



A 3-D model to analyze environmental effects of dredging operations – application to the Port of Marin, Spain

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Abstract. Historically, the study of dredging processes has depended on physical laboratory tests. The IH-Dredge model has been developed to simulate these processes numerically. It simulates the evolution of the seabed, sediment and toxic substances involved in dredging operations. The model has been calibrated and validated with experimental data, and it has been applied in a dredging operation in the Port of Marin, Spain.

1 Introduction

Dredging processes effects have been largely tested through physical experiments (Vlasbom, 2005). However, the development of mathematical models allows predicting those effects without the need of expensive physical models. Nowadays, there are widely trusted sediment transport models that can estimate the suspended solids and the dredging operations as a final configuration with its effect in the water column (Song and Haidvogel, 1994; Jacobsen and Rasmussen, 1997; Deltares, 1999; Hervouet and Bates, 2000; Bai et al., 2003).

2 IH-Dredge model description

The finite-difference model presented herein (IH-Dredge) is a three-dimensional Eulerian code which solves the advection-diffusion equation (Eq. 1) to simulate sediment transport (Eq. 2) and evolution of toxic substances, in both dissolved and particulate fractions in water and sediment.

$$\frac{\partial \phi}{\partial t} + \frac{\partial u\phi}{\partial x} + \frac{\partial v\phi}{\partial y} + \frac{\partial w\phi}{\partial z} = \frac{\partial}{\partial x} \left(D_x \frac{\partial \phi}{\partial x} \right) + \frac{\partial}{\partial y} \left(D_y \frac{\partial \phi}{\partial y} \right) + \frac{\partial}{\partial z} \left(D_z \frac{\partial \phi}{\partial z} \right) + R \quad (1)$$

$$\frac{\partial c_s}{\partial t} + \frac{\partial uc_s}{\partial x} + \frac{\partial vc_s}{\partial y} + \frac{\partial (w - w_s)c_s}{\partial z} = \frac{\partial}{\partial x} \left(\varepsilon_{s,x} \frac{\partial c_s}{\partial x} \right) + \frac{\partial}{\partial y} \left(\varepsilon_{s,y} \frac{\partial c_s}{\partial y} \right) + \frac{\partial}{\partial z} \left(\varepsilon_{s,z} \frac{\partial c_s}{\partial z} \right) \quad (2)$$

where ϕ is the pollutant concentration, D_x , D_y , D_z are the turbulent diffusion coefficients, R is the reaction term, c_s is the mass concentration of sediment fraction, w_s is the settling velocity of sediment fraction and $\varepsilon_{s,x}$, $\varepsilon_{s,y}$, $\varepsilon_{s,z}$ are the eddy diffusivities of sediment fraction. The σ -coordinate is used for the vertical discretization.

Sedimentation is obtained as a function of the critical shear stress for deposition τ_d , the critical shear stress for erosion τ_e and the bed shear stress τ_b . The model allows using different formulations for computing critical shear stress for deposition: Wu and Falconer (2000), Alvera-Azcárate et al. (2003), Cancino and Neves (1999), Huang et al. (2006), Wu et al. (2005), Zheng et al. (2004), Vidal et al. (2005), or a user-defined value. The critical shear stress for erosion is calculated by either Cancino and Neves (1999), Huang et al. (2006), Vidal et al. (2005), or a user-defined value. Finally, the bed shear stress can be calculated by Cappucci et al. (2004), Alvera-Azcárate et al. (2003), Lumborg and Pejrup (2005), or a user defined value.

The model allows the interaction of suspended particles with the pollutants present not only in the water column, but also in the seabed. Adsorption-desorption, biodegradation,

