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EVALUATION OF MODELLING METHODOLOGIES TO SIMULATE PLACEMENT OF DREDGE MATERIAL: A CASE STUDY

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The numerical modelling of sediment transport and the associated morphological changes is routinely done during engineering and environmental projects. In this study two modelling approaches are presented with associated parameter settings. The different sediment deposition patterns for the two approaches are illustrated for a particular test case. The case study includes the placement of dredge material at a site within a lough and at an offshore site. This example illustrates the importance of understanding the processes and system being modelled. It also highlights the need for further investigations into the initiation of motion of cohesive sediments as well as the sediment-bed interactions.

KEY WORDS: numerical modelling, sediment transport, cohesive sediments.

NOTATION

c_m	Mud concentration (kg/m^3)
D	Deposition flux (kg/m^2/s)
E	Erosion flux (kg/m^2/s)
m_e	Erosion parameter (kg/m^2/s)
w_m	Settling velocity (mm/s)
τ_b	Bed shear stress (Pa)
τ_d	Critical shear stress for deposition (Pa)
τ_e	Critical erosion shear stress (Pa)

1. BACKGROUND AND OBJECTIVES

Even though the numerical modelling of sediment transport processes that govern the behaviour of cohesive and non-cohesive sediments with the aim of simulating morphological changes for engineering and environmental purposes has become routine, there are still uncertainties. Non-cohesive sediments such as sand and gravel are considered to be transported as bedload and suspended load (Van Rijn, 1993). Numerous studies have been conducted to evaluate the performance of different sediment transport formulae (e.g.

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Camenen and Larroudé, 2003) and to investigate the initiation of motion (e.g. Dean and Dalrymple, 2013). In many numerical models the initiation of motion of non-cohesive sediments is linked to the critical Shields parameter.

Cohesive sediments are considered to only move as suspended load, and the initiation of motion is linked to a critical shear stress for erosion. For the erosion and deposition of cohesive sediments the model of Parthniades-Krone is generally used. In this model when the bed shear stress exceeds the critical value for erosion, erosion will occur. According to Parthniades (1965), the erosion flux is given by

$$E = m_e\left(\frac{\tau_b}{\tau_e} - 1\right) \quad \text{for } \tau_b > \tau_e, \tag{1}$$

where E is the erosion flux, m_e the erosion parameter, τ_e the critical erosion shear stress, and τ_b is the bed shear stress.

When the critical erosion shear stress is exceeded, the particles are immediately suspended and transported as suspended load. The suspended cohesive material will only be deposited when the bed shear stress falls below the critical shear stress for deposition. According to Krone (1962), the deposition flux is given by

$$D = \left(1 - \frac{\tau_b}{\tau_d}\right) w_m c_m \quad \text{for } \tau_b < \tau_d, \tag{2}$$

where D is the deposition flux, w_m the settling velocity, c_m the mud concentration and τ_d the critical shear stress for deposition.

In the classical modelling approach, the critical shear stress for erosion is higher than the critical shear stress for deposition. In this approach, erosion and deposition do not occur simultaneously, which implies that there is no equilibrium sediment concentration. However, there is an intermediate period when the bed shear stress lies between the two critical values implying that no erosion or deposition takes place and the suspended particles remain in transit (Dyer, 1986). In this period the mud bed is stable.

In a post-classical modelling approach, Winterwerp (2007) suggests that for cohesive sediments simultaneous erosion and deposition occur and that a critical shear stress for deposition does not exist. A pragmatic approach to these suggestions is to still use the Parthniades-Krone model, but to set the shear stress for deposition very high and to use the erosion parameter as a calibration parameter. At present, this approach is used quite often in modelling studies, although further research is required (Manning et al., 2011).

From a modelling perspective it often necessary to select one of these approaches and, furthermore, the critical shear stresses and erosion parameter need to be specified. Different erosion-deposition-resuspension parameters may be needed for different modelling approaches and the type of physical environment. For example, the manner in which sedimentation and erosion occur on tidal mud flats may be different to the manner in which a heap of dredge spoil erodes and flattens. The main objective of this study is to illustrate the consequences of the assumptions that users often make for a particular case study with the aim of highlighting where research efforts can be directed.

