An analytical model for preliminary assessment of dredging-induced sediment plume of far-field evolution for spatial non homogeneous and time varying resuspension sources

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Abstract
In recent years, increasing attention has been paid to assess the dispersal of resuspended sediments and related water quality problems due to dredging operations. This paper presents an analytical model aimed to predict the temporal evolution and spatial distribution in the far field of the suspended sediments concentration increase related to dredging activities or open water sediments disposal. In particular, whatever the dredging source strength and geometry can be considered to define the suspended sediments concentration leaving the immediate vicinity of the resuspension source. A further feature of the model is the removing of the hypotheses of continuous source and steady state, peculiar to the majority of available theoretical models. Hence, the proposed model is able to describe different dredging resuspension sources and to provide the temporal and spatial picture of the resulting plume. Of course, some hypotheses have to be assumed in order to make possible to achieve the analytical solution of the governing equation: the model is two dimensional in the horizontal plane; the ambient currents are assumed to be homogeneous in space and slowly time varying; the turbulent diffusion coefficients and flocculent settling velocity are homogeneous in space; the water depth is constant; the domain is infinite. Even with its limitations, the model is still able to provide a worst case preliminary assessment of sediments plume migration very useful to guide more detailed numerical analysis and to select the more appropriate simulation scenarios. The analytical model is detailed in order to be used for numerical model testing purposes. A series of practical applications is described through the paper (i) to catch the general features of the involved far field phenomena, (ii) to compare the model results to those of previous researches and (iii) to provide a series of benchmark cases useful for the testing of numerical models. The proposed model may be also used as a first rough prediction of the area affected by plume dispersion by considering different dredging scenarios (i.e. different equipment and operational techniques and forced by site-specific environmental conditions), and thus to provide a basis for more sophisticated modeling aimed to support dredging projects' planning and management.

Keywords
Analytical model; Dredging; Resuspension sources; Advection-diffusion equation; Benchmark cases

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Abstract

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1. Introduction

Estuarine and coastal areas often undergo dredging activities to maintain or improve the designed depth of navigation channels or basins (i.e. ports and harbors, e.g. Nichols & Howard-Strobel, 1991), for creation or improvement of facilities (i.e. embankments), for beach nourishment (e.g. Di Risio et al., 2010) and to carefully remove and relocate contaminated sediments (i.e. remedial or environmental dredging, e.g. Bridges et al., 2008). Basically, these activities involve processes of removing sediments from the bottom and relocating them elsewhere. Nevertheless, some of the sediments removed from the bottom are not captured by the dredge, and the fine-grained fraction of resuspended sediments is dispersed in the water column (Palermo et al., 2008). The increase of the suspended sediments concentration and the subsequent resettling of sediments transported as a dredging plume can bring adverse impacts on water quality, on aquatic ecosystem and on the human health (e.g. Roman-Sierra et al., 2011; Manap & Voulvoulis, 2014; Jones et al., 2016; Pourabadehei & Mulligan , 2016). In recent years, increasing attention has been paid to the environmental impact due to dredging activities and four issues relevant to environmental dredging (the so called "four Rs") were identified (Bridges et al., 2008, 2010): sediments Resuspension, contaminants Release, Residual contaminated sediments produced by and/or remaining after dredging, and environmental Risk. The present paper deals with the first "R", i.e. the resuspension, and dispersion as well, of dredged sediments. It has to be stressed that the term "resuspension" is commonly used to describe the sediments mobilization due to currents and waves action. Nevertheless, it is is used hereinafter to describe the effect related to dredging activities and the practical applications illustrated in this paper are carried out by assuming that resuspension due to currents and waves does not occur within the whole domain.

Meaningful criteria to limit environmental impacts are related to the knowledge of the dredging induced plumes

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extension that requires the estimate of the resuspended sediments concentration close to the dredge location or to the disposal area during the work progression (i.e. source strength and geometry, e.g. Collins, 1995; Becker et al., 2015; Lisi et al., 2016). Moreover, the sediments loss rate close to dredging sources and the spatial and temporal variability of resulting plumes can significantly vary based on site and operational parameters as well as environmental conditions (Pennekamp et al., 1996; Bridges et al., 2008).

In particular, as far as dredging is concerned, the sediments can be resuspended by dredges in different locations during the work progression due to a wide range of mechanisms and at different elevations within the water column. Usually, three phases are identified for the dredging plume development at different distances from the dredging location (e.g. Palermo et al., 2008): the dredging zone; the near field zone; and the far field zone (or passive plume). In the dredging zone the plume development is strongly dependent upon equipment types (i.e. hydraulic and mechanical dredges), operational techniques (dredge-head movements, dredge cut depth, environmental operating precautions, velocity of dredging cycles, etc.) and sediments properties (i.e. volumes, quality and sedimentological and geological properties of sediments to be removed). These site and operational parameters affect the volume and distribution of the sediments spill at different elevations within the water column (Henriksen, 2012; Feola et al., 2015, 2016). Using conventional mechanical dredges, sediments resuspension can occur when the grab (or the bucket) hits the seabed and during the raising phase. In such a case, the sediments loss rate is generally assumed constant through the water column (Collins, 1995). On the contrary, using conventional hydraulic dredges, operating on an almost continuous dredging cycle, the resuspension is mainly due to fractions of the dislodged sediments that escape to the suction pipe during dredge-head disturbance at the bottom. Thus, in this case, the source is expected to be confined approximately few meters around the moving dredge-head equipment (e.g. Henriksen, 2012). In the near field zone, the resuspended sediments plume experiences differential settling (i.e. the coarser particles settle close to the dredging zone) and only the finer fraction moves out from the near field to the far field zone (e.g Nakai, 1978). Within the far field zone the plume dynamic is mainly driven by environmental forcing. Depending on the plume dynamic in the far field, there can be significant spatial and temporal variations of the resuspended sediments distribution and of the related environmental effects.

This paper deals with the evolution of the sediments plume in the far field. Indeed, relying both on mathematical modeling and on field measurements, appropriate management and monitoring measures have to be designed prior to the dredging execution and the dredging plan has to be optimized to achieve the environmental objectives while maintaining desired production rates (Cutruneo et al., 2012; Savioli et al., 2013). To date, well established international guidelines and past researches aimed at supporting environmental studies for projects that involve the handling of sediments are available (e.g. Foster et al., 2010). Most of these guidelines include the use of numerical modeling as a valuable tool to predict the far field area interested by an increase of suspended sediments concentration (e.g. Lisi et al., 2009; De Marchis et al., 2014). To be truly effective as a dredging project management tool, models should be capable of simulating different dredging sources (i.e. continuous or time varying sources). This allows the evaluation of a number of alternative dredging scenarios so that those with the least probabilities of detrimental impacts with respect to different environmental site conditions can be identified.

If numerical models are used, two problems arise. On one hand the simulations may be highly time consuming, on the other hand the numerical models have to be tested against theoretical solutions, at least during their development. It has to be stressed that, also in the case of integral solution, analytical models are quite less time consuming with respect to numerical models. Indeed, the (integral) solution is numerically evaluated only for given location and time without the needing of computing the solution in the whole domain and for all the time steps (as for numerical models). Consistently, this paper has two main goals. It aims to propose a practice-oriented analytical model and to provide a series of benchmark cases for numerical models testing. Moreover, the proposed model is a helpful tool for a fast estimate of the far field temporal evolution and spatial distribution of the sediments plume resuspended by different dredging scenarios.

In order to achieve an analytical solution, some hypotheses had to be made: the model is two dimensional in the horizontal plane; the ambient currents are assumed to be homogeneous in space and slowly time varying; the turbulent diffusion coefficients and flocculent settling velocity are homogeneous in space; the water depth is constant; the domain is infinite. Even with its limitations, the model is still able to provide a worst case preliminary assessment of sediments plume migration very useful to guide more detailed numerical analysis and to select the more appropriate simulation scenarios. It has to be stressed that the model hypotheses allow to use the proposed model also for the fate in the far-field of sediments plume due to the cloud disposal in open water (e.g. Ruggaber, 2000; Gensheimer et al., 2012; Becker et al., 2015).

The paper is organized as follows: the next section illustrates the analytical model and the method useful to describe whatever the dredging scenarios; section 3 illustrates the results of a sensitivity analysis aimed to catch the influence of model's parameters; section 4 illustrates the application of the method to a series of benchmark cases, useful for numerical models testing and to highlight the capabilities of the proposed model in describing the big picture of the involved phenomena; concluding remarks close the paper.