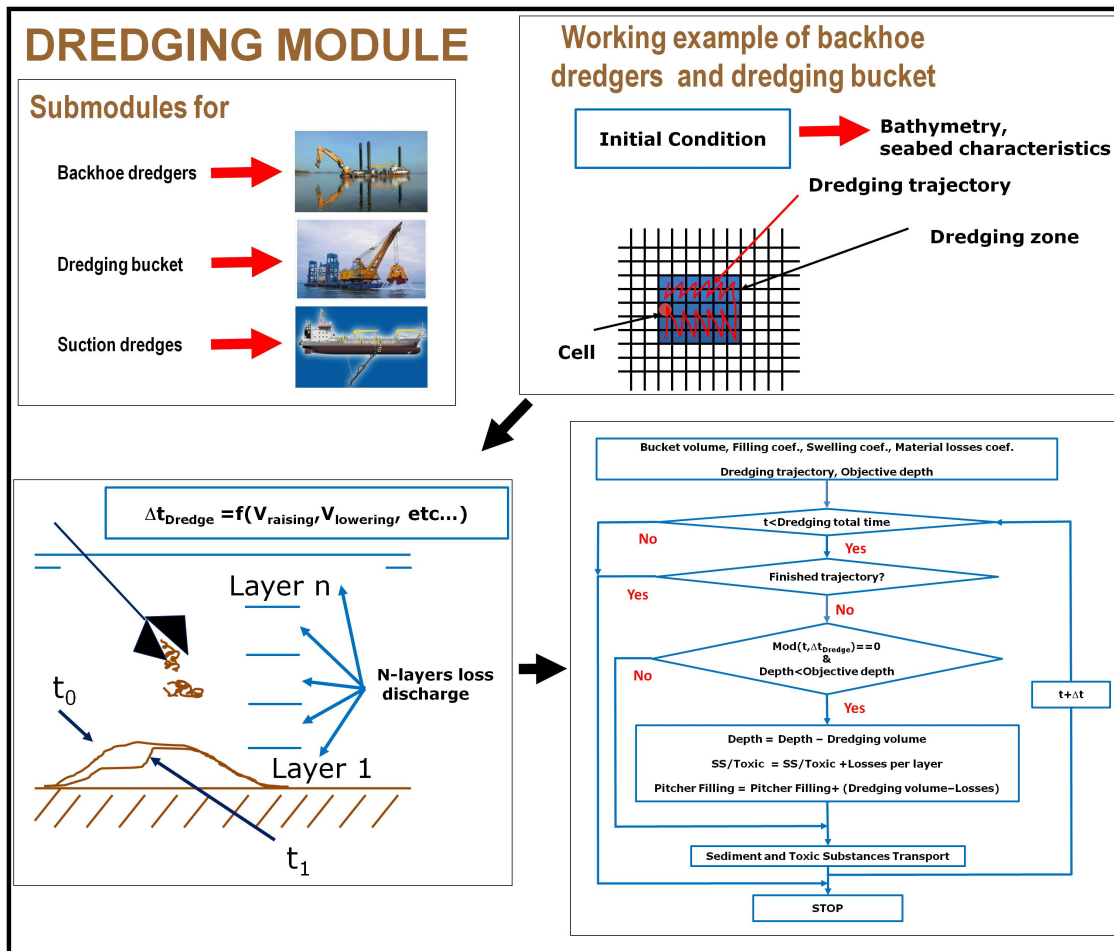


Fig. 1. Example of IH-Dredge working model.

volatilization, photolysis, hydrolysis and water-sediment diffusion processes are taken into consideration to simulate the pollutants behaviour. Moreover, the model considers the removal of the seabed material effect on the pollutants concentration in the water column (de Boer, 2007).

Unlike final configuration models, IH-Dredge simulates at each time step the effects of different dredging techniques such as: suction dredges, backhoe dredgers and dredging buckets. The backhoe and bucket dredging simulation algorithms are based on the net extraction in a dredge cycle considering material losses and specific filling and swelling coefficients (associated with each one of the involved cells in the lifting process simulation). Suction dredging algorithms allow considering, in real time, the pitcher filling and the overflow losses while traveling through the dredging area. An example of the IH-Dredge working model scheme is shown in Fig. 1.

3 Calibration and validation with experimental data

The model has been calibrated and validated with laboratory experiments at the IHLab-Hydro at the IH Cantabria. Material loss effects of dredging bucket rising has been simulated in a stagnant medium and with a current of 0.1 m s^{-1} . The rising effect of the dredge with its associated losses has been studied with the rise of a 10^{-3} m^3 cylindrical plastic container, a duquesa pot, using an overhead crane. Dredger losses were simulated by sand poured through holes made in the base of the duquesa pot. The crane raised the pot at a constant speed of 1.25 cm s^{-1} . The water level during the test was maintained at 0.6 m. The loss of material as the duquesa pot raised was measured as $1.4545 \times 10^{-5} \text{ m}^3 \text{ s}^{-1}$. Five acoustic doppler velocimeters (ADV) were placed vertically at 5, 13.5, 21, 26.5 and 32.5 cm from the bottom to measure the velocity profile during experimental tests. An optical backscatter sensor (OBS) was used to record the concentration of suspended solids at 5 cm above the bottom. The

