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Modelling the sensitivity of suspended sediment profiles to tidal current and wave conditions

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ABSTRACT

Seawater turbidity due to suspended particulate material (SPM) is an important property of a marine ecosystem, determining the underwater light environment and many aspects of biological production and ecology. SPM concentrations are largely determined by patterns of sediment resuspension from the seabed due to shear stress caused by waves and currents. Hence planning for the construction of large scale offshore structures which will alter regional hydrodynamics needs to consider the consequences for SPM concentrations. Here we develop a one-dimensional (vertical) model of SPM dynamics which can be used to scope the effects of changes in wave and tidal current properties at a site. We implement the model for a number of sites off the east coast of Scotland where we have extensive data sets to enable numerical parameter optimisation. The model performs well at simulating fluctuations in turbidity varying from flood-ebb tidal cycles, spring-neap cycles, storm wave events, and an annual cycle of SPM concentration which is attributed to seasonal consolidation of seabed sediments. Sensitivity analysis shows that, for the range of seabed sediment types in the study (water depth 16–50 m; mud content 0.006–0.380 proportion by weight), relatively large (50%) attenuations of tidal current speed are required to produce changes in water column turbidity which would be detectable by observations given the variability in measurements. The model has potential for application to map the large scale sensitivity of turbidity distributions to the installation of wave and tidal energy extraction arrays.

1. Introduction

Sea water turbidity due to suspended particulate matter (SPM) determines the depth to which sunlight penetrates below the sea surface. This is one of the key factors determining the species composition and productivity of marine ecosystems. The effects include the rate and fate of primary production, the performance of visual predators such as fish, potential for refuge from predators by vertically migrating species, and the scope for seabed stabilisation by algal mats. Hence, turbidity is a key property of an ecosystem, but one which has proved to be particularly difficult to model in shelf and coastal systems.

Some of the material contributing to turbidity may be of biological origin, but in coastal waters the majority is mineral particles originating ultimately from seabed disturbance and land erosion, the latter being deposited in the sea by rivers and aerial processes. SPM is maintained in the water column or deposited on the seabed depending on combinations of hydrodynamic processes including baroclinic (density-driven) or barotropic (mainly tidal and wind driven) currents, and wave action (Ward et al., 1984; Huettel et al., 1996). Spatial and temporal variations in hydrodynamics, or interventions such as engineering structures which alter hydrodynamics, should therefore be a major determinant of turbidity.

Full simulation of the impact of waves and currents on suspended sediment concentrations requires the solution of equations representing erosion and deposition of sediment from the seabed, together with vertical mixing and horizontal transport in the water column. Typically the mixing and advection terms are posed as partial differential equations embedded in a computational scheme for solving the equations of fluid dynamics (e.g. Teisson, 1991). There are several systems available for this task (e.g. Gerritsen et al., 2000; Mercier and Delhez, 2007; Warner et al., 2008; Danish

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Hydraulics Institute, 2013). However, in each case the inclusion of SPM simulation adds considerably to the computational demand and requires extensive and costly calibration of area-specific parameters. For many applications, this may be prohibitively demanding. Some authors have explored alternative ‘short-cut’ approaches involving e.g. blending of satellite remote sensing data on SMP concentrations and simulated hydrodynamic flow fields (Wu et al., 2011). Here, we propose a ‘lightweight’, one-dimensional (vertical), modelling approach for basic simulation of SPM dynamics, incorporating simple caricatures of the fundamental erosion and deposition processes which can be used to quickly scope the effects of hydrodynamics on turbidity distributions. Our approach is to simulate time-dependent vertical profiles of suspended sediment concentrations at point locations, given seabed depth and mud content, and time-dependent bed shear stress and sediment erodibility. Clearly, this approach cannot take account of lateral transport of suspended sediment, so its use must be limited to areas where the majority of sediment material in the water column arises from local seabed resuspension rather than horizontal transport.

2. Key processes affecting the vertical distribution of suspended sediment

In a closed, one-dimensional (vertical) system the mass of SPM in the water column represents the balance between erosion and suspension rates of seabed sediment, and deposition rates of suspended material. The main proximate drivers of these rates are time-varying vertical diffusivity and shear stress arising from friction between the seabed and flowing water, in particular the orbital flows which occur beneath surface waves, and directed flows due to tides and residual currents. However, the context is set by a variety of seabed sediment properties including bedform architecture, grain size composition, cohesion, consolidation and compaction. Cohesion arises primarily from electrochemical attraction forces between particles, compaction from gravitational compression leading to extrusion of pore-waters, and consolidation from adhesion forces between particles due to inorganic chemical reactions and organic molecules produced by microbiological activity. In addition, bioturbation of sediments by sifting and burrowing fauna may lead to modification of erodibility.

