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Integrating complex numerical approaches into a user-friendly application for the management of coastal environments

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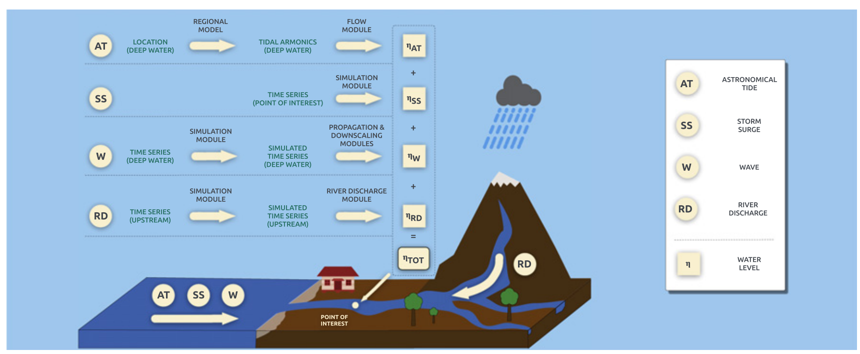
HIGHLIGHTS

- A software platform to estimate the total water level is presented.
- It was applied to address management problems at three sites in southern Spain.
- The maximum number of docks to extend a fluvial marina in an estuary was obtained.
- We estimated the relation between the operability and dredged volume in an inlet port.
- We proposed a design curve for artificial nourishments on an eroding deltaic beach.

GRAPHICAL ABSTRACT



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ABSTRACT

This paper presents a software platform to compute the total water level, one of the key variables for the environmental management of coastal zones. The platform integrates six modules: (1) simulation of deep-water wave variables, storm surge and river flow; (2) wave downscaling; (3) wave propagation; (4) contribution of the river discharge; (5) astronomical tide; and (6) total water level. It was applied to three case studies in southern Spain. The first case study consisted of designing the extension of a fluvial marina in a highly dynamic area (Guadalete estuary, Cádiz), and the maximum number of floating docks to avoid flooding events was obtained. The second case study involved calculating the operation conditions for navigation purposes in an inlet with sedimentation problems (Punta Umbría, Huelva), and a relationship between the percentage of operation hours and the dredged volume was obtained. The third case study consisted of estimating the number of overwash events as a function of the height of the berm on a deltaic beach with erosion issues (Guadalfeo, Granada), and a simple design curve to help managers during the decision-making process of artificial nourishment projects was provided. These results highlight the potential of the developed software, whose methodology is feasibly extensible to other coastal areas worldwide, to help managers handle a wide range of environmental problems related to the total water level. This is especially relevant due to the expected sea level rise in the coming years.

1. Introduction

Coastal environments are arguably the most important and intensely exploited areas settled by humans (Masselink and Hughes, 2003). Over the last decades, human activities have changed the natural dynamics of numerous coastal systems worldwide (Anthony et al., 2014; Brown and Nicholls, 2015; Syvitski et al., 2005; Zhao et al., 2017)

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and caused both erosion problems and sedimentation issues. The former generate frequent material and personal damages, which will be increased by the sea level rise due to climate change (Genua-Olmedo et al., 2016; Sánchez-Arcilla et al., 2016), whereas the latter directly affect the port operation (García-Morales et al., 2015; Reyes-Merlo et al., 2015). Thus, management practices such as artificial nourishments and dredging activities have been increasingly performed in recent years (Chu et al., 2014; Erftemeijer and Lewis, 2006).

Transitional zones, such as estuaries, inlets and deltas, are particularly sensitive to both natural and human-induced changes (Schuttelaars et al., 2013; Syvitski and Saito, 2007). These areas provide a wide variety of uses and economic activities such as real estate, recreation, energy generation, mining, shipping and tourism (Long et al., 2007; Turner, 2000). Consequently, their management is particularly difficult because of the lack of coordination among the administrations (Bergillos and Ortega-Sánchez, 2017; Billé, 2008). These systems present additional problems due to the inherent complexity of river mouths, which are highly dynamic areas where atmospheric, climatic and maritime agents simultaneously interact (Anthony, 2015; Dalrymple et al., 2012). Consequently, to properly assess the effect of flooding events (Chaumillon et al., 2017) and design sustainable strategies in these zones, it is essential to estimate the total water level with advanced climate simulation techniques (Antolínez et al., 2015; Solari and van Gelder, 2011).

