A REVIEW OF THE PROCESSES CONTROLLING THE DYNAMICS OF WAVE-DOMINATED INLETS

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Abstract

This paper presents a review of the processes controlling wave-dominated inlets, based on several studies conducted at two inlets located on the West Coast of Portugal. Once the observed hydrodynamics and morphological changes are reasonably simulated, numerical experiments are performed to explain the development of the inlet during fair weather conditions and its shoaling and closure during winter storms. The former behaviour is explained by a tidal distortion that promotes ebb-dominance while the latter is explained by the combination of several wave-related processes: (1) the "bulldozer effect" due to the shore-normal component of wave forces; (2) the presence of lateral barotropic pressure gradients, accelerating longshore flows towards the inlet; (3) wave blocking during the ebb and (4) a rise in mean sea level in late autumn. Recent results also suggest that infragravity waves may play a major role.

Key words: Tidal inlets, wave-induced processes, wave blocking, infragravity.

1. Introduction

The economic and environmental importance of tidal inlets has been growing worldwide, while their sustainable management faces many conflicting challenges, such as the maintenance of open navigation routes, the stability of the adjacent shoreline or the water renewal in the back-barrier lagoons. The combined action of waves and tides and the presence of shallow channels often drive a fast and intense sediment dynamics and make their behaviour difficult to predict. These problems are particularly relevant at wave-dominated inlets, where this intense dynamics can drive fast and large morphological changes within a few days/weeks. Eventually, wave-dominated inlets can episodically or seasonally close, although the responsible physical processes remain only partly understood.

To improve the understanding of tidal inlet dynamics, a promising avenue is the development and application of morphodynamic modelling systems. These modelling systems consist of a set of modules to simulate tidal hydrodynamics, wave propagation, sediment transport and bottom evolution. The morphodynamic modelling of tidal inlets already met several successes over the last decade (Cayocca, 2001; Dastgheib et al., 2008; Bertin et al., 2009a; Bruneau et al., 2011). Nevertheless, to date, the successful simulation of tidal inlet closure is restricted to simplified/empirical approaches (Ranasinghe et al., Walstra et al. 2009). This problem suggests that the dominant physical processes are not all captured by most modelling systems. This paper reviews the knowledge gained from previous modelling-based studies performed at two wave-dominated inlets located on the west coast of Portugal (Bertin et al., 2009b; Bruneau et al., 2011; Dodet et al., 2013) and synthesizes the physical processes controlling the dynamics of wave-dominated inlets, including their closure.

2. Study sites

This study is based on results obtained at two wave-dominated inlets located on the West Coast of Portugal: the Albufeira Lagoon Inlet and the Óbidos Lagoon Inlet (figure 1). Tides are semi-diurnal and range from 0.5 m to 3.5 m (meso-tidal). When tides propagate into the lagoons, the semi-diurnal tidal constituents are severely damped, with the amplitude of M2 typically decreasing by 50 to 80 % at both lagoons (Oliveira et al., 2006; Bertin et al., 2009b; Dodet et al., 2013). Tidal amplitude in the lagoon experiences a seasonal cycle, with a maximum at the end of the summer and a minimum at the end of the winter at Óbidos while the Albufeira Lagoon Inlet usually closes in late autumn-early winter. In contrast, quarter-diurnal and fortnightly non-linear tidal constituents develop inside the lagoons, resulting in a strongly distorted tidal signal, with ebb lasting 7 to 8 hours and floods 4.5 to 5.5 hours.

The continental shelf in front of both inlets is very narrow (< 20 km), which causes these inlets to be exposed to a very energetic wave climate, particularly in winter. Based on a 57-year wave numerical hindcast (Dodet et al., 2010), the mean annual deep water (10.0ºW; 38.0ºN; ~ 3000 m deep) significant wave height (H_S), mean direction (MWD) and peak period (T_P) are respectively 1.9 m, 312 º, and 10.5 s. During winter (resp. summer) the corresponding values are: 2.5 m, 305 º, and 12.1 s (resp. 1.3 m, 8.4 s and 319 º). This severe wave climate combined to the meso-tidal range and shallow channels leads to very dynamic inlets, with channel migration often exceeding 10 $m.day^{-1}$. Both systems are characterized by a seasonal cycle, with an enlargement and deepening of the main channel during the summer period and a strong shoaling during the winter period.

