Effects of freshwater inflow on sediment transport

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Lead Author Biography

Alejandro Souza graduated in Oceanology at the UABC, Mexico in 1989, before carrying out his MSc and PhD in Physical Oceanography at the UCNW, UK. After a short time at Harvard University he joined the now NOC at Liverpool in 1998, where he is currently leader of the BLAST research group (boundary layer and sediment transport).

Synopsis

This study investigates the effect that freshwater inflow has on the transport of dredged material in Liverpool Bay. The sediment dispersal is first simulated using constant density throughout the domain, and then density gradients and stratification will be allowed to develop from riverine inputs. The first case shows the sediments slowly being transported east-westwards away from the estuary; while the simulation with freshwater shows the sediment being rapidly transported south-eastward towards the estuary. Model simulations such as these may inform decisions of where to put the dredging spoil to minimise the likelihood of it returning directly to the estuary.

1. Introduction

Each year, between 1.5 and 3 million tonnes of sand and mud is dredged from the Mersey Estuary and shipping channels and discarded at one of the designated spoil grounds in Liverpool Bay. To ensure the effectiveness of the expensive and time-consuming dredging operations, an important question is: when is the best time and where in Liverpool Bay should dredged material be placed so that it is not immediately transported back into the estuary?

Liverpool Bay is a very complicated system: it is a macro-tidal shelf sea (tidal range up to 10 m), with three adjacent large estuaries (Dee, Mersey and Ribble), which generates a complex region of freshwater influence (ROFI)[1]. Strong tidal currents in the bay are predominantly in an east-west direction, while density driven flows are one of many factors controlling the weaker, variable residual circulation. Sediment instantaneous movements depend mainly on the tidal flow, but the longer term transport will be mainly driven by residual currents and shear dispersion, which are significantly modified by tidal straining and density circulation resulting from freshwater run-off; they are also influenced by turbulence, mixing and the wind forcing.

Asymmetric strained stratification occurs when vertically homogeneous horizontal (salinity) density gradients interact with the vertically sheared tidal velocities. During ebb, tidal currents transport fresher water further at the surface than at the bottom, hence generating stratification. This is reversed on the flood tide, and if there is denser water overlying less dense water, the resulting instability causes it to mix. This asymmetry on stratification and mixing generates an extra component of the residual circulation[2,3] in the same direction as the density driven circulation.

The River Mersey and its approach channels have been dredged since 1833; the average maintenance dredging carried out on behalf of the Mersey Docks and Harbour Company between 2005 and 2009 was 1.9 million tons per year. During that period the majority of the dredged material was dumped at site “Z” west of Jordan’s Spit; the actual amounts deposited vary from a maximum of 96% in 2005 to a minimum of 66% in 2008[4]. This study will investigate the prediction of the sediment movement under homogenous density, as is the case of most 2DH models used by engineers, and under more realistic conditions, when density gradients and periodic asymmetric strained stratification are allowed to develop from the introduction of freshwater from the rivers.

2. The Numerical model

Sediment movements are generally simulated using the Eulerian advection-diffusion equation to calculate changes in suspended sediment concentrations (Equation 1). These can be computed readily, but information such as the provenance of sediments cannot be stored. Alternatively, a Lagrangian particle-tracking model is capable of recording the positions of each particle, which can have differing sediment characteristics such as, mass (or volume and density), settling speed (or mean diameter). However, a large number of particles may be needed to represent the observed sediment concentrations, e.g., at least 10,000 particles for the Mersey Estuary.

The Lagrangian particle tracking module replicates the processes in the Eulerian advection-diffusion equation for non-cohesive sediments following Lane[5].

$$\underbrace{\frac{\partial C}{\partial t}}_{\text{change in conc.}} + \underbrace{u\frac{\partial C}{\partial x} + v\frac{\partial C}{\partial y}}_{\text{advection}} - \underbrace{w_s\frac{\partial C}{\partial z}}_{\text{settling}} = \underbrace{\frac{\partial}{\partial z}\left[K_z\frac{\partial C}{\partial z}\right]}_{\text{diffusion}} + \text{source} \tag{1}$$

Solutions involve calculations for successive model time steps Δt of the height above the bed, z of each particle (Fig. 1):

- vertical settling is $-w_s \Delta t$ (downwards),
- diffusive (random up or down) displacement[6], $l = \sqrt{(2 K_z \Delta t)}$, where $K_z = k \hat{U} D$ is the eddy diffusivity, k is the bed friction coefficient, $\hat{U}$ is the tidal current amplitude, and D is the water depth,
- horizontal advection is $U \Delta t$,
- erosion of an available particle from the sea bed to a height $z = l$ occurs when the cumulative erosion potential $\gamma \tau_b$ exceeds a threshold value equivalent to the particle mass per unit area per model time step, $M/(\Delta x \Delta y \Delta t)$; where the coefficient γ is $0.0003 \text{ kg m}^{-2} \text{ s}^2$ and bed stress $\tau_b = k \rho U_b^2$; density of water is ρ, and U_b is the current at the sea bed.

