Numerical modeling evaluation of the impacts of shrimp farming operations on long-term coastal lagoon morphodynamics

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Abstract

In coastal systems occupied by large clusters of pond aquaculture farms, hydro-sedimentary processes may be impacted by the combination of water management strategies that are individually performed by each cultivation unit. In this study, a numerical model was used to evaluate 100-year morphological alterations in two different idealized coastal lagoons surrounded by shrimp ponds. One is broadly based on the Guaraíras Lagoon System (RN, Brazil) where shrimp farming has developed since 1924 and the other is highly simplified to systematically investigate pond aquaculture impacts. Information obtained through numerical simulations (*e.g.*, hypsometry changes, evolution of morphological parameters, balance of sediment volumes, bed level changes and residual bed shear stress variations) provided coastal impact assessments for a wide variety of aquaculture occupation scenarios. Key findings include: *i*) water exchange operations performed by aquaculture farms are capable of modifying the morphological equilibrium state of a coastal lagoon system, especially if carried out synchronously to the local tidal oscillation; *ii*) water intake operations regularly performed by pond aquaculture activity increase sediment import to the system; *iii*) depth and configuration of tidal channels are modified when pond aquaculture is present. The modelling approach and analyses presented here can be extended to other systems that are under the

influence of shrimp farming activity and be adopted to support novel regulations for the conservation of coastal habitats and to contribute to the sustainable development of pond aquaculture in the coastal zone.

Keywords: *coastal aquaculture management; hydro-morphodynamic modeling; shrimp farming; coastal impact analysis*.

1. INTRODUCTION

1.1. Pond aquaculture interference in coastal environments

Coastal lagoons and tidal basins provide important ecosystems, which usually host many valuable species and create opportunities for the development of essential socioeconomic activities. Predominantly in Latin America and Asia, but also in other parts of the world, marine aquaculture has grown significantly, occupying extensive coastal lands around brackish water bodies (Bostock et al. 2010; White et al. 2013; FAO 2018). Such aquaculture occupations may form large clusters of excavated ponds, holding significant volumes of water. This is the case of shrimp farms in many estuarine environments in the Northeastern coast of Brazil and elsewhere, especially in Southeast Asia, India and China, where aquaculture ponds may cover an area of hundreds of km^2 along the coast. For example, Ottinger et al. (2017) recently reported on the total aquaculture area in the Mekong, Red River, Pearl River and Yellow River Deltas, amounting to 2,659, 299, 1,050 and 863 km^2, respectively. As an additional illustration, Steinmetz (2016) has captured a video for National Geographic which shows unambiguously how vast the area for aquaculture can be, a business which reached US$ 19.4 billion in 2017, only for prawn trade between Europe and Asia.

Typically, the extension of the total aquaculture area installed around shallow coastal lagoons is comparable to the water surface of the lagoon itself (Roversi et al. 2017). Therefore, one might expect that the volume of water exchanges between all ponds and the estuary is significant, depending on the management procedures. Two situations may arise: large pond areas belong to one single owner, who controls and/or optimizes the intake and discharge of several ponds, or several small ponds belong to a multitude of individual owners, each one with a different purpose and management practice. Discharge of large amounts of effluents from the ponds into the estuaries in Southeast Asia has proven to be catastrophic to the production as well as to the environment. For instance, one farm in Thailand, established in an area of 80 km^2, employing around 9,000 people and producing 58,000 t of shrimp per year, collapsed the whole shrimp production in the region because the volume and quality of pond effluents were far above the assimilative capacity of the estuary (Primavera 1994). In Brazil, legislation does require EIA (Environmental Impact Assessment) for large shrimp farms but does not impose any restriction to the owner of smaller ponds up to an area of 10 ha. Hence, it would be reasonable to question what might be expected if combined water management operations would be performed simultaneously by many small ponds. This includes investigating whether many intakes and discharges around the lagoon could effectively modify the local tidal circulation, resulting in morphological changes within a time span of the order of 100 years as this is an adequate timescale for sustainable coastal management.

A clear understanding on the morphodynamic behavior of these complex environments requires extensive, careful, methodical and expensive observations (*e.g.*, Callaghan et al. 2010; Wang 2018). Yet, such knowledge is essential to develop appropriate water usage and coastal management policies, in order to guarantee the sustainability of human activities in the coastal zone. At the same time, the very concept of “morphodynamic equilibrium”, as it has been discussed by Zhou et al. (2017), can be neither easily nor precisely quantified. These authors argue about the “permanency of the change”, which is caused by the continuous evolution of the natural agents (sea level, river discharge, sediment availability, human interventions) and present three possible definitions of equilibrium as applied to coastal morphology. This is a timely discussion in the framework of climate changes and increasing anthropogenic pressures, within the time scale of 100 years.

Various studies have demonstrated that process-based models are powerful tools to analyze the long-term morphological evolution of coastal systems (Roelvink and Reniers, 2012; Coco et al. 2013) and are capable to provide relevant information to decision making. The concepts presented by Zhou et al. (2017) are relevant for evaluating the behavior of these numerical models (virtual world) as compared to the actual environment (real world).

Despite concerns that human interventions can modify tidal circulation and sediment transport patterns, playing a relevant role in the morphological evolution of coastal systems (Kjerfve 1994; Zhao et al. 2018), only a limited number of morphodynamic modeling studies have focused on the long-term effects of anthropogenic pressures. Zarzuelo et al. (2018) recently used a morphodynamic model to simulate the effects of dredging a navigation channel and building a bridge and a port terminal at the Cádiz Bay, Spain. Their findings emphasized the usage of hydrodynamic information, such as tidal asymmetry and residual currents, to provide insights into short- and long-term bathymetric changes induced by human interventions. Other long-term modelling studies include assessing the impacts of enhanced sediment supply generated by hydraulic mining (van der Wegen et al. 2011), reduced river discharge and sediment supply through water diversion and dam building (Luan et al. 2017) and land reclamation (Xie et al. 2009; Nnafie et al. 2018). However, the impacts of aquaculture activities, and in particular shrimp farms, have so far been unexplored.