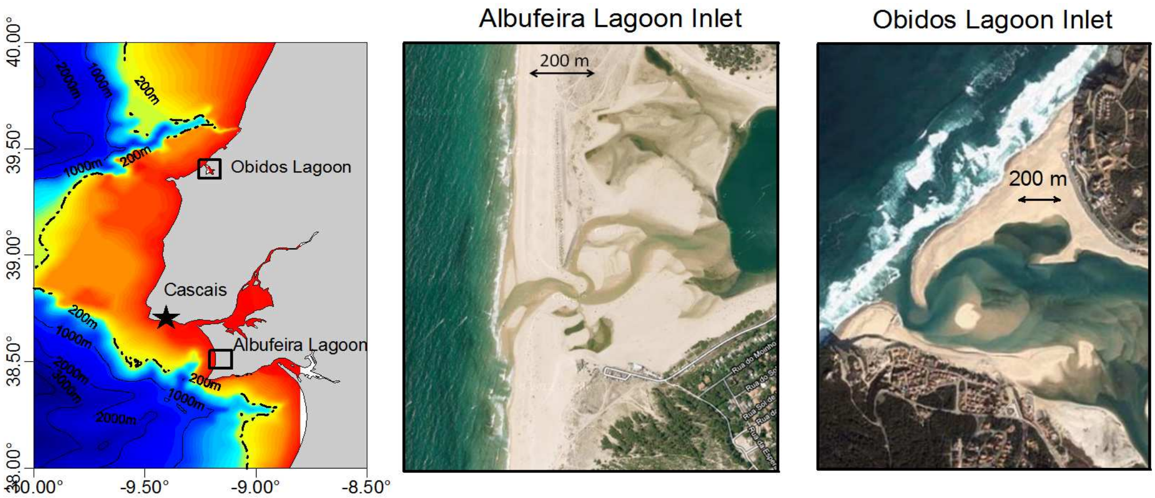

Figure 1. Bathymetric map of the central western coast of Portugal and aerial view of the Albufeira and Óbidos lagoon inlets.

3. Data and methods

2.1. *Field measurements*

At both sites, several field campaigns were carried out over the last decade, where pressure sensors, electromagnetic current-meters and ADCPs were deployed over both the flood and the ebb deltas, in order to characterize wave and tide transformation along their propagation through the inlets. Pressure sensors were also deployed during several months inside the lagoons in order to characterize properly the seasonal evolution of tidal amplitude. Finally, repetitive bathymetric and topographic surveys were carried out to quantify the fast morphological changes observed at both sites. Details on these field measurements and data processing can be found in Oliveira et al. (2006), Bertin et al. (2009b), Dodet et al. (2013) and Fortunato et al. (submitted).

2.2. *Numerical modelling system*

The numerical results presented in this study rely on the modelling systems MORSYS2D (Fortunato and Oliveira, 2004; Bertin et al., 2009b) and SELFE (Dodet et al., 2013; Roland et al. 2012). These modelling systems share the same philosophy and fully couple a spectral wave model (either SWAN, Boiij et al., 1999; or WWMII, Roland et al., 2012), a 2DH circulation model (either ELCIRC, Zhang et al., 2004; or SELFE, Zhang et al; 2011) and a sediment transport/bottom update model (SAND2D, Fortunato and Oliveira, 2004; Bertin et al., 2009b).

The numerical procedure can be seen on figure 2 and includes three main steps:

1-First, the propagation of short waves is simulated using a spectral wave model forced along its open boundary by time-series of spectra originating from the regional wave model of Dodet et al. (2010). The spectral wave model is fed by fields of elevation and currents originating from the circulation model.

2-The horizontal circulation is simulated using SELFE or ELCIRC, which is forced along its open boundary by the 16 main tidal constituents whose amplitude and phase are computed with the regional tidal model of Bertin et al. (2012). A full coupling is achieved with the spectral wave model through gradients of radiation stresses, horizontal viscosity and bottom friction.

3-Sand fluxes are computed based on time-series of currents, water levels and wave parameters by means of total transport empirical formulae (e.g. Soulsby and Van Rijsn, 1997). The Exner equation is then solved using a node-centered finite volume method.