In recent decades, significant improvements were achieved to address coastal problems. Solari and Losada (2012a,b) proposed a simulation methodology for obtaining the multivariate time series of the state variables that characterize the predominant forcing agents of coastal and transitional areas. Egbert and Erofeeva (2002) presented a relocatable system for the generalized inverse modelling of astronomical tides. Lesser (2009) developed a model (Delft3D) that included a module (FLOW) to simulate tide propagation and river discharges (Lesser et al., 2004). This model also has a wave propagation module (WAVE), based on the SWAN model (Holthuijsen et al., 1993), to simulate random, short-crested waves in coastal regions. By combining a numerical wave model with mathematical tools, Camus et al. (2011, 2014) developed a hybrid downscaling methodology to transfer deep-water wave variables to coastal areas and statistically downscale the multivariate wave climate over different time scales. However, to our best knowledge, these methodologies are frequently categorized by managers as intricate and they have not been jointly implemented in a software platform with the involvement of governments and stakeholders to help address different management problems.

Previous works in coastal areas of southern Spain mainly focused on the assessment of the hydrodynamic and morphodynamic response to human interventions at different study sites. Zarzuelo et al. (2015) assessed the impact in a highly altered bay by means of field measurements and numerical modelling, whereas Reyes-Merlo et al. (2017) quantified the efficiency of dredging strategies in a tidal inlet based on energetic approaches. The implications of bed level changes in a eroding delta, partly due to river damming, on coastal processes were studied by Bergillos et al. (2016a) through the analysis of bathymetric data, wave propagation patterns and longshore sediment transport trends. This work was continued by the characterization of the morphological and sedimentary dynamics of a mixed sand-gravel beach by means of field observations (Bergillos et al., 2016b) and the analysis of the response of a deltaic coast after an artificial nourishment project through field observations and application of the one-line model (Bergillos et al., 2017b). Finally, recent studies focused on the modelling of storm response along a mixed sand-gravel coastline under varying wave directions (Bergillos et al., 2017a) and the forecasting of shoreline evolution of a deltaic coast forced by different scenarios of nourishment (Bergillos et al., 2018). However, to our best knowledge, computations of the total water level have not been applied to address actual environmental management issues.

The main objective of this work is to present a software platform specifically designed to manage coastal areas in a region with more than 1100 km of coastline in southern Spain (Andalusia) along with its application to three different case studies. The methodology to develop the platform, which was designed in collaboration with public administrations, is feasibly extensible to other coastal environments across the world to support the decision-making process of a wide range of management strategies related to the total water level. This is particularly relevant in transitional areas, which are specially vulnerable to the expected consequences of global warming in the coming years (Alfieri et al., 2015; Duong et al., 2016). The paper is structured as follows. Section 2 describes the six modules of the software. Section 3 presents possible uses of the tool to address different problems at three locations along the Andalusian coastline of southern Spain. Finally, the conclusions of the work are summarized in Section 4.

2. Description of the tool

The development of the software platform consisted of the joint implementation and integration of six modules, which were coded mainly in Python: simulation of state variables, wave downscaling, wave propagation, river discharge, tidal flow and total water level (Fig. 1). Management administrations were involved in the design of the graphical user interface (GUI); they provided feedback and helped to improve the results interface during periodic meetings and testing of the tool. This process ensures that the GUI is easy to use and adapted to their requirements. The software is freely available on this website: https://gdfa.ugr.es/levels (registration is required for statistical purposes).

The GUI has three different windows: selection of the study site and the result location; selection of the agents and the simulation parameters for future water level calculations; and selection of the agents and the period to model for past water level calculations (Fig. 2). Note that the future calculation is based on the simulated time series of the state variables, whereas the past total water level is calculated based on actual records.

2.1. Module of state variables simulation

This module is based on the parametric methodology proposed by Solari and Losada (2012a,b). This approach enables the simulation of series of significant wave height in deep water (H_0), storm surge and river flow with the same marginal probability distribution as the original series. The approach accounts for the seasonal and inter-annual variations of the statistical descriptors and maintains the autocorrelations, persistence, storm, peak over threshold regimes and rate of annual maximums.

Based on the simulated time series of H_0, the spectral peak period (T_p) and mean wave direction in deep water (θ_0) are simulated using a vector autoregressive model (López-Ruiz et al., 2016). The input requirements for this module are records of H_0, T_p, θ_0, storm surge and river flow; whereas the outputs are simulated series of these variables, which are automatically used as the input for the other modules (Fig. 1).

2.2. Wave downscaling module

This module synthesizes the complete data set of the deep-water wave climate in a group of fewer than 300 sea states, which represent low-energy, mean and extreme wave conditions, using the downscaling methodology that Camus et al. (2011, 2014) presented. These sea states range in un-equally distributed intervals to account for the most likely sea states and are propagated with the wave propagation module (Section 2.3). Finally, these results are used to reconstruct the wave set-up series during the period selected by the user. This