Journal of Coastal Research	SI	95	1016–1020	Coconut Creek, Florida	2020

Recent Advances in Tidal Inlet Morphodynamic Modelling

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ABSTRACT

Bertin, X.; Mengual, B.; de Bakker, A.; Guérin, T.; Martins, K.; Pezerat, M., and Lavaud, L., 2020. Recent advances in tidal inlet morphodynamics modelling. *In:* Malvárez, G. and Navas, F. (eds.), *Global Coastal Issues of 2020*. *Journal of Coastal Research*, Special Issue No. 95, pp. 1016–1020. Coconut Creek (Florida), ISSN 0749-0208.

Tidal inlets connect the ocean to inner water bodies and are present worldwide. Complex interactions between tides, waves and shallow bathymetry often drive fast morphological changes but the underlying processes remain only partly understood. To better understand these processes, the development and application of morphodynamic models represents a unique perspective. This paper evaluates the impact of recent developments in the modelling system SCHISM, which include: a WENO method to solve the Exner Equation, a 3D coupling between waves and currents using a vortex force formalism, an adaptive parameterization for the dissipation of short waves by breaking and improved representations for wave-induced sediment transport. In order to evaluate the relevance of these developments, SCHISM is applied to the Maumusson Inlet, a mixed-energy inlet located on the Western Coast of France. Model-data comparison reveals firstly that complex wave-current interactions take place over the inlet ebb-delta, that include partial wave blocking during the ebb. Compared to classical 2DH approaches, our improved modelling system better reproduces the dynamics of adjacent beaches, inlet migration under oblique waves and sediment infilling of the main channel under storm waves. The relevance of these developments is demonstrated at the mixed-energy Maumusson Inlet (France).

ADDITIONAL INDEX WORDS: *Tidal inlet, morphodynamic modelling, sediment transport, wave-current interactions.*

INTRODUCTION

Tidal inlets connect the ocean with inner water bodies (back-barrier bays or lagoons) and develop all along the world's coastlines, although they form preferentially along low gradient plains, exposed to micro- to meso-tidal regimes combined with low to moderate wave energy (Hayes, 1979). Depending on the available estimations, tidal inlets and barrier island systems represent between 10 and 17 % of the world's coastlines (Stutz and Pilkey, 2011), but they concentrate socio-economic and environmental issues compared to other types of coasts. For instance, tidal inlets constitute navigation routes that allow for the development of commercial navigation activities. Barrier islands provide pleasant environments to live in and are often heavily urbanized, despite the high mobility of the shoreline controlled by neighbouring inlets (*e.g.* Adams *et al.*, 2016). Tidal inlets also control the exchanges of water, sediments, dissolved material and larvae between the ocean and back-barrier lagoons, which are often used for aquaculture. For these reasons, tidal inlets are of critical socio-economic and environmental importance worldwide. At the same time, tidal inlets are often very dynamic coastal systems, due to the superimposition of tides, waves and the presence of shallow channels and sandbanks. This complex dynamics drives fast and large morphological changes, but the underlying physical processes are is still partly understood only. Consequently, tidal inlet behaviors are hard to predict and the sustainable management of these coastal systems is difficult to achieve.

To address these challenges, the development and application of morphodynamic modelling systems combined with comprehensive field observations appear as the best strategy. However, most applications employ 2DH approaches (*e.g.* Bertin *et al.*, 2009; Duong et al., 2018; Orescanin *et al.*, 2017; Roelvink et al., 2009), which cannot represent the vertical circulation that takes place in bended channels or in surf zones. As 3D modelling systems can represent adequately these complex flows, one could expect that such models will result in improved morphological predictions, although 3D applications are very scarce in the literature. This suggests that the 3D modelling of coastal zones is still challenging, for instance due to a lack of consensus on the representation of wave-current interactions in 3D or heavy computational times. Indeed, solving an advection diffusion equation for each vertical layer times each sediment class rapidly dominates the computational time. This study presents recent developments integrated in the 3D morphodynamic modelling

DOI: 10.2112/SI95-198.1 received 31 March 2019; accepted in revision 13 February 2020.
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system SCHISM (Zhang *et al.*, 2016). The relevance of these developments in the predictive skills of SCHISM is demonstrated through a one-year application to the Maumusson Inlet, located on the Western coast of France.

