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Sediment dynamics and budget in a microtidal lagoon — A numerical investigation

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ABSTRACT

The water circulation and sediment transport in a shallow microtidal basin (the Lagoon of Marano-Grado, Italy) were investigated by means of a 3D finite element modelling system. The framework of the numerical model consists of a 3D finite element hydrodynamic model, a third generation unstructured spectral wave model and a sediment transport and morphodynamic model for both cohesive and non-cohesive sediments. In order to describe the exchange of water and sediment through the lagoon's inlets, the model was applied to a domain comprising the lagoon itself and the whole Adriatic Sea. The developed model reproduces well the tidal motion and the wind induced circulation in the lagoon and the adjacent open sea. The transport of the fine sediments, resuspended by wind waves in the shallow tidal flats, resulted to be strongly related to the residual circulation induced by wind stress and nonlinear interaction between the tidal flow and bottom topography. The westward residual flow influences the exchange with the open sea through the six inlets, which therefore contribute with either a positive or negative net supply of water and sediment to the lagoon. The model provides estimates of the lagoon sediment budget revealing a net loss of about $40 \cdot 10^3$ m^3 of sediment in 2007. The results demonstrate the potential application of numerical models to simulate the recent morphological evolution and to improve the understanding of sediment dynamics in coastal embayments.

1. Introduction

Lagoons are shallow water bodies partially isolated from the adjacent sea by a sedimentary barrier and connected to it through one or several tidal inlets. Their evolution depends on the interaction between natural processes, human interventions and hydromorphological responses to such activities (Kjerfve and Magill, 1989). Lagoons and other coastal wetlands are threatened by sea-level rise (Carrasco et al., 2016) and land subsidence (Tosi et al., 2013), and are actually affected by a global tendency in salt marsh losses (Sarretta et al., 2010; Deegan et al., 2012; Fontolan et al., 2012; Kirwan and Megonigal, 2012).

The sediment balance in a tidal lagoon is the results of a complex set of processes occurring inside the basin and is also regulated by the interactions between the tidal motion at the inlets and the long-shore transport (see de Swart and Zimmerman, 2009, and references therein) . The dynamic of the inlet area is very complicated and involves many processes such as wave contribution to long-shore currents and to the total water level, the influence of tide and surge on the water depth, the depth and current refraction of waves, the sediment resuspension and the morphological evolution feedbacks on the hydrodynamics (Hubbard et al., 1979; Tambroni et al., 2010; Bruneau et al., 2011).

The understanding of the sediment dynamics in such complex environments is crucial for the correct management of these important ecosystems and the mitigation of the impacts of human activity. Unfortunately, the direct observation of these dynamics would require a great effort, which is often not achievable. The Venice Lagoon is a rare examplewhere the sediment transport processes were experimentally investigated (Amos et al., 2004, 2010; Villatoro et al., 2010) and the sediment budget was derived, both

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from the comparison of bathymetric surveys (Molinaroli et al., 2009; Sarretta et al., 2010) and from time series of turbidity measured at the three inlets (Defendi et al., 2010).

Modelling tools have recently been used intensely to integrate field data sets in order to improve understanding of morphological evolution of coastal seas (Lumborg and Pejrup, 2005; Amoudry and Souza, 2011). Simulation of water circulation and of the principal physical processes affecting these coastal areas requires the use of both numerical models at high spatial and temporal resolution and downscaling techniques capable of reproducing mass exchange between the open sea and the lagoon (Bellafiore and Umgiesser, 2010; Ferrarin et al., 2010a). This goal could be achieved through implementation of numerical models based on unstructured grids able to describe processes at variable spatial resolutions (Lesser et al., 2004; Ferrarin et al., 2008; Bertin et al., 2009; Villaret et al., 2011; Carniello et al., 2012).

In this study, we describe the water and sediment fluxes between the Lagoon of Marano-Grado (Italy) and the Adriatic Sea through the use of numerical models. Although it is clear that the model has to resolve the appropriate coastal scales, it is maybe less clear that for the open boundary conditions the model needs an upscaling effort to the basin scale where the boundary conditions can be supplied by a model at a larger scale. For this reason, the computation was carried out over a numerical domain which comprises the Lagoon of Marano-Grado and the whole Adriatic Sea.

This work follows a first application of the SHYFEM hydrodynamic model to the Lagoon of Marano-Grado by Ferrarin et al. (2010b). In that work, the numerical domain comprises the lagoon in isolation and nocurrent–wave–sediment interactions were considered.

1.1. Study area

The Lagoon of Marano-Grado (Fig. 1), located in the northern Adriatic Sea, is a coastal system influenced both by fresh and saline water. It is connected with the Adriatic Sea through six inlets (Lignano, S. Andrea, Buso, Morgo, Grado and Primero from west to east) and receives, mostly in the western region, about 70–80 m^3 s^{-1} of fresh water (Ferrarin et al., 2010b). The lagoon surface stretches out for about 160 km^2, with a length of nearly 32 km and an average width of 5 km. The lagoon has an average depth of 1.1 m and is characterized by a complicated network of channels, shallow tidal flats and marshes (Ferrarin et al., 2010b; Fontolan et al., 2012).