This Lagrangian module was coupled to POLCOMS, a 3D baroclinic hydrodynamic model (on an Arakawa B-grid), which makes use of numerical methods that allow it to resolve and maintain sharp gradients: the PPM (Piecewise Parabolic Method) computes advective terms accurately, and the TVD (Total Variation Diminishing) hyperbolic conservation scheme calculates volume fluxes which determine the wetting and drying in the model[7,8]. The General

Ocean Turbulence Model (GOTM, www.gotm.net) provides the turbulence closure, using the 'k-ε' model. The 3D POLCOMS provides the hydrodynamics for the Lagrangian module and is run on a multi-processor cluster computer. The eddy diffusivity, K_z in the expression for displacement l, above, is obtained directly from the turbulence closure.

The present application in Liverpool Bay is based on a 180-m resolution, with 10 sigma levels in the vertical. The hydrodynamic part of the model was spun-up first for at least 30 days before introducing the sediment.

2.1 Modelling scenarios
Dredged mud and sand are deposited at the spoil ground "Z", to the west of Jordan's Spit offshore from Formby Point (marked with + in Fig. 2); this is approximately 3 km north-east of the Liverpool Coastal Observatory mooring Site A. Sediments in the model are represented by muddy sand with settling velocity $w_s = 1.0$ cm s^{-1} and each of the 10,000 particles has a mass of 0.5 kg. In the first two simulations, one is forced with tides only and the other one also has climatologic river flows added. An additional more realistic simulation was carried out using finer mixed sediments ($w_s = 0.05$ cm s^{-1} for mud and 0.1 cm s^{-1} for sand), each particle now represents 10 kg and observed daily-mean river flows, to examine further the sediment transport under natural conditions.

3. Results

3.1 Tides only
Muddy sand has a relatively fast settling velocity hence it is confined close to the sea bed: at high water almost all particles have settled. The material disperses slowly northwards from the release point as tidal currents advect it in an east-west direction. Its progress at three, seven and 15 days are shown in Fig. 2 a, b and c. After 15 days, the eastern edge of the sediment patch reaches the shore, and although most of it has moved northwards, a small proportion of it begins to drift south towards the River Mersey.

3.2 Tides and climatologic river flow
Including climatologic river flows (derived from daily average over years 1950–2005) causes the coarse sediment to move quickly southwards with the near-bed, due to the density and tidal straining driven circulation, with a much clearer pathway than tides-only case. Sediment reaches the shipping channels after just seven days and into the Mersey Estuary after 15 days (Fig. 2 d, e and f).

3.3 Transport of fine sediment under realistic river flow
The fine sediments transport under realistic tides and river flows (Fig. 2 g, h, i), better reflect the density-driven circulation and sediment transport: near surface particles travel northwards away from the coast, while those near the sea bed move rapidly south-eastwards. The model predicts that fine sediments can reach the shore within seven days, and after 15 days have made its way into the inner Mersey Estuary.

4. Discussion

The residual circulation in Liverpool Bay flows away from the coast northwards in the surface layer and towards the coast near the sea bed following Heaps[9], as shown by Verspecht et. al[10].

At spring tide, during the ebb Liverpool Bay usually stratifies moderately, and the stratification almost completely breaks down on the flood. The tidal currents can resuspend coarse and fine particles from the sea bed and keep them in suspension over the tidal cycle. However, at neap tides, the stratification during the ebb is greater (up to twice the value of spring tide) and remains during the flood although slightly reduced in strength. Finer sediments can be resuspended, but particles are likely to be confined to the lower mixed layer. Three circulation regimes are identified in Liverpool Bay[11]:

1) fully mixed giving rectilinear east-west flow,
2) continuously stratified with counter-rotating current ellipses in the upper and mixed layers,
3) periodic asymmetric strained stratification: the water column stratifies tidally and the currents only oppose during the stratified part of the tide.

Observations at the Liverpool Coastal Observatory Site A show: at spring tide mixed conditions during 29 Feb–1st Mar and 5–7 & 17–18 Mar, but periodic stratification is more common. The strongest stratification occurs at low water, with the tidal currents flowing northward near the surface and south-westward near the bed. The water column during neap tides corresponds to continuously stratified conditions, with the current ellipses in the upper mixed layer rotating clockwise and those in the lower layer rotating anti-clockwise[12]. Fine sediment in the upper mixed layer will move north during ebb and to lesser extent south during flood, while sediment in the lower layer will move in the opposite direction – residual currents and net transport are expected to be smaller than during periodic stratification.

The particle tracking model results highlight the importance of sediment type (sand or mud) and settling velocity on the speed of transport from the spoil ground: coarse sediments are transported slowly as they stay close to the sea bed (slower current) and may settle and resuspend repeatedly, while finer sediments can reach the sea surface and are advected more readily. Tidal residual currents alone give the incorrect impression that dredged sediments will not return to the estuary. Inclusions of daily-mean river flows in the model introduce baroclinic processes, which drive near bed sediments towards the shipping channels and the estuaries.