2. The analytical model

In the far field, resuspended sediments undergo dispersion, diffusion and settling phenomena, mainly driven by environmental forcing. Then, the well-known depth-averaged advection-diffusion equation may be used (e.g. Je et al., 2007; Shao et al., 2015; Singh et al., 2015):

$$\frac{\partial C}{\partial t} + U\frac{\partial C}{\partial x} + V\frac{\partial C}{\partial y} - D_x\frac{\partial^2 C}{\partial x^2} - D_y\frac{\partial^2 C}{\partial y^2} = q\left(x, y, t\right) - \frac{w_s}{h}C, \tag{1}$$

where x, y (m) are the horizontal coordinates, t (s) is the elapsed time, $C(x, y, t)$ (g/m^3) is the depth-averaged sediments concentration; U and V (m/s) are the x- and y-component of the ambient current respectively, D_x, D_y (m^2/s) are the diffusion coefficients, w_s (m/s) is the settling velocity; h (m) is the water depth; $q(x, y, t)$ $(g/m^3/s)$ is the source term, often referred to as "resuspension source strength" (Collins, 1995). It has to be stressed that the source term in equation (1) is intended to describe the sediments actually available to the far-field passive transport (Becker et al., 2015). The estimate of the intensity, location and temporal evolution of the source term allows to describe the role of the dredging activities parameters upon the large scale spatial and temporal evolution of sediments plumes.

Equation (1) may be used to model the phenomena at hand only if vertical flow stratification may be considered as negligible. Indeed, it relies on the two dimensional approximation of the advection-diffusion phenomena. Moreover, the ambient currents (i.e. U and V) are intended to be homogeneous in space, while they can vary in time. The water depth (h), the diffusion coefficients (D_x, D_y) and the settling velocity (w_s) are intended to be homogeneous in space and constant in time. Then, from a practical point of view, equation (1) may be used if the spatial gradient of ambient current can be neglected (i.e. for riverine dredging and far from the boundaries of the considered water body, or for offshore sediments disposal). Furthermore, the water depth has to be low enough in order to neglect flow stratification effects and the variability of source strength along the vertical direction. For hydraulic dredges, this assumption is reasonable if the water depth is lower than twice the characteristic dimension of the dredge-head (Collins, 1995). It has to be noticed that the hypothesis of negligible vertical gradient is not verified when water depth is large. A further limitation is due to the hypothesis of infinite domain needed to obtain the analytical solution that can be accepted if the boundaries of the considered domain is far enough from the dredging area. As far as the hypothesized ambient currents pattern is concerned, it could be observed that the model is able to model only local acceleration as the velocity may vary only in time while assuming the same value in the whole domain. As the water depth is assumed to be constant, the considered circulation has to be characterized by slow time variation (i.e. tidal oscillation) in order to satisfy the equations governing the hydrodynamics. Basically, equation (1) is able to model only the diffusion and the advection of the sediments plume as the velocities does not change in space. As the vertical dimension is not resolved, the second term in the right hand side of equation (1), aimed to describe deposition phenomena, has to be interpreted as a sink term whose effect is to subtract sediments from the system. Nevertheless, even with its limitations, the model is still able to provide a worst case preliminary assessment of sediments plume migration very useful to guide more detailed numerical analysis and to select the more appropriate simulation scenarios (Shao et al., 2015).

The solution of equation (1) may be achieved only if initial and boundary conditions are known and, of course, if the source term (q) is defined. Here, the source term is aimed to describe the sediments resuspended during dredging operations. in order to simplify the solution of the governing equation, several past researches considered steady state conditions (e.g. Je & Hayes, 2004) or continuous source (e.g. Kuo & Hayes, 1991; Shao et al., 2015, 2016). This paper aims to include into the governing equation the resuspension source term, representative of different dredging techniques and operations, in such a way it may be used to compare different dredging scenarios. To this end, this paper resorts to the application of the theory of linear dynamic system. Indeed, this approach has been successfully used to solve other engineering problems (e.g. Cecioni et al., 2011; Pasquali et al., 2015). The main idea is to find the instantaneous response function of the dynamic system to a local, instantaneous and unit sediments resuspension source. Then, time evolution and space distribution of the sediments concentration due to whatever the source term may be estimated as the (continuous) superposition of infinite number of instantaneous sources, i.e. by performing a

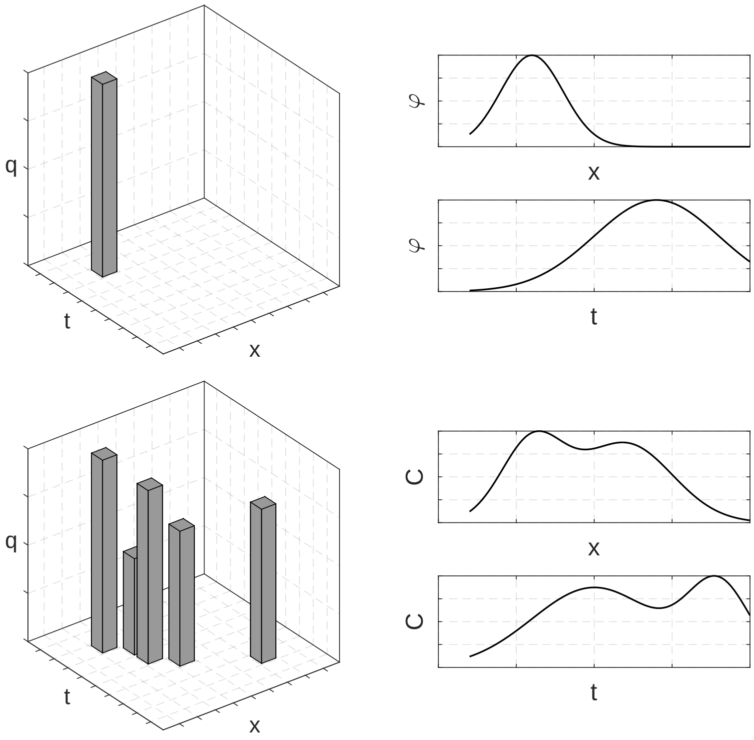

Figure 1: Sketch of the main features of the proposed model (one dimensional domain is depicted only for graphical purposes). In the upper panels the finite duration impulse (left panel) inducing the unit response φ of the system (right panel) is depicted. In the lower panels, the application of the method to whatever the source term is sketched.

convolution integral. Nevertheless, from a practical point of view, it is preferable to discretize the source term (both in time and space) as a temporal succession of finite duration impulses (with time resolution Δt) occurring within a finite area (with spatial resolution Δx and Δy). Then, the unit response function of the dynamic system to a finite duration unit sediments resuspension source occurring within a finite area is needed and time evolution and space distribution of the sediments concentration due to whatever the source term discretized in time and space may be estimated as a convolution summation. Figure 1 sketches the main features of the model (one dimensional domain is depicted only for graphical purposes): the unit response function meaning is depicted in the upper panels, the application to a resuspension sources is sketched in the lower panels.

In order to achieve the instantaneous response function of the dynamic system, the source term has to represent an ideal local, instantaneous and unit sediments resuspension source:

$$q_{inst}(x, y, t) = \delta(x)\delta(y)\delta(t), \tag{2}$$

where $\delta(\cdot)$ is the impulsive Dirac Function. Hence, equation (2) describes an impulsive sediments resuspension, $\delta(t)$, occurring at the origin of the reference frame, $\delta(x)\delta(y)$. The solution of equation (1) with the source term expressed by relationship (2) is the instantaneous response function $\psi(x, y, t)$ of the considered dynamic system. If infinite domains are considered (i.e. $-\infty < x < +\infty$, $-\infty < y < +\infty$) and Fourier transform technique employed, the solution reads as follows (e.g. Wexler, 1992):

$$\psi(x, y, t) = \frac{1}{4\pi t\sqrt{D_x D_y}} \exp\left[-\frac{(x - U_0\lambda_u)^2}{4D_x t}\right] \exp\left[-\frac{(y - V_0\lambda_v)^2}{4D_y t}\right] \exp\left(-\frac{w_s}{h}t\right), \tag{3}$$

where

$$\lambda_u(t) = \int u(t)dt \qquad , \qquad \lambda_v(t) = \int v(t)dt, \tag{4}$$

with the ambient currents, i.e. U and V in equation (1), expressed as functions of time only:

$$U(t) = U_0 u(t) \qquad , \qquad V(t) = V_0 v(t). \tag{5}$$

By using the theory of linear dynamic systems, the instantaneous response function $\psi(x, y, t)$ may be used to obtain the unit response function. Indeed, if a finite duration (Δt) resuspension source impulse occurring within a finite area ($\Delta x \cdot \Delta y$) is considered, the source term may be defined as follows:

$$\begin{aligned} q_{imp}(x, y, t) = \frac{1}{\Delta t\Delta x\Delta y}&[H(t) - H(t - \Delta t)]\times \\ &\times[H(x + \Delta x/2) - H(x - \Delta x/2)]\times \\ &\times[H(y + \Delta y/2) - H(y - \Delta y/2)], \end{aligned} \tag{6}$$

where $H(\cdot)$ is the Heaviside step-function. It has to be noted that the denominator of the first ratio (i.e. $\Delta t \Delta x \Delta y$) is used to preserve the unity of the source strength, i.e. the whole resuspension area is fed by a 1 $g/m^3/s$ source strength. The solution of equation (1) with the source term expressed as (6), i.e. the unit response function $\varphi(x, y, t)$, can be obtained by computing the convolution integral:

$$\varphi(x,y,t) = \int_0^t \int_{-\infty}^x \int_{-\infty}^y q_{imp}(\xi, \varepsilon, \tau)\psi(x-\xi, y-\varepsilon, t-\tau) d\xi d\varepsilon d\tau \tag{7}$$