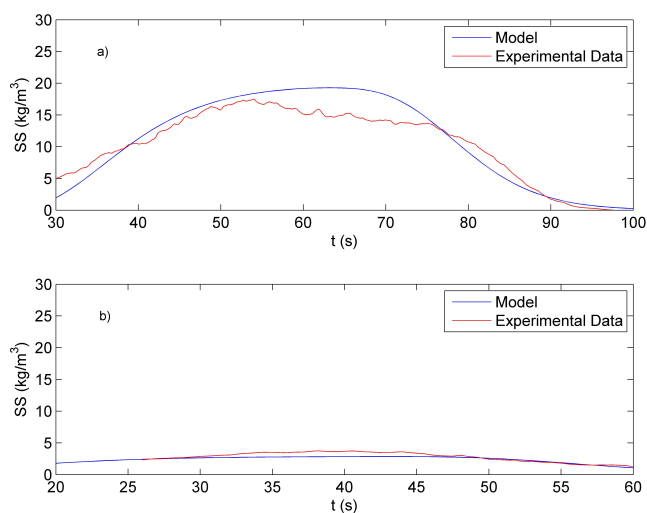


Fig. 2. (a) Comparison of model results with the recorded data in the trial without current. (b) Comparison of model results with the recorded data in the experiment with the presence of 0.1 m s^{-1} currents.

OBS was previously calibrated with the same sand used for the experiment (siliceous arid with D_{50} of 0.4 mm).

Calibration of the IH-Dredge model was carried out through numerical reproduction of the laboratory experiments. A domain of 81×40 square regular cells of 0.05 m with a constant depth of 0.6 m was considered. Vertical direction was discretized into 10σ -layers.

The calibration was made comparing the sediment concentration obtained by the model with the one recorded by the OBS. We obtained a value of $10^{-6} \text{ m}^2 \text{ s}^{-1}$ for the horizontal eddy diffusivity of the sediment fraction, with a CE (Nash and Sutcliffe, 1970) of 0.65 (good), a correlation coefficient of 0.85 and mean square error of 2.3 mg L^{-1} (Fig. 2a).

The model validation was conducted with the obtained OBS data with a uniform current of 0.1 m s^{-1} , as measured with the array of ADVs. Field currents were introduced in the model as a constant and homogeneous value of 0.1 m s^{-1} . During the validation process we obtained a skill CE of 0.91 (excellent), a correlation coefficient of 0.89 and mean square error of 0.41 mg L^{-1} (Fig. 2b).

4 IH-Dredge application to the Port of Marin

IH-Dredge has been applied to a dredging operation conducted in the Port of Marin, in an area of $18\,750 \text{ m}^2$. Marin is a Spanish town located in the province of Pontevedra, in the autonomous community of Galicia, located on the southern shore of the Ria de Pontevedra. DELFT3D model was applied in the study area to derive the hydrodynamics forcing conditions (Three dimensional currents, salinity and temperature fields). Modeled free surface elevations were compared to the Port of Marin tidal gauge data. Modeled salin-

ity and velocity profiles were verified with the measurements obtained during a field survey performed on 26 April 2012.

The following dredging characteristics have been used in the simulation:

- Dredging process with a dredging bucket of 4 m^3 capacity.
- Objective depth in dredging zone of 12 m .
- Dredging sediment density of 2650 kg m^{-3} .
- Critical shear stress for erosion of $0.6531 \text{ kg m}^{-1} \text{ s}^{-2}$.
- Critical shear stress for deposition of $0.5477 \text{ kg m}^{-1} \text{ s}^{-2}$.
- Rising and download velocity of bucket are equal to 1 m s^{-1} .
- The time of digging was 10 s for each dredging event.
- Operation time of dredge turning to barge was 6 s .
- Filling, swelling and material losses coefficients were 0.6 , 0.7 and 1.15 , respectively.

Cadmium presence in the sea bottom has been considered with the following characteristics:

- Bottom concentration of 1.27 ppm .
- Henry constant: $3.1 \times 10^{-2} \text{ atm m}^3 \text{ mol}^{-1}$.
- Partition coefficient K_p : 5.01×10^4 .
- Water-octano coefficient K_{OW} , hydrolysis coefficient K_{hid} , photolysis coefficient K_{for} and biodegradation coefficient K_{bio} equal to zero.

A mesh of 122×102 square regular cells of 25 m and a vertical discretization with 5σ -layers was used. A null concentration of suspended solids and cadmium in the water column was considered as initial condition. Open boundaries were modelled with a Dirichlet condition for suspended solids and cadmium concentration with null value. Suspended solids concentration (Fig. 3a) and cadmium concentration (Fig. 3b) on the 5σ -layers and depth evolution (Fig. 3c) during the dredging process were obtained.

The concentration of suspended solids and cadmium in each of the 5 vertical layers is shown in Fig. 3a and b. Material losses of dredging process have a larger effect on the surface layer than on the bottom layer due to advection processes, which in this case (mixing dominated to velocity profile) are more important than dispersion processes. Dredging bucket simulation results show that the dredging process would need continuous work for 195 h to achieve the objective depth in the full intervention area. To achieve such goal the removal of $55\,627 \text{ m}^3$ was required. Numerical results (spatial and temporal variation of suspended solids and toxic concentrations) have been used to estimate the environmental risk of dredging operations (Gómez et al., 2014).