METHODS

The Numerical Modelling System

The 3D modelling system SCHISM (Zhang *et al.*, 2016), fully couples a 3D circulation model with the spectral wave model WWMII (Roland *et al.*, 2012) and the sediment transport and bed update model SED3D (Pinto *et al.*, 2012). Waves and currents are fully coupled in 3D using a vortex force formalism and accounting for breaking wave-induced turbulence, as described in Guérin *et al.* (2018). The dissipation of short waves by breaking uses an adaptive approach, based on the local bed steepness (Pezerat *et al.*, this issue). Suspended sediment transport is computed by solving an advection diffusion equation, where the restrictive CFL condition associated with the vertical advection is bypassed using an implicit TVD method (Zhang *et al.*, 2016). Bedload sediment transport is computed using the model of Soulsby and Damgaard (2005) and the Exner equation is solved using a Euler-WENO approach, which bypasses the necessity to use filters or artificial diffusion (Guérin *et al.*, 2016).

This modelling system is implemented over the study area (Figure 1) using an unstructured grid with a horizontal spatial resolution ranging from about 1 km along the open boundary and 25 m at the inlet. The vertical discretization uses a hybrid S-Z grid with 22 levels. The roughness length Z_0 varies spatially from 0.1 mm on intertidal mudflats of the back-barrier bay to 5 mm on rocky zones surrounding the northern part of Oléron Island (Figure 1B). In this application, a single class of sediment is considered, with a d_{50} of 0.5 mm. Although time steps can be decoupled in the different models composing SCHISM, a unique time step of 20 s was selected in this application. The circulation model is forced with amplitudes and phases of the 18 main tidal constituents, linearly interpolated from the regional tidal model of Bertin *et al.* (2012). The wave model is forced with time series of directional wave spectra, originating from the regional wave model described in Bertin *et al.* (2015). Over the whole domain, the model is forced with fields of sea-level atmospheric pressure and 10 m winds originating from the CFSR reanalysis (Saha *et al.*, 2010).

The Study Site and Field Experiment

The Maumusson Inlet (Western Coast of France) connects the Marennes-Oléron Bay to the Atlantic Ocean (Figure 1). Incoming tides are semi-diurnal and range from 1.1 m during neaps and 5.5 m during springs, with a mean tidal range of about 3.5 m (Dodet *et al.*, 2019). The local wave climate is characterized by mean spectral significant heights (hereafter H_{m0}) of 1.6 m in 30 m water depth (Dodet *et al.*, 2019) while during winter storms, the deep water H_{m0} can episodically reach 10 m (*e.g.* Bertin *et al.*, 2015; Guérin *et al.*, 2018). Short waves preferentially originate from W to NW, which drives a net littoral drift to the South along the adjacent shorelines of the Maumusson Inlet (Bertin *et al.*, 2005). Understanding the morphodynamics of this coastal system is essential, firstly because the updrift coast experiences a very severe erosion since 1965. Secondly, the main channel migrates towards the South while it is used for navigation. Finally, the Maumusson Inlet connects the ocean to the Marennes-Oléron Bay, which is the first oyster farming area in Europe, thereby requiring a high water quality (Bertin *et al.*, 2005).

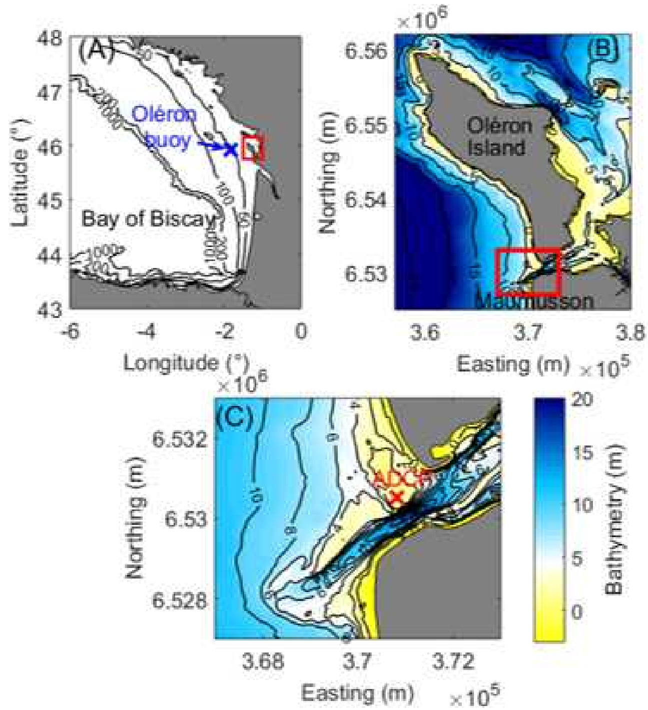

Figure 1. (A) Location of the study area in the Bay of Biscay, (B) bathymetry of the study area and (C) detailed bathymetric map of the Maumusson Inlet, showing the deployment of the ADCP during the field campaign of May 2017.