The convolution integral (7) may be analytically solved to obtain the integral form of the unit response function:

$$\begin{aligned}
\varphi(x,y,t,\Delta x,\Delta y,\Delta t) = & \frac{1}{4\Delta t \Delta x \Delta y} \times \\
& \times \int_0^{\Delta t} \left\{ \mathrm{erf}\left[\frac{x + \Delta x/2 - U_0\lambda_u(t) + U_0\lambda_u(\tau)}{\sqrt{4D_x(t-\tau)}} \right] + \right. \\
& \left. -\mathrm{erf}\left[\frac{x - \Delta x/2 - U_0\lambda_u(t) + U_0\lambda_u(\tau)}{\sqrt{4D_x(t-\tau)}} \right] \right\} \times \\
& \times \left\{ \mathrm{erf}\left[\frac{y + \Delta y/2 - V_0\lambda_v(t) + V_0\lambda_v(\tau)}{\sqrt{4D_y(t-\tau)}} \right] + \right. \\
& \left. -\mathrm{erf}\left[\frac{y - \Delta y/2 - V_0\lambda_v(t) + V_0\lambda_v(\tau)}{\sqrt{4D_y(t-\tau)}} \right] \right\} \times \\
& \times \exp\left[-\frac{w_s}{h}(t-\tau) \right] d\tau
\end{aligned} \tag{8}$$

where the time integral cannot be further simplified and numerical integration is needed (e.g. Di Risio & Sammarco, 2008). Figure 2 shows a series of snapshots of the unit response function (see the caption for parameters' values). It could be observed that the sediments concentration is high close to the dredge location. Then the plume is dispersed downstream by the ambient current while also diffusion and deposition phenomena occurs at a progressive distance from the dredging zone: the model retains the main features of the phenomenon, at least from a qualitative point of view.

The unit response function, given by solution (8), can be used to evaluate temporal evolution and spatial distribution in the far field of the resuspension plume induced by whatever the resuspension source discretized in time (Δt)

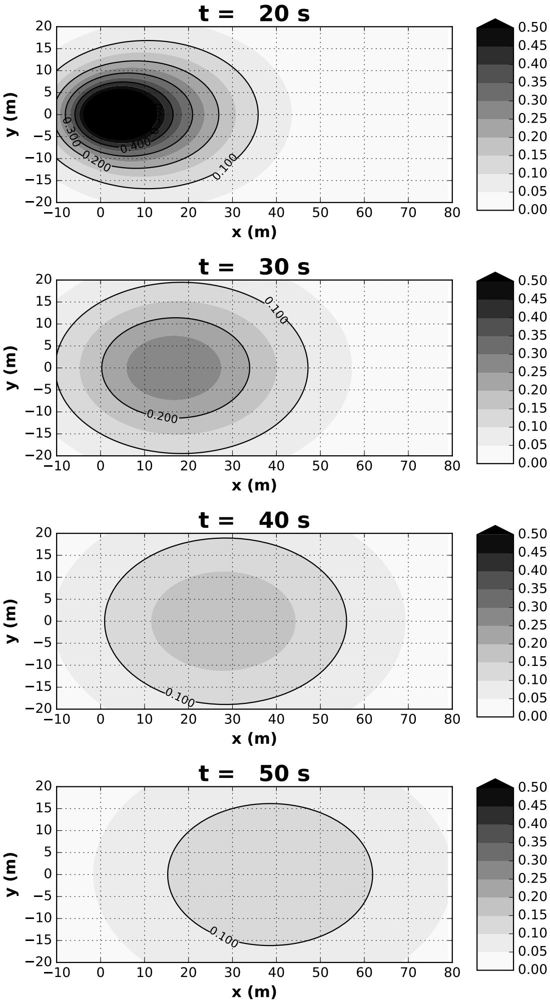

Figure 2: Snapshots of unit response function ($\Delta x = \Delta y = 5\,m$, $\Delta t = 20\,s$, $D_x = 10\,m^2/s$, $D_y = 5\,m^2/s$, $w_s = 0.0\,m/s$, $U = U_0 = 1\,m/s$, $V = 0\,m/s$).

and space (Δx, Δy) as a series of resuspension impulses q_i^*:

$$C(x,y,t) = \sum_{i}^{M(t)\leq M_0} q_i^* \varphi(x - x_i, y - y_i, t - t_i, \Delta x, \Delta y, \Delta t) \tag{9}$$

where q_i^* (g/m) may be inferred from the source strength q_i $(g/m^3/s)$ of the $i-th$ resuspension impulse:

$$q_i^* = q_i \cdot (\Delta t \Delta x \Delta y)\,, \tag{10}$$

and where x_i and y_i represent the mean location of the resuspension impulse, t_i the time the $i-th$ resuspension impulse occurs, M_0 the total number of resuspension impulses and $M(t)$ the number of resuspension impulses occurred up to the time t.

Basically, equation (9) and the unit response function expressed by (8) are the core of the proposed analytical model. The method consists of two parts: the first one is the definition of the unit response function by equation (8) obtained by considering a unit source strength; the second one is the estimate of the discretized convolution integral (9) aimed to achieve the response of the system to whatever the resuspension source term. It has to be observed that the unit response function may be also estimated by means of whatever the numerical model able to solve the governing equation (1). Then, the selected numerical model may be used once for all in order to estimate the unit response function (say it φ^*) and then the discretized convolution integral (9) may be used to obtain the evolution of resuspended sediments plume for whatever the dredging scenario.

In order to apply the proposed model, some model parameters have to be given, at least estimated. Inspection of equations (8) and (9) reveals that discretization of the resuspension source, both in time and space, have to be selected (i.e. Δx, Δy and Δt). Furthermore, the source strength has to be estimated: the reader may refer to the works of Becker et al. (2015) and Lisi et al. (2016) for a comprehensive review of available tools useful to estimate the source strength depending on the dredging activity features. As an alternative, it is possible to resort to direct measurements. The ambient currents have to be characterized in terms of both intensity (i.e. U_0 and V_0 have to be estimated) and temporal variation (i.e. functions λ_u and λ_v have to be selected). This problem can be roughly tackled by estimating (numerically or on the basis of monitoring) the main characteristic of the ambient currents of the dredging site, keeping in mind that spatial variation cannot be accounted for by the proposed analytical model. Finally, previous works may be referred for the diffusion coefficients definition (i.e. D_x and D_y, e.g Fischer et al., 1979; Riddle & Lewis, 2000; Jouon et al., 2006; Lisi et al., 2009; Shao et al., 2015) and bathymetric configuration has to be considered to define the water depth (h). It has to be stressed that diffusion coefficients depend upon the ambient velocity (e.g Riddle & Lewis, 2000) as they describe the horizontal spreading due to velocity shear (absent in the present model) and to turbulent motion along both the longitudinal and transversal direction (e.g Jouon et al., 2006): the higher the current velocity (then the turbulent fluctuations), the higher the diffusion coefficients. Their estimation is usually based on empirical or physics-based formulations by relating them to the current speed (e.g Fischer et al., 1979). When time varying currents are considered, the selection of diffusion coefficient has to take into account the main aim of the proposed model, i.e. to provide a worst case preliminary assessment of sediments plume migration. Then, based on the results of sensitivity analysis illustrated in section 3, the selection of diffusion coefficients based on the lowest velocity (i.e. low values of the diffusion coefficients) represents the worst case scenario.