Fig. 1 Top: Evolution of the shrimp farming activity occupation (emphasized in orange) around the Guaraíras Lagoon System, RN, Brazil, since 1985, by Landsat images (https://landsat.usgs.gov/). Bottom: Sentinel-2 satellite image (https://sentinel.esa.int), from 23/05/2017, acquired at low tide, showing the current pond areas around the system. Band combination adopted in all images displayed (RGB compositions): SWIR - Short-wave Infrared / NIR - Near Infrared / Blue

1.2. Study aim and approach

The aim of this study is to evaluate 100-year changes in the morphological evolution of coastal lagoon systems surrounded by land-based aquaculture pond (shrimp) farms. These findings are derived using a process-based model to simulate hydro-morphodynamical effects generated by specific scenarios of aquaculture management and occupation. Despite the environmental complexity of these systems, which can be characterized by the traditional tide-wave-river ternary diagram (e.g. Zhou et al., 2017), the present investigation focuses solely on tidal forcing and the impacts of the water exchanges between the ponds and the lagoon, which is assumed to be shallow and well mixed.

Insights are obtained from idealized numerical experiments that incorporate typical choices of water management operations for shrimp farm ponds. Two idealized cases are considered with different lagoon geometries and forcing conditions. The Guaraíras Lagoon System in Brazil (Fig. 1), where shrimp farms have bloomed over the last few decades, inspired one of the modelled lagoons. Here conflicts between policy makers, environmental officials and fishermen emerged regarding the impacts that shrimp farm activity may bring to the aquatic environment. As observational data on hydro-sedimentary processes and detailed bathymetric information for this lagoon is lacking, a direct data-model comparison is not possible. Therefore, an idealized modelling approach, while maintaining the geometry of the Guaraíras Lagoon and incorporating available information on the evolution of shrimp farming activity, is most appropriate. This also allows investigating the effects of aquaculture pond activities on morphodynamic behavior over large spatial and temporal scales (Roelvink and Reniers 2012). At the same time, from a more scientific point of view, it would be necessary to address more general questions, to test diverse combinations of pond area/volume relative to the lagoon's area/volume and to experiment with different water management procedures. By doing so, it would be possible to broaden the results and develop more general insights. For this reason, another idealized model of a lagoon, which had already been used in other process-based modelling studies, was adapted to include shrimp farms along its contour.

Therefore, the present investigation focuses on two numerical models: one that brings some resemblance with the Guaraíras Lagoon, but it is idealized, and a second truly hypothetical lagoon, which establishes connection with other studies in the literature, and which proved useful to draw broader conclusions.

1.3. Water management in aquaculture pond farms

Aquaculture pond management involves the following stages during a cultivation cycle:(*i*) pond preparation/conditioning, (*ii*) stocking (*e.g.*, fish fingerlings or shrimp post larvae addition), (*iii*) feeding/fertilization, (*iv*) water management, (*v*) pond maintenance, and, (*vi*) harvesting (Baluyut 1989). Hydrodynamic interactions between the pond system and the adjacent estuary/coastal lagoon/tidal stream occur primarily in the following stages: (*i*) when the pond is dried, treated and filled with estuarine water; (*iv*) when pond water is drained to, and/or estuarine water is taken from, the adjacent body of water in order to keep certain water level and/or water quality condition within the ponds; and (*vi*) when the cultivated organisms have reached an expected size, the pond is totally drained and the harvesting effluent is released to the estuary. Water exchanges with the adjacent water body (phase iv) is performed during the entire cultivation period, which may take several months to complete, depending on the growth rate of cultured species, final weight desired and marketing strategies (Stickney 2000).

Most marine aquaculture farms require daily estuarine water intake in order to control water losses due to evaporation and seepage in the ponds (Tidwell 2012; Stickney 2000). Such operation can be carried out continuously by mechanical pumping, or intermittently by gravity according to tidal flow. In the intertidal zone, pump operation may be restricted to time intervals when water column reaches a minimum height at the intake location (Fast and Lester 1992). Taking estuarine water during flood tide cycles also ensures more adequate water quality conditions for aquaculture farming, *e.g.*, higher salinity levels, lower suspended particle concentrations, and reduced fluvial load influence. Generally, total water loss rates are around 5%/day (Chien 1992; Verdegem and Bosma 2009). In cases of very permeable soils (or not well-constructed ponds) and high evaporation in tropical areas, pond water losses can be greater than 7%/day (Fast and Lester 1992).

During the cultivation period, critical water quality parameters, *e.g.*, salinity, temperature and dissolved oxygen levels, may drastically fluctuate inside the ponds as a result of weather changes. Moreover, unconsumed feed loads and individuals' excretion may continuously accumulate and pollute the cultivation environment especially in intensive culture systems (Baluyut 1989). In order to prevent water quality deterioration inside the pond, to remove excess metabolites and to ensure optimal growth of the culture organisms, some farms perform water exchange operations. Thus, pond water may be continuously or intermittently renewed by the entry of new water, while old pond water is drained to the estuary. Average daily water exchange rates range between 5%/day and 50%/day (Fast and Lester 1992), depending mainly on culture intensity and environmental conditions (Tidwell 2012; Santhanam et al. 2015).