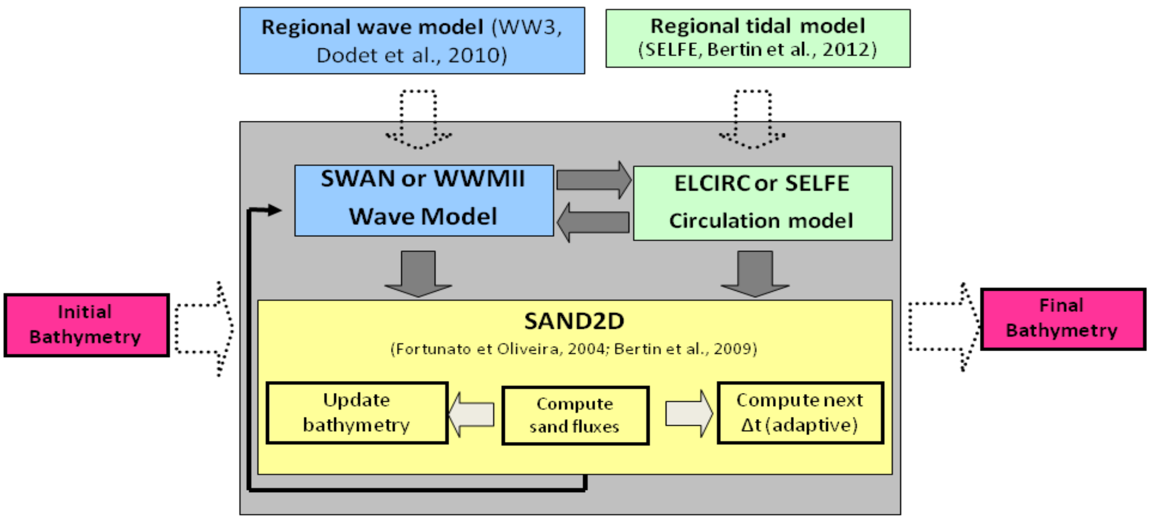

Figure 2. Flowchart of the modelling system procedure.

4. Results and discussion

Previous studies conducted by our team have demonstrated that our modelling system was capable to reproduce waves and currents at the studied sites with a normalized root mean square error (hereafter NRMSE) of the order of 10-15 %. Water levels are predicted more accurately, with a NRMSE of the order of 5 % (Bertin et al., 2009b; Bruneau et al., 2011; Dodet et al., 2013). Morphological predictions have larger errors and their accuracy deteriorates with the duration of the simulation, although the main patterns are reproduced qualitatively. In particular, the enlargement of the main channel during fair weather conditions and its shoaling during winter months are well captured (Bertin et al., 2009a; Bruneau et al., 2011). In some cases, the model can also reproduce the meandering of the channels (Bruneau et al., 2011) and the inlet migration (Bertin et al, 2009). Under these conditions, we made the hypothesis that the dominant physical processes responsible for these morphological changes were well captured by our modelling system. In this section, we present the results of numerical experiments that aim at describing and quantifying these processes.

4.1. Inlet development during fair weather conditions

In order to understand why wave-dominated inlets enlarge during fair weather conditions, we performed synthetic simulations at the Óbidos lagoon under tidal forcing only. We considered simplified tides represented by M2 only, whose amplitude was set to 0.75 m (mean neap conditions) and 1.5 m (mean spring conditions). Time series of water depth at the inlet reveal firstly that tides are strongly distorted at the inlet, with a shorter flood than ebb. This distortion is stronger for spring tides with an ebb duration of 7.5 h and a flood duration of 5.0 h. According to classical theories on tidal distortion for estuaries (e.g. Friedrichs and Aubrey, 1988), longer ebb would result in higher current velocities during flood. Yet, the opposite behaviour is observed at both inlets, with slightly larger velocities occurring during the ebb and lasting more than maximum flood velocities (figure 3-C). This paradoxical behaviour is related to the fact that maximum flood occurs for a water depth twice as large as maximum ebb, which causes ebb currents to be stronger so that mass conservation is ensured. Higher velocities in shallower depth during ebb cause associated sand fluxes to be 1.4 to 2.0 times larger than on flood (figure 3-D). As a consequence, under tidal forcing only, the Óbidos and Albufeira Lagoon Inlets remain strongly ebb-dominated from velocity and sediment transport viewpoints, with a stronger ebb-dominance for spring tides compared to neap tides. This ebb-dominance explains why wave-dominated inlets enlarge during fair weather conditions, when wave-related processes are not dominant.