The selection of w_s is worth to be discussed herein. The formulation proposed by Özer (1994) may be employed to get an estimate of the flocculent settling velocity when fine sediments are considered (e.g. Je & Chang, 2004; Je et al., 2007; Shao et al., 2015):

$$w_s = -\frac{az}{(1+b)\,t}, \tag{11}$$

where t is the settling time, z is the vertical distance from the mean water level, a and b are parameters estimated on the basis of ad hoc settling column test site specific (e.g. Shao et al., 2015). It could be noted that the parametric formulation proposed by Özer (1994) is time dependent, i.e. the settling velocity changes with time. Equation (11) was inferred by analyzing settling column test data with the aim to describe flocculent settling. Then, the temporal evolution of the settling velocity is related to the suspended sediments concentration within the water column during the test: the higher the instantaneous sediments concentration, the higher the instantaneous settling velocity. In the case at hand, the suspended concentration exhibits a stronger variation in space than in time, being larger close to the resuspension source (the dredge-head) than in the far field. In order to estimate a mean value of w_s, equation (11) may be averaged over the depth (e.g. Je & Chang, 2004):

$$\overline{w_s} = \frac{1}{h}\int_0^h w_s dz = -\frac{ah}{2t\,(1+b)} \tag{12}$$

by conceptually considering a depth averaged suspended sediments concentration affecting the settling velocity, being the temporal variation still retained. In order to give an overall mean of the settling velocity, Shao et al. (2015) performed a time average of equation (12) by using parameters a and b proposed by Je et al. (2007), then by selecting a reasonable estimate of the value of settling velocity to be used for their model. It is proposed herein to perform an initial estimation of the average (over space) suspended concentration by neglecting the settling velocity ($\overline{w_s} = 0$) and to estimate an average settling velocity depending on the suspended sediments concentration, keeping in mind

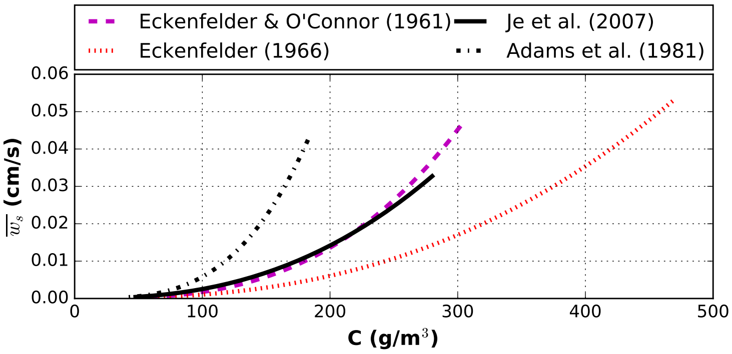

Figure 3: Depth averaged settling velocity ($\overline{w_s}$) as a function of remaining concentration (C) estimated for paper mill wastewater (Eckenfelder & O'Connor, 1961), activated sludge (Eckenfelder, 1966), sediments from Savannah River dredging project (Je et al., 2007) and from unknown suspension (Adams et al., 1981)

that overestimation of w_s may lead to unwanted underestimation of the concentration. Then, it is possible to resort to the model proposed by Özer (1994) and used by Je & Chang (2004) with the aim to obtain a formulation of w_s taking into account the influence of the (depth averaged) suspended sediments concentration. Özer (1994) proposed the following relationship:

$$P_r = f t^a z^b \tag{13}$$

giving the percentage remaining concentration P_r with respect to the initial concentration C_0, being f, a and b constants where a and b are the same of relationship (11). Then, the depth averaged remaining concentration (C) can be inferred by using equation (13) for given initial concentration. Figure 3 shows the depth averaged settling velocity ($\overline{w_s}$) as a function of the depth averaged (remaining) concentration obtained by using the parameters a, b and f analyzed by Je & Chang (2004) for settling column test data of past studies (e.g. Eckenfelder & O'Connor, 1961; Eckenfelder, 1966; Adams et al., 1981) along with the parameters estimated for a real case dredging project carried out at Savannah River (Collins, 1995; Je et al., 2007). As expected, it could be observed that the higher the concentration, the higher the depth averaged settling velocity, then by describing the role of flocculation in the settling processes. Similar approach may be used to the specific study in order to select the correct, at least the most appropriate, value of depth averaged settling velocity.

3. Sensitivity analysis

This section aims to describe the influence of model parameters on plume dispersion in the case of a resuspension impulse of finite duration ($\Delta t = 200$ s) occurring close to the origin of the reference frame within an area ($\Delta x = \Delta y = 1$ m). In particular, the effects of current velocity (U_0), diffusion coefficients (D_x, D_y), and sediments settling velocity (w_s) are investigated. The sensitivity analysis has been carried out by looking at the temporal variation of the suspended sediments concentration computed at 200 m downstream the resuspension source location. Typical result of plume dispersion is similar to snapshots of Figure 2, while Figure 4 shows the influence of U_0, D_x, D_y and w_s upon the temporal evolution of the sediments concentration. It has to be noticed that dimensionless time t^* ($= U_0 t/h$) is considered as proposed by Shao et al. (2015). Within the frame of the sensitivity analysis described herein, the model parameters were changed one by one, by ignoring their mutual dependence. In particular, this could be a strong assumption for the diffusion coefficients that depend upon the current velocity, still retaining the validity of the sensitivity analysis that makes possible the comparison against previous studies (e.g. Shao et al., 2015, 2016).

Figure 4-(a) shows the influence of the velocity of the current (U_0): the higher the value of U_0, the higher the maximum value of sediments concentration during its temporal evolution and, of course, the faster the plume migration downstream (note that the time is expressed in dimensionless form). The results in terms of sediments concentration is not consistent with previous findings (e.g. Shao et al., 2015), at least at a first glance: as the current speed increases, sediments concentration decrease is expected. Nevertheless, while this is true for the steady state related to continuous resuspension source, it is not true for a finite duration resuspension source, for which the finite extension of the plume is quickly advected downstream by the current with the turbulent diffusion (related to diffusion coefficients D_x and D_y) playing a minor role and inducing only a slight decrease of sediments concentration. If the model is applied by considering a continuous resuspension source, an increase of suspended sediments concentration for decreasing current velocity is observed (Figure 5, right panel), consistent with the findings of previous researches (e.g. Shao et al., 2015). Indeed, suspended sediments concentration is allowed to reach the steady state whose spatial distribution is similar, at least qualitatively, to the results shown in Figure 6 (see the next section). It has to be stressed again that the higher the current velocity, the higher the diffusion coefficient. Then, the sediments concentration shown in panel 4-(a) for the highest current velocity has to be considered as an high limit.

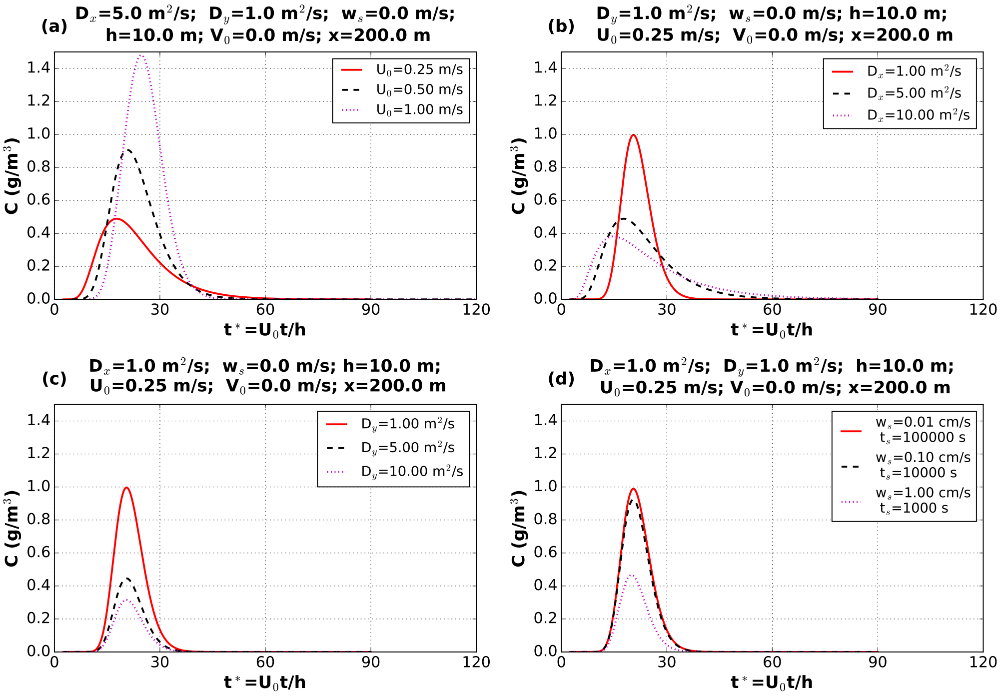

Figure 4: Sensitivity analysis: temporal evolution of suspended sediments concentration (C) estimated at 200 m (x = 200 m, y = 0 m) away the resuspension source as a function of time for different (a) current velocity U_0, (b) diffusion coefficient D_x, (c) diffusion coefficient D_y and (d) sediments settling velocity. The source term is characterized by a finite duration of Δt = 200 s occurring at the origin within a 1 m^2 area ($\Delta x = \Delta y$ = 1 m).

As far as the influence of longitudinal diffusion coefficient (D_x) is concerned, Figure 4-(b) shows that its increase induces the decrease of the maximum value of the sediments concentration during its temporal evolution. In turn, as expected, the temporal evolution is affected by the diffusion coefficient that enhances the diffusive evolution of the finite extension plume, with fast increase during the initial stage and slow decrease during the early stage of the sediments concentration evolution.

Figure 4-(c) shows how the increase of transversal diffusion coefficient (D_y) induces the decrease of the maximum value of sediments concentration while temporal evolution remains almost unchanged.