2. METHODS

2.1. Numerical model description

In this study, the Delft3D hydro-morphodynamic model (Lesser et al. 2004) was applied to simulate the 100-year morphological evolution of both a conceptual half-circular lagoon and an idealized coastal lagoon in Brazil, with some geographical resemblance with Guaraíras (Fig. 1), both subject to aquaculture activity with a variety of water management procedures. This model has been previously shown to be capable of successfully simulating long-term morphodynamic behaviour of tidal systems (*e.g.*, van der Wegen et al. 2008; Dastgheib et al. 2008). Here the Delft3D-FLOW module was used to solve the depth-averaged (2DH) continuity and momentum equations for an incompressible fluid, under the shallow water and the Boussinesq assumptions (Deltares 2017). The hydrodynamic module allows for the inclusion of source and sink terms in the continuity equation to represent water intakes and discharges performed by aquaculture installations. Computed flow fields are then coupled to a sediment transport model. In this research the Engelund and Hansen (1967) formulation was adopted to estimate the total load transport. Bed level changes are based on the sediment mass balance at each grid cell, and result from the gradients in sediment transport rates. To facilitate long-term morphological simulations, a morphological acceleration factor was applied to increase the rate of bed level changes by a constant factor in each time step (Roelvink 2006). The model domain was discretized by a rectangular grid to solve the system of partial differential equations using the finite differences numerical method. A more extensive description of the model is presented by Lesser et al. (2004).

2.2. Model set-up of reference simulations

Process-based models, as any scientific investigation tool, need to be carefully tested, so that the modeler can carefully interpret the results. In this sense, the knowledge about the actual Guaraíras Lagoon turned out to be useful to understand the characteristics and the capabilities of the numerical model itself. For this reason, the set-up is described first for the idealized Guaraíras Lagoon, and then for the conceptual lagoon, which is oriented to broader questions.

For both cases a reference simulation was carried out to represent the morphological evolution of each coastal system over a period of 100 years, without any anthropogenic interference. In these experiments, the only major forcing mechanism to shape the coastal lagoon morphology in regular hydrodynamical conditions was the astronomical tide. Other processes such as waves and river discharges were disregarded.

Both model domains were discretized by a regular grid with 50 m resolution and the time step was set to 1 minute. This choice was based on numerical experiments which were conducted with the conceptual tidal lagoon, as explained in Section 2.2.2. As initial condition, an idealized flat bathymetry with 2 m depth was prescribed for the interior of the lagoons, and a random perturbation between -1.0 and +1.0 cm was added to the depth value at each grid point to trigger channel pattern formation (van Maanen et al. 2013a). Bottom roughness was uniformly defined by a Chézy coefficient, which was set to 65 $m^{1/2}/s$ as adopted in previous studies (Marciano et al. 2005; Dastgheib et al. 2008; van Maanen et al. 2011). To enhance morphological changes, the morphological acceleration factor was set to 100 which is within the range of values adopted in the literature (Dastgheib et al. 2008; van der Wegen et al. 2008; Dissanayake et al. 2009).

2.2.1. Application to the idealized Guaraíras Lagoon

The Guaraíras Lagoon System, located on Brazil’s Northeast coast (Fig. 1), is composed by three interconnected lagoons, Guaraíras, Papeba and Nísia Floresta. Originally, the inlet was a 10 km long narrow channel which connected Nísia Floresta Lagoon to the sea at a location about 10 km North from the present position. Guaraíras, being the farthest one from the former inlet, used to be a freshwater lagoon. The system’s history is marked by an exceptional rainfall period that started in 1923, raising the water level inside the Guaraíras Lagoon to an abnormal elevation. In order to release water from the lagoon to the ocean a narrow channel (about 15 m wide) was urgently dug. However, in April 1924 a second storm brought more runoff water from the to the lagoon, which resulted in the overnight widening of the channel to 100 m, the destruction of the small village of Tibau do Sul, and the formation of a permanent tidal inlet across the dune barrier, which has widened to 350 m since then and has remained active up to now. This opening triggered a broad transition in the ecosystem: the original inlet channel closed, the salinity in Nísia Floresta Lagoon gradually decreased, a dam was built to avoid salt water penetration to Papeba Lagoon, and Guaraíra turned from a freshwater lagoon to an estuarine environment, thus favoring the later development of local shrimp farming activity (Roversi et al. 2017; Roversi 2018). The local aquaculture growth concomitant with the system's morphological evolution makes this coastal system a relevant test case for the methodology proposed here.

The implementation of the Guaraíras model (**Error! Reference source not found.**b) used bathymetric data of the adjacent coastal region, obtained from Nautical Charts of the Brazilian Navy (www.marinha.mil.br/chm). Model domain boundaries were extended up to 2.5 km offshore nearby the 10 m isobath, and inside the basin boundaries were constrained by shorelines, channels' margins and mangrove edges, mapped through Sentinel-2 satellite images (Fig. 1). In order to represent a realistic tidal oscillation, 34 tidal constituents from the global tide model FES2014 (Lyard et al. 2016) were prescribed in each grid cell along the offshore boundaries. A uniform 10 m thick sediment layer, characterized by D_{50} = 200 µm, was defined in the entire model domain.

2.2.2. Conceptual lagoon

The implementation of the conceptual lagoon model considered an idealized sandy bottom tidal basin, configured by a semi-circle geometry with radius approximately 6 km, connected to the sea through a 2.8 km wide inlet (**Error! Reference source not found.**a). Such a configuration was broadly applied in previous modeling experiments focusing on morphological pattern development and tidal basin behavior (Marciano et al. 2005; van Maanen et al. 2011; Coco et al. 2013; van Maanen et al. 2013a; van Maanen et al. 2013b; Jimenez et al. 2014a; van Maanen et al. 2015). Along the coastal sea area, depth was increased from 2 m up to 8 m. Bottom sediment was composed by fine sand, D_{50} = 120 µm, within a uniform layer of 10 m thickness. At the offshore boundary a semidiurnal sinusoidal tide (M2 constituent) with 1 m amplitude was prescribed.