In order to better understand the dynamics of the Maumusson Inlet, repetitive bathymetric surveys of the inlet channel and sandbanks were carried out in November 2016, May 2017 and May 2018. In May 2017, a field experiment was conducted under spring tides and moderate energy wave conditions. 3 pressure sensors and a high resolution ADCP were deployed over the Northern part of the ebb-delta (Gatseau Bank, Figure 1-C) over a one-week period. These sensors were accurately positioned using a RTK GNSS and allowed measuring short waves, current velocity profiles, water levels as well as the slope of the free surface elevation.

RESULTS

Hydrodynamics

Incoming tides ranged from 3.7 m to 5.0 m during the field experiment, and drove tidal currents up to 2.0 m/s at the location of the ADCP (not shown). Water levels are very well reproduced at the inlet, with a Root Mean Squared Difference (hereafter RMSD) below 0.10 m and a negligible bias. Once normalized by the mean tidal range (hereafter NRMSD), the error on water levels is of the order of 3% (Figure 3). Tidal currents at the ADCP are also well reproduced, with a RMSE ranging from 0.1 and 0.3 m/s, depending on the tidal phase (not shown). Offshore wave conditions measured at the Oléron Buoy (Figure 1-A) during the field experiment were characterized by a H_{m0} ranging from 0.4 to 1.4 m, a peak period T_p from 8.5 to 13.5 s and a mean direction from W to WNW. At the Inlet, H_{m0} reached up to 1.8 m at high

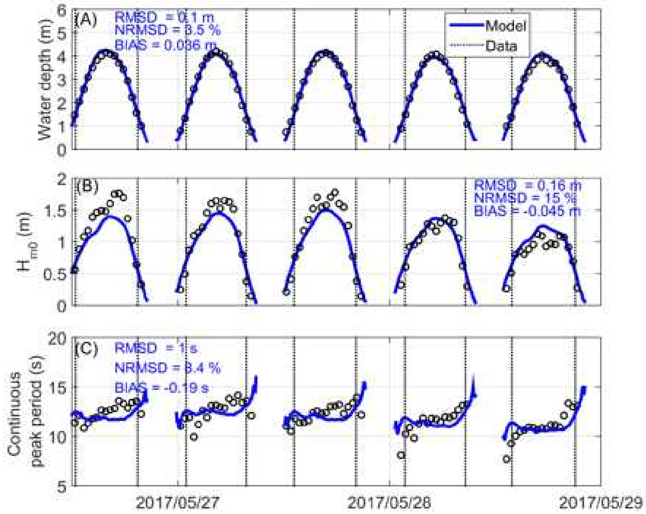

Figure 2. Observed (black circles) against modeled (blue line) water depth (A), significant wave height (B) and continuous peak period (C) at the ADCP deployed over the ebb delta. Vertical dotted lines correspond to water depths of 1.5 m and highlight differences for significant wave heights and wave periods between flood and ebb.

tide, implying that they gained energy compared to the offshore Oléron Buoy. H_{m0} are overall well predicted by the model, although a negative bias can be observed at high tide, which results in a RMSD of 0.2 m and a NRMSD below 20% (Figure 2). This problem could be partly explained by the development of diffraction patterns, visually observed on the field and on satellite images, but not represented in the wave model. For a given water depth, H_{m0} are about two times smaller during the ebb compared to the flood (see the vertical dashed lines on Figure 2) and these differences increase as the water depth decreases. Thus, for a water depth lower than 0.5 m, waves are almost completely blocked during the ebb. At the inlet, T_p ranged from 8 to 15 s and displayed a strong tidal modulation, with an increase by 40 to 50 % from mid-flood to mid-ebb. This behavior is very well captured by the model, with a RMSD of 0.7 s, corresponding to a NRMSD of about 6 %.