The site for the investigation is Carlingford Lough which is a cross-border system shared between Ireland and Northern Ireland. This site is selected since hydrodynamic data is available for calibration and the question has been posed whether maintenance dredge spoil can be placed within the lough instead of outside the lough as is presently done. A placement routine has been developed and evaluated by numerical modelling. The intent of this paper is to focus on two modelling methodologies, but it is informative to show the modelling results in context of a particular question or problem. In this case, the impact of the different modelling strategies and parameter selections on the sediment transport and morphology are investigated for the situation of placing the dredged material within the lough near the entrance. It is believed that the results are general and can also be applied to other similar environments.

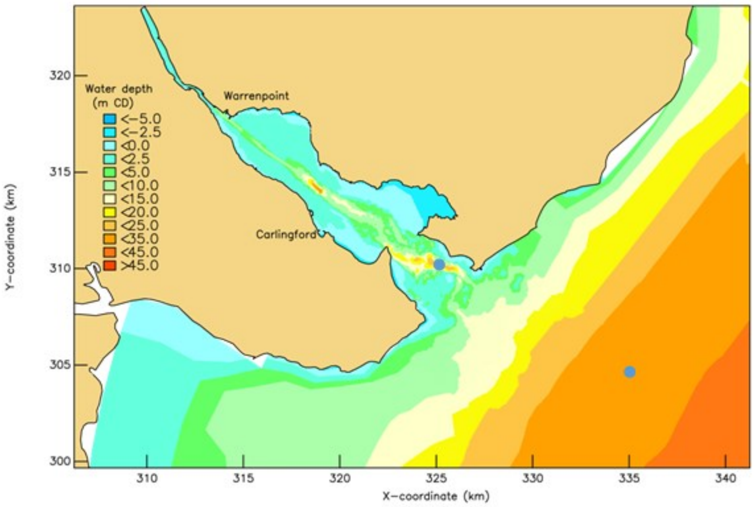

Figure 1. The bathymetry in Carlingford Lough and the surrounding sea area. Also shown are the offshore and evaluated placement sites.

2. DESCRIPTION OF THE ENVIRONMENT

2.1 PHYSICAL

Carlingford Lough is a cross-border system with an area of about 50 km^2 with a length of 15 km from the mouth to Warrenpoint and is 4 km wide at its widest point (Ferreira et al., 2007). The Newry River upstream from Warrenpoint is the major freshwater source with a flow rate that can vary from 1 m^3/s in summer to 9 m^3/s in winter. Furthermore, Carlingford Lough is a shallow, well-mixed system with an average depth between 2 m and 5 m and a deeper narrow channel along the centre of the lough as shown in Figure 1. In some locations near the seawards part of the lough, the channel is as deep as 30 m to Chart Datum. There are shallow areas located in the mouth of the lough with scattered channels that are fairly deep between these areas. Towards the landward side of the lough is a dredged channel up to Warrenpoint Port with a depth of approximately 5.6 m to Chart Datum.

2.2 SEDIMENT CHARACTERISTICS AND DREDGING ROUTINE

A classification of seabed types obtained from the INIS Hydro project shows that the inner part of Carlingford Lough contains Class 1 sediments (the softest type) with the majority of the lough consisting of Class 2 sediments (second softest type). Class 4 sediments (hard seabed) are present seawards of Carlingford Lough.

Grab samples were taken at various locations in the lough and analyzed in terms of sediment content. At the grab locations nearest to the evaluation site there is practically no silt and clay and the majority of the sediment is fine sand. This is as expected in a channel of fairly high velocity indicating that fine material will be moved away. The grab locations in the central channel near the center of the lough show the presence of fine sand (48% - 69%) and silt (36%). The surficial sediments on the tidal flats have high percentages of silt (82%) with limited clay (4%) and the remainder being fine sands.

The material to be disposed of is dredged in and around Warrenpoint Port. From sediment and dredge information it was determined that the dredge material consists of gravel (0.9%), sand (20.8%) and mud (78.3%). The mud consists of silt (66.5%) and clay (11.8%). The sediments have been classified as inert and placement at sea has been the accepted practiced methodology for over two decades. For the modelling, a fairly realistic dredging routine was developed where the dredge material is placed at the in-lough site only during the outgoing phase of the tide otherwise placement takes place outside the lough at the standard placement site.

