Correlation between suspended solid concentration (SSC) and recorded turbidity was determined by gravimetric analysis of samples taken at the same time. While direct comparison between optically measured NTU and grams-per-litre suspended sediment concentration is problematic, this calibration revealed that an approximate calibration of 1 NTU = 1 mg/l could be assumed. A standard algorithm was employed to determine salinity from conductivity and temperature measurements. Instrument calibration was checked before and immediately following deployment. Hourly wind speed and direction data were obtained by a basic Automatic Weather Station, situated 500 metres to the north of point FC. Further details of experimental procedure may be found in University of Brighton [10].
Results

Time series showing typical measured water level, salinity and turbidity are shown in Figure 2. Water levels have been multiplied by a factor of 10 for increased clarity on the given axes. Although both graphs depict measured conditions for a similar, neap, tidal condition, the predominant wind conditions are different between the two tides. For the case of Figure 2(a) (26 October 2001 second tide) the mean 6-hour wind condition is relatively high (4.2 m/s from direction 207°). In Figure 2(b) (9 December 2001 second tide), the mean 6-hour wind condition is lower (1.7 m/s from direction 36°). In both cases, the rise in
water level at the start of the flood tide coincides with a sharp rise in turbidity, which continues until saline water arrives when turbidity levels peak and start to fall. Towards the end of the ebb tide there is a second peak in turbidity that coincides with the drop in salinity levels and the opening of the tidal flap gate. In both cases, the salinity peaks at a level of around 30, and for much of the ebb tide, the salinity remains above 10, even when the incoming water is from land drainage. This is probably due to the presence of a lens of salinity that remains behind until flushed away by the next flood tide.

Comparing Figure 2(a) with 2(b) suggests that the larger waves produced by higher wind conditions on 26 October may have re-suspended greater quantities of sediment than for the similar tide on 9 December. In addition to the observed higher peak turbidity observed, it can be seen that there is also a greater variability in concentrations of suspended sediment for the more windy conditions of 26 October.

In order to explore further the relationship between the magnitude of the observed turbidity peak and forcing factors of tidal range and wind speed, analysis was carried out for the entire data set, in which the peak turbidity during the flood tide was obtained for each tide. In an attempt to smooth out unrepresentative ‘spikes’, an average of three values centred on the peak was calculated. The complete time series of these, together with the corresponding peak tidal water level and salinity, and 6-hour average wind speed and direction, are shown in Figure 3. 6-hour average wind speed and direction [Figure 3(a)] were obtained by calculating a vector average of hourly values yielded by the weather station.

![Figure 3a Time Series Wind speed and Direction](image)
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Discussion

During the 70-day monitoring period, the data logged by the CTD shows regular patterns of turbidity, which correlate with the changes in salinity and water level. During the first half-hour, as the water level starts to rise with the incoming tide, turbidity levels increase sharply. This suggests that sediment within the creeks of the harbour is re-suspended by the movement of the flooding water. This relationship between the inundation of water within the creeks and increases in SSC levels has also been noted in the Tavy estuary (Uncles and Stephens, [11]).

Salinity readings over individual tides indicate that the incoming tidal wave initially forces the fresh water back up this creek, causing a lowering of observed salinity at the start of the flood tide (Figure 2). Saline water eventually arrives at the landward reaches of the harbour at a minimum of 20 minutes after water levels have started to rise. The arrival of salinity marks the peak in observed turbidity, suggesting that the chemical properties of the seawater cause the sediment to flocculate and thus settle out of suspension.

Regression analyses of the peak turbidity with peak water level and wind speed suggest that the magnitude of the initial peak appears to correlate better with peak water level, related to the spring-neap tidal cycle, than with wind speed. Although both the best-fit lines in the graphs of turbidity against water level (Figure 4) and turbidity against wind speed (not shown) show positive gradients, the $R^2$ value is higher in Figure 4 (0.105 compared to 0.032). This observed increase in turbidity is very likely to be related to the increase in bottom shear stress; probably a result of higher water velocities caused by greater volumes of water entering the harbour during spring tides.
Although not observed on every tide, the turbidity peak during the ebb tide tends to be lower in magnitude than the initial peak. This suggests that more sediment is transported landwards on the flood tide, than seaward on the ebb tide. Although possibly linked to the opening of the tidal flaps, it is suggested that this final increase in turbidity may also be a result of sheet flow as the final run-off waters drain back into the creeks re-suspending the recently deposited sediments. This is in agreement with the findings of Uncles and Stephens [11], who made similar observations on the Tavy estuary.

Conclusions

Preliminary analysis of continuously monitored turbidity, salinity, water level, wind speed and wind direction at Pagham Harbour, UK between 11 October and 18 December, 2001, has yielded the following useful conclusions in relation to the hydrodynamic and sediment transport characteristics:

1. Relatively fast flood-tide currents generally coincide with a short-lived turbidity peak at the observation point, which is at a landward extreme in the harbour. At the same instant, fresh water is forced landwards by the incoming tidal waters. It is suggested that this action re-suspends loosely bound sediments and transports them landwards.

2. Although a considerable degree of scatter is observed, the magnitude of these turbidity peaks appears to correlate more closely with peak tidal water level than with wind speed.

3. With the arrival of saline water, saline-induced flocculation and slower currents cause the newly re-suspended sediments to settle, and the observed turbidity to decrease. A final peak in turbidity, coincident with re-opening of
a local tidal flap gate is probably linked to one or more of the following factors:

(a) A fresh water surge as the tidal flaps reopens
(b) Sheet flow of sediment off of the flats, when water levels drain down.
(c) Run off from precipitation that coincides with the exposure of the flats.

4. Further work is needed to identify the spatial distribution of this observed distribution of suspended sediment, by re-deployment of the CTD logger to other sites within the harbour. At the same time, further investigation is required to address the influence of locally-generated wave height the presence of chlorophyll and, possibly, the effect of precipitation on the turbidity signal obtained from the CTD logger.

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References

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