Using this conceptual lagoon model, we tested the sensitivity of simulated channel networks to grid size and time steps. In the end, a 50 m grid was adopted as such a resolution is typically applied in morphodynamic modelling studies (Jimenez et al. 2014a; Jimenez et al. 2014b; Zhou et al. 2015). Also, based on this setting, properties from the final simulated channel network (*i.e.*, channel drainage width) were comparable with those reported in van Maanen et al. (2013a), van Maanen et al. (2013b) and Marciano et al. (2005). For the chosen grid resolution, a time step of 1 minute proved to be most appropriate as time steps greater than 1 minute generated numerical instabilities and smaller values (*e.g.*, 0.5 minute) did not effectively change model results.

Fig. 2 Computational model domains and the location of aquaculture operations: **a)** Conceptual lagoon (water intakes and discharges, following practices *A*, *B* and *C*, were prescribed in the black points); **b)** Idealized Guaraíras Lagoon System (total flow rates for each region of the system, as shown in Fig. 3, were distributed over the colored points following the same color classification). Bed levels represent initial morphologies prescribed for each case

2.3. Evaluation of different aquaculture scenarios

Based on the model set-up of reference simulations, which ignored any interference from aquaculture (Section 2.2), additional scenarios were implemented to evaluate potential changes in the long-term morphological evolution caused by different water management operations that are usually performed by shrimp farms.

2.3.1. Scenarios for the idealized Guaraíras Lagoon

For the Guaraíras case, two evaluation scenarios were developed, named *G1* and *G2*, which differ in the temporal variation of aquaculture operations intensity, as follows:

G1) *Constant operation:* Constant water intake rates along the full simulation period is assumed, considering the current aquaculture occupation in the region.

G2) *Real operations:* The development history of the shrimp farming activity in the region is considered. Time series of water intake rates were calculated for each main lagoon, based on pond area growth (Fig. 3).

Fig. 3 Time series of water intake rates proportional to the shrimp farming activity occupation. Growth is based on the occupation history around the main water bodies that form the Guaraíras Lagoon System. In 1970, pond areas were mapped by aerial photogrammetry. From 1985 to 2016, pond areas were mapped by Landsat satellite images. From 1924 (lagoon bar breach) to the first records for each locality, data were linearly interpolated. From 2016 to 2024, areas were extrapolated with constant values

Both consider a continuous water intake of 7%/day (Fast and Lester 1992) as a typical water level control operation adopted by producers to compensate seepage and evaporation losses in the ponds (see Section 1.3). The volume of water stored within the farms was estimated through the pond area mapped by remote sensing analysis (Fig. 1), multiplied by a mean water column of 1.2 m, as this represents the average pond depth in Guaraíras. Water intake rates were distributed over 126 grid cells (**Error! Reference source not found.**b) based on the occupation distribution in the region.

Model results were evaluated in terms of bed level changes in Guaraíras Lagoon (main water body of the system), comparing final morphologies achieved by scenarios *G1* and *G2* to the reference scenario's final morphology, and by comparing time series of sediment volume stored in the lagoon for each scenario simulation. Hydrodynamic effects generated by the aquaculture operations were analyzed through the comparison of residual bed shear stress maps.

2.3.2. Scenarios for the conceptual lagoon

The use of a conceptual modelling domain allows easy modification of boundary conditions and aquaculture strategies, so that the impacts of human activities can be systematically explored. In this study, three different types of typical water management operations combined with three levels of aquaculture occupation were proposed for analysis, producing a total of nine evaluation scenarios. Based on consultation with shrimp farmers in Guaraíras, three water management practices were considered, which are also applicable to other regions in the world (Fig. 4):

A) *continuous water intake of 5%/day* (usual water quantity control);

B) *intermittent water intake of 5%/day* - performed only when water level is above mean tide (usual water quantity control, with operation restricted by tidal oscillation);

C) *water exchange of 25%/day synchronized to the tidal oscillation added to practice B*, *i.e.*, estuarine water intakes and pond water discharges are only performed when water level is above and below mean tide, respectively (usual water quality and quantity control, with operation restricted by tidal oscillation).

Variations in occupation levels were represented by the total volume of water held by all farms, considering different values proportional to the local tidal prism (1.25×10^{8} m³): *50%*, *100%* and *200%*. These values represent a realistic range of occupation levels observed in coastal areas around the world (Roversi 2018). Fig. 4 illustrates the total water intake and water discharges, generated by an overall occupation level of 50% of the tidal prism. The total water flow rate was distributed over 132 grid cells, equally spaced along the margins of the conceptual lagoon (**Error! Reference source not found.**a), generating a time series of water flow rate for each point.

Fig. 4 Time series of total discharge generated by the proposed water management operations (colored lines). Positive values indicate water intake and negative values indicate water discharge. Gray line represents water level oscillation in the domain

Alterations by aquaculture activity on the conceptual coastal lagoon morphology were evaluated in terms of: final tidal basin hypsometry, evolution of morphological parameters relevant to classical equilibrium relationships, changes in sediment volumes of coastal sea and tidal basin areas, and the formation of intertidal areas and tidal channels. Hydrodynamic alterations were analyzed in terms of: ratio of peak ebb and peak flood velocities at the inlet and residual bed shear stress maps. Results obtained for each proposed scenario were compared to the reference simulation.

3. RESULTS

Contrary to the previous section, here the description of results will first be directed to the conceptual tidal lagoon, assuming that this case is more appropriate to develop general insights, and then focus on the more restricted case, related to the idealized Guaraíras Lagoon application.