The model simulations imply that the timing of the dredging operations may be more important for finer sediments, as the first particles can reach the estuary mouth after one week especially during spring tides. Coarser material taking at least two weeks may be less sensitive.

Conclusions

This work shows the application of a state-of-the-art modelling system, comprised of: a three-dimensional baroclinic model coupled with a turbulence model and a particle tracking sediment model, applied to dumped dredge material in Liverpool Bay. The study investigated the importance of baroclinic processes in order to assess the validity of some commonly used simplifications used by engineers, i.e. the use of barotropic 2DH models.

Numerical results of the sediment transport of dredged spoil have shown the importance of baroclinic processes driven by horizontal density gradients. The presence of horizontal density gradients driven by riverine freshwater, modify completely the sediment pathways, from being mainly east-west with a slight diffusion northward to becoming a very rapid south-eastward flow back into the Mersey Estuary.

These results clearly suggest that barotropic sediment transport models are unsuitable for use in estuaries and ROFIs. They also suggest that the type of model presented here should be used to assess the best place and time to carry out dredging and dumping operations, either to make it more economically efficient or to comply with regulations, which might require the sediment to return to the system.

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Fig. 1. The Lagrangian particle tracking module simulates the sediment erosion, advection, settling and diffusion processes.

Fig. 2. Predicted sediment distribution, 3, 7 and 15 days after the release of muddy sand (w_s = 1.0 cm s^{-1}) for tides (a, b and c), and 'climatologic' river flow & tides (d, e, f), sandy mud with measured river flow (w_s = 0.05 and 0.1 cm s^{-1}) (g, h, i). + marks the initial release point ● suspended, ● on sea bed.

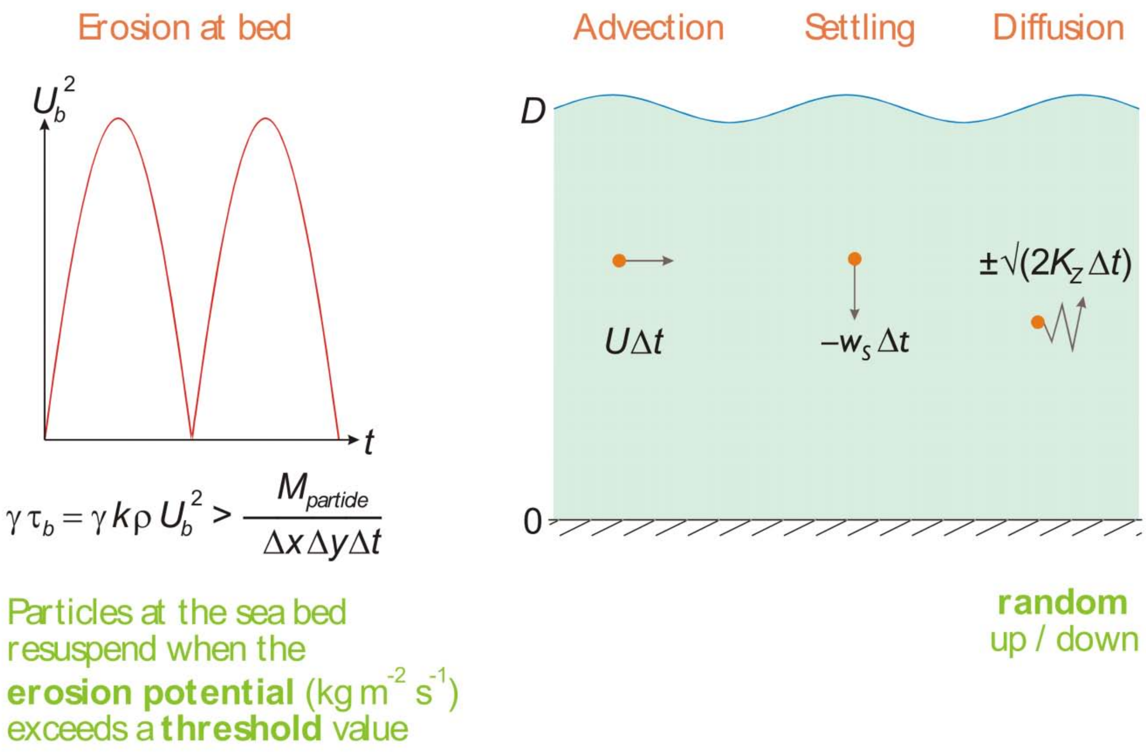

Fig. 1

HW after 3 days
HW after 3 days
HW after 3 days
a
d
g
HW after 7 days
HW after 7 days
HW after 7 days
b
e
h
HW after 15 days
HW after 15 days
HW after 15 days
c
f
i

Fig. 2