The temporal evolution still remains almost unchanged, as expected, if the settling velocity (w_s) is varied, as shown by Figure 4-(d): the higher the settling velocity the lower the maximum value of sediments concentration. As suggested by Shao et al. (2015), fine silt ($w_s \simeq$ 0.01 cm/s), coarse silt ($w_s \simeq$ 0.1 cm/s) and fine sand ($w_s \simeq$ 1.00 cm/s) are considered. It could be noted that different settling velocity may be also related to different suspended concentration of flocculent mixtures (see Figure 3). Furthermore, it could be noted that the variation of settling

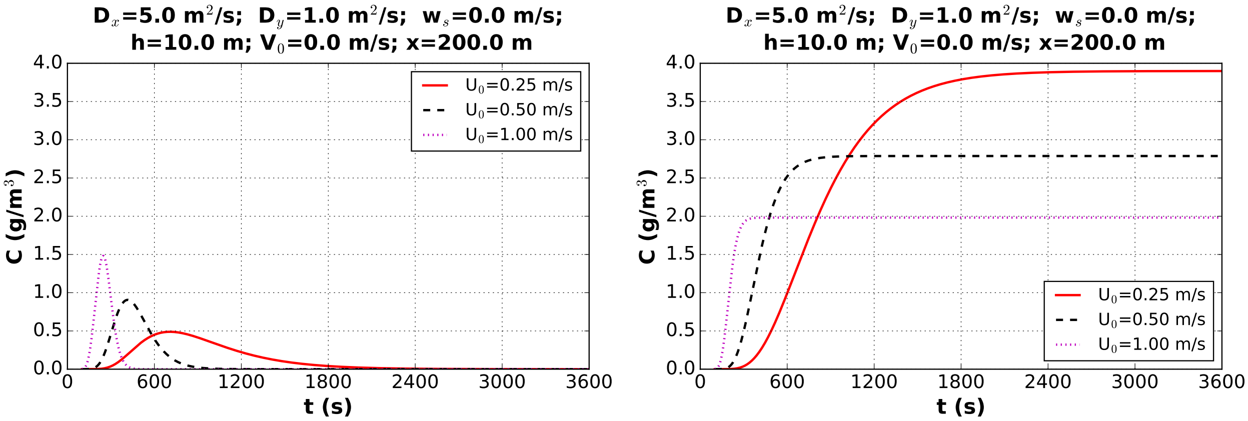

Figure 5: Temporal evolution of suspended sediments concentration (C) estimated at 200 m ($x = 200$ m, $y = 0$ m) away the source when finite duration (left panel) and continuous (right panel) resuspension sources are considered. The same parameters of case (a) of Figure 4 are used while the temporal axis is not dimensionless.

velocity is related to the variation of water depth. Indeed, the water depth and settling velocity appear in the sink term of the governing equation (1) and a characteristic settling time t_s ($= h/w_s$) ranging from 1’000 s up to 100’000 s in the results of Figure 4-(d) may be used to appreciate the roles played by settling velocity and water depth simultaneously.

4. Practical applications and discussion

4.1. Savannah River case study

The proposed model has been applied to the documented real case of Savannah River dredging project (Georgia, US) carried out some years ago (July 1983) by Waterways Experimental Station (WES) in order to gain insight about sediment resuspension rates and sediments plume dispersion induced by dredging activities (Je et al., 2007). In particular, cutter-head dredging field study was carried out during the maintenance dredging of the middle area of the lower portion of the Back River (about 500 m wide, coordinates 32.086°N, 81.054°W) connected to the Savannah River at both ends. This site was selected in order to compare the results of the proposed model with the results illustrated by the previous studies of Je et al. (2007) and Shao et al. (2015). Actually, the model assumptions may be accepted only for a first rough estimate. The sediments were characterized in terms of settling velocity by estimating Ozer’s parameters (i.e. $a = -0.402$, $b = 0.047$, $f = 126.3$, see solid black line in Figure 3 and Je et al., 2007). The dredging project was performed by a hydraulic cutter-head suction dredge (cutter-head diameter 1.83 m, cutter-head length 1.52 m, ladder length of 20.82 m) and suspended sediments concentration profiles were collected close the dredging area and up to about 250 m downstream (Collins, 1995). Je et al. (2007) give the main parameters needed to model the plume dispersion: the lateral diffusion coefficients (D_y) ranged from 10 m^2/s up to 28 m^2/s; the current velocities ranged 0.07÷0.34 m/s during the ebb tide and 0.20÷0.48 m/s during the flood tide; the water depth is 13.5 m and representative maximum dredging depth equal to about 15.2 m (Collins, 1995). Based on the regional analysis carried out by Herbich & Brahme (1991) for the Savannah Harbour Area, the median grain diameter of the dredged sediments may be estimated as 0.023 mm, a soft, organic clay/silt mixture (i.e. OH-OL, USCS classification). The background concentration was estimated as 17 g/m^3 and 67 g/m^3 close to the free surface and to the bottom respectively (Collins, 1995). During the dredging activities the resuspended sediments concentration rose up to about 38 g/m^3 and 500 g/m^3 as reported by Je et al. (2007), depending on the dredging activities.

Figure 6 shows the results obtained for the validation cases proposed by Je et al. (2007). Dredging scenarios (from A to E in Figure 6) differ each other in terms of source concentrations during dredging operations. However, Je et al. (2007) highlight “the lack of field data on actual dredging events”, further observed by Collins (1995). The left panels represent the computed distribution of sediments concentration in the overall domain, while the right ones show the analytical solution along the centerline of the domain compared to field data (markers). The results refer to the steady solution. The values of elapsed time needed to reach the steady solution in the whole domain (i.e. $x < 250$ m) are reported in Table 1 (t_{steady}). It should be noticed that the values of t_{steady} are low if compared to the local tidal time scale. The same parameters suggested by (Je et al., 2007, solid lines) and a further current velocity equal to 0.05 m/s (dashed lines) were used. It has to be stressed that Je et al. (2007) assumed a constant current velocity of 0.3 m/s by considering the local tidal conditions, and different values of transversal diffusion coefficient without illustrating the estimation procedure. As any information about dredging-induced source strength q have been suggested by Je et al. (2007), it has been calibrated in order to get the concentration close to the dredge-head. The settling velocity has been selected by using the concentration estimated with $w_s = 0$ at a downstream distance equal to 50 m and then by using the black line curve shown by Figure 3. Table 1 synthesizes the main parameters used to achieve the results of Figure 6. In order to model a continuous source terms a series of equal resuspension impulses were used to compute the discretized convolution given by (9).

Results inspection reveals that the proposed model catches the main features of the downstream plume dispersion.

CASE	C_0 (g/m^3)	C_{50} (g/m^3)	D_x (m^2/s)	D_y (m^2/s)	w_s (cm/s)	U_0 (m/s)	q (g/m^3/s)	t_{steady} (hrs)
A	37.7	16.20	0.1	10	2.73E-05	0.30	12.80	0.28
A*		5.42			1.79E-06	0.05	3.27	3.28
B	204.3	74.40	0.1	22	1.21E-03	0.30	85.50	0.28
B*		49.90			4.48E-04	0.05	22.14	1.78
C	504.3	190.20	0.1	18	1.25E-02	0.30	198.38	0.28
C*		127.80			4.65E-03	0.05	51.35	1.83
D	227.8	80.30	0.1	28	1.46E-03	0.30	103.63	0.28
D*		53.40			5.31E-04	0.05	26.73	1.83
E	142.2	58.40	0.1	12	6.63E-04	0.30	50.26	0.28
E*		39.20			2.46E-04	0.05	12.90	1.78

Table 1: Numerical values of model parameters used to achieve results of Figure 4. C_0 is the computed resuspended sediments concentration at the dredging zone, C_{50} is the sediments concentration 50 m downstream the dredging zone, D_x and D_y are the diffusion coefficients along x and y directions respectively, w_s is the settling velocity, q is the intensity of the resuspension source.

Nevertheless, it tends to overestimate the concentration along the main axis of the domain. This overestimation decreases as the current velocity decreases due to the lower dredging-induced source strength to be used to reproduce the same concentration close to the dredge-head. For comparison, the resuspension source strength inferred by Shao et al. (2015) to reproduce case (A) of Figure 6 (upper panels) has been tested (dotted line in the upper left panel). Indeed, Shao et al. (2015) estimated the resuspension source strength by trials and errors method aimed to find the best match to the observed data instead of comparing the concentration close to the dredging area only. Moreover, it has to be stressed that, as observed by Collins (1995), the field data of Savannah river are "not controlled", i.e. boundary conditions (e.g. current velocities and dredging activities features) are not known. Then, the dashed lines in Figure 6 may be viewed as the best case (being the minimum current velocity at the dredging area equal to 0.05 m/s). In general, it could be observed that the proposed analytical model, despite its simplicity and low computational costs, gives an estimate of the observed values comparable to the results obtained with more accurate numerical models.