3.1. Reference simulation for the conceptual lagoon

After 100 years of simulation, the initially flat bathymetry has evolved to a channelized tidal basin with intertidal areas (Fig. 5a). Two deep channels formed through the entrance of the inlet and an ebb tidal delta developed in the offshore area. Theoretical analyses, such as the one described by Dronkers (1998), prescribe that under equilibrium conditions the basin geometry satisfies the following relationship:

$$\left(\frac{\mathrm{h_{HW}}}{\mathrm{h_{LW}}}\right)^2 = \frac{\mathrm{A_{HW}}}{\mathrm{A_{LW}}} \qquad (1)$$

where $\mathrm{h_{HW}}$ and $\mathrm{h_{LW}}$ are the averaged channel depths at high and low water; and $\mathrm{A_{HW}}$ and $\mathrm{A_{LW}}$ are the total basin areas inundated at high and low water. Morphological change is more accentuated at the beginning of the simulation as the initially flat basin is far from equilibrium (Fig. 6). Especially during the first 30 years, the formation and deepening of channels causes a decrease in $\mathrm{h_{HW}/h_{LW}}$. At the same time, $\mathrm{A_{HW}/A_{LW}}$ increases due to the development of intertidal areas. Morphological activity slows down once the tidal basin gets closer to equilibrium and after 100 years the simulated tidal basin has attained a geometry that nearly approaches Dronker’s (1998) equilibrium relationship (Fig. 6). Similar tendencies are observed when the simulated morphological evolution is compared to other available equilibrium relationships for tidal basins (see Zhou et al. (2018) for an overview), further confirming that morphodynamic adjustment is first rapid and then slows down. Large-scale bathymetric changes can also be visualized by the hypsometric curve (Fig. 5b), which after 100 years has approached the typical sigmoidal shape usually observed in nature (Boon and Byrne 1981). Again, hypsometric changes show erosion and formation of tidal channels accompanied by deposition and the formation of intertidal areas.

Fig. 5 a) Reference scenario morphology after 100 years and **b)** its respective hypsometric curve. Hypsometry describes the tidal basin area that would be submerged at different water levels. Values were scaled from 0 to 1, proportional to the maximum area, *i.e.*, relative to the submerged area at high water level

Fig. 6 Evolution of morphological parameter ratios for the reference scenario simulation. Diagonal dashed line represents a theoretical equilibrium relationship, adapted from Dronkers (1998). Vertical color scale indicates simulation time. The gray dots correspond to measurements of natural tidal basins presented by Dronkers (1998)

3.2. Impacts of aquaculture activity on the conceptual lagoon

3.2.1. Morphological effects

Final morphologies of the nine evaluation scenarios, obtained after 100 years of simulation, are shown in Fig. 7 by means of bed level maps. Channel patterns produced by water management types *A* and *B* (representing water losses compensation only) are generally similar to the reference scenario, whereas water management type *C* (which also considers water exchange) produced distinct morphological characteristics. The increase of aquaculture occupation enhanced landward expansion of the tidal channel network and intertidal area development for the cases of water management types *A* and *B*, generating deeper tidal channels near the margins of the coastal lagoon. An opposite effect was observed for water management type *C*. For this case the increase of aquaculture occupation resulted in a less extensive channel network in the tidal basin, while a more pronounced ebb delta in the coastal sea area formed instead.

The bed level maps discussed so far provide a rather qualitative picture on the effects of aquaculture activity. A more quantitative analysis is provided by an overall sediment volume balance in the tidal basin and in the coastal sea area (Fig. 8), and trends in the development of intertidal areas and tidal channels, both in terms of areas and volumes (Fig. 9). The intertidal area is defined here as the difference between the submerged area at high water and low water. The intertidal volume refers then to the sediment volume stored between low water and high water. Tidal channel area and volume correspond to the water surface at low water and to the water volume below low water, respectively.

As shown in Fig. 8, in most cases the sediment volume from the coastal sea area is decreased and sediment is imported to the tidal basin throughout the simulation. After 100 years, the reference scenario simulation shows a net sediment importation of 1.9×10^{7} m^{3}, which corresponds to an increase of 0.3 m in mean tidal basin bottom elevation. Intertidal surface area increased for the reference simulation by a total of 2.5×10^{7} m^{2} and tidal channel area was inherently reduced by the same proportion (Fig. 9a). Intertidal volumes increased for all scenarios and showed similar trends as the development of intertidal areas (compare Fig. 9a and 9b).

Although the different scenarios vary in terms of the magnitude of change, all of them reveal qualitatively similar trends, except scenario *C200* (water management type *C* with an aquaculture occupation level of 200%) that reached a contrasting net sediment balance after 65 years (Fig. 8). In general, sediment importation occurred throughout the entire simulation and this was increased by the operations of water intake for losses compensation (scenarios *A* and *B*) but reduced when applying water exchange operations (scenarios *C*). Scenario *A200* corresponded to the largest increase in final net sediment importation. It elevated the mean tidal basin height by 0.05 m (Fig. 8b) relative to the reference scenario. Continuous water intake operations (scenarios *A*) thus implicate a greater sediment importation than intermittent water intake operations (scenarios *B*) despite the same total daily discharge considered.

Also, a contrasting trend in tidal channel volume (Fig. 9b) is observed for scenario *C200*; while tidal channel area (Fig. 9a) and intertidal volume (Fig. 9b) rapidly reached constant values, tidal channel volume grows through the entire simulation, indicating that tidal channels are continuously deepened and sediment from these channels continues to be exported from the tidal basin to the coastal sea area. In the other cases, the volumes of tidal channels generally decreased rapidly within the first 5 years of simulation but then stabilized after approximately 20 years (Fig. 9b).