Morphological Changes

Morphological changes at the Maumusson Inlet were characterized by the difference of digital elevation models computed for May 2018 and May 2017 (Figure 3). This difference shows that the inlet main channel and the ebb delta migrated Southward by about 350 m, which corresponds to a mean migration rate in the order of 1 m/day. In more details, this migration rate ranges from 0 and 3 m/day and is well correlated with the offshore wave height (R=0.51). The longshore sand transport might better explain the migration rate variability, which hypothesis will have to be verified in the future. The top of the ebb-delta also eroded by approximately 1.0 m and the secondary flood channels accreted by 0.5 to 1.0 m. These morphological changes are overall well predicted by the model, with a Brier Skill Score (BSS) of 0.37. In more detail, the model predicts more accretion in front of the updrift coast compared to the observations, which is explained by the use of a single sediment class of 0.5 mm while the updrift coast is made of finer sands. Considering a particular section crossing

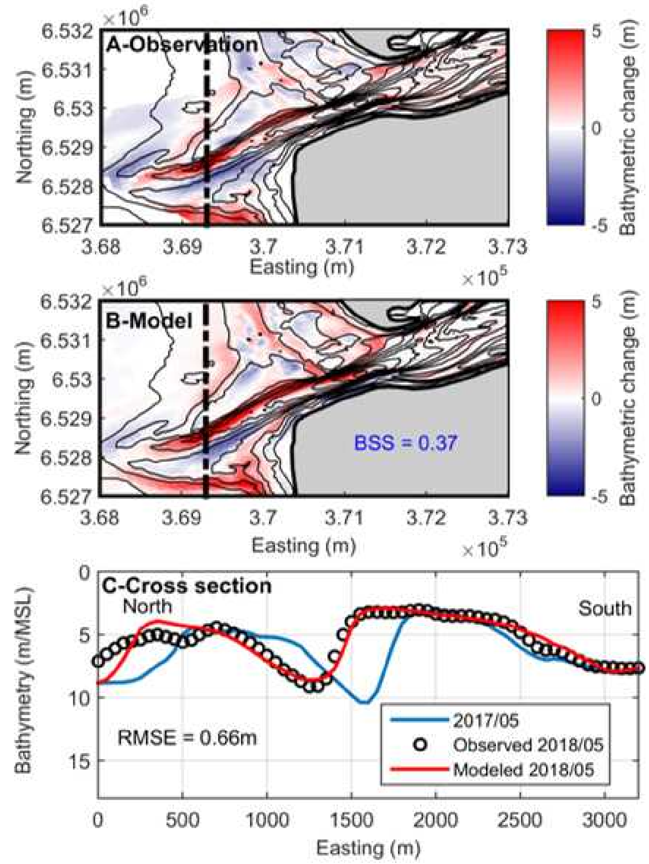

Figure 3. Observed (A) against modelled (B) bathymetric changes of the Maumusson Inlet from May 2017 to May 2018 and selected cross-inlet profile (C), showing the Southward migration of the main channel by about 350 m.

the inlet and the ebb delta (Figure 3-C), the model reproduces the observed migration with a RMSD of 0.66 m.

DISCUSSION

Wave-current Interactions

Modeled and observed wave heights revealed firstly that H_{m0} were strongly tidally-modulated, which is explained by their depth-limited breaking over the ebb delta. In more detail, model-data comparison revealed that this tidal modulation is not symmetric as for a given water depth, H_{m0} are about two times smaller at mid-ebb compared to mid-flood and these differences increase as the water depth decreases. This behavior is explained by tidal current feedback on the wave field, which causes partial wave blocking during the ebb. Along a tidal cycle, T_p also suffered a clear tidal modulation, with a 40-50% increase from mid-flood to mid-ebb. This behavior is well captured by the model and explained firstly by a Doppler shift, where following flood currents decrease the period of short waves while opposing ebb currents increase their period. Opposing ebb-currents also decrease wavelengths and increase H_{m0} through shoaling, until the wave steepness is high-enough to induce their dissipation by whitecapping. This process affects primarily the highest frequency part of the wave spectrum (not shown), which explains the further increase in wave period and partial wave blocking observed after mid-ebb. This process was already observed and analyzed at shallow wave-dominated inlets, where full wave blocking can even occur in the end of the ebb due to strong currents in depths lower than 1.0 m (*e.g.* Bertin *et al.*, 2019; Dodet *et al.*, 2013). This study shows that partial wave blocking can also occur at a deep inlet, when the ebb delta is tilted with respect to the main channel axis, which causes the short waves to encounter strong ebb tidal currents in shallow water. As short waves play a major role in the sediment dynamics of ebb deltas, this study also shows that reproducing these complex wave-current interactions is essential for morphodynamic simulations.