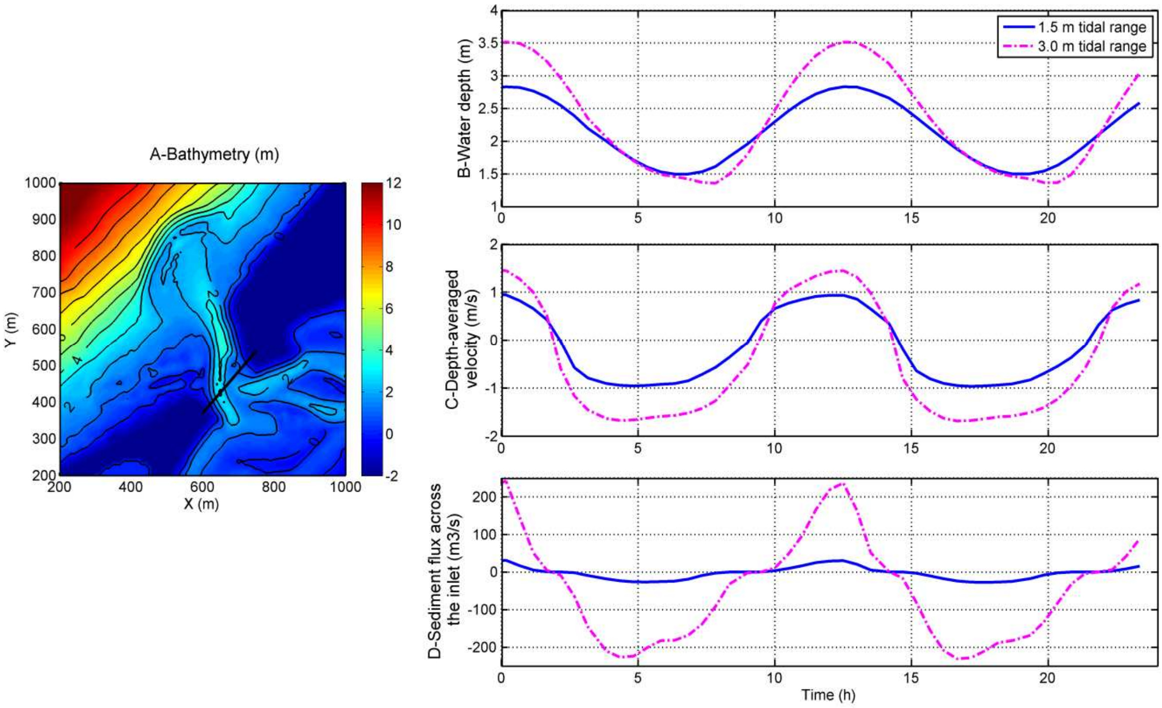

Figure 3. (A) Bathymetry of Obidos Lagoon Inlet in July 2001 showing the profile where model output were averaged, (B) mean water depth acrross the inlet, (C) mean depth-averaged velocity across the inlet and (D) sediment fluxes integrated accross the inlet.

4.2. Inlet shoaling during winter period

4.2.1. *The "bulldozer effect"*

Field observations revealed that wave-dominated inlets in Portugal experience shoaling during winter storms, eventually leading to their closure. In order to understand which wave-related processes can induce the shoaling of wave-dominated inlets during winter storms, we performed a synthetic simulation at the Óbidos Lagoon considering energetic (H_s = 3.0 m; T_p = 12s) shore-normal wave conditions with a 1.1 m tidal amplitude (mean annual tidal range). Figure 4-B shows that wave dissipation over the ebb-delta and at adjacent beaches results in large gradients of radiation stress (wave forces) directed onshore (figure 4-C). These forces induce a setup reaching 0.25 m at adjacent beaches, which itself induces a barotropic pressure gradient. At adjacent beaches, this barotropic pressure gradient nearly balances wave forces (figure 4-F) and the residual forces are very weak. In front of the inlet, large wave forces on the ebb delta are no longer balanced by a barotropic pressure gradient because the wave-induced setup is spread within the lagoon. As a result, a strong residual forcing occurs on the ebb delta, which was referred to as "bulldozer effect" by Hageman (1969). This phenomenon is well captured by our modelling system, which is able to reproduce the migration of ebb-delta sandbars towards the lagoon (not shown here).