The Lagoon of Marano-Grado floor consists of sediments that are mainly cohesive; the silty fraction prevails over the clay fraction (Marocco, 1995; Acquavita et al., 2012). However, sandy regions can be identified both inside the lagoon and close to the inlets (Fontolan et al., 2007). Sandy sediments characterize the northern Adriatic coastal area in front of the Lagoon of Marano-Grado.

The coastal circulation of the North Adriatic Sea is mainly driven by the tide and winds, which dominantly blows from E-NE (Bora) (Kuzmić et al., 2006; Jeffries and Lee, 2007). The lagoon system is geographically delimited northwards by the River Isonzo and southwards by the River Tagliamento. These rivers, which have a torrent-like character, greatly influence the hydrodynamics of the coastal area (Brando et al., 2015). Consequently, the long-shore drift in the area occurs mainly westwards from the Isonzo River to Lignano (Fontolan et al., 2007).

2. The modelling system

The unstructured grid-based numerical model used in this study is a coupled 3D current, wave and sediment transport model working simultaneously on a common finite element grid. The finite element method has the advantage of describing accurately complicated bathymetry and irregular boundaries in shallow water. It can also solve the combined large-scale oceanic and small-scale coastal dynamics in the same discrete domain by using unstructured meshes.

The 3D hydrodynamic finite element model SHYFEM solves the primitive equations, vertically integrated over each layer, with a semi-implicit algorithm that is unconditionally stable for gravity waves. SHYFEM accounts for tidal, wave, atmospheric and density-driven currents (induced by salinity, temperature and suspended sediment gradients). A more detailed description of the model equations and of the discretization method is given in Umgiesser et al. (2004) and Bellafiore and Umgiesser (2010).

The third generation spectral wind wave model WWMIII uses triangular elements in geographical space to solve the Wave Action Equation (WAE) (Roland et al., 2009). The WAE describes the evolution of wind waves in a slowly varying medium. In this work it is coupled to the hydrodynamic model to account for wave refraction induced by variable depths and currents. The spatial variation of the wave action spectra in coastal waters causes a net momentum flux known as the radiation stress (Longuet-Higgins and Steward, 1964). Such effect has been simulated by implementing the vortex force formalism by Uchiyama et al. (2010) in the coupled numerical model SHYFEM-WWMIII.

The sediment transport model SEDTRANS05 (Neumeier et al., 2008) simulates erosion and sedimentation rates under either steady currents or the combined and time-dependent influence of waves and currents. The model adopts the Grant and Madsen (1986) continental shelf bottom boundary layer theory to predict bed shear stresses and the velocity profile in the bottom boundary layer. The velocity computed by the 3D hydrodynamic model in the bottom layer and the bottom orbital velocity are used to calculate the bed shear stress.

The morphological model takes into account time and spatial-dependent sediment distribution and bed armouring. Modifications to bed elevation and to the grain size distribution are updated at each time step based on the net erosion and deposition rates. The new depth is used to compute the hydrodynamics in the subsequent time step. The morphodynamic model has been extensively described in Ferrarin et al. (2008) and Ferrarin et al. (2010a).

2.1. The simulation set-up

The numerical computation was carried out on a spatial domain that represents the Lagoon of Marano-Grado and the whole Adriatic Sea by means of a grid that consists of38,737 triangular elements with a resolution that varies from about 10 km in the open sea to few hundred meters along the coast and tens of meters in the inner lagoon channels. The use of elements of variable sizes, typical of finite element methods, was fully exploited, in order to suit the complicated geometry of the basin and the rapidly varying topographic features. Bathymetry of the lagoon and the Adriatic Sea was interpolated and superimposed on the finite-element mesh as shown in (Fig. 1). Bathymetrical data surveyed in 2009 was used to represent the bottom morphology of the Lagoon of Marano-Grado (Triches et al., 2011). The bathymetry of the whole area was obtained merging severaldata sets, having different spatial resolution and measuring approach, which produces depth discontinuities in the inlet areas.

The hydrodynamic model was applied in its 3D version. In this application the water column was discretized into 27 vertical layers with variable thickness ranging from 1 m, in the topmost 10 m, to 200 m for the deepest layer of the Adriatic Sea. In this study, 24 frequencies, ranging from 0.07 to 1.8 Hz, and 24 uniformly distributed directions were considered in the wind wave model.

The spin-up time of the simulation is two months and the initial conditions of salinity and water temperature of 1 November 2006 were obtained by interpolating the results of the Adriatic Sea operational model (AREG2, Oddo et al., 2006) onto the finite element grid.