3. NUMERICAL MODELLING

3.1 GENERAL MODEL SETUP

The model being used for the simulations is the DELFT3D modelling system developed by Deltares. The DELFT3D model consists of various modules that can be coupled. The module DELFT3D-FLOW is a three-dimensional, finite volume hydrodynamic and transport model which was used to simulate the flow, sediment transport and resulting morphological changes to the seabed.

A discussion of the online sediment component of Delft3D-FLOW is presented by Lesser et al. (2004) and Tonnon et al. (2007). Additional information regarding the transport of cohesive sediments is presented by Van Ledden et al. (2004a). Since the online sediment module forms part of the Delft3D-FLOW model, the local velocities and eddy diffusivities are based on the results of the hydrodynamic computations. Computationally, the three-dimensional transport of suspended sediments is computed in a similar manner as the transport of any other conservative constituent such as heat and salinity. However, there are some critical differences between sediment and other constituents such as the exchange of sediment between the bed and the flow and the settling velocity of sediment under the action of gravity. The sediment also has an effect on the local mixture density and may cause turbulence damping. These processes are described by different formulations depending on whether one is modelling cohesive or non-cohesive fractions.

The modelling approach also includes the simulation of short waves with the module DELFT3D-WAVE (Holthuijsen, 2007; Van der Westhuysen, 2012). The waves and hydrodynamics are coupled in such a way that every three hours the water levels from

Delft3D-FLOW are passed to Delft3D-WAVE where the waves are calculated and the various derived quantities are then passed back to Delft3D-FLOW. Within DEFLT3D-FLOW the hydrodynamics, transport of cohesive and non-cohesive sediments and morphology were calculated in an online manner (Tonnon et al., 2007).

The computational grid for Carlingford Lough that was set up for the simulations has 67 x 246 cells in the horizontal and is designed so that the grid sizes are refined to a size of 70 m x 100 m in the immediate vicinity of the proposed placement location. In the vertical, 8 sigma layers were used with the thickness of the layers being of equal percentages (12.5% of the water depth). Tidal forcing, temperature and salinity were specified at the open boundaries. Bottom friction is modelled with a Chézy coefficient obtained from the White-Colebrook formulation defined by the Nikuradse roughness length which was set to 0.03 m.

3.2 MODEL CALIBRATION

Given that most of the response of the system is tidally driven and that the sediment dynamics depend mostly on the tidal energy input and consequent bottom shear stress, the calibration of the hydrodynamic model was focused on comparing the tidal harmonic response of the model with observations, both historical and collected in the course of the this study. Harmonic analyses were performed on historical tide gauges at Warrenpoint and Greenore, together with pressure sensors on board of ADCPs deployed during the study. The analysis indicated that the semi-diurnal components M2, N2 and S2 explain most of the response to the tide.

3.3 SEDIMENT MODELLING

The main purpose of the numerical modelling is to predict the transport and fate of the dredged spoil. The first modelling decision in the present model implementation for the calculation of the deposited sediment thickness is that the contribution from each fraction is considered independently from the other fractions. Besides the dredging sequence and the general modelling approach, the simulation of the fate of the material also requires two sets of parameters, namely transport parameters (i.e. deposition-resuspension-erosion parameters) and parameters to determine the consolidation of the material that is deposited. For the non-cohesive sediments (sand and gravel) the sediment transport method of van Rijn (van Rijn, 1993) has been selected.

At the placement site, most of the material will be transferred to the seabed by convective descent of the sediment mass. Kirby and Land (1991) state that less than 5% of the material disposed of will stay in suspension. For the modelling, it has been conservatively assumed that 10% of the cohesive sediment (mud) will initially enter the water column as suspended load, while 90% will be deposited on the seabed. The material deposited on the seabed may subsequently be resuspended and transported away from the site as a turbid plume.