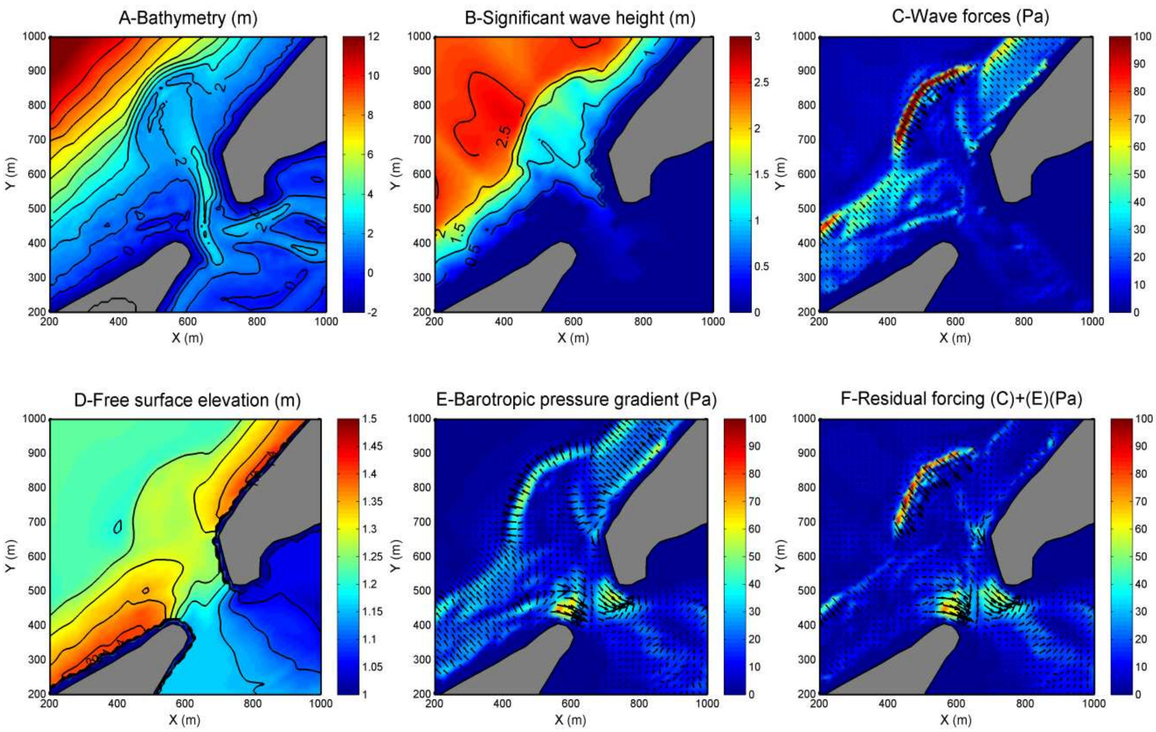

Figure 4. (A) Bathymetry (m), (B) significant wave height (m), (C) wave forces (Pa), (D) free surface elevation (m), (E) barotropic pressure gradient (m) and (F) resultant forces at the Óbidos Inlet for shore-normal offshore waves of Hs = 3.0 m.

4.2.2. *Lateral barotropic pressure gradients*

Figure 4 shows that wave forces induce a setup at adjacent beaches of the order of 10 % the wave height at the breaking point. At the inlet, this setup is interrupted, which induces a lateral barotropic pressure gradient. This barotropic pressure gradient is not compensated by any wave forces so that a strong residual forcing directed towards the lagoon occurs on both sides of the inlet. These pressure forces result in an acceleration of longshore currents towards the lagoon, which tend to push large quantities of sediments into the lagoon. At high tide, this phenomenon is further enhanced by wave refraction over the ebb-delta, which causes wave-induced longshore currents to converge towards the inlet (not shown, Bertin et al., 2009b).

4.2.3. *Wave blocking during the ebb*

A field campaign was carried out at the Albufeira Lagoon Inlet in September 2010 where pressure transducers were deployed on both the ebb and the flood deltas (figure 5-A). A time series of significant wave heights on the flood delta (PT2, figure 5-B) revealed firstly that the wave height inside the lagoon is modulated along the tidal cycle and becomes almost nil at low tide. This behaviour is due to wave energy dissipation by breaking on the ebb delta, which increases as water level decreases. Furthermore, H_s are not symmetrical for a given water level and experience a fast drop when ebb currents start to establish. To better understand this behaviour, the modelling system was run with and without current feedback on wave propagation. Figure 5-B shows that the fast drop in H_s is only reproduced if the feedback of currents in the wave model is taken into account. The modelling results show firstly that waves propagating against currents experience whitecapping dissipation (Dodet et al., 2013). This process is represented in our modelling system following the approach of Westhuysen (2012). Two hours after the beginning of the ebb, wave heights inside the lagoon become almost nil. The analysis of modelled tidal currents reveals that, in the inlet main channel, waves propagate against tidal currents locally exceeding 2.0 m/s. Such large velocities almost correspond to the wave group velocity, which causes the waves to be blocked locally (Dodet et al., 2013).