Morphological Predictive Skills

Due to their ability to represent sheared flows in surfzones or secondary flows in bended channels, 3D morphodynamic modelling systems are expected to yield considerably improved morphological predictions compared to their 2DH counterpart. Yet, the application of 3D morphodynamic modelling systems to coastal zones is very scarce in the literature, suggesting that such approaches still pose important challenges, such as heavy computational times. Here, a recently-improved 3D morphodynamic modelling system was applied with realistic forcings and without any acceleration factor (*i.e.* the so called “morfac”). This application shows, for the first time, realistic morphological predictions of a tidal inlet over a one-year period that includes storm waves in winter. In terms of computational time, this one-year simulation runs within one week on 40 cores, that is about 50 times faster than real time. Such an acceptable computational time is only possible due to the advanced numerical methods used in SCHISM, which allow for large time steps to be used even with fine horizontal and vertical resolutions. In particular, the implicit TVD scheme recently developed by Zhang *et al.* (2016) is a key improvement for tidal inlet morphodynamics as strong ebb currents pushing on a steep ebb delta cause large vertical velocities, which would impose a strong reduction of the time step using an explicit method for the advection of momentum and suspended sediments. A sensitivity analysis conducted at the beginning of this study also reveals that solving the Exner equation using a WENO scheme yield considerable improvements compared to previous approaches that employed artificial diffusion to avoid the development of spurious numerical oscillations in the bed elevation. In particular, the depth of the main channel is much better preserved with the WENO approach, which meets the conclusions of Guérin *et al.* (2016) based on simulations carried out at idealized morphologies. Lastly, 3D modelling results were compared against those obtained from a 2DH simulation. This comparison showed that the 3D run outscores the 2DH one, the latter resulting in a negative BSS. However, this comparison is not fully consistent as the bed shear stress is computed using the total water depth for the 2DH runs while near-bottom velocities are used for the 3D case. Investigating the added value of 3D vs 2DH approaches is relevant as little literature is available on the subject, but further efforts are needed to improve the consistency of such comparisons.

CONCLUSIONS

The fully-coupled modelling system SCHISM was recently improved to represent adequately the depth-varying circulation and sand fluxes driven by short waves. Recent improvements also concerned advanced numerical methods to compute suspended sand fluxes and morphological changes, which optimize the balance between numerical accuracy and computational time. The application of SCHISM to the mixed-energy Maumusson Inlet showed firstly that this modelling system was capable to reproduce accurately complex wave-current interactions that take place over the ebb delta, including partial blocking when waves propagate against counter currents. The modelled morphologic changes over a one-year period encompassing storm waves in winter reveal that SCHISM has good predictive skills and realistically reproduced the downdrift migration of the inlet and ebb delta by about 350 m. A preliminary comparison with a 2DH approach reveals that the improvements brought by the 3D approach are considerable, although the comparison is not strictly consistent due to differences in the way the bed shear stress is computed. Further improvements are expected from a multiclass/multilayer approach, namely at the updrift coast, which is made up of finer sands compared to the single class used in this study. SCHISM is also being applied to other study sites to verify its predictive skills, including the Tagus Estuary Mouth and the Albufeira Lagoon Inlet in Portugal.

ACKNOWLEDGMENTS

The study was conducted in the scope of the Regional Chair Program EVEX and AdB was partly funded by the program Prestige of Campus France (grant agreement n◦ PCOFUND-GA-2013-609102). BM is funded by Fondation de France in the scope of the program “Segundo Torrão”. K. Martins greatly acknowledges the financial support from the University of Bordeaux, through an International Postdoctoral Grant (Idex, nb. 1024R-5030). We thank the crew of the RV Haliotis (IFREMER) for their valuable assistance during the interferometric bathymetric survey (EMEMO Cruise) and E. Chaumillon and T. Coulombier for their contribution to bathymetric data acquisition and processing.

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