The material that is deposited on the bottom will begin to consolidate, which is the process whereby the deposited grains are compacted under the influence of gravity, leading to the expulsion of the pore water and the increase in density of the material and a reduction in the deposition thickness (van Ledden et al., 2004b). To compute the deposition thickness in the model, a typical consolidation condition less than one month has been assumed. For the mud, this is characterized by a porosity of 90%, a wet density of 1176 kg/m^3 and a dry density of 265 kg/m^3. The sand and gravel fractions were assumed to have dry weights of 1458 kg/m^3 and 1776 kg/m^3 and porosities of 45% and 33%, respectively.

4. MODELLING SCENARIOS AND RESULTS

4.1 CLASSICAL APPROACH

For the deposition and erosion of the mud, medium mobility parameters that are limited by the erosion rate have been selected. This is typical for engineering type studies of relatively short duration. For the mud, the shear stress for deposition is, $\tau_d = 0.1$ Pa, the critical shear stress for erosion is, $\tau_e = 0.2$ Pa (van Ledden et al., 2004a), the erosion parameter, $m_e = 0.00005$ kg/m^2/s and the fall velocity is 0.5 mm/s. For a hypothetical scenario the depositional thickness at the end of the campaign period is shown in Figure 2.

4.2 POST-CLASSICAL APPROACH

For a comparative study, the settings for the classical approach were kept the same except for the depositional shear stress that has been set as, $\tau_d = 1000$ Pa. This effectively eliminates the second term from Equation (2) and the depositional flux is determined only by the settling velocity and the near-bed sediment concentration. For a hypothetical scenario the depositional thickness at the end of the campaign period is shown in Figure 3.

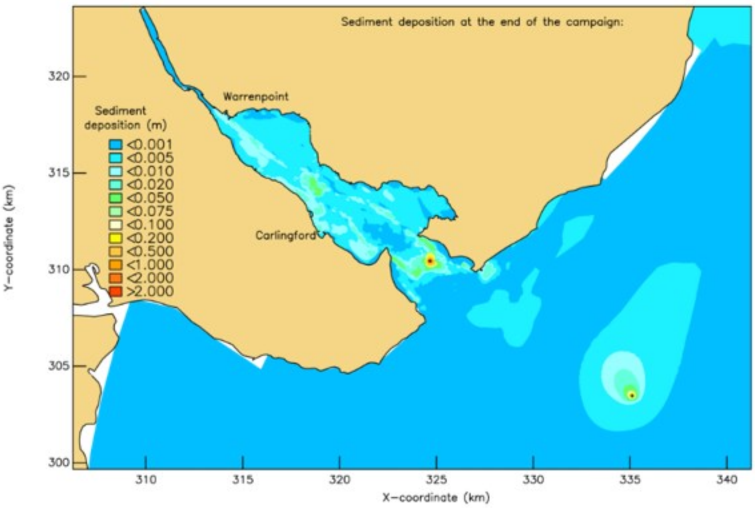

Figure 2. Simulated depositional thickness with the classical approach for a hypothetical scenario.

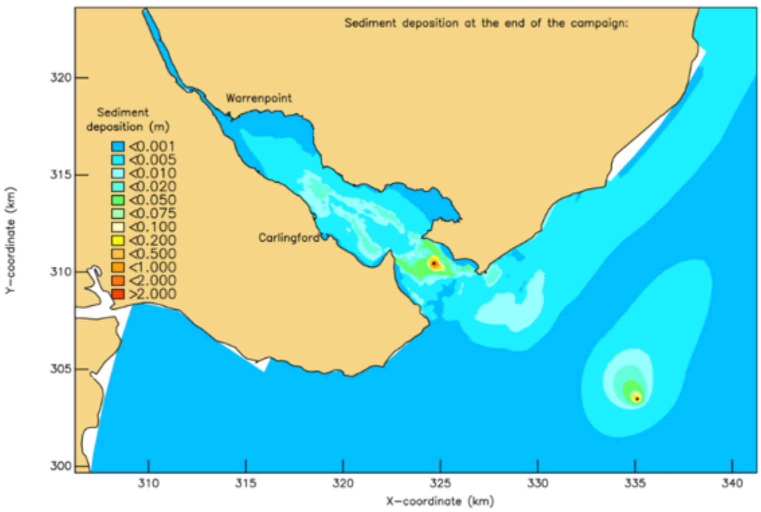

Figure 3. Simulated depositional thickness with the post-classical approach for a hypothetical scenario.

