AN INTEGRATED APPROACH FOR THE PLANNING OF DREDGING OPERATIONS IN ESTUARIES

M. Álvarez [a], R. Carballo [a*], V. Ramos [a], G. Iglesias [b]

[a] Univ. of Santiago de Compostela, Hydraulic Eng, EPS, Campus Univ. s/n, 27002 Lugo, Spain

[b] Univ. of Plymouth, School of Marine Science and Engineering, Marine Building, Drakes Circus, Plymouth PL4 8AA, United Kingdom

ABSTRACT

Ports are often located in naturally sheltered areas such as estuaries. The strong tidal currents that occur in many of these areas drive a dynamic morphodynamic regime, with the result that the approach channels to these ports are gradually infilled. Periodic dredging is therefore necessary to maintain the operativity of the port. A case in point is Ribadeo (NW Spain), an important port for the economy of the area. In this work, the sediment transport patterns of the estuary (Ria de Ribadeo) are investigated through high-resolution numerical modelling and field measurements covering a 4-year period. On this basis, a decision-aid tool is developed that enables to predict the time evolution of the approach channel and thus contributes to the planning of dredging operations and, more generally, the maintenance of adequate operativity levels in a cost-effective way.

Keywords: estuary; dredging; port; sediment transport; navigation channel; numerical modelling.

*Corresponding author. Tel.: +34 982 285900; fax: +34 982 285926. E-mail address: rodrigo.carballo@usc.es (R. Carballo).

1. INTRODUCTION

Shipping may be affected by a number of coastal processes (López and Iglesias, 2013; López et al., 2015; Teodoro et al., 2014; Rosa-Santos et al., 2009), not least sediment transport and its repercussions on restricted or semi-restricted navigation channels. Sediment infilling may affect port operativity by limiting the time for vessels to access, or depart from, a port. This is the case of a number of ports located in rias in Galicia (NW Spain).

A ria is a particular type of estuary: a drowned river valley in which the accumulation of sediment since the Holocene transgression has not kept pace with sealevel rise, and therefore the bathymetry reflects closely the topography of the original river valley. Galician rias are generally characterised as positive, partially mixed estuaries (Iglesias et al., 2008).

The Port of Ribadeo is located in the middle section of the Ribadeo ria (in the vernacular, Ria de Ribadeo or Ria del Eo, after the name of the river), at 43º 32.865´ N, 007º 02.054´ W (**Figure 1**), and is the largest in trade volume of all the ports managed by the Regional Port Authority (Ports of Galicia). It has a great importance for the local and regional economy, with a hinterland exceeding a radius of 50 km from the port, which generates a considerable Short Sea Shipping.

[FIGURE 1]

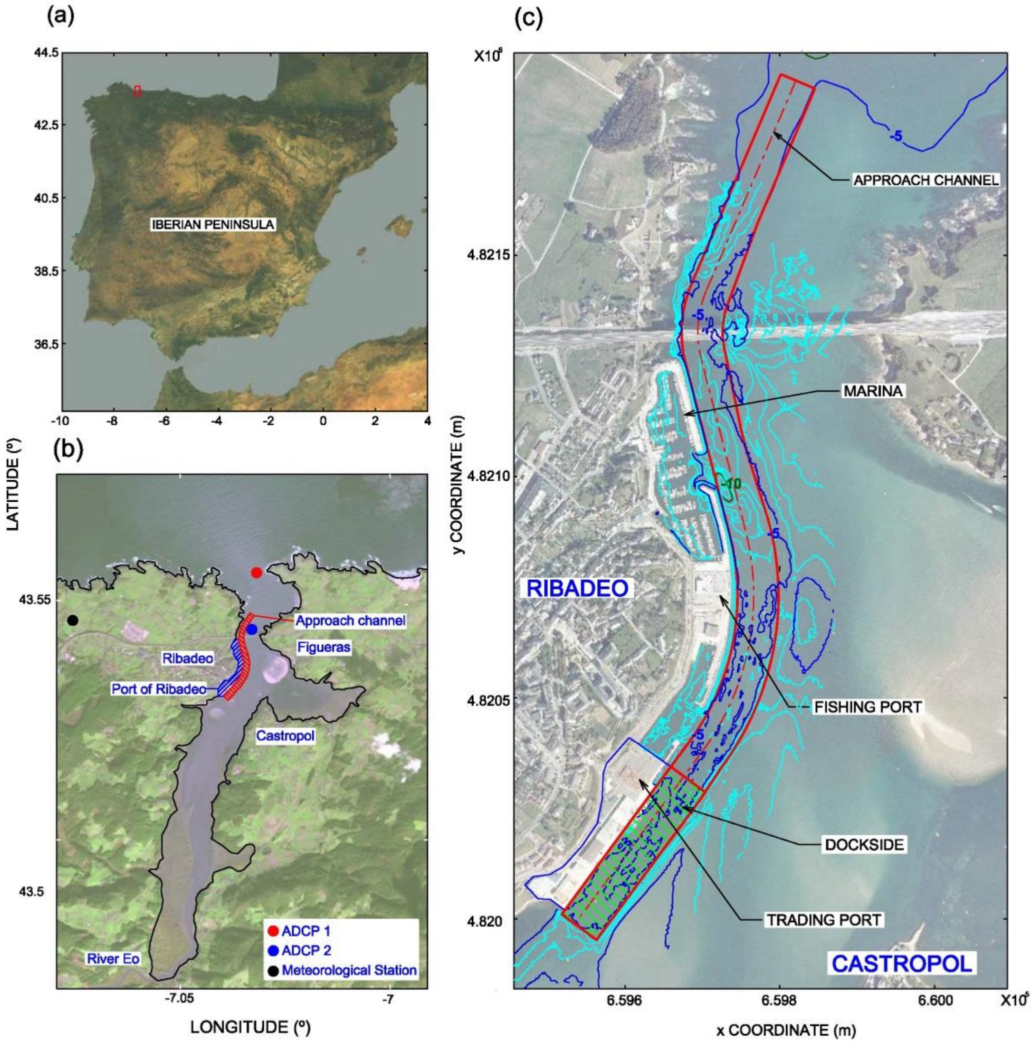

Figure 1. Location of Ría de Ribadeo (b) and Port of Ribadeo (c) in NW Spain (a).

The strong tidal currents in the Ria of Ribadeo (up to 2 ms^{-1}) and the resulting residual circulation patterns (Ramos et al., 2013) cause large amounts of sediments to be transported, steadily infilling the approach channel to the Port of Ribadeo. A reduction in depth in the approach channel means that larger tidal levels are required for ships to access the Port, thereby limiting the operativity of the port and, consequently, threatening the economic activity in the area (García-Morales et al., 2015). For this reason, the port authority undertakes periodic dredging of the approach channel so as to maintain operativity.

The aim of this work is to define a new integrated approach for the analysis of dredging operations in shallow coastal areas, such as estuaries, allowing the definition of an appropriate plan ensuring an adequate operativity at lower maintenance costs. With this aim, firstly, in Section 2, the requirements of the approach channel to the Port of Ribadeo are thoroughly defined. Next, in Section 3, high-resolution numerical simulations based on accurate field measurements are conducted covering a 4-year period. In Section 4, the tidal levels at the Port of Ribadeo computed through numerical modelling are analysed. Then, the results obtained in the aforementioned sections are combined leading to a decision-aid tool for the planning of dredging operations. Finally, in Section 5 the main conclusions of this work are presented.

2. REQUIREMENTS OF THE APPROACH CHANNEL

2.1. Determining factors

A correct definition of the geometry of the approach channel and harbour basin of a port located in a depth-limited area is of great importance for its appropriate functioning. The requirements for these areas are calculated in the present work for the Port of Ribadeo following a comprehensive methodology based on the *Recommendation for Design of Maritime Configuration of Ports, Approach Channels and Harbour Basins* (Puertos del Estado, 1999b; Álvarez, 2013) .

The geometric definition of the navigational channel and harbour basin, both in terms of cross section and layout, should be based on a thorough knowledge of: i) the area occupied by the vessel (Sutulo et al., 2010; Briggs et al., 2015), which depends on the vessel dimensions, ii) the different factors affecting its movements, iii) and the water level. Furthermore, in the study area it is necessary to consider that the orientation of the approach channel is similar to that of the breakwaters and dock of the Commercial Port of Ribadeo (**Figure 1**), and their foundations are at –5.00 m relative to the datum (LAT, lowest astronomical tide); therefore, the maximum dredging depth relative to the datum should not exceed 5 m to avoid undermining the structures. This is indeed the depth at which the approach channel is currently dredged during maintenance operations, and the depth retained for the following analysis.

