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A New Management Tool to Monitor Salinity Intrusion in the Guadiana Estuary Under Average and Extreme River Discharge Conditions

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Abstract. At the Guadiana Estuary (southern Iberia), strong river flow regulation and the intensification of droughts pose a significant threat to the freshwater resource due to enhanced saltwater intrusion. To accurately predict the salinity dynamics under various river discharge conditions (i.e., average and extreme), a 3-dimensional idealized model (Delft3D) has been developed, calibrated and validated. The overall performances of the model make it a powerful and versatile tool to design and evaluate mitigation management strategies to control salt intrusion during prolonged periods of low river flow. This paper provides a detailed description of the numerical framework and the validation process, together with examples of the future model applications.

Keywords: Salinity · Idealized Modelling · Freshwater Management · Estuary

1 Introduction

Estuaries are amongst the most valuable ecosystems in the world, providing multiple socioeconomic and environmental benefits. These systems are affected by multiple human pressures [1] that alter their hydro-morphodynamics and salinity structure, thus compromising the water quality and the provisioning of ecosystem goods and services. In particular, anthropological activities such as dredging or river regulation promote salinity intrusion, which poses a significant risk for ground and surface freshwater resources.

To control salt intrusion, effective tools need to be developed (1) to assess the vulnerability of estuaries to changes in the salinity field, (2) to predict the impact of future interventions and (3) to design and evaluate mitigation and adaptation solutions to the identified problems. In each of the above cases, the relationship between the estuarine morphology, external forcings and estuarine dynamics must be clearly established [2]. For instance, the control of salt intrusion based on flow regulation requires an advanced knowledge of the salt dynamics in response to a freshwater discharge that can vary by

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several orders of magnitude at a daily scale. In this context, numerical models, and particularly those based on idealized domains, are considered as efficient tools to obtain primary evaluations and to support management decisions [3].

In this paper, a 3-dimensional idealized model (Delft3D) of the Guadiana Estuary (GE), which river outflow is strongly regulated by dams, was developed to predict the salinity intrusion under varying river flow conditions. The model was calibrated and validated to adequately reproduce the estuary hydrodynamic behavior and the salt transport under low flow conditions, and to simulate the estuary response to transient changes of the river discharge. The provided tool enables to predict the salt intrusion in the estuary and thus to evaluate the efficiency of distinct mitigation strategies.

The document is organized as follows. Section 2 details the model setup (Sect. 2.1) and calibration (Sect. 2.2). The model performances under high and low river flow conditions are presented in Sect. 3. Finally, Sect. 4 outlines various management options proposed by stakeholders to control salt intrusion, which results are currently being evaluated using the model.

2 Numerical Framework

2.1 Model Setup

The physical domain in which the Delft3D numerical model was implemented consists of two parts: (1) the inner shelf, and (2) the channel. The shelf was defined with a constant slope of 0.0025 and seaward extension of 10 km, yielding a maximum depth of 25 m at the offshore boundary. The estuarine channel geometry is idealized, considering a width B(x) which reduces exponentially landward as:

$$B(x) = B_0 exp(-x/b) \quad (1)$$

where B_0 represents the width at the mouth, b represents the convergence length and x indicates the distance along the longitudinal axis, defined from the mouth (x = 0) to the head (x = L). According to the specific geometry of the Guadiana Estuary ([4, 5]), the numerical model was built considering B_0 = 700 m, b = 38 km and L = 78 km.

The cross-channel bathymetry follows a symmetric Gaussian shape [6] which was defined at each section along the cross-channel coordinate y ϵ [−B(x)/2, B(x)/2] by:

$$H(x, y) = H_{thal}(x)\, exp\left(-y^2/2c^2\right) \quad (2)$$

where $H_{thal}(x)$ represents the channel thalweg and varies between H_{thal} = 10 m (at x = 0) and H_{thal} = 9 m (at x = L). The standard deviation (c) was set to 152 to produce a cross-channel average slope of 0.04. To optimize the computational effort and the output files size, the physical domain was divided into three numerical grids using the domain decomposition technique [7], so that the horizontal and vertical resolutions were adapted to adequately simulate the physical processes involved in each region.

The numerical framework and the boundary condition types are shown in Fig. 1. The model is forced by tides and river discharge. The offshore boundary prescribes a harmonic water level condition representing an astronomical tide with 13 harmonics, among which the main is represented by the semidiurnal M_2 component (amplitude = 1 m; phase = 56 °). On the other hand, the freshwater inflow enters the estuary through the upstream section of the river, where a total discharge boundary condition (with uniform vertical distribution of velocities) was established.