Fig. 7 Model domain bed levels after 100 years of morphodynamic evolution. The nine evaluation scenarios considered the combination of different water management practices with different aquaculture occupation levels

Fig. 8 Changes of total sediment volume stored **a)** in the coastal sea area and **b)** in the tidal basin for each simulated scenario. Values indicated on the y-axis correspond to the volumetric difference related to the initial bathymetry. Right y-axis of graph b indicates the corresponding change in mean elevation of the tidal basin

Fig. 9 Changes of **a)** areas and **b)** volumes of intertidal flats (solid lines) and tidal channels (dashed lines) related to the initial bathymetry

To facilitate the comparison between the final morphologies, the tidal basin hypsometric curve for each evaluation scenario was determined (Fig. 10a). Fig. 10b illustrates the effective hypsometric changes for each scenario related to the reference scenario. Negative changes indicate that the total submerged area became smaller at a certain water level, *i.e.*, bathymetry became more elevated when compared to the reference scenario. Positive changes indicate an increase in the submerged area at a given water level.

Scenarios *A* and *B* present the same tendency to increase the proportion of bed levels that occurs above -2.0 m and simultaneously increase the area of the channels below that. However, scenario *C* has the tendency to keep morphology underdeveloped, as observed that hypsometry remains closer to the initial condition as occupation rises. The mainly positive changes observed above the -2.0 m level for scenarios *C* (Fig. 10b) indicate an increase of submerged areas, highlighting the reduced intertidal area formation, compared to the reference simulation.

Fig. 10 a) Final hypsometric curves for each scenario. Dashed line represents the hypsometry of the initial condition (flat bathymetry). **b)** Effective changes in the hypsometric curve related to the reference scenario's final hypsometry

Evaluating the final values of the morphological equilibrium parameter ratios (Equation 1) for each simulation, it can be observed that scenario *C* results in final morphologies being farther from the theoretical equilibrium condition, whereas scenarios *A* and *B* are closer to the reference simulation and approach more closely the equilibrium condition (Fig. 11).

Fig. 11 Final values of morphological parameter ratios for each scenario. Diagonal dashed line corresponds to a theoretical equilibrium relationship, adapted from Dronkers (1998). Gray dot in bottom right corner indicates the position where all scenarios started from

3.2.2. Hydrodynamic effects

Alterations in hydrodynamics were first analyzed in terms of cross-sectional averaged velocities through the tidal inlet during a tidal cycle. Fig. 12 shows a comparison of velocity vectors at respective tidal levels for the reference scenario in the initial (left) and in the final morphological condition (right). A strong tidal wave distortion was observed at the beginning of the simulation, marked by a slow rise and a faster fall of the tide, which then transitions into a more regular tidal wave shape (sinusoidal) in the end. It is noticed that the difference between flood and ebb durations decreases over the simulation period, and slack water moments get closer to high and low tides. During the initial condition, flood duration is 2 h and 12 min shorter than ebb duration, whereas, in the final condition such difference is reduced to 42 min. Current velocities decrease over the simulation period, which is a consequence of inlet erosion and increase of the cross-sectional area. In the beginning, maximum flood and ebb velocities are 1.45 m/s and 1.15 m/s, respectively; in the end maximum flood and ebb velocities are 0.49 m/s and 0.42 m/s, respectively (Table 1).

Fig. 12 Cross-sectional averaged velocities through the tidal inlet for the reference scenario simulation. Values extracted at the beginning of the simulation (left), considering the initial bathymetry prescribed (Fig. 2a), and at the end of the simulation (right), after 100 years of morphological evolution

Examining these velocity curves for each scenario, it was observed that peak current velocities during flood tide are always higher than during ebb tide, which confirms the system's flood dominance that was previously assessed through sediment budget analysis. Comparing the ratio between flood and ebb peak velocities for each scenario (Table 1), it was found that such flood dominance was increased when applying scenarios *A* and *B*, but decreased when applying scenarios *C*. Scenario *C200* even produced an ebb dominant condition by the end of the simulation (Flood/Ebb peak velocity ratio < 1).

Table 1 Peak velocities during flood and ebb tide. Values correspond to cross-sectional averaged velocities through the tidal inlet, obtained during the initial and the final morphological condition for each simulation. Flood/Ebb peak velocity ratio provides an indication of the intensity of flood (>1) or ebb (<1) dominance

Peak velocities (m/s)	Initial condition			Final condition		
	Flood	Ebb	Flood/Ebb*	Flood	Ebb	Flood/Ebb*
Reference scenario	1.45	1.15	1.26	0.49	0.42	1.17
Scenario A50	1.45	1.14	**1.27**	0.49	0.42	**1.18**
Scenario A100	1.46	1.14	**1.28**	0.49	0.41	**1.19**
Scenario A200	1.47	1.15	**1.30**	0.50	0.41	**1.21**
Scenario B50	1.45	1.15	**1.26**	0.49	0.42	**1.17**
Scenario B100	1.45	1.14	**1.27**	0.49	0.41	**1.18**
Scenario B200	1.45	1.13	**1.28**	0.48	0.40	**1.21**
Scenario C50	1.39	1.14	*1.22*	0.47	0.41	*1.16*
Scenario C100	1.34	1.15	*1.17*	0.48	0.43	*1.14*
Scenario C200	1.27	1.16	*1.10*	0.63	0.65	*0.97*

***** Flood/Ebb peak velocity ratio: **higher** or *lower* than the reference scenario

Spatially distributed hydrodynamic changes in the entire model domain were investigated in terms of residual bed shear stress maps calculated over one tidal cycle. Bed shear stress is an appropriate parameter for analysis as it is directly dependent on flow velocity and directly influences sediment transport rates and thus morphological change.

In order to isolate the effect of water management operations, we calculated the differences between residual bed shear stress found in each evaluation scenario and the residual bed shear stress found in the reference scenario. Fig. 13 shows residual bed shear stress differences resultant from each water management type (*A*, *B* and *C*) considering the same occupation level (100%). Scenarios *A* and *B* amplified residual bed shear stress vectors pointing to the interior of the coastal lagoon, which represents the enhanced sediment import caused by the water intake performed by aquaculture farms. Vectors from scenario *B* are weaker than scenario *A* due to the intermittent operation. Scenario *C* which includes water exchange operations reduces residual bed shear stress vectors pointing towards the basin, as demonstrated by the resultant vectors pointing towards the sea in Fig. 13c. Such a result corroborates the reduction of the system's flood dominance already identified.