4.2. Hydraulic dredging

Dredging performed by means of hydraulic dredges may be modeled by considering the dredge-head that moves, from board to starboard (and vice versa), toward the undisturbed bottom to be dredged (e.g. Collins, 1995). Hence, during the movement of the dredge-head, overcutting and undercutting dredging occur: the resuspension strength differs during dredging work progression (Hayes et al., 2000). Consistently, in order to describe the resuspension source related to hydraulic dredges, the source term to be used in equation (9) has to vary in time in term of both

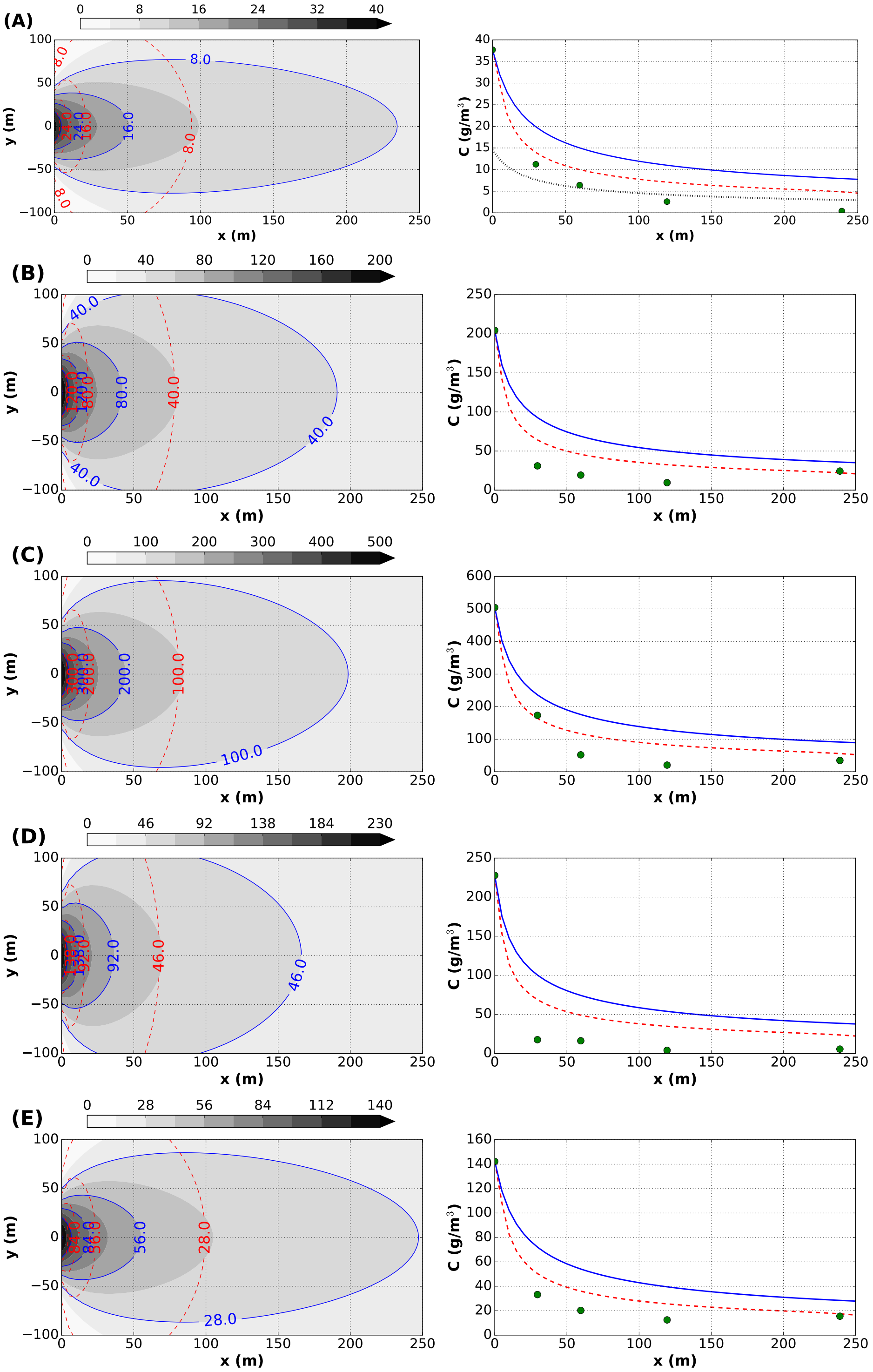

Figure 6: Analytical solution (lines in the Cartesian plots, right panels) compared to field data of Savannah River dredging project (markers in the Cartesian plots, right panels) and computed distribution of sediments concentration in the overall domain (gray scale maps, left panels). Solid lines of Cartesian plot and gray scale maps refer to ambient current equal to 0.3 m/s, dashed lines to ambient current equal to 0.05 m/s (concentration expressed as g/m^3). Dotted line shown in upper left panel refers to the resuspension source strength and settling used by Shao et al. (2015).

source strength and location. The impulse mean location (x_i, y_i) of the dredge-head occurring at time t_i $(= i\Delta t)$ may be described by the following relationship:

$$x_i = \lfloor i/N_y \rfloor \Delta x \tag{14}$$

$$y_i = \begin{cases} y_{i-1} + V_d \Delta t & \text{if } \lfloor i/N_y \rfloor \text{ is even and } x_{i-1} = x_i \\ y_{i-1} - V_d \Delta t & \text{if } \lfloor i/N_y \rfloor \text{ is odd and } x_{i-1} = x_i \\ y_{i-1} & \text{if } x_{i-1} \neq x_i \end{cases} \tag{15}$$

where N_y is the number of impulses along the y direction, V_d is the swing speed of the dredge-head and the operator $\lfloor\cdot\rfloor$ is used to indicate the round down operation. The impulse strength may be described as follows:

$$q_i = \begin{cases} \alpha_{oc} q_0 & \text{if } \lfloor i/N_y \rfloor \text{ is even} \\ \alpha_{uc} q_0 & \text{if } \lfloor i/N_y \rfloor \text{ is odd} \end{cases} \tag{16}$$

where q_0 is a reference resuspension strength, α_{oc} and α_{uc} are coefficients to be applied to q_0 in order to describe the overcutting ($\alpha_{oc} < 1$) and the undercutting ($\alpha_{uc} > 1$) resuspension (e.g. Hayes et al., 2000; Henriksen, 2012).

Figure 7 shows the results obtained for hydraulic dredging scenario in terms of a series of snapshots of the sediments concentration. Typical values of α_{oc} (= 0.6), α_{uc} (= 1.4) and swing speed V_d (= 0.2 m/s) were used as suggested by Hayes et al. (2000). The reference resuspension source q_0 was set to 200 g/m^3/s. The dredging temporal evolution was discretized as a series of finite duration impulses 25 s long occurring within a square area ($\Delta x = \Delta y = 5$ m) for a total duration of dredging of 2000 s (about 33 minutes). The current velocity U_0 was selected as constant ($\lambda_u = t$) and equal to 0.25 m/s. Two scenarios were considered in order to highlight the role of diffusion coefficients (D_x and D_y) upon the sediments plume evolution. In the first case negligible diffusion was modeled (left panels of Figure 7) and the plume is expected to be advected downstream by the current. In the second case isotropic diffusion was considered ($D_x = D_y = 5$ m$^2/s$) and the plume is expected to be advected downstream by the current while it is diffused also along the transversal direction (right panels of Figure 7). Inspection of the results reveals that the model is able to describe the transient features of the resuspension source in terms of both location and intensity. Indeed, the plume

