Topic 4.6 Understanding of the sediment transport profile

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Aim To calculate the mass settling flux of flocculated cohesive sediment in a turbulent estuarine water column.

Scientific background

For predicting the transport and fate of sediment movement in estuaries, the determination of the various spatial and temporal mass fluxes is essential. One area which has caused numerous problems, is the modelling and parameterised description of the vertical mass settling flux of fine cohesive sediment, which becomes the depositional flux close to slack water. This flux is the product of the suspended particulate matter (SPM) concentration and the settling velocity. For non-cohesive sediment this is a relatively simple process as the settling velocity is proportional to the particle size. Whereas estuarine muds, which are composed of combinations of clay minerals and different types of biological matter, have the potential to flocculate in to larger, low density aggregates called flocs.

Turbulent shear generated in estuarine water columns is recognised as having a controlling influence on both the formation of mud flocs, and their break-up (Manning, 2004a). However, to date there have been no *in-situ* studies which have quantified the flocculation process with the specific emphasis of taking floc effective density, and consequently particulate mass distribution variations, into account, within both continually changing estuarine suspended concentration gradients and varying intensities of turbulent mixing. This is mainly due to the fragility of the fastest settling macroflocs, which are easily broken-up upon sampling.

The new flocculation model, developed as part of the EstProc project, is based entirely on empirical observations made using low intrusive floc and turbulence data acquisition techniques, from a wide range of estuarine water column conditions. In particular, the floc population size and settling velocity spectra were sampled using the unique video-based INSSEV: *IN-Situ* SEttling Velocity instrument, which was developed at the University of Plymouth. This provided a total of 157 floc data sets, from experiments conducted within the framework of three recent European Commission funded projects: COSINUS, SWAMIEE and INTRMUD (see Manning, 2004b).

The algorithms were generated by a parametric multiple regression statistical analysis of key parameters which were generated from the raw spectral data (detailed derivations and testing of the algorithms are described in: Manning, 2004c; Manning and Dyer, 2004). The multi-regression identified the key components which best quantitatively describe a floc population as being: the changes in the macrofloc (flocs size > 160 μm) and microfloc (flocs size < 160 μm) settling velocities ($Ws_{macroEM}$ and $Ws_{microEM}$), together with how the suspended matter is distributed across each floc sub-population ($SPM_{ratioEM}$).

Improvement in understanding

The new method improves on existing methods because:

- The algorithm is based on a multiple regression analysis of 157 uniquely comprehensive empirical flocculation and turbulence data sets, which were acquired from three different estuarine field experiments and two laboratory studies.

- The algorithm can estimate the settling velocity of both the macrofloc and microfloc sub-populations, in response to changes in turbulence and SPM concentration at an individual temporal and spatial point in an estuarine water column simulation. This method can also apportion the concentration distribution between the macrofloc and microfloc fractions, and correlate this floc mass to the respective settling velocities of each fraction.
- Typically these algorithms only require the input of two variables (turbulent shear stress and SPM concentration), which simplifies their inclusion in numerical simulation sediment transport models, and reduces computer processing time.
- The flocculation algorithm has extreme flexibility in adapting to a wide range of estuarine environmental conditions, specifically for applied modelling purposes, by producing reliable mass settling flux predictions in both quiescent waters, and on the rare occurrence of very turbulent events experienced during extremely high flow velocity conditions, where near-bed shear stresses could potentially reach the order of 1-10 N m^{-2}. The derived mass flux values are also valid for both water columns of very low turbidity and highly saturated benthic suspension layers with concentration approaching 8.6 g l^{-1}.
- It has been tested against independently acquired *in-situ* data sets, and gives good agreement.

Implementation

The algorithm is written in a step-by-step “recipe” style, which can easily be coded for numerical computer applications. The complete algorithm will calculate mass settling flux, or the three main components (equations 1, 2 and 4) can be used in a stand-alone mode if required.

Algorithm

Inputs

The algorithm requires three-dimensional grid (node) data inputs of the following parameters:

Turbulent shear stress (N m^{-2})	τ
Suspended particulate matter concentration (mg l^{-1})	SPM
Root mean square of the gradient in turbulent velocity fluctuations (s^{-1})	G
Von Karman constant (no units)	κ
Kinematic viscosity (m^2 s^{-1})	ν
Water density (kg m^{-3})	ρ_w
Distance above the estuary bed (m)	z

Outputs

The algorithm can calculate the following outputs for each point (node) on a predetermined three-dimensional numerical model grid:

Macrofloc settling velocity (mm s^{-1})	$Ws_{macroEM}$
Microfloc settling velocity (mm s^{-1})	$Ws_{microEM}$
Suspended particulate matter ratio (no units)	$SPM_{ratioEM}$
Total mass settling flux (mg.m^{-2} s^{-1})	MSF_{EM}