The shear stress on a seabed particle is a function of its size, the flow speed, and the densities of the fluid and particles (Wilcock et al., 2009). When the shear force exceeds resisting forces due to gravity, cohesion and consolidation, then a particle can become mobile. As shear forces increase, particles initially undertake short hops along the seabed (saltations), or rolling motions. Such particles are said to be part of the ‘bed-load’. When the value of the bed-shear velocity becomes sufficiently high relative to the particle fall velocity, then bed-load particles can be lifted into suspension. The vertical flux of particulate mass can be described by the differential equation:

$$\omega_s \cdot C = -K_s \cdot \frac{dC}{dz}$$

or

$$C(z) = C_a \cdot exp\left(-\int_{z_a}^{z} \frac{\omega_s}{K_s} dz \right)$$

where $C(z)$ is the suspended sediment concentration at altitude z above the seabed, C_a is the concentration at a reference altitude z_a close to the seabed, K_s is the vertical diffusivity, and ω_s is the fall velocity of particles. Predictions of vertical distributions of concentration therefore depend on assumptions about the vertical profile of diffusivity. Commonly used alternatives are to assume a constant diffusivity with altitude above the seabed, a linear increase, or a parabolic variation with peak diffusivity in mid-water. Assuming a linear increase with altitude, the concentration profile is given by

$$C(z) = C_a \left(\frac{z}{z_a} \right)^{-\left(\frac{\omega_s}{\beta \cdot \kappa \cdot u^*} \right)}$$

where u^* is the shear velocity at the seabed, κ is the von Kármán constant (0.4), and β is a coefficient relating eddy viscosity to eddy diffusivity (taken to be 1) (Rouse, 1937; Van Rijn, 1984, 1993). The exponent $\omega_s/(\beta \cdot \kappa \cdot u^*)$ is referred to as the Rouse number. Alternative assumptions regarding the vertical distribution of diffusivity give different expectations for the vertical profile of concentration, but the linear Rouse approach is most commonly applied (Camenen and Larson, 2007).

Sinking velocity is a critical term for both the initiation of particle motion on the seabed, and the structure of vertical profiles of SPM concentration in the water column. At equilibrium - where the sum of the gravity force, buoyancy force and fluid drag force are equal to zero - the downward sinking velocity of particles depends on the density and viscosity of the fluid, and the density, size, shape, and surface texture of the particle. The classical Stokes equation for the fall velocity of a particle assumes a spherical shape and laminar flow (Reynolds numbers less than 1). Despite extensive research there is still no analytical solution to predict the fall velocity of natural shaped particle, or particles large enough to generate turbulent flow (Camenen and Larson, 2007). Many investigators have proposed empirically based relationships to predict particle fall velocities with varying degrees of complication and success (Sadat-Helbar et al., 2009).

Although particle shape is certainly a factor contributing to uncertainty in sinking rates, part of the variability arises from particle-particle collisions during suspension in the water column. Collisions of fine grained particles can lead to aggregation and formation of flocs with potentially enhanced sinking rates, depending on the physical cohesive properties of particle grains and their stickiness due to biological coatings (e.g. Krone, 1978; Mehta, 1989; Andersen and Pejrup, 2002; Winterwerp, 2002; You, 2004). The probability of collisions will be a function of the suspended sediment concentration. Experimental studies have found that settling velocity for mud and silt particles is independent of concentration below 0.4 g/l. Between 0.4 and 2.0 g/l, settling velocity increases with concentration due to flocculation. Above 2.0 g/l settling velocity rapidly decreases due to the break-up of flocs, mutual hindrance, and interactions between the flows around adjacent flocs that tend to increase upward friction (Cancino and Neves, 1999). A widely used empirical relationship describing this process (Burt, 1986) is of the form:

$$\omega_s = k \cdot \left(\frac{C}{\rho_s} \right)^{\gamma}$$

where k and γ are constants, and C lies between a lower threshold for particle-particle interactions, and an upper threshold at which particles begin to interfere and the effective settling velocity is reduced. The upper concentration corresponds to values found in e.g. mud slides, where the water-sediment mixture forms a super-dense liquid which dampens turbulence and reduces shear stress as a feedback process (e.g. Richardson and Zaki, 1954). Whilst this phenomenon may occur in highly turbid estuaries, it is not

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