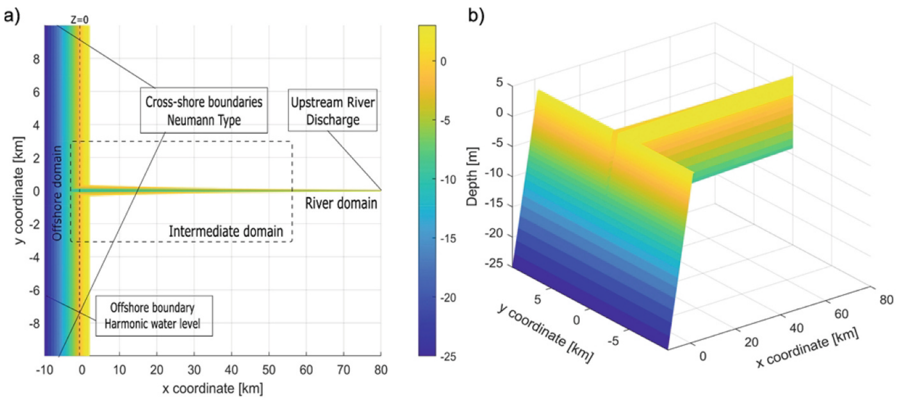

Fig. 1. Numerical model setup: (a) Top view, including boundary conditions and delimitation of subdomains. (b) 3D view of the channel bathymetry and the inner shelf. The color bar indicates depth in meters in a and b.

2.2 Model Calibration and Validation

For calibration, the model was tested considering 12 variants representing different combinations of the roughness coefficient and of the horizontal and vertical eddy viscosities and diffusivities. The performance of each variant was assessed using three different parameters representing the hydrodynamic conditions during distinct periods with low river flow (between 3 and 15 m^3s^{-1}), during which the estuary is well-mixed: (1) the tidal propagation along the estuary [5], (2) the hourly surface salinity near the mouth from March 8 to March 15, 2009 [8], and (3) the depth averaged axial salinity distribution at high water slack, measured at neap (August 31, 2017) and spring (September 8, 2017) tides.

For validation, a high river flow event (March 3 to May 6, 2013, see Fig. 2d for discharge magnitude), was considered to ensure that the model operates correctly under different river flow regimes and adequately reproduces the transient response to high river discharge events. The along channel velocity and salinity simulated during that period were compared with observations near the mouth. The model performance was assessed using the correlation (R) and skill (S) coefficients ([9, 10]).

3 Results: Model Performance

Regarding the low flow conditions analysis, the model configuration giving the best agreement with the field data corresponded to the variant Mod12. The physical parameters in this model configuration are given by a Chezy coefficient of C = 50 $m^{0.5}s^{-1}$, horizontal diffusivity and viscosity of $K_h = A_h = 0.1\ m^2s^{-1}$, vertical diffusivity of $K_v = 2.5{\cdot}10^{-4}\ m^2s^{-1}$ and vertical viscosity of $A_v = 5{\cdot}10^{-4}\ m^2s^{-1}$. With this setup, correlations R of 0.70 and 0.82 were obtained between the computed (15-day average) and measured tidal amplitudes and phases along the channel, respectively (see Fig. 2a, c).