In the present study the cross section and layout requirements are defined based on the design vessel, i.e. the vessel which best represents the different types of vessels operating in the area of interest. With this aim, a comprehensive study of the shipping at the Port of Ribadeo was conducted. In total, during 2014 a total of 176 vessels operated at this Port, of which 158 were of general cargo, the remaining being composed of nine passenger ships, 4 gearless container vessels, 4 research vessels, 3 fishing trawlers and 1 bulk carrier. After a thorough analysis of the characteristics of the different types of vessels, the design vessel at this Port is defined. Its characteristics are shown in **Table 1**.

[TABLE 1]

Table 1. Characteristics of the design vessel at the Port of Ribadeo

Parameter	**Measure**
Gross Tonnage	2,700 GT
Length	90 m
Length between perpendiculars	85 m
Draught	5.72 m
Deep load draught	5.41 m
Moment of inertia	11,449 kg m^2
Freeboard	1.79 m
Depth	7.2 m

2.2. Cross-section requirements

The cross section of a channel is sometimes designed in a deterministic way, i.e. on the basis of a single parameter (i.e. the draught of design vessel); it is more adequate, however, to take into account a number of factors (Puertos del Estado, 1999a) (**Figure 2**).

[FIGURE 2]

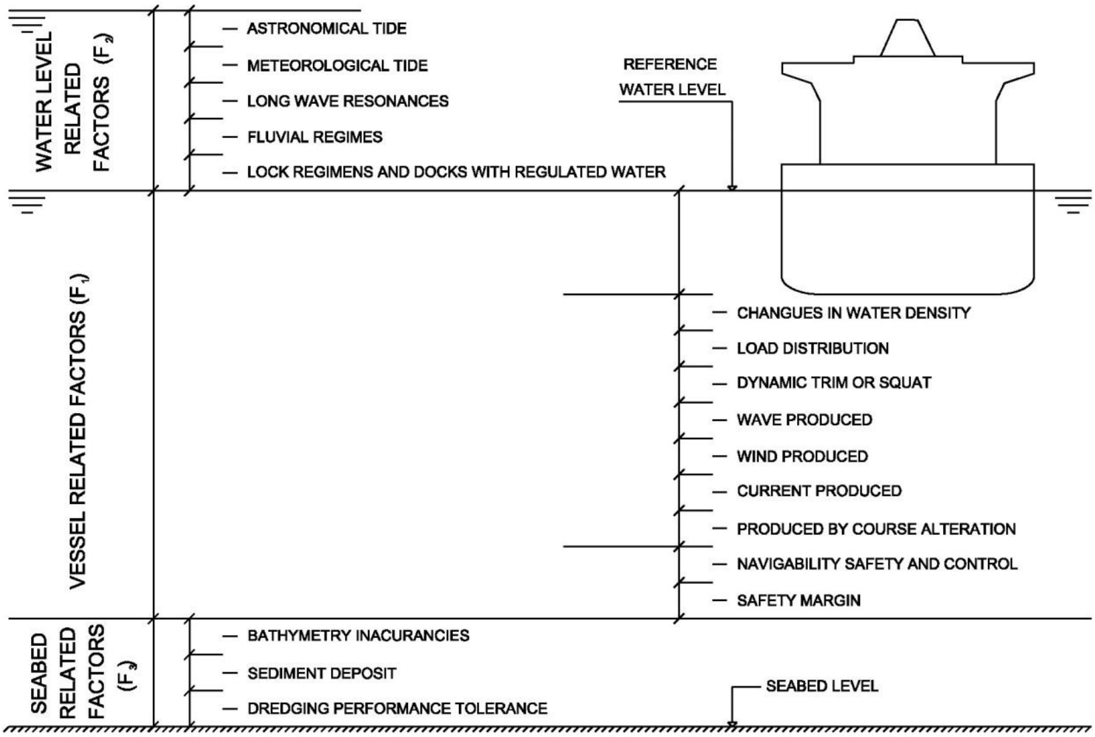

Figure 2. Sketch showing the factors considered in the design of the cross section of the approach channel. [Source ROM 3.1 99 Part VII].

The first set of factors, represented by F_1, integrates all the factors depending on the vessel itself. It represents the lowest level that any point of the vessel can reach in relation to the mean level of the water where it is located. For the definition of F_1, in the present work a thorough study of the sea conditions in the area is conducted (Álvarez, 2013). This information combined with the characteristics of the design vessel allows the computation of F_1. The second set of factors, represented by F_2, provides an analysis of the tides and other variations in the mean water level (astronomical and meteorological tides, variations in river flows, etc…), i.e. a factor determining the reference level of the water where the vessel is located. This is a key factor given that in the case of a vessel with specific depth requirements (larger than 5 m depth in the present application), a certain tidal level is required for them to operate in the area. Finally, F_3 includes the last set of factors depending on the seabed, including bathymetry inaccuracies, sediment deposits and dredging performance tolerances (Álvarez, 2013). The values of the different factors considered in the present work are summarised in **Table 2**.

[TABLE 2]

Table 2. Parameters for prevention of grounding in the channel

PARAMETERS		VALUE (m)
Vessel related factors (F_1)	Static draught	5.41
	Additional draught due to changes in water density	0.16
	Additional draught due to cargo distribution	0.20
	Dynamic trim or squat	0.62
	Motions caused by waves	0.10
	Heeling caused by wind	0.08
	Clearance for safety control of the vessel´s maneuverability	0.5
	Total (F_1)	**7.07**
Water level related factor (F_2)	Astronomical tide	Variable
	Total (F_2)	**F_1+F_3-channel depth**
Seabed related factors (F_3)	Margin for bathymetry inaccuracies	0.07
	Deposit of sediments	Variable (0 after dredging)
	Dredging performance tolerance	0.37
	Total (F_3)	**0.37**

The required water depth will be the result of considering both the vessel and seabed related factors, F_1 and F_3, respectively. Therefore, a total of 7.44 m is required for the design vessel to access or leave the Port of Ribadeo. Given that the water depth of the approach channel for operation purposes at LAT is set to 5 m, the required tidal level or F_2 is 2.44 m.

2.3. Layout requirements

The layout of the channel has to be adapted to the local morphological aspects, as well as to technical, economic and environmental constraints. In the case of the Port of Ribadeo, the approach channel has a total length of 2,262 m in three straight and two curved stretches. The two curved stretches have a radius, r, of 260.5 m and 639 m, respectively. For technical and safety reasons the approach channel to this port consists of a single lane fairway whose requirements are calculated in the present study for the design vessel.

As a result of the implementation of the aforementioned methodology the overall width of the fairway is set to 90 m and 100 m in straight sections and curves, respectively. Finally, due to the presence of moorings lines in the dockside, the straight section in this area is increased 15 m (Álvarez, 2013). The cross section and layout requirements thus obtained are shown in **Figure 3** and the resulting plan view of the area occupied by the approach channel in **Figure 4**.

[FIGURE 3]

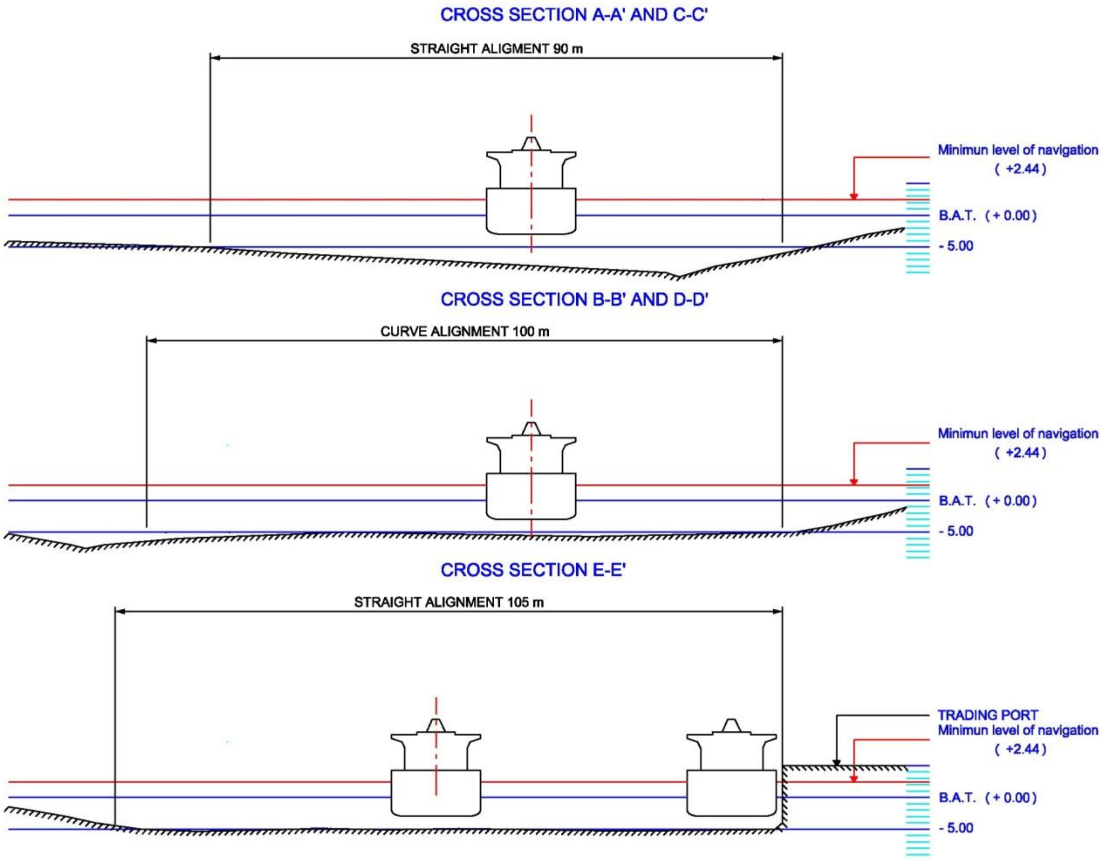

Figure 3. Cross section and layout requirements of the approach channel to the Port of Ribadeo.