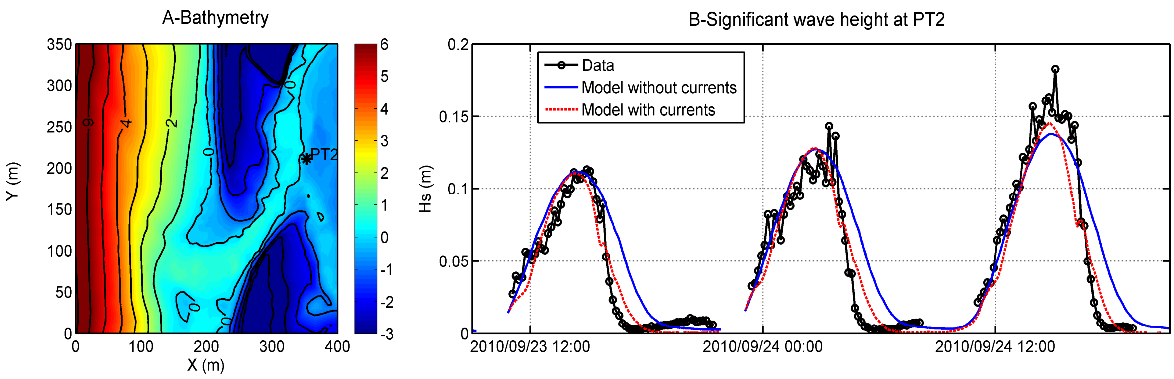

Figure 5. (A) Bathymetry of the Albufeira Lagoon Inlet and (B) measured and modelled time series of significant wave heights on the flood delta in September 2010.

Dodet el al. (2013) investigated the impact of these phenomena on the dynamics of tidal inlets. On flood, the presence of waves superimposed on tidal currents in the main channel increases sediment transport rates. During the ebb, waves are first dissipated by whitecapping, and then blocked, so that the transport capacity of ebb currents is no longer enhanced. Over a tidal cycle, these processes decrease the capacity of the inlet to flush sediments out of the lagoon. Nevertheless, further research is needed to determine whether this conclusion can be extended to other wave conditions and inlet configurations. Further experiments will have to be carried out during more energetic wave conditions and/or at wider inlets, where larger waves can propagate in the main channel.

4.2.4. *Infragravity waves*

A spectral analysis of pressure transducer and current data collected at the Albufeira Lagoon Inlet in September 2010 (figure 5-A) showed that a significant part of spectral energy was found in the infragravity band (0.004 Hz - 0.04 Hz). This low-frequency energy is expressed as low-frequency fluctuations of the free-surface elevation, wave heights and current velocities.

These fluctuations were particularly visible in the measured data at PT2, when comparing the 1-min running averaged with the 60-min running averaged time-series (figure 6). Such oscillations reached up to 10 %, 20 % and 50 % of the 60-min filtered signal, for free-surface elevation, wave heights and currents, respectively. While determining the physical processes that could explain these infragravity fluctuations is beyond the scope of the present study, estimating their contribution to the sediment dynamics of the inlet - aside from the effect of wave-current interactions - appeared to be relevant. In this context, the total transport induced by waves and currents was computed at ECM2, using the Soulsby and Van Rijn formula (Soulsby, 1997), fed on the one hand by the 60-min filtered time-series of elevation, H_s and velocity (the wave orbital velocity was computed using the linear theory) and on the other hand the 1-min filtered time-series that include the low-frequency oscillations. During the third tidal cycle, where low frequency fluctuations were the largest, the total sediment transport was locally up to 8 times as large when taking into account low-frequency fluctuations and 2 times as large when integrated over a tidal cycle. It can also be noted that these low-frequency fluctuations appear mostly during the flood, which suggests that infragravity waves are also damped or blocked by ebb currents. Therefore, in terms of inlet morphodynamics, this behaviour implies that these low-frequency fluctuations rather contribute to fill the lagoon with sediments. This process can play a key role during storms, where it can significantly contribute to inlet closure. However, according to the author's knowledge, it is the first time that the importance of infragravity waves at tidal inlets is demonstrated and thus further research is needed. Namely, comparisons at other sites are required and the implementation of infragravity waves in modelling systems (e.g. Roelvink, 2009) would be a promising perspective.