5. CONCLUSIONS

At the offshore placement site both approaches show similar deposition thickness. This is because the bed shear stress is low at the depth of the site and for both approaches the deposition dominates. With the selected parameter settings, the classical approach shows deposition over a wider area within the lough, especially in the dredge channel, than the post-classical approach. This is indicative of the intermediate transit period which allows material to travel with the flow before being deposited. In the post-classical approach the material will drop out of the water column to be deposited when the bed shear stress drops below the critical shear stress for erosion which leads to a smaller overall area of deposition in the lough. This also applies to the sediment that exits the lough on the ebb tide. For the classical approach, the bed shear stress remains in the intermediate state and the material drifts away and hence the smaller deposition zone outside the lough. Conversely, for the post-classical approach the material drops out of suspension and is deposited in close vicinity if the lough when the bed shear stress drops below the critical shear stress for erosion. Over time, resuspension can then be initiated by wave action. This example illustrates the importance of understanding the processes and system being modelled. It also highlights the need for further investigations into the initiation of motion of cohesive sediments as well as the sediment-bed interactions.

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REFERENCES

1. Camenen, B., Larroudé, P., 2003. Comparison of sediment transport formulae for the coastal environment, Coastal Engineering 48, 111-132.
2. Dean, R.G., Dalrymple, R.A., 2013. Coastal Processes with Engineering Applications, Cambridge University Press.
3. Dyer, K.R., 1986. Coastal and Estuarine Sediment Dynamics, Wiley and Sons, Chichester.
4. Ferreira, J.G., Hawkins, A.J.S., Monteiro, P., Service, M., Moore, H., Edwards, A., Gowen, R., Lourenco, P., Mellor, A., Nunes, J.P., Pascoe, P.L., Ramos, L., Sequeira, A., Simas, T., Strong, J., 2007. SMILE Sustainable Mariculture in northern Irish Lough Ecosystems, Ed. IMAR, ISBN 978=927-99923-1-5.
5. Holthuisjen, L.H., 2007. Waves in oceanic and coastal waters, Cambridge University press.
6. Kirby, R., Land, J.M., 1991. Impact of dredging: A comparison of natural and man-made disturbances to cohesive sedimentary regimes, CEDA-PIANC conference: Accessible Harbours, Paper B3, Amsterdam.
7. Krone, R.B., 1962. Flume studies of the transport of sediment in estuarial shoaling processes: Final Report, Hydraulic Engineering Laboratory and Sanitary Engineering Research Laboratory, University of California Berkeley, California.
8. Manning, A.J., Baugh, J.V., Soulsby, R.L., Spearman, J.R., Whitehouse, R.J.S., 2011. Cohesive Sediment Flocculation and the Application to Settling Flux Modelling, Sediment Transport, Ed.: Ginsberg, S.S., ISBN: 978-953-307-189-3.
9. Pan, S., Chen, Y., Wolf, J., Du, Y., 2009. Modelling of waves in the Irish Sea: effects of oceanic wave and wind forcing, Ocean Dynamics 59, 827-836.
10. Partheniades, E., 1965. Erosion and deposition of cohesive soils, Journal of Hydraulics Division, Proceedings of ASCE 91, 105-139.
11. Tonnon, P.K., van Rijn, L.C., Walstra, D.J.R., 2007. The morphodynamic modelling of tidal sand waves on the shoreface, Coastal Engineering 54, 279-296.
12. Van der Westhuysen, A.J., 2012. Modelling nearshore wave processes, ECMWF Workshop on Ocean Waves, 25-27 June.
13. Van Ledden, M., Wang, Z-B, Winterwerp, H., De Vriend, H., 2004a. Sand-mud morphodynamics in a short tidal basin, Ocean Dynamics 54, 385-391.
14. Van Ledden, M., van Kesteren, W.G.M., Winterwerp, J.C., 2004b. A conceptual framework for the erosion behaviour of sand-mud mixtures, Continental Shelf Research 24, 1-11.
15. Van Rijn, L.C., 1993. Principles of sedimentation and erosion engineering in rivers, estuaries, and coastal seas, Aqua, Blokzil, The Netherlands.