[FIGURE 4]

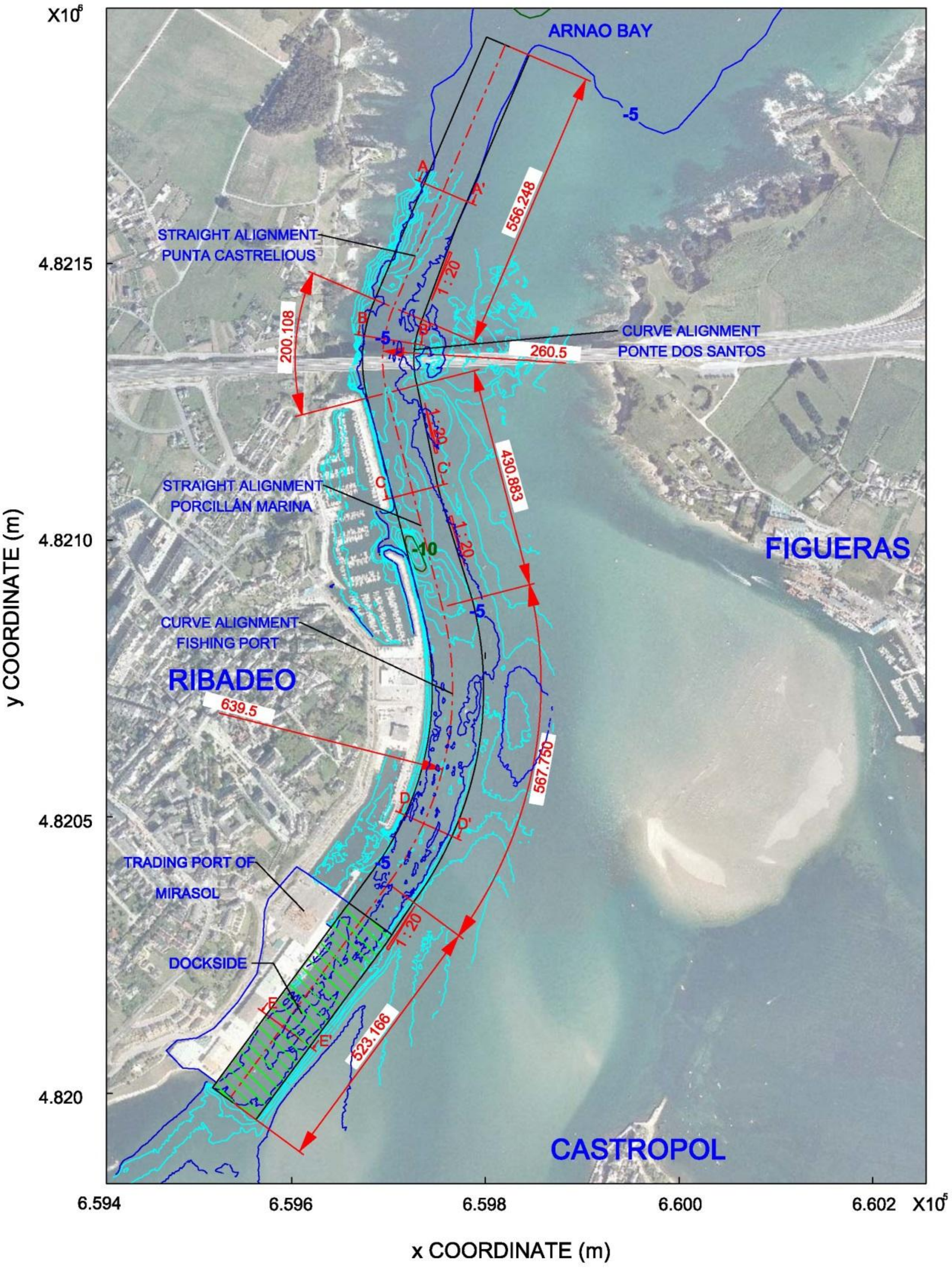

Figure 4. Plan view representation of the area occupied by the approach channel.

3. NUMERICAL MODEL

3.1. Model equations

The next step consists in studying the evolution of the bottom of the approach channel defined in Section 2 through a 4-year period, accounting for the complex morphodynamics of this ria. With this aim a finite-difference Navier-Stokes 3D solver, Delft3D, is implemented on the ria, which has been successfully used in other Galician Rias [e.g. (Carballo et al., 2009a; Iglesias and Carballo, 2009; Prumm and Iglesias, 2016; Sanchez et al., 2014; Iglesias et al., 2008; Carballo et al., 2009b; Sánchez et al., 2013)]. Delft3D-FLOW is a hydrodynamic and transport model which solves the Navier–Stokes equations for an incompressible fluid under the shallow water and Boussinesq assumptions. The model equations read:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=Q\,, \tag{1}$$

$$\left.\begin{aligned}\frac{Du}{Dt}&=fv-g\frac{\partial \zeta}{\partial x}-\frac{g}{\rho_0}\int_{z'=z}^{z'=\varsigma}\frac{\partial \rho}{\partial x}dz'+\upsilon_h\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)+\upsilon_v\left(\frac{\partial^2 u}{\partial z^2}\right)\\ \frac{Dv}{Dt}&=-fu-g\frac{\partial \zeta}{\partial y}-\frac{g}{\rho_0}\int_{z'=z}^{z'=\varsigma}\frac{\partial \rho}{\partial y}dz'+\upsilon_h\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)+\upsilon_v\left(\frac{\partial^2 v}{\partial z^2}\right)\end{aligned}\right\},\tag{2}$$

$$\frac{\partial p}{\partial z}=-\rho g\,, \tag{3}$$

$$\frac{Dc}{Dt}=D_h\left(\frac{\partial^2 c}{\partial x^2}+\frac{\partial^2 c}{\partial y^2}\right)+D_v\frac{\partial^2 c}{\partial z^2}-\lambda_d c+R\,. \tag{4}$$

where u, v and w represent the components of the velocity in the directions x, y and z, respectively; Q represents the sources of mass per unit area; f is the Coriolis parameter; g is the gravitational acceleration; ζ is the free surface elevation relative to z = 0; υ_h and

υ_v stand for the horizontal and vertical kinematic eddy viscosity coefficients, respectively; ρ and ρ_0 are the water density and the reference density of sea water, respectively; c represents the mass concentration of any constituent (e.g. salinity and temperature); D_h and D_v stand for the horizontal and vertical eddy diffusivity coefficients, respectively; λ_d represents the first order decay process; finally, R is the source term per unit area.

In addition, the model computes sediment transport and morphological updating by simulating both bed-load and suspended load transport. In the case of suspended load, the advection-diffusion equation (mass balance) is solved, which reads:

$$\begin{aligned}&\frac{\partial c^{(l)}}{\partial t}+\frac{\partial uc^{(l)}}{\partial x}+\frac{\partial vc^{(l)}}{\partial y}+\frac{\partial (w-w_s^{(l)})c^{(l)}}{\partial z}\\&-\frac{\partial}{\partial x}\left(\epsilon_{s,x}{}^{(l)}\frac{\partial_c{}^{(l)}}{\partial x}\right)-\frac{\partial}{\partial y}\left(\epsilon_{s,y}{}^{(l)}\frac{\partial_c{}^{(l)}}{\partial y}\right)-\frac{\partial}{\partial z}\left(\epsilon_{s,z}{}^{(l)}\frac{\partial_c{}^{(l)}}{\partial z}\right)=0\end{aligned} \qquad (5)$$

where $c^{(l)}$ is the mass concentration of the sediment fraction (l);; $\epsilon_{s,x}{}^{(l)}$, $\epsilon_{s,y}{}^{(l)}$, $\epsilon_{s,z}{}^{(l)}$ stands for eddy diffusivities of the sediment fraction (l); finally, $w_s{}^{(l)}$ is the sediment settling velocity of the sediment fraction (l). The local flow velocities and eddy diffusivities are computed by the hydrodynamic model. The sediment transport is computed in the same way as the transport of any other constituent (e.g. salinity or temperature); nevertheless, there exist a number of important differences between sediments and other constituents —exchange of sediment between the bed and the flow, or parameters such as the settling velocity, whose appropriate computation is of major importance for obtaining accurate results (Deltares, 2011).