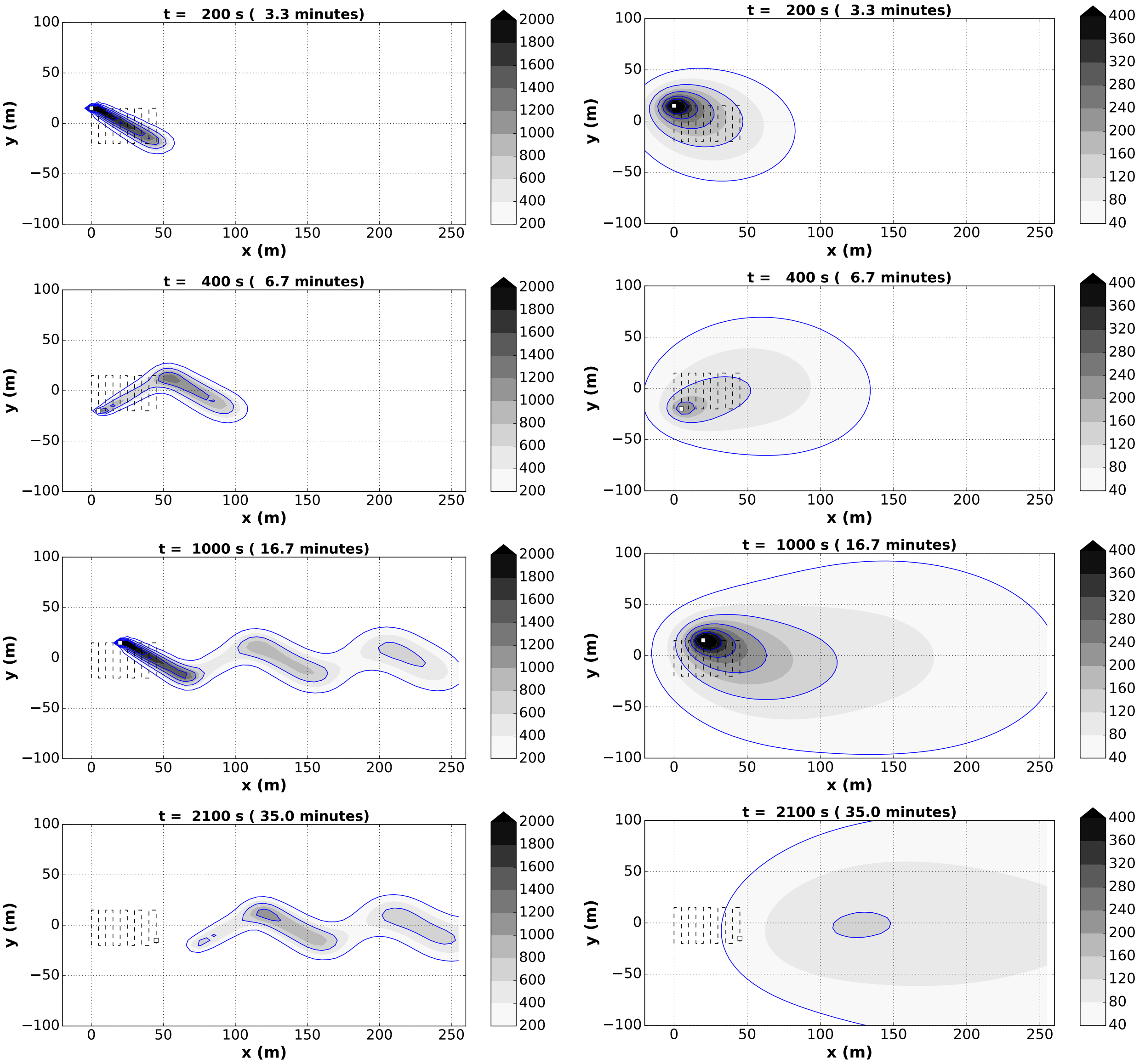

Figure 7: Sediments plume evolution due to hydraulic dredging activities. Left panels refer to negligible diffusion (D_x=D_y =0.1 m^2/s). Right panels refer to D_x=D_y =5.0 m^2/s. Dashed lines depict the dredge-head path, square markers indicate the instantaneous location of dredge-head (velocity of the dredge-head equal to 0.2 m/s), contour lines refer to sediments concentration levels indicated close to the colorbar (g/m^3). Physical parameters: U_0 = 0.25 m/s, V_0 = 0 m/s, w_s = 0.0 m/s, Δx = Δy = 5 m, Δt = 25 s. See the related video animation in the on line version of the paper.

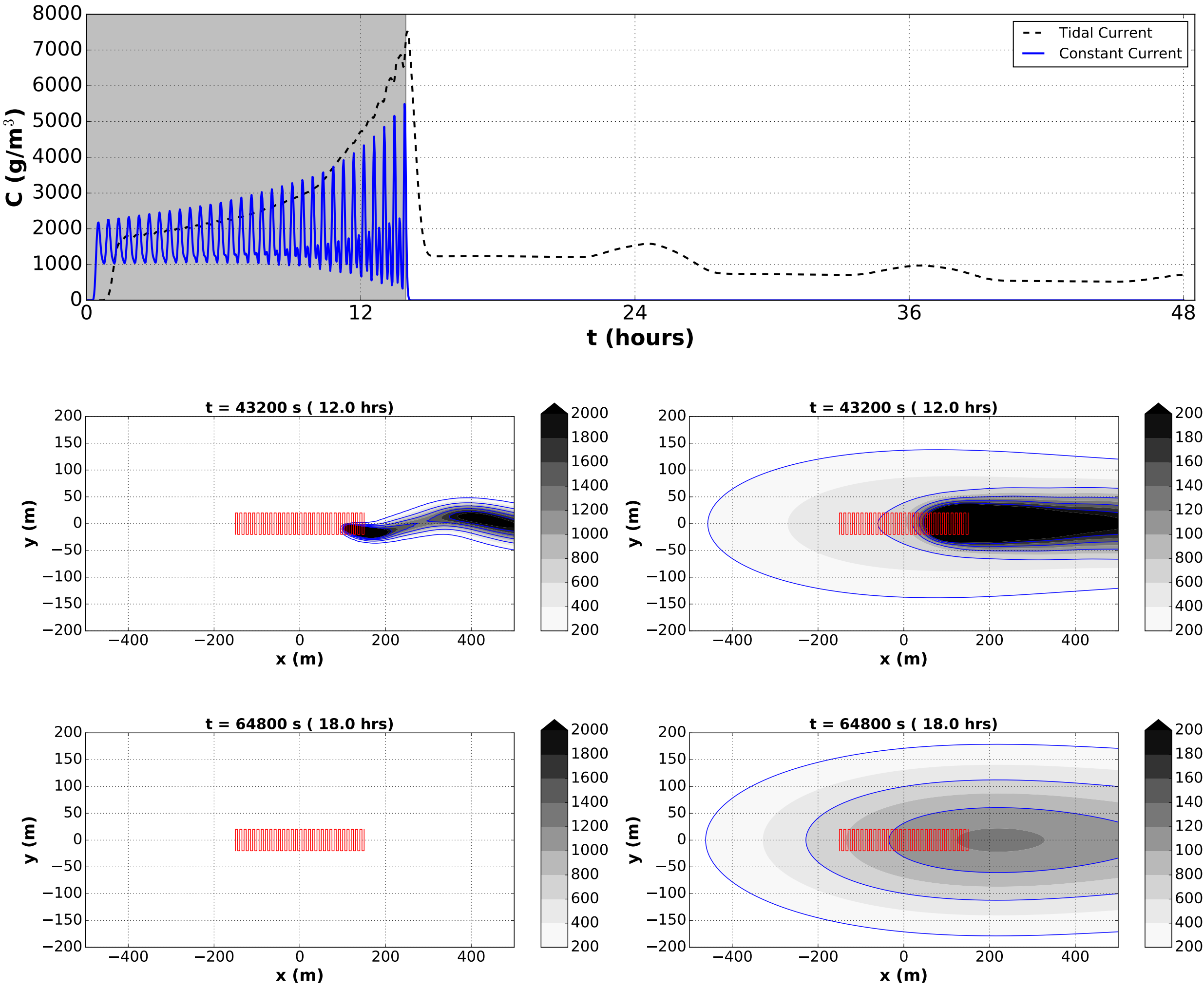

Figure 8: Sediments plume evolution due to hydraulic dredging activities. Upper panel refers to the time series of sediments concentration computed at the point x =200 m, y =0 m (shaded area indicate the time interval during which the dredging induced sediment resuspension takes place). Left lower panels refer to constant velocity (U_0=0.25 m/s, $\lambda_u = t$). Right lower panels refer to tidal current (U_0=0.25 m/s, $\lambda_u = \omega^{-1} \cos \omega t$, $u(t) = \sin \omega t$). Physical parameters: $D_x = 1.00$ m^2/s, $D_y = 0.10$ m^2/s $V_0 = 0$ m/s, $w_s = 0.0$ m/s, $\Delta x = \Delta y = 5$ m, $\Delta t = 25$ s, $T = 2\pi\omega$ =12 hours.

evolution mimics the source geometry and temporal evolution, with the role of diffusion and advection clearly observable. When diffusion is neglected, it is clear the effects of undercutting and overcutting resuspension: high sediments concentration areas are followed by low sediments concentration areas. Moreover, it has to be stressed that negligible diffusion induces higher sediments concentration with respect to the sediments concentration obtained when diffusion is accounted for. Nevertheless, the area suffering of increase of sediments concentration is larger in the latter case.

A further application has been considered in order to gain insight about the model capability in catching the effects of temporal variation of the ambient current upon the evolution of sediments plume. Figure 8 aims to compare the sediments concentration due to hydraulic dredging when both a typical semidiurnal tidal current ($u(t) = \sin\omega t$, $T = 2\pi/\omega$ =12 hours) and constant current are considered. Results inspection reveals that when constant current is concerned (left panels) the sediments plume are quickly advected downstream just after the end of the dredging activities. On the other hand, when tidal current is considered (right panels), the sediments plume remains close to the dredging area and the increase of sediments concentrations may persist for long time due to the advection of the time varying current (Figure 8 show concentration patterns up to 48 hours, upper panel). By inspecting the evolution of the sediments concentration just downstream the dredging area (upper panel) it could be observed that also in the case of constant ambient current the concentrations fluctuate due to the temporal evolution of the location of the source term (and they drop to small values just after the end of the dredging activities), then by catching the main features of the phenomenon.

4.3. Mechanical dredging

When mechanical dredging is concerned, the source term has to describe an intermittent resuspension source that moves slowly in space. Then, it can be simplified as a series of finite duration (Δt) resuspension source occurring at the location $x_i(t), y_i(t)$ ($\Delta x = \Delta y = b$, being b the bucket characteristic dimension) and a series of nil resuspension source of finite duration ($\Delta t_p = \Delta t$) during which the dredge bucket is completely out of the water.