Fig. 13 Maps of residual bed stress difference for scenarios *A100* (**a**), *B100* (**b**) and *C100* (**c**) relative to the reference scenario. Residual values (N/m²) were calculated over one tidal cycle for each grid cell of the domain (colored vectors). Large black arrows illustrate the variation of overall residual bed stress intensity and the dominant direction resultant from each water management type investigated

3.3. Idealized Guaraíras Lagoon application

After 100 years, the Guaraíras Lagoon morphology, which was modeled through the reference scenario simulation (Fig. 14a), had developed branched tidal channels and intertidal areas, with extensive sand bars shaped qualitatively similar to those observed in recent satellite images (Fig. 1). The deep channel through the tidal inlet branches towards the interior of the lagoon and developed preferably along the north margin, eroding up to 8 m depth. A large intertidal area with a typical flood-tidal delta shape developed in the central region of the domain and smaller bars separated by narrower tidal channels formed in the southern area.

Fig. 14 Guaraíras Lagoon bed levels after 100 years of morphodynamic simulations: **a)** Reference scenario, **b)** scenario *G1* and **d)** scenario *G2*. Bed level changes observed in scenarios *G1* (**c**) and *G2* (**e**), related to the reference scenario

Final morphologies achieved by the evaluation scenarios *G1* (Fig. 14b) and *G2* (Fig. 14d) show that aquaculture operations changed the configuration of Guaraíras Lagoon's main tidal channels and the position of intertidal areas. The effective bed level changes are presented in Fig. 14c (*G1*) and Fig. 14e (*G2*), and show: i) enhanced erosion trends (blue) in the tidal inlet channel, which was deepened from the lagoon mouth towards the southwest region of the domain, and in narrow tidal channels located along the western margin of the lagoon, which also extended further landward; and ii) main sedimentation trends (red) at the southwest area, where higher sand bars were formed, and at the central region towards the northern portion of the lagoon, where wide tidal channels became shallower and narrower.

In the long-term, aquaculture operations produced larger tidal channels towards the southern end of the Guaraíras Lagoon instead of the northern end, as a consequence of the intense shrimp farm occupation around the south-western side of the lagoon (Fig. 1) and the relative larger amount of water used in that region (Fig. 3). The isolated hydrodynamic effect caused by the shrimp farming water intake operations is highlighted in Fig. 15a and Fig. 15c, where the strongest residual vectors predominantly oriented towards the southern region can be observed. In addition to the water intake effect, different morphological pathways driven by aquaculture activities cause bed shear stress variations (Fig. 15b). The “disoriented” vector pattern of residual bed shear stress differences points out the expressive alterations that are generated by displacement and depth change of main channels.

Comparing Fig. 14*c with* Fig. 14*e it is clear that scenario G1, with constant operations, resulted in more intense bed level changes than scenario G2***,*** *which considers the local history of shrimp farming development. In* Fig. 16 *it is also observed that scenario G2 results in only minor increases in sediment import****,*** *while scenario G1 enhances sediment transport into the basin especially within the first few decades of morphodynamic evolution. On the longer term, sediment import rates become similar and aquaculture effects diminish which is in agreement with results of the conceptual lagoon simulations (Fig. 8b). Realistic aquaculture operations growth, represented by scenario G2****,*** *increased sediment importation only by 2.2% (6.6×10^4 m^3) and elevated the final mean height of the lagoon bed by 4.6 mm in comparison to the reference scenario (*Fig. 16

Fig. *16*). Adopting constant water intake values for the entire simulation may overestimate final morphological alterations.

Fig. 15 Maps of residual bed stress difference in Guaraíras Lagoon: **a)** Difference between scenario *G1* and the reference scenario considering the initial morphological condition (flat bathymetry); **b)** difference between scenario *G1* and the reference scenario considering the final morphological condition achieved by each simulation; and **c)** difference between scenario *G1* and the reference scenario, using the same final morphological condition achieved by scenario *G1* in both experiments

Fig. 16 Changes of total sediment volume stored in the Guaraíras Lagoon. Values indicated on the left y-axis correspond to the volumetric difference related to the initial bathymetry. Right y-axis indicates the corresponding change in the mean elevation of the lagoon bed

4. DISCUSSION

4.1 Exploring equilibrium

Results obtained through the reference simulation for the conceptual lagoon (Section 3.1) are consistent to previous studies that also evaluated the morphological equilibrium and evolution of tidal basins via process-based modeling (van der Wegen et al. 2008; Dastgheib et al. 2008; Dissanayake et al. 2009; van Maanen et al. 2013a; van Maanen et al. 2013b). The evolution of morphological parameters towards the theorical relationship $(\mathrm{h_{HW}}/\mathrm{h_{LW}})^2=\mathrm{A_{HW}}/\mathrm{A_{LW}}$ (Fig. 6), and the formation and stabilization of intertidal areas (Fig. 9) are well-defined indicators of an equilibrium condition approximation (Dronkers 1998). Moreover, the equalization of flood and ebb tide durations (Fig. 12) and the decrease of flood/ebb peak velocities ratios during the simulation (Table 1) also point to the achievement of a steady tidal basin morphology. The development of intertidal areas increases rising tide duration and ebb currents intensity (Speer and Aubrey 1985), therefore weakening the system's flood-dominance, and the residual sediment importation (Fig. 8).