The effect of sediments on fluid density is considered by using the empirical relationship formulated by UNESCO (Unesco, 1981) which accounts for the varying temperature and salinity. In the case of the sediment transport, this relationship is extended in order to consider the density effect of sediment fractions in the fluid mixture. For this purpose the mass of the different sediment fractions is added and the displaced water mass subtracted. This can be expressed as:

$$\rho_{mix}\left(S,c^{(l)}\right)=\rho_w\left(S\right)+\sum_{l=1}^{lsed}c^{(l)}\left(1-\frac{\rho_w\,(S)}{\rho_s^{(l)}}\right) \tag{6}$$

where $\rho_w\ (S)$ is the specific water density with salinity concentration S; $\rho_s{}^{(l)}$ is the specific density of the sediment fraction (l); finally $lsed$ is the number of sediment fractions.

The settling velocity for non-cohesive and cohesive sediment fractions is computed with different formulations. In the case of non-cohesive sediments the Van Rijn method is implemented (Van Rijn, 1993), which depends on the diameter of the sediment in suspension:

$$w_{s,0}{}^{(l)}=\begin{cases}\dfrac{\left(s^{(l)}-1\right)gD_s{}^{(l)2}}{18\nu}, & 65\ \mu m< D_s\leq 100\ \mu m\\[2ex] \dfrac{10\nu}{D_s}\left(\sqrt{1+\dfrac{0.01\left(s^{(l)}-1\right)gD_s{}^{(l)3}}{\nu^2}}-1\right), & 100\ \mu m< D_s\leq 1000\ \mu m\\[2ex] 1.1\sqrt{\left(s^{(l)}-1\right)gD_s{}^{(l)}}, & 1000\ \mu m< D_s\end{cases} \tag{7}$$

where $s^{(l)}$ is the relative density of sediment fraction (l) ($s^{(l)}=\frac{\rho_s{}^{(l)}}{\rho_w}$), $D_s{}^{(l)}$ accounts for the representative diameter of the sediment fraction (l), and ν stands for the kinematic viscosity coefficient of water.

With respect to the cohesive sediment fraction, a complex formulation is used which includes the computation of two settling velocities, for fresh water and salt water. For full details about the methodology for modelling this and other processes related to the cohesive sediment fraction, such as dispersion, erosion or deposition, the reader is referred to Delft Flow Manual (Deltares, 2011).

3.2. Model implementation

In the present study, and following previous works on the hydrodynamics of this ria (Ramos et al., 2013), the hydrodynamic and sediment transport model is implemented in its 2D form with a high spatial resolution (Periáñez et al., 2013). Given that the aim of this research is to conduct an accurate assessment of the morphological evolution of the approach channel over a 4-year period, the numerical grid (**Figure 5**) covers not only the area of interest (the middle ria) but the entire estuary (including the inner and outer ria), whose morphodynamics may affect the bedload sediment transport in the channel. The resolution within the ria is set to 40 m, with the size of the cells increasing progressively towards the sea boundary, which is located sufficiently distant that numerical disturbances do not affect the area of interest.

[FIGURE 5]

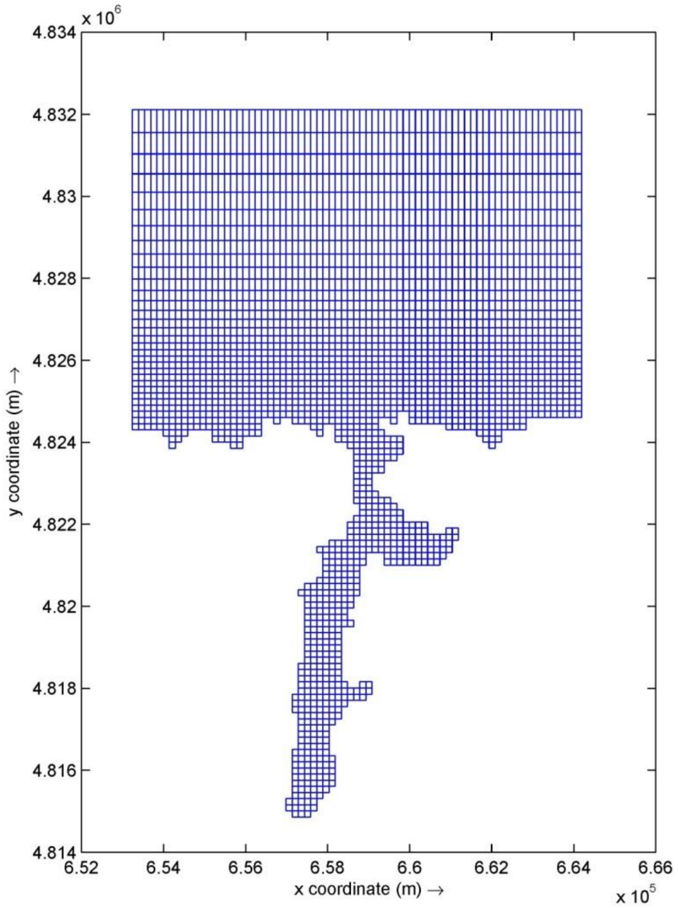

Figure 5. Numerical grid used for hydro-morphodynamic computations. For clarity only 1 in 4 grid lines are plotted.

The bathymetric data of the ria and the adjoining continental shelf (**Figure 6**) are obtained from the relevant nautical charts, which are digitised and interpolated onto the computational grid. In addition, the most recent bathymetric data from previous dredging operations in the approach channel were also included in the numerical grid. Finally, the intertidal areas are modelled by considering topographic data with 5 m of resolution. Given that this ria presents large shallow areas, a spatially varying value of the Manning coefficient, *n*, is input to the model, defined as a function of the water depth (**Table 3**) (e.g. Cheng et al., 1993; Dias and Lopes, 2006).

[FIGURE 6]

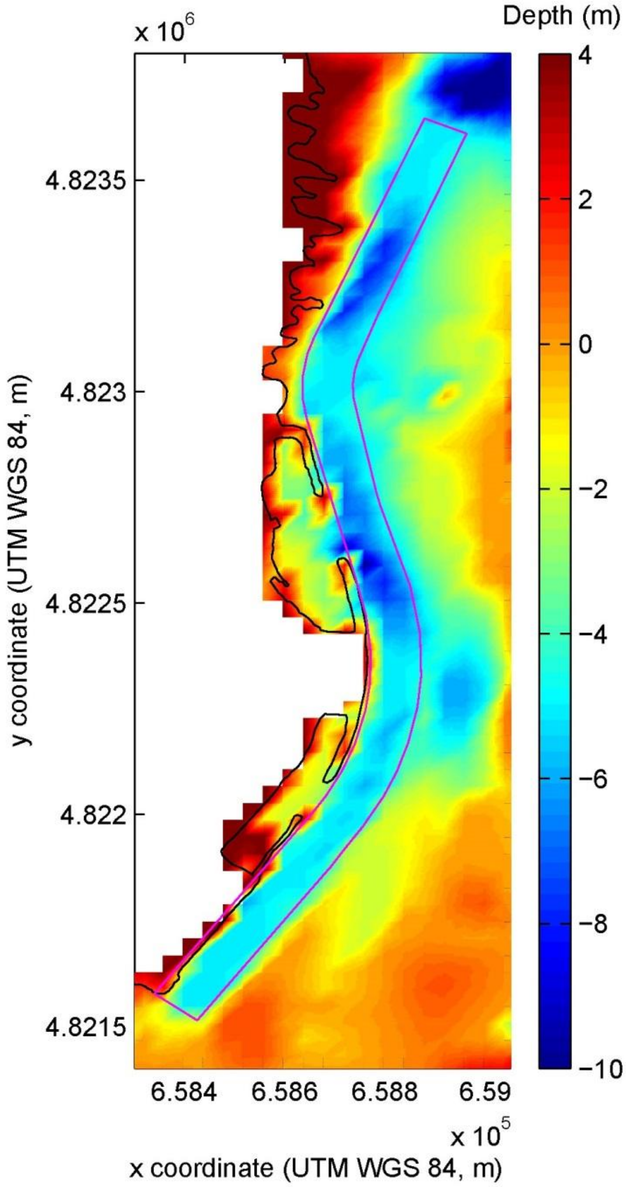

Figure 6. Bathymetry of the area of study.