The impulse mean location (x_i, y_i) of the dredge-head occurring at time t_i ($= 2i\Delta t$) may be described by the following relationships:

$$x_i = \lfloor i/N_y \rfloor \Delta x \tag{17}$$

$$y_i = \begin{cases} y_{i-1} + \Delta y & \text{if } \lfloor i/N_y \rfloor \text{ is even and } x_{i-1} = x_i \\ y_{i-1} - \Delta y & \text{if } \lfloor i/N_y \rfloor \text{ is odd and } x_{i-1} = x_i \\ y_{i-1} & \text{if } x_{i-1} \neq x_i \end{cases} \tag{18}$$

The impulse strength is constant (equal to q_0, set to 200 g/m^3/s).

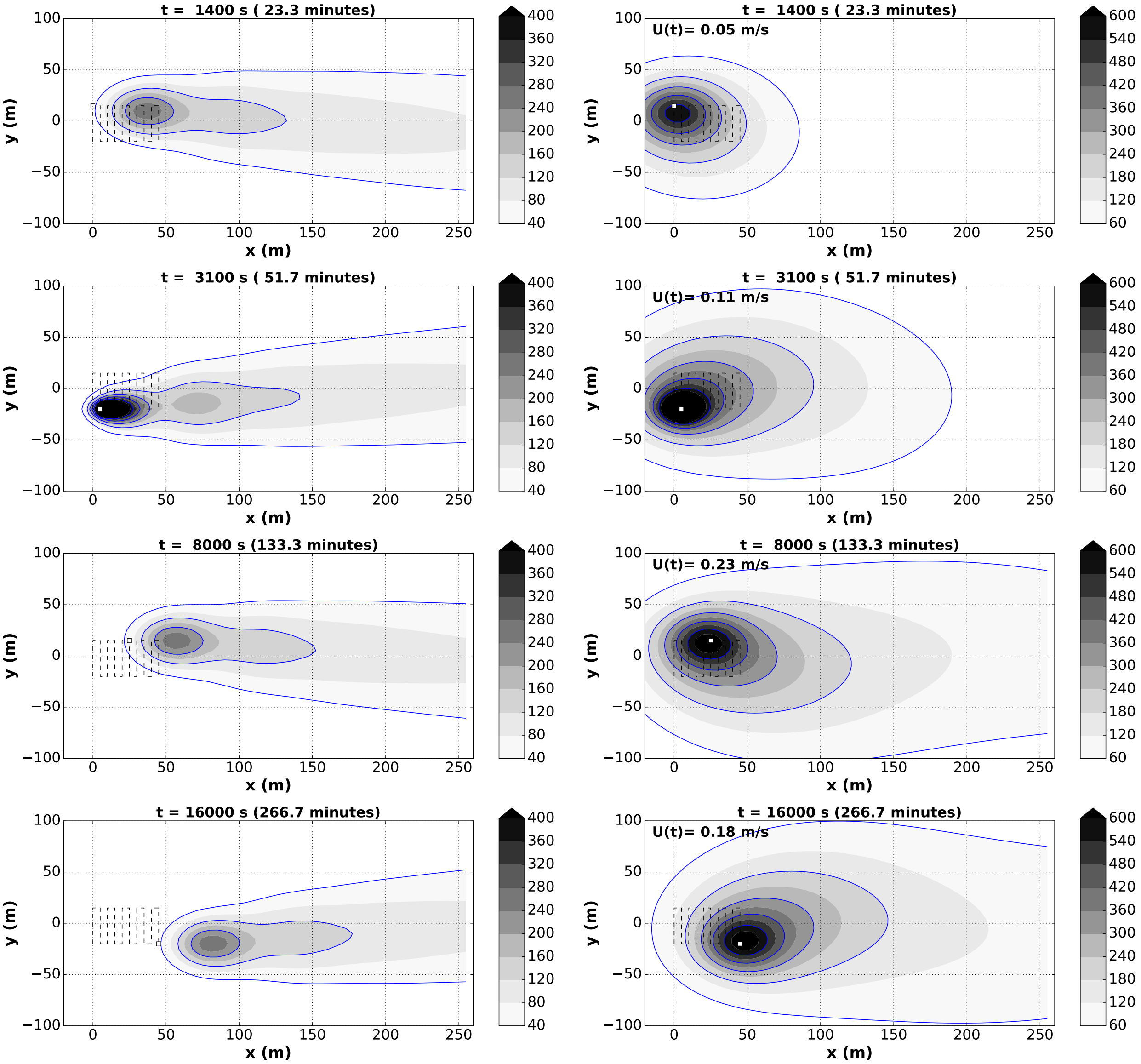

Figure 9: Sediments plume evolution due to mechanical dredging activities. Left panels refer to constant velocity (U_0=0.25 m/s, $\lambda_u = t$). Right panels refer to time varying velocity (U_0=0.25 m/s, $\lambda_u = \omega^{-1}\cos\omega t$, $u(t) = \sin\omega t$) and instantaneous velocity is indicated in each panel. Dashed lines depict the dredge-head path, square markers indicate the instantaneous location of dredge-head, contour lines refer to sediments concentration levels indicated close to the colorbar (g/m^3). Physical parameters: $D_x = D_y = 1.00$ m^2/s, $V_0 = 0$ m/s, $w_s = 0.0$ m/s, $\Delta x = \Delta y = 5$ m, $\Delta t = 100$ s. See the related video animation in the on line version of the paper.

The dredging temporal evolution was discretized as a succession of a finite duration impulse 100 s long occurring within a square area ($b = \Delta x = \Delta y = 5$ m) followed by a temporal window of $\Delta t = 100$ s during which any resuspension occurs (i.e. when the dredge bucket is completely out of the water). The total duration of dredging was set equal to 16000 s (about 4.4 hours). Isotropic diffusion was considered ($D_x = D_y = 1$ m$^2/s$). Two scenarios were considered in order to highlight the influence of temporal variation of current velocity, as suggested by Shao et al. (2015). On one hand, constant current is considered ($U_0 = 0.25$ m/s, $\lambda_u = t$, left panels of Figure 9), on the other hand a typical semidiurnal tidal current ($U_0 = 0.25$ m/s, $\lambda_u = -\omega^{-1} \cos \omega t$, $u(t) = U_0 \sin \omega t, \omega = 2\pi/T, T = 12$ hours, right panels of Figure 9) was investigated. When results of constant velocity are inspected, it is almost noticeable the effect of the temporal windows during which the dredge does not induce any resuspension that influence the shape of the plume (see t=3'100 s, left panel of Figure 9). When time varying current is considered, it could be observed that higher sediments concentration occurs during the early stage of the dredging when the current velocity is very low, and diffusion effects induce a large plume. As the current increases, the large plume is advected downstream. It could be argued that the sediments concentration is high if the dredging operations at estuaries are carried out during the slack waters, from the flooding and ebbing and vice versa, at least from a qualitative point of view. Also in this case, as observed for hydraulic dredging scenarios, it could be noted that the model is able to catch the main features of the plume dispersion when the resuspension source changes in both time and space.

5. Conclusions

This paper aims to propose a new analytical model able to estimate the temporal evolution and the spatial distribution of resuspended sediments concentration in the far field during the execution of dredging activities. The proposed model takes into account the variation, in both time and space, of location and strength of the resuspension source during the work progression. Thus it provides the temporal and spatial picture of the resulting plume evolution.

In order to achieve an analytical solution, some hypotheses had to be made: the model is two dimensional in the horizontal plane; the ambient currents are assumed to be homogeneous in space and slowly time varying; the turbulent diffusion coefficients and flocculent settling velocity are homogeneous in space; the water depth is constant; the domain is infinite. Even with its strong limitations, the model is still able to provide a worst case preliminary assessment of sediments plume migration very useful to guide more detailed numerical analysis and to select the more appropriate simulation scenarios. Furthermore, it can be used for the estimation of the fate in the far-field of sediments plume due to the cloud disposal in open water.

Basically, the method consists of two parts:

- the definition of the unit response function expressed in integral form;
- the evaluation of the discretized convolution integral aimed at achieve the response of the system to whatever the resuspension source term.

It has to be stressed that the unit response function may be also estimated by means of whatever the numerical model able to solve the governing equation, by applying different boundary conditions and by removing some of the assumed hypotheses (i.e. to describe the role of water body boundaries or to describe the effects of silt curtains). In this case the selected numerical model has to be used once for all (for each configuration) to achieve the unit response function.

The model capabilities are shown thorough the paper by means of a series of benchmark cases dealing with both mechanical and hydraulic dredges when current is constant or time varying.

Despite its simplicity, the model is demonstrated to be able to describe the big picture of the phenomenon at hand. Hence, it could be used to compare the effects of different dredging scenarios and to address general environmental issues; thereby allowing a first rough prediction of dredging environmental impacts. Finally, it is crucial to underline that the model may be used to test numerical models during their development stage and basic theoretical solutions are needed.

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