Calculate macrofloc settling velocity

For τ ranging between 0.04-0.7 N m^{-2}:

$$\mathrm{Ws}_{macroEM} = 0.644 + 0.000471\ \mathrm{SPM} + 9.36\ \tau - 13.1\ \tau^2 \qquad (1a)$$

For τ ranging between 0.6-1.5 N m^{-2}:

$$\mathrm{Ws}_{macroEM} = 3.96 + 0.000346\ \mathrm{SPM} - 4.38\ \tau + 1.33\ \tau^2 \qquad (1b)$$

For τ ranging between 1.4-5 N m^{-2}:

$$\mathrm{Ws}_{macroEM} = 1.18 + 0.000302\ \mathrm{SPM} - 0.491\ \tau + 0.057\ \tau^2 \qquad (1c)$$

- Continuity between each relationship can be achieved by calculating a $\mathrm{Ws}_{macroEM}$ value using both adjacent equations (at a specific τ) and obtaining a single transitional $\mathrm{Ws}_{macroEM}$ value from linear interpolation.
- The transition shear stress zone between equations 1a-1b is 0.6-0.7 N m^{-2}.
- The transition shear stress zone between equations 1b-1c is 1.4-1.5 N m^{-2}.

Calculate the microfloc settling velocity

For τ ranging between 0.04-0.55 N m^{-2}:

$$\mathrm{Ws}_{microEM} = 0.244 + 3.25\ \tau - 3.71\ \tau^2 \qquad (2a)$$

For τ ranging between 0.51-10 N m^{-2}:

$$\mathrm{Ws}_{microEM} = 0.65\ \tau^{-0.541} \qquad (2b)$$

- Continuity between each relationship can be achieved by calculating a $\mathrm{Ws}_{microEM}$ value using both adjacent equations (at a specific τ) and obtaining a single transitional $\mathrm{Ws}_{microEM}$ value from linear interpolation.
- The transition shear stress zone occurs between a τ of 0.51-0.55 N m^{-2}.

Calculate an alternative turbulence parameter format (optional)

If both equations 1 and 2 are to be incorporated into the framework of a numerical model where the turbulence input parameter is of the turbulent shear G format, all the τ functions must be replaced with the following τ_{mod} equation:

$$\tau_{\mathrm{mod}} = \rho_w\ [(G^2\ .\ \kappa\ .\ \nu\ .\ z)^{1/3}]^2 \qquad (3)$$

This is because unlike the τ parameter, corresponding values of G are dependent on their height in the water column relative to the estuary bed.

Calculate the suspended particulate matter ratio

$$\mathrm{SPM}_{ratioEM} = 0.815 + 0.00318\ \mathrm{SPM} - 0.00000014\ \mathrm{SPM}^2 \qquad (4)$$

Calculate the total mass settling flux

$$\mathrm{MSF}_{EM} = \left[\left(1 - \frac{1}{1+\mathrm{SPM}_{ratioEM}}\right)\cdot\left(\mathrm{SPM}\cdot \mathrm{Ws}_{macroEM}\right)\right] + \left[\frac{1}{1+\mathrm{SPM}_{ratioEM}}\cdot\left(\mathrm{SPM}\cdot \mathrm{Ws}_{microEM}\right)\right] \quad (5)$$

Limits of applicability

The algorithm is applicable where there is high resolution, fully three dimensional coverage of SPM concentration and turbulent shear stress; either as an empirical data set or values generated by a numerical model.

No multiple regression data points were available for SPM concentrations over 1 g l^{-1} when the turbulent shear stress fell below 0.1 N m^{-2}, and therefore this should be regarded as a further boundary limit to equation 1a.

Validation

The algorithms were tested against data acquired from a series of field experiments funded by the Natural Environmental Research Council which were conducted in the upper reaches of the Tamar estuary (UK), and placed the measurements within the tidal trajectory of the turbidity maximum. For spring tide measurements made on the 15th April 2003, a concentrated benthic suspension layer formed in close proximity to the bed on the ebb producing a peak concentration of 4.2 g l^{-1}. Turbulent shear stresses for the tidal cycle ranged from 0.04-1.6 N m^{-2}. The algorithms calculated the cumulative total mass settling flux for the entire 12.5 hour tidal cycle to within 93% of the measured flux.

It is anticipated that the algorithms will be tested within an HR Wallingford TELEMAC-3D numerical model of a cross-section of the Thames estuary. If this test is successful, it will be followed by testing the algorithms in a 3D beach cross-section.

References

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