[TABLE 3]

Table 3. Manning value, *n*, as function of water depth, *d*

d **(m)**	***n***
$d < -2.0$	0.042
$-2.0 \leq d < -1.5$	0.038
$-1.5 \leq d < -1.0$	0.034
$-1.0 \leq d < -0.5$	0.030
$-0.5 \leq d < 0.0$	0.027
$0.0 \leq d < 0.5$	0.024
$0.5 \leq d < 1.0$	0.022
$1.0 \leq d < 3.0$	0.020
$3.0 \leq d < 10.0$	0.018
$d > 10$	0.015

The turbulent eddy viscosity, υ, and diffusivity, D, are calibration parameters. For the calibration, field data of water levels and currents measured by an Acoustic Doppler Profiler (ADCP) (location ADCP 2, **Figure 1**) during three weeks (from 16th of October 2011 to 4th of November 2011) are compared with model data obtained with different values of υ and D. The values of the correlation coefficient, R, for the horizontal velocities, u and v and water levels, η, are presented in **Table 4**. On the basis of these results, the turbulent eddy viscosity and diffusivity are set to 5 m^2s^{-1}. Then, the performance of the model using these values is checked at an additional location (ADCP 1) for the same period (**Table 5**). The good agreement obtained between simulated and observed values shows that the model is capable of appropriately capturing the ria hydrodynamics.

[TABLE 4]

Table 4. Correlation coefficient, R, between simulated and observed data for different eddy viscosities and diffusivities at location ADCP 2.

	Velocities correlation		**Sea level correlation**
$\boldsymbol{\upsilon, D}\ (\boldsymbol{m^2 s^{-1}})$	$\boldsymbol{R_U}$	$\boldsymbol{R_V}$	$\boldsymbol{R_\eta}$
1	0.8200	0.8912	0.9920
5	0.9449	0.9710	0.9938
15	0.9345	0.9294	0.9920
30	0.9256	0.9277	0.9920
50	0.9024	0.9177	0.9921
100	0.8607	0.8933	0.9920

[TABLE 5]

Table 5. Correlation coefficient, *R*, between simulated and observed data for turbulent eddy viscosity and diffusivity set to 5 m^2s^{-1} at locations ADCP 1 and 2.

	$\boldsymbol{R_U}$	$\boldsymbol{R_V}$	$\boldsymbol{R_\eta}$
ADCP 1	0.9451	0.9556	0.9919
ADCP 2	0.9449	0.9710	0.9938

3.3. Case study

With the aim of analysing the evolution of the bathymetry of the approach channel resulting from the complex morphodynamics of Ria de Ribadeo, the model is run for a total of 4 years, from 2012 to 2016. The initial date for the simulations corresponds to the date when the last dredging was conducted and therefore accurate depth data of the approach channel are available (which in turn is the initial depth considered for numerical modelling).

All the relevant hydrodynamic and morphodynamic forcing factors are considered in the simulation: tide, river discharges, and salinity and temperature at open boundaries, as well as the spatial distribution of the sediments. The tide is introduced by considering the values of the seven major tidal constituents provided by TPXO data (Egbert et al., 1994) (**Table 6**); river discharges are set to the mean historic discharge (April 2009 to December 2012) (18,83m^3s^{-1}); finally, the salinity and temperature at the open boundaries are computed through ROMS (Regional Ocean Modelling System) (Otero et al., 2008). Regarding the mophological data, the principal model forcing parameters considered are shown in **Table 7** (Hu et al., 2009).

[TABLE 6]

Table 6. Tidal constituents at the ocean boundary of the numerical grid.

Constituent	**Amplitude (cm)**	**Phase (°)**
M_2	125.13	91.40
S_2	43.96	112.17
N_2	26.47	71.45
K_2	12.27	120.23
K_1	7.14	73.27
O_1	6.23	324.20
P_1	2.16	64.82

[TABLE 7]

Table 7. Principal morphological parameters used in the implementation of the numerical model.

Parameter	Value
Specific density (Kg/m^3)	2650
Dry bed density (Kg/m^3)	1600
Initial sediment layer at bed (m)	5
Median sediment diameter (D_{50})	Spatial distribution

With respect to the grain size, the ria has a complex distribution that must be characterised if the evolution of the approach channel is to be appropriately modelled (Flor et al., 1983; Encinar and Rodríguez, 1983; Flor et al., 1992). The spatial distribution of the mean grain size diameter, D_{50}, is input to the model following previous studies, and in particular using measured data (**Figure 7**) provided by the Port Authority from the latest dredging operations. As a result, the configuration of the seabed in the channel and the sediment input to the model (**Figure 8**) correspond exactly with the initial data of the numerical simulation —a prerequisite for ensuring the accuracy of the model results.

[FIGURE 7]

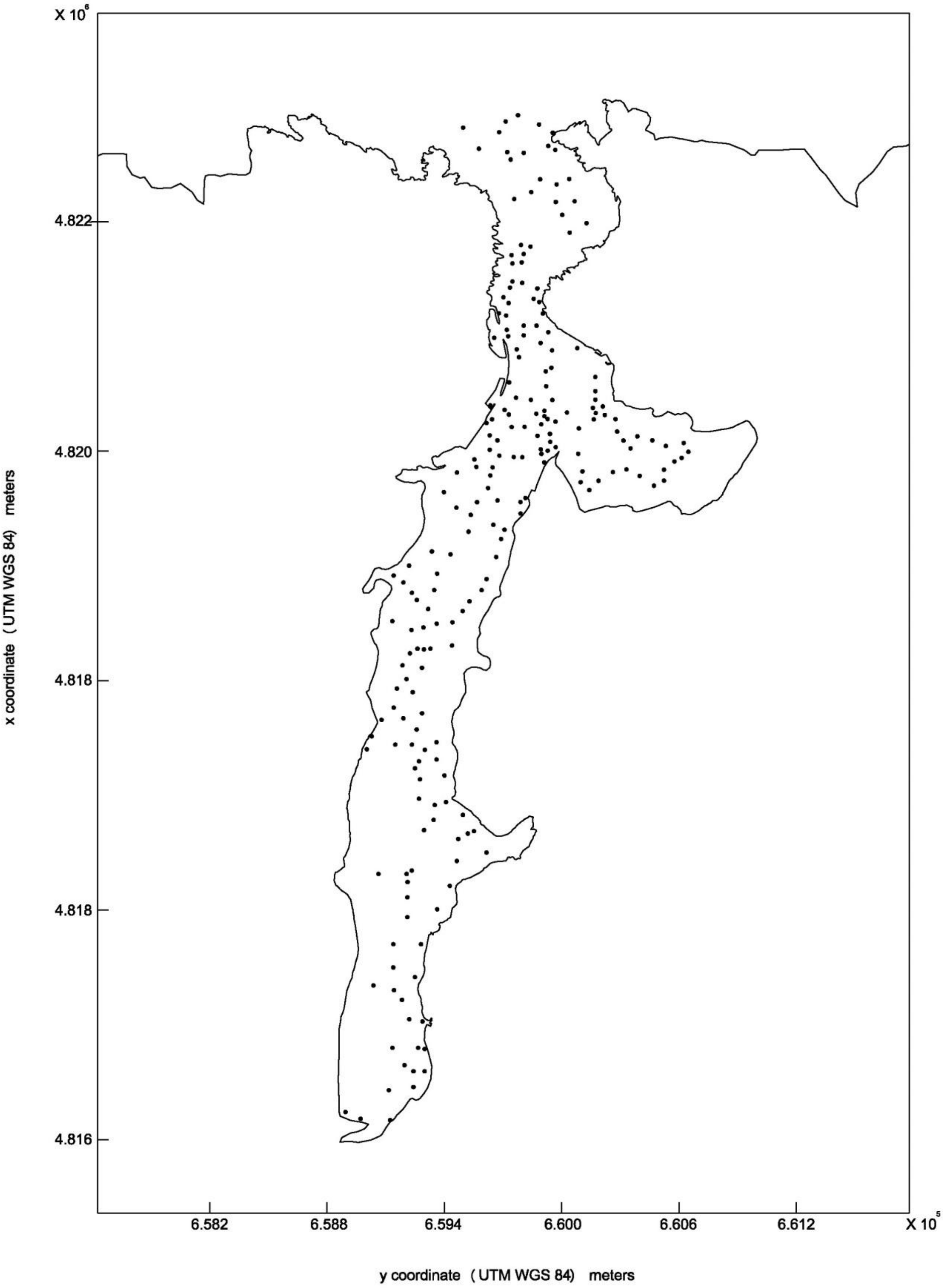

Figure 7. D_{50} sampling stations.