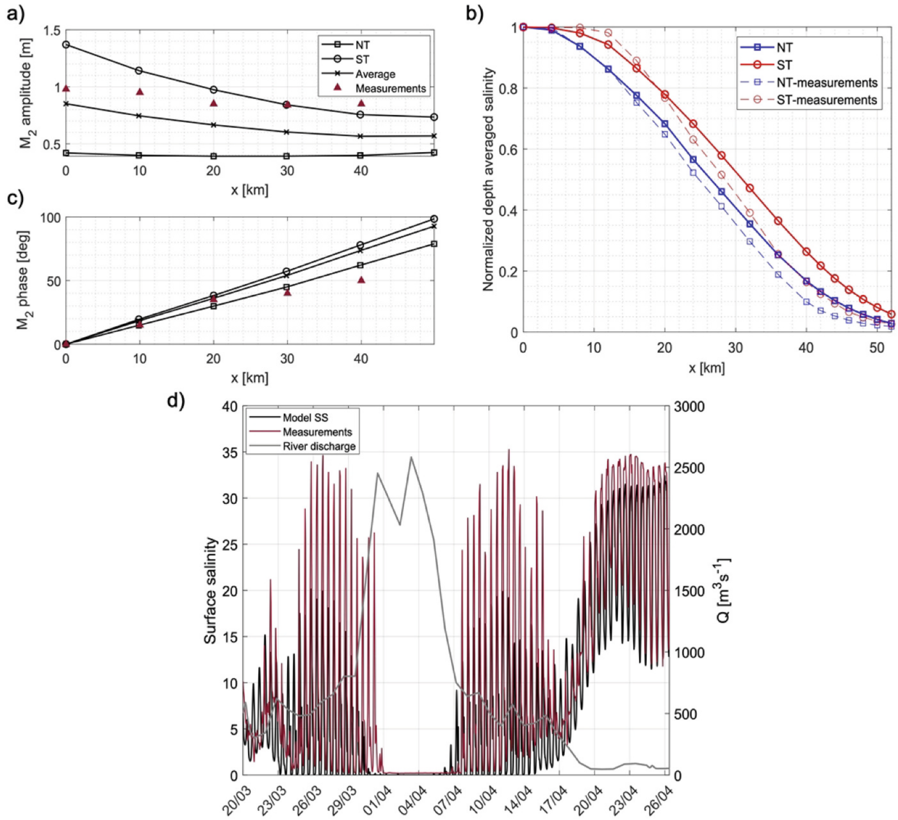

Fig. 2. Model performance. (a) M2 tidal level at neap tide (NT), spring tide (ST) and considering 15-day average (Average). (b) Along-channel depth averaged salinity profiles (high water slack) at neap (NT) and spring (ST) tide. Salinity values are normalized using the seawater salinity. (c) M2 tidal phase at neap tide, spring tide and considering 15-day average regarding symbology from panel (a). (d) Surface salinity near the mouth (left axis) and river discharge (right axis).

Regarding the surface salinity time series, R = 0.94 and S = 0.84. At high water slack of both neap and spring tides, the coefficients for the depth averaged salinity were R = 0.94 and S = 0.99, respectively (Fig. 2b). Based on the isohaline of 5 psu (corresponding to a normalized value of 0.14), the predicted intrusion length was 42 km at neap tide and 46 km at spring tide, 4 km more upstream than observed.

Figure 2d represents the salinity at the mouth during the high flow conditions (with river discharge values on the right axis) simulated by the calibrated model. The observations show that the increasing freshwater inflow between March 20 and April 1 steadily reduced the salinity to zero at the time of peak discharge (2500 m^3s^{-1}). The salinity changed from 35 psu to zero in 20 h. Once reached the peak discharge, the estuary remained filled with freshwater for 6 days. After this time, the decreasing discharge led to the resalinization of the estuary, which occurred in two stages: (1) between April 7 and April 16 (when the river flow decreased from 2500 to 500 m^3s^{-1}), and (2) between April 16 to April 20 (when the river flow decreased to 50 m^3s^{-1}). Hence, it took about 2 weeks to recover the salinity values observed before the high discharge event at the mouth.

The model predictions were similar to the above observations. The correlation R was 0.95 for along channel currents and 0.92 for the surface salinity. In particular, the sharp salinity variation in response to the increase in river flow was well reproduced. Likewise, the predicted resalinization period was close to observations. Overall, this validation shows that the model is able to accurately simulate the salinity dynamics in response to transient changes in river flows.

4 Model Application

Through the organization of a workshop with stakeholders, various management scenarios were defined that could impact the salinity intrusion at the GE. These scenarios were organized in four groups of numerical experiments aiming at predicting the salinity distribution after modifications of the bathymetry (Group 1), changes in the river discharge (Group 2), the installation of a freshwater intake station at the upper estuary (Group 3), and various combinations of options from these three groups (Group 4). Group 1 is constituted by three different dredging scenarios: (1) at the lower estuary, (2) at the upper estuary (to allow navigability until the estuary head at Mértola) and (3) throughout the entire channel. Group 2 includes six scenarios with river discharge values varying between 2 and 15 m^3s^{-1}. Group 3 contemplates the pumping of up to 30 hm^3 of freshwater between October and April. Of particular interest, this scenario corresponds to a controversial project which is currently being implemented despite the lack solid scientific evidence backup. The results of these experiments will be presented at the conference.

5 Conclusions

This paper presented the performances of a 3D hydrodynamic model of the GE, represented with an idealized geometry, that requires significantly reduced computational effort compared to more complex numerical models. The results support that the proposed model can successfully predict the salinity dynamics during prolonged periods of low river inflows affected by pulses in the freshwater discharge. Furthermore, the model setup (e.g., bathymetry, inflow or outflow) can be quickly updated with new setup (e.g., bathymetry, freshwater inflow) for the prediction of individual or combined effects of future human interventions – related to freshwater management or not – on the salinity field. In this manner, the model constitutes a useful management support tool for the development and evaluation of mitigation strategies to control salinity intrusion in the estuary.

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