At the same time, as pointed out by Zhou et al. (2017), the term “morphodynamic equilibrium” might be an oxymoron. The concept of equilibrium may not be easy to define, as it implicitly assumes a given time scale, as well as incremental changes on a given spatial region. Using the ternary diagram proposed by Zhou et al. (2017), both the “river” and the “wave” vertices were neglected in the present investigation. The first because fluvial contributions are usually small in the actual Guaraíras as well as in many other river mouths (rias) in Northeastern coast of Brazil, the latter because coastal nearshore dynamics can vary widely from place to place but, in case of Guaraíras, the mouth of the lagoon is protected by a line of beach rock reef. Therefore, the focus of the present investigation was restricted to confined shallow estuarine environments, with negligible freshwater intake during most part of the year, except in rare extreme events, such as Guaraíras Lagoon and other similar water bodies elsewhere in the world.

4.2 Effects of aquaculture

The first and most important question to be answered is whether a simple activity, such as a shrimp pond operation, is able to impact the dynamics of the entire lagoon. Surprisingly, the idea of an “isolated impact”, as opposed to an “orchestrated impact”, still governs the environmental agencies in Brazil, disregarding the disastrous experience in Southeast Asia, and other international experiences that have motivated the establishment of the concept of “environmental sustainability” or “carrying capacity” of an estuary (Primavera 1994).

Our modelling results indicate that strategies for pond water management, which are typically adopted by marine aquaculture farms worldwide, can indeed generate distorted flow patterns and sedimentary processes in estuarine and lagoon systems. As a result, the long-term morphodynamic behavior can be disturbed in two main ways: *i*) Continuous and intermittent water intake operations predominantly increase flood and decrease ebb currents, respectively (Table 1), causing enhanced flood-dominated residual bed shear stresses for both cases (Fig. 13a, Fig. 13b, Fig. 15a and Fig. 15c). This increases the importation of sediments (Fig. 8b and Fig. 16) from the inlet and neighboring ocean beaches, promoting the development of intertidal areas (Fig. 9). *ii*) Water exchange operations predominantly increase ebb currents due to the timing of water release from the ponds which is concomitant with the falling tide. This strongly enhances ebb-dominated residual bed shear stresses (Fig. 13c), which reduces sediment importation (Fig. 8b) and can keep basin morphology underdeveloped (Fig. 7 and Fig. 10a). Model results highlighted that morphological changes are intensified by larger levels of pond occupation, and that tidal basins’ morphology may diverge from an expected equilibrium state when marine aquaculture activity in land-based ponds is present (see Fig. 11). Overall, we show that marine aquaculture has the potential to control the sediment budget of tidal basins. Sediment budgets have recently been highlighted as an important indicator of the estuarine ecosystem resilience against sea level rise, with net sediment import indicating higher ecosystem resilience while net export indicates higher ecosystem vulnerability (Donatelli et al. 2018a; Donatelli et al. 2018b; Castagno et al. 2018; Benninghoff and Winter 2019). In this context, our modeling results show that water exchange operations might also have negative implications for the tidal basin development in the face of sea level rise as sediment import is hindered.

For the idealized Guaraíras application, a typical water intake operation, which is actually adopted to compensate pond water seepage and evaporation losses, caused long-term changes in the lagoon's morphology. In spite of a small increase on the final volume of sediment imported to the system (~2%), the position of intertidal areas was displaced and the main tidal channels' depth and configuration was modified (Fig. 14c and Fig. 14e). Morphological changes occurred mainly towards the southern region of the lagoon, where the local aquaculture activity has started and reached largest occupation areas earlier (Fig. 3). Water exchange operation, as defined in Section 1.3, is not a regular management practice adopted in Guaraíras' shrimp farms. Such operation is only considered by local producers in events of drastic water quality issues, aiming at a rapid recovery of conditions inside the ponds. If local producers start implementing such a strategy into the pond daily routine, more relevant morphological changes in Guaraíras Lagoon may be expected, with potential reductions of intertidal area and tidal channel extent, as demonstrated by the conceptual lagoon simulations (scenarios *C*).

4.3 Model extensions

The present study was motivated by the real case of Guaraíras Lagoon, a shallow water body, located in a semi-arid climate, with very little freshwater inflow, even during the rainy season. Currently, most aquaculture ponds installed in this region are continuously and simultaneously taking water from the lagoon in order to control water losses and keep the shrimp cultivation running. This scenario is quite similar to what is found in shrimp farms placed elsewhere in the world. Clearly, it is common perception that a lagoon surrounded by shrimp farms does not respond to a single pond. The reasoning that a large number of small ponds will not affect the lagoon is obviously false and is highlighted by our modelling results. Yet, there is typically no legislation to avoid over-exploitation of the lagoon. Logical extensions of the modelling approach could include an assessment of different management strategies. Instead of uniform water management strategies for the overall area, as defined in this study, studies for licensing operations or environmental impact assessment could consider real operation rules that would be adopted by each farm or projected for each pond independently. Specific operation strategies with any water flow rate could easily be prescribed in process-based models like Delft3D.

The present study focused on the balance between tidal prism and pond volume, as the major physical driver. However, in order to develop more realistic models of actual estuarine systems for management purposes, other physical processes should be included. Following Zhou et al. (2017), three major realms describe the (natural) estuarine system: Hydrodynamics (tide, river, wave), sedimentology (sand, silt, clay), and landscape setting (river valley, embayment, land surface deformation). These processes or effects should be included in the numerical simulation of the estuary. However, a fourth dimension should be added to this “triangular” concept: the uses of the water, the sediments, the land contour and the aquatic space by humans. Although much needed, accounting for these anthropogenic interventions would be certainly of major complexity and very few locations in the world could afford to have all the environmental monitoring needed to feed such numerical models, in order to obtain reliable results and fully capture the dynamics of these human-coastal systems (see also Lazarus et al. 2016).