[FIGURE 8]

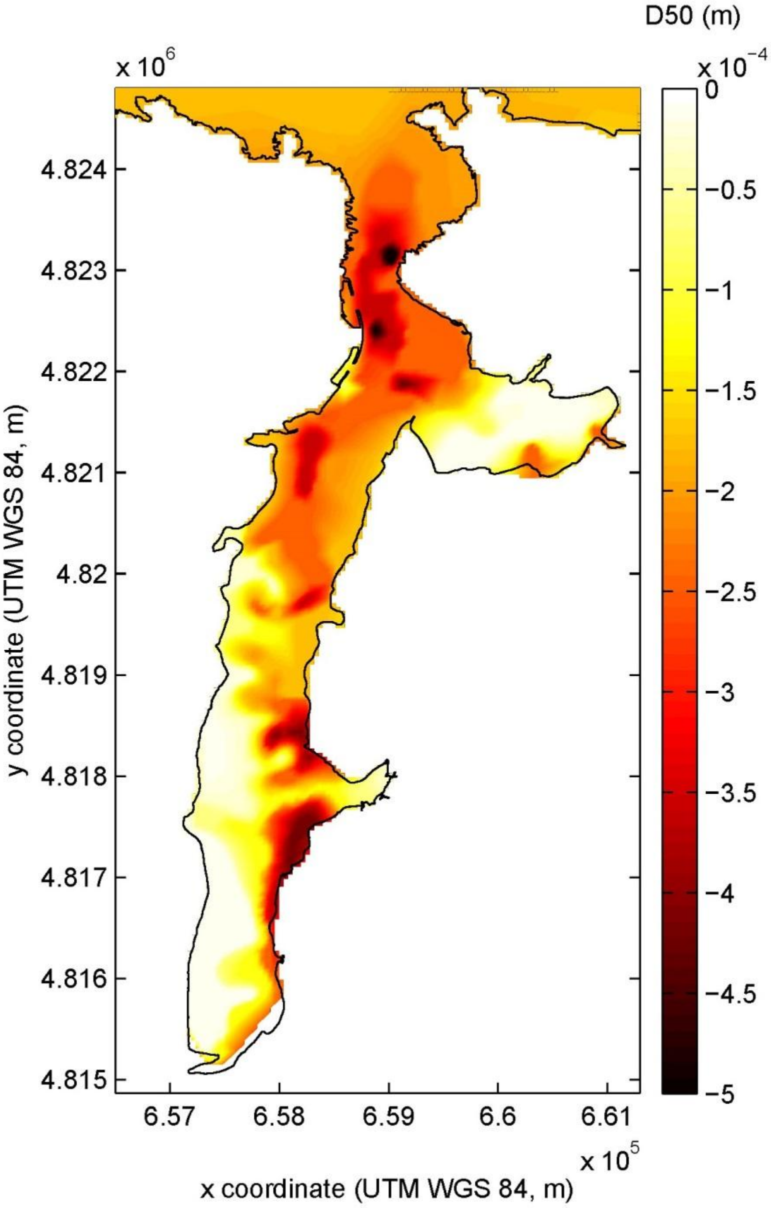

Figure 8. Spatial distribution of the mean grain size diameter, D_{50}.

The model capability for predicting the evolution of the approach channel is analysed. For this purpose, the seabed position computed by the model at the end of 4-year period is compared with high-resolution in situ measurements in the area occupied by the approach channel and surroundings gathered at the end of model simulations (year 2016) (**Figure 9**). The correlation coefficient, R, between the bathymetry configuration predicted by the model (left) and measured (right) is 0.71.

[FIGURE 9]

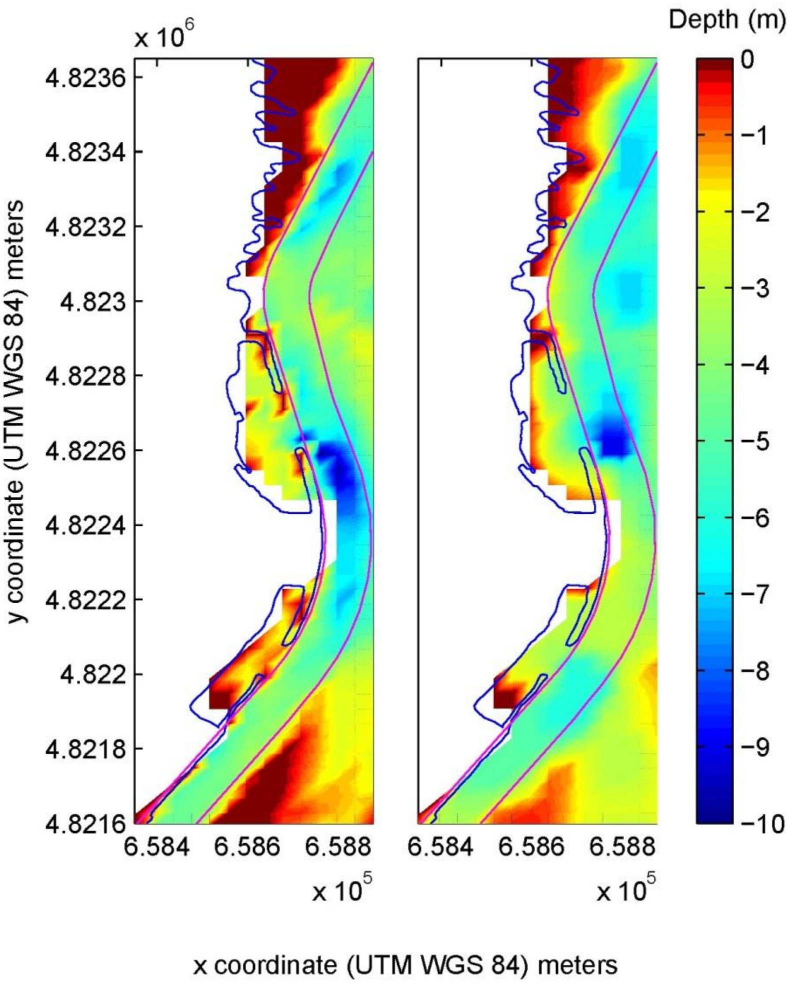

Figure 9. Bathymetry configuration computed by the model (left) and measured (right) at the end of model simulations.

The results obtained prove the ability of the model for accurately reproducing the bathymetric trends in the approach channel, not least considering the complexity of the problem.

4. HYDROMORPHOLOGICAL RESULTS

The hydrodynamic results obtained through numerical modelling clearly show the strong currents that occur in the ria, and in particular within the approach channel, which in part explain the need for frequent dredging discussed in the Introduction. In **Figure 10** the flow velocities in the middle and outer Ria the Ribadeo are plotted during mid-flood and mid-ebb of a spring tide (10 March 2012). It can be observed that strong current velocities occur both during ebb and flood throughout the ria, and in particular within the approach channel, where velocity magnitudes exceed 1 ms^{-1} over large areas, reaching 1.5 ms^{-1} at specific locations. In addition, a tidal asymmetry can be observed, with larger velocities during flooding. This asymmetry, which has been observed in other Galician rias (Iglesias and Carballo, 2011; Iglesias and Carballo, 2010), which may contribute to sediment entrapment in the inner ria and, ultimately, to bedforms such as megaripples and sand banks.

[FIGURE 10]

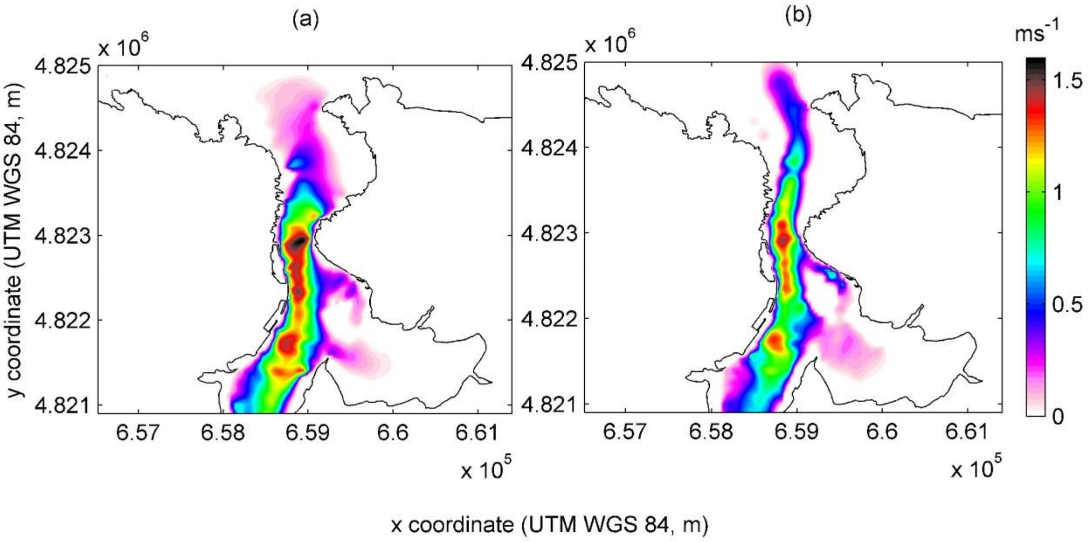

Figure 10. Mid-flood (a) and mid-ebb (b) depth-averaged flow velocities in the Ría of Ribadeo.