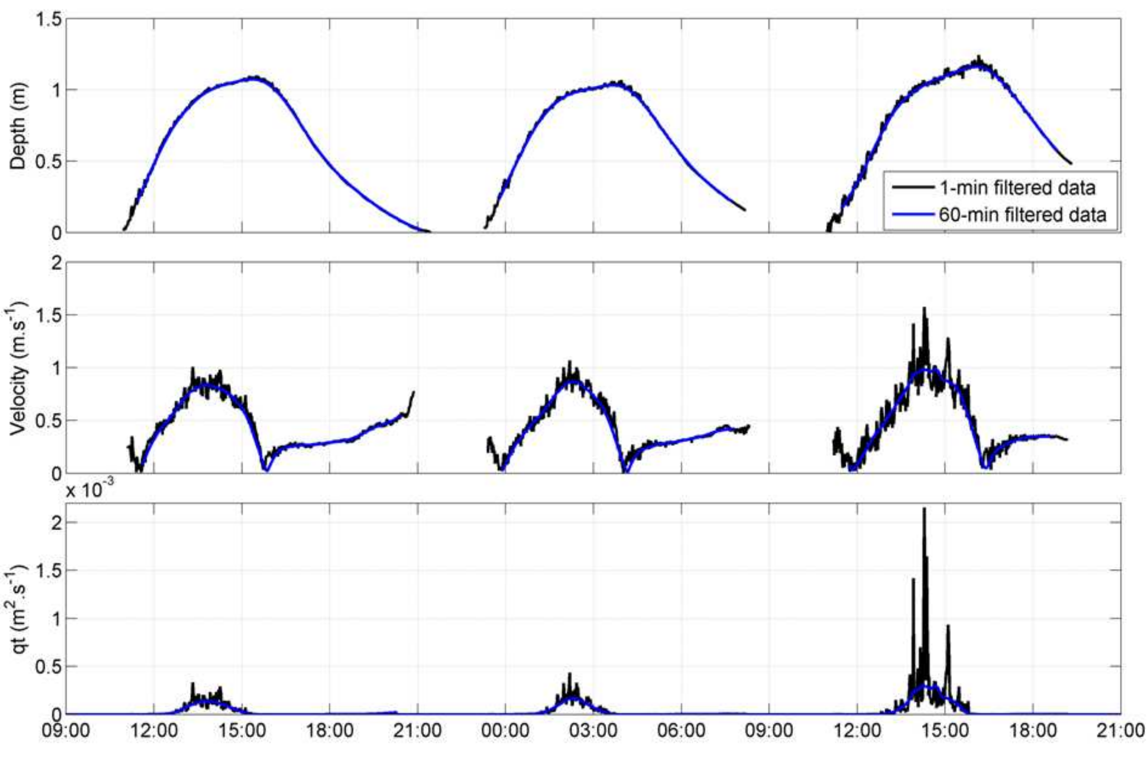

Figure 6. 1-min and 60-min running averaged time-series of water depth, velocity, and total sediment transport (Qt) at PT2 (figure 5).

4.2.5. *Variations in mean-sea level*

Previous studies have shown that at both Óbidos (Bertin et al., 2009b) and Albufeira (Dodet et al., 2013), the setup induced by wave breaking in front of the inlet propagates inside the lagoon and reaches roughly 10 % of the wave height at breaking. Energetic waves and winter storms can thus induce variations of mean sea-level (hereafter MSL) of a few tens of centimetres. Since both inlets are very shallow, such variations in MSL are expected to impact tidal asymmetry and thereby sediment dynamics significantly. To better quantify this phenomenon, morphodynamic simulations were performed at the Óbidos inlet under tidal forcing only and varying MSL between -0.2 m and +0.4 m. Changes in tidal asymmetry were characterized through the ratio between the amplitude of M4 and M2. The impact on sediment transport was characterized through the ratio between the sediments flushed at the inlet during the ebb and entering the lagoon during the flood. Results show that higher water levels reduce tidal asymmetry (figure 7-B), strongly decrease ebb-dominance, and the ratio between ebb ad flood sand transport across the inlet tends to 1 (figure 7-C).

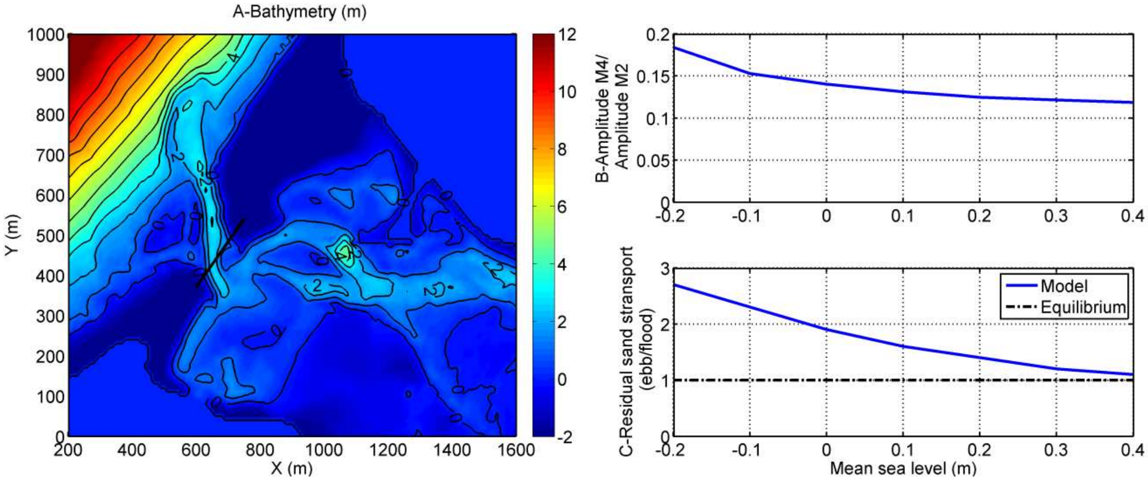

Figure 7. (A) Bathymetry of the Óbidos lagoon with the cross-section where sand transport was integrated, (B) ratio between the amplitudes of M2 and M4 in the lagoon and (C) residual sand transport across the inlet (ebb/flood).