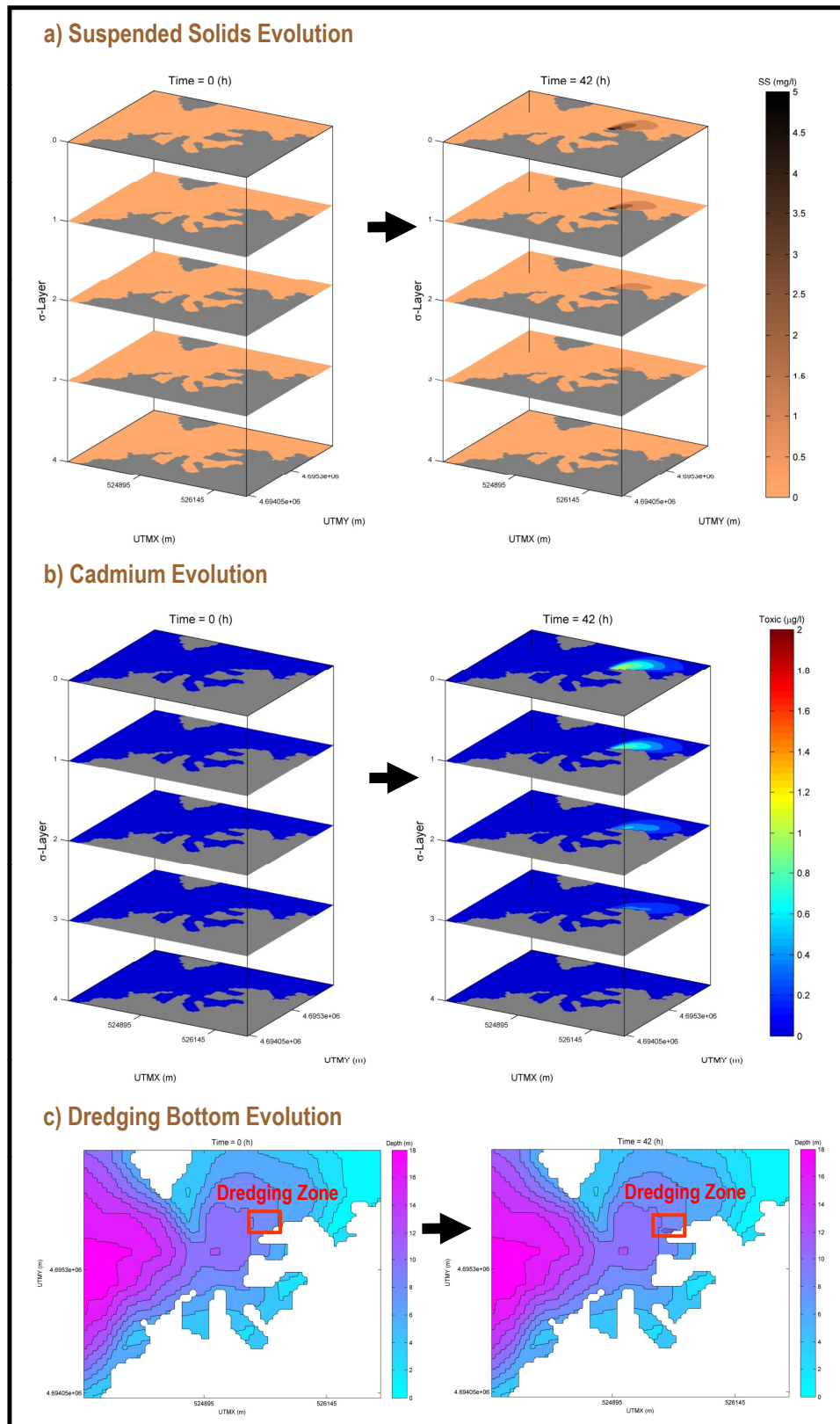


Fig. 3. (a) Suspension solids evolution during dredging process. (b) Cadmium concentration evolution during dredging process. (c) Depth evolution in the study area during dredging process.

5 Conclusions

The IH-Dredge model advances the understanding of the selected dredging processes. Calibration and validation of the model were successfully carried out at the IHLab-Hydro at IH Cantabria. We have shown that the results from the numerical model (spatial and temporal variation of suspended solids and toxic concentrations) can be used to estimate the environmental risks associated with dredging operations. IH-Dredge has been applied to a real dredging operation conducted at the Port of Marin in the NorthernWest coast of Spain.

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