These strong currents, as stated, generate an important transport of sediments resulting in a significant variation of the bed configuration on this coastal area. In **Figure 11** the evolution of the bed level over a 4-year period is shown. Overall, a relationship can be observed between current velocities and sediment transport, with accretion associated with the areas of weaker current velocities and erosion with those boasting stronger velocities.

[FIGURE 11]

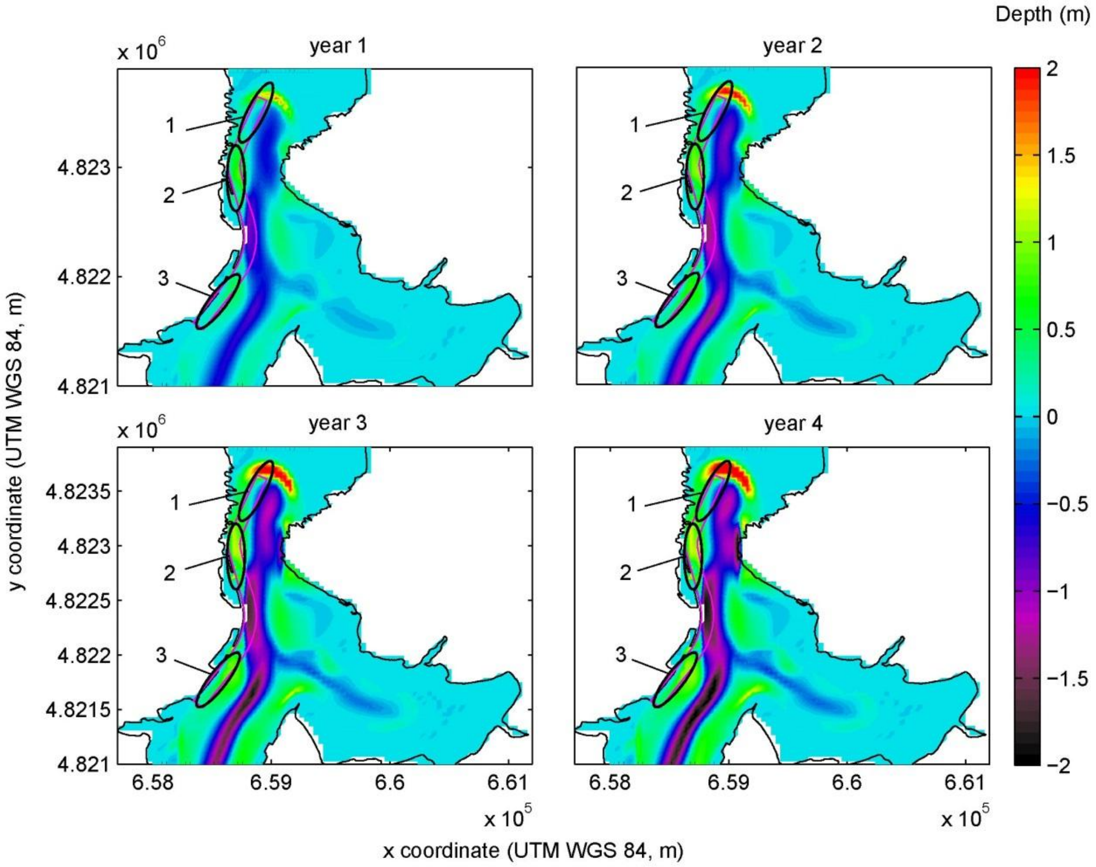

Figure 11. Bed update of the Ría de Ribadeo over a 4-year period (the approach channel is represented with a red line). Positive and negative values indicate an increase and reduction of the bed level, respectively.

In the case of the approach channel to the Port of Ribadeo defined in Section 2, three important accretion areas can be identified: (1) the outer approach channel, with accretion of up to 2 m at the end of the 4-year period analysed, (2) the area in front of the marina, with an increase in the seabed level of about of 1.5 m, and (3) finally, a large area at the end of the channel (dockside), with less than 1 m. Yet, their importance for the functioning of the port widely differs stemming from their total depth at the end of the 4-year period analysed, with more than 5 m in the case of the first area (1) and less than 4-5 m in the second and third areas (2, 3) (**Figure 12**).Within the rest of the channel (roughly the middle sections, corresponding to the area in front of the fishing port), significant erosion occurs which naturally does not pose a threat for the appropriate functioning of the port from a navigational standpoint. Still, this erosion can lead to scour problems at the breakwater, which was projected for a water depth of 5 m (LAT) and should be further analysed.

[FIGURE 12]

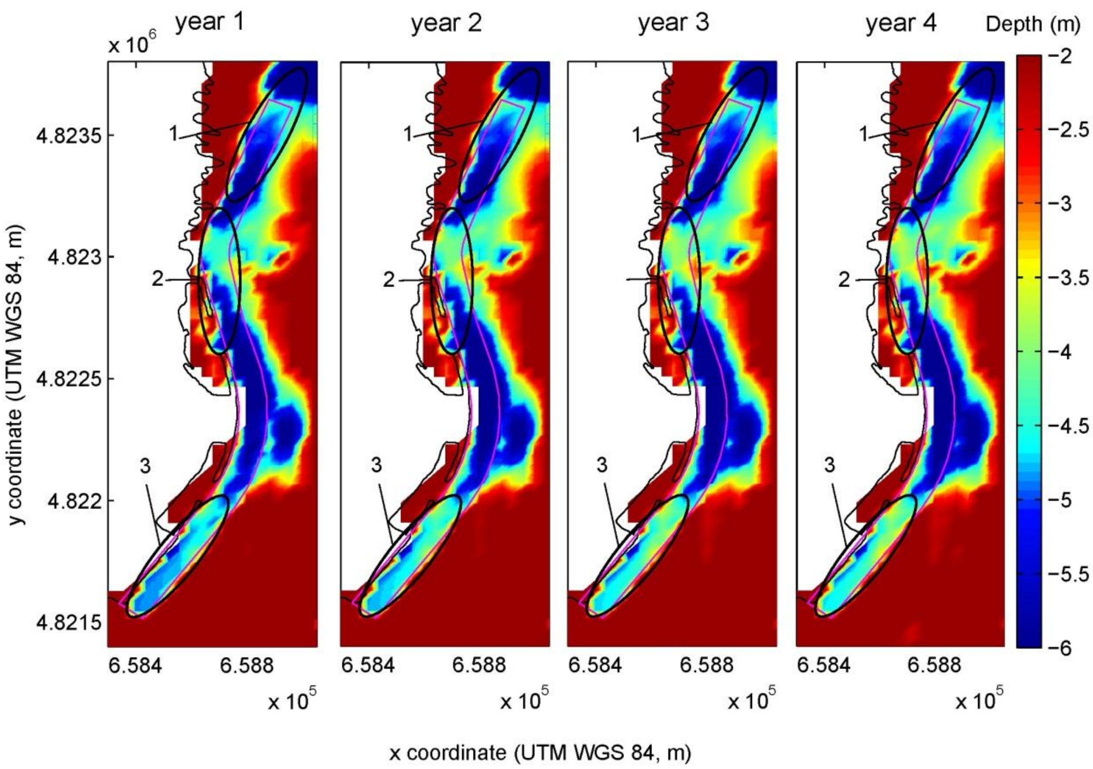

Figure 12. Evolution of the depth within the approach channel to the Port of Ribadeo over the a 4-year period.

5. OPERATIVITY AND DREDGING: AN INTEGRATED APPROACH

It has been shown that a total of 7.44 m is necessary for the design vessel to operate at the Port of Ribadeo. Therefore, given that the water depth within the approach channel cannot exceed 5 m (LAT) for constructive reasons, the required astronomical tidal level is 2.44 m (Section 2). On this basis, the operativity can be computed, i.e. the period of time during which there is the adequate level for port operation (2.44 m). For this purpose, the tidal levels at the Port of Ribadeo are computed in this work by means of numerical modelling throughout a complete year, and on that basis their monthly discrete frequency, *f*, and cumulative frequency, *F*, obtained. In **Figure 13** the discrete and cumulative frequencies are shown in terms of annual figures for clarity purposes.