Because floods occur, on average, at higher water levels than ebbs (Fortunato and Oliveira, 2007), the water flows more freely into, than out of, the lagoon. Floods are therefore shorter than ebbs, which would contribute to higher velocities on flood than on ebb. However, mass conservation also implies that the higher water depths on flood reduce the flood velocities relative the ebb currents. While the former process is usually the dominant one in large estuaries and inlets, we found the latter to dominate in our two shallow lagoons. Raising the mean sea level has therefore two opposite effects. On the one hand, the higher water depth in the inlet facilitates the water outflow, thereby reducing the ebb duration and the flood dominance. For instance, the mean water level in the lagoon explains 50 % of the difference between ebb and flood durations in the Albufeira lagoon (Fortunato et al., submitted), which longer floods corresponding to higher mean water levels. On the other hand, the relative differences between the water depths on ebb and flood decrease, which reduces the distinction between ebb and flood velocities due to continuity. This process is illustrated on Figure 7C. Since tidal asymmetry is dominated by the mass conservation effect in shallow lagoons, raising the mean water level reduces the predominance of ebb currents in these systems.

In addition to the wave-induced setup which develops in the nearshore, MSL experiences a seasonal cycle along the west coast of Portugal. A permanent tide gauge is located in the Cascais marina between both studied sites (figure 1). A Demerliac filter was applied to a time series of water level originating from this station and daily and monthly MSL were computed (figure 8). This figure reveals that mean sea-level reaches its maximum in late autumn and its minimum in late winter, with a 0.2 m difference between both. Although outside the scope of this study, investigations in progress in our team show that this seasonal cycle results from the superimposition of atmospheric forcing and steric effects. The Albufeira Lagoon Inlet usually closes in late autumn (e.g. Dodet et al., 2013): it is likely that the decrease in ebb-dominance related to a higher MSL can contribute to inlet closure significantly.

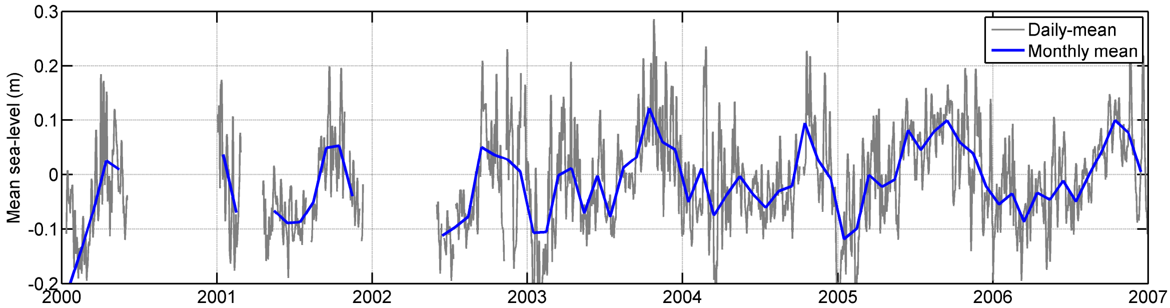

Figure 8. Daily and Monthly mean sea-level in Cascais between 2000 and 2007.

5. Conclusions and future works

This study presented a synthesis of the physical processes controlling the dynamics of wave-dominated inlets and revealed firstly that the inlet development during fair weather conditions was caused by a huge tidal distortion that promotes ebb-dominance. The shoaling or closure of wave dominated inlets was explained by the superimposition of several wave-related processes: (1) the "bulldozer effect" due to the shore-normal component of wave forces; (2) the presence of lateral barotropic pressure gradients, accelerating longshore flows towards the inlet; (3) wave blocking during the ebb; (4) a rise in mean sea level in late autumn and (5) the presence of infragravity waves. While the impact of processes (1), (2) and (4) on inlet morphodynamics were already quantified at the Óbidos Lagoon Inlet, the contribution of wave blocking and infragravity waves remains to be investigated. It is expected that the proper representation of all these processes in our modelling system will allow simulating the closure of wave-dominated inlets.

However, hydrodynamic conditions display relatively modest variations along the West Coast of Portugal so that the physical processes analysed in this study may be partly site-specific. Their importance will have to be investigated at other wave-dominated inlets, such as in SW Australia, South Africa, California and Central and Southern America.

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