[FIGURE 13]

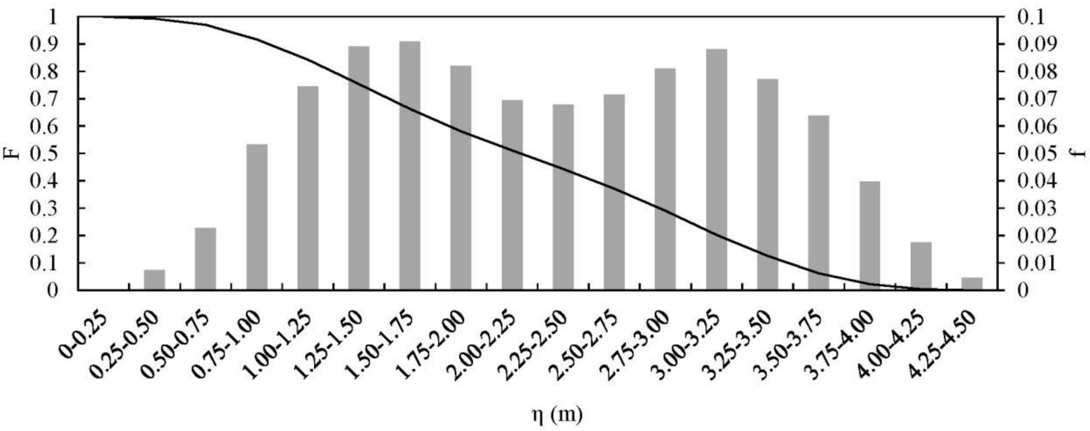

Figure 13. Annual discrete, *f*, and cummulative frequencies, *F*, of tidal level at the Port of Ribadeo computed through numerical modelling.

From the cumulative frequency of tidal levels, an annual figure of operativity of 4,025 h/year is obtained (operativity after dredging), i.e. the time during which the tidal level exceeds 2.44 m. In addition, based on the results of the monthly cumulative frequencies, the monthly operativity can be also computed. The corresponding results are shown in **Table 8**. It emerges that the operativity is virtually constant throughout the year resulting from the almost negligible intra-annual differences in the water level distribution, thereby the dredging planning in the Port of Ribadeo can be determined on the basis of annual figures of operativity.

[TABLE 8]

Table 8. Average monthly operativity (hours) of the Port of Ribadeo

Month	**Total hours**	**Operativity hours**
January	744	341.5
February	672	309.5
March	744	342
April	720	331.5
May	744	341.5
June	720	329
July	744	343
August	744	340.5
September	720	331
October	744	342.5
November	720	330.5
December	744	342

On the other hand, it has been shown (Section 4) that after dredging there are areas within the approach channel where the depth is progressively reduced resulting from sediment transport, which in turn provokes a reduction of the operativity of the port. For technical and economic reasons, the operativity should never be less than 1,750 h/year, which corresponds to 20% of the time (Álvarez, 2013). On these grounds, the depth reduction allowing the minimum operativity level for a design vessel (requiring at least 7.44 m depth) is determined in this work. In the case of considering annual figures —operativity is virtually constant throughout the year (**Table 8**)— the tidal level available for the design vessel at the operativity limit (1750 h/year) is 3.29 m (**Figure 13**), which corresponds with the required level for its operation. In addition, given that the design vessel requires a total of 7.44 m, the operativity limit occurs when the depth within the approach channel is reduced to 4.15 m (7.44-3.29 m). This means that the reduction of water depth resulting from sediment accretion should not exceed 0.85 m in the considered most restrictive locations —those originally set to 5 m depth after dredging.

Now, the 4-year hydro-morphodynamic high-resolution simulations are used so as to establish both the time point and location within the channel where this depth limitation (4.15 m) will firstly appear. From the numerical results, this limitation is determined to occur in first place in the area close to the marina (2) (**Figure 12**) in approximately 3.5 years after dredging. Furthermore, the numerical model results yields the high resolution bathymetry configuration of the seabed channel at the end of this period; therefore, the amount of sediments to be dredged so as to rise the operativity to a certain level can be accurately computed. In the present study if a new dredging is to be planned at the time point when the operativity limit is reached, a total of 145,760 m^3 should be dredged for restoring the initial level of operativity established at 4,025 h/year.

Given the complexity of the method developed, a flowchart containing the whole procedure presented in this work and implemented in the Ria de Ribadeo is shown in **Figure 14**.

[FIGURE 14]

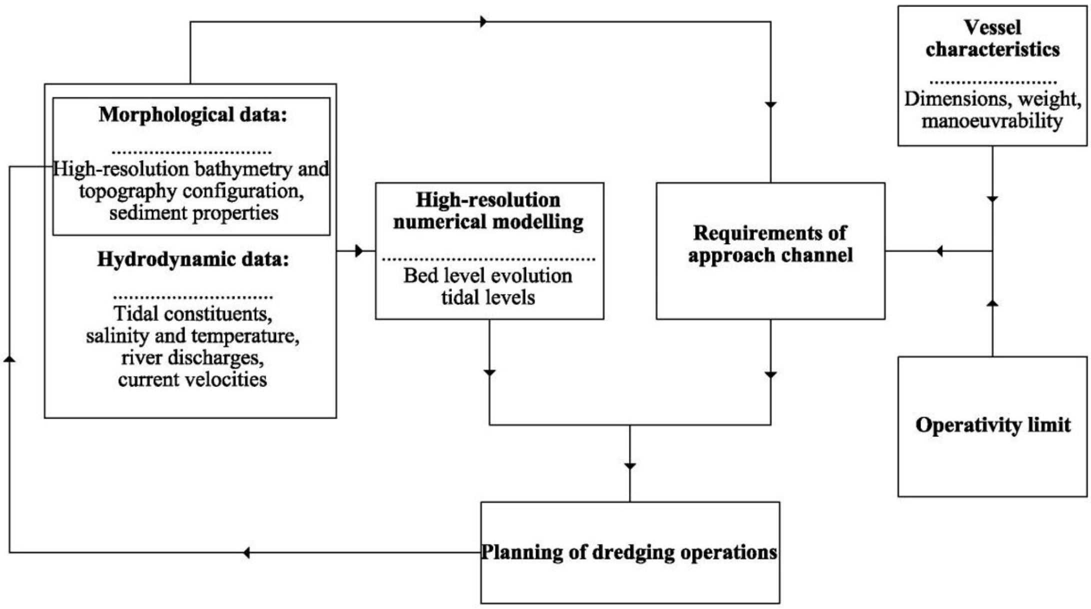

Figure 14. Flowchart of the decision-aid tool.

6. CONCLUSIONS

The Port of Ribadeo is the largest by trade volume of the ports managed by Ports of Galicia Regional Authority. Owing to great importance for the region, a well-defined plan for maintaining adequate levels of operativity is fundamental for it to continue being a mainstay of the economic activity of the area. The complex morphodynamics of the ria, characterised by intense sediment transport, has been shown to affect the approach channel, posing a threat to the operativity of the port. With this in view, in the present work an integrated approach for defining accurate dredging operation plans was developed and implemented to this coastal area. Based on a state-of-the-art numerical model, calibrated and validated with field measurements, together with accurate data of navigational requirements and tidal levels in the area, the implementation of this method provides the necessary information for conducting cost-effective dredging operations.

For this purpose, in the first place the dimensions of the approach channel to the Port of Ribadeo are accurately defined on the basis of a thorough analysis of the vessels operating in the area —a total width ranging from 90 m to 105 m depending on the section considered, and a minimum water depth of 7.44 m. Given that the maximum depth of the approach channel could not exceed 5 m at some locations (roughly the area close to the trading port) so as to avoid undermining problems, a tidal level of 2.44 is necessary for the design vessel to operate in the area. Then, high resolution hydro-morphodynamic computations are conducted with the aim of characterizing the time evolution of the bed configuration of the approach channel during a 4-year period (starting at the last dredging operation). The numerical results clearly show three areas of significant accretion (approx. 1-2 m at the end of the 4-year period analysed) but only two of them are critical for the appropriate functioning of the Port —roughly the areas located in front of the marina and the dockside.

The next step of the procedure consists in analysing the tidal level distribution so as to define the required level for maintaining the minimum operativity, which is established at 1,750 h/year. This analysis is conducted by determining the monthly and annual frequencies of the tidal levels at the Port of Ribadeo which are computed in the present work through numerical modelling. From the results obtained it emerges that a tidal level of 3.29 m is required for achieving the operativity limit, i.e. the water depth within the approach channel should not be less than 4.15 m.

Finally, the integration of the resulting information allows the determination of the time point for conducting cost-effective dredging operations. It is found that the minimum water depth (4.15 m) is firstly achieved in the area close to the marina, approximately 3.5 years after the previous dredging. Furthermore, the present procedure also provides a detailed bathymetric configuration of the channel and therefore the accurate computation of the volume to be dredged for increasing the operativity up to a certain level. In the case of the Port of Ribadeo, should the initial level of operativity is to be restored (4,025 h/year corresponding to the period during which at least a tidal level of 2.44 m is available), a total of 145,760 m^3 would have to be dredged.

In sum, the proposed integrated approach herein presented can contribute to an appropriate decision making for the planning of dredging operations in shallow water areas such as estuaries. The procedure was illustrated through the case study of the Port of Ribadeo, but it could be implemented elsewhere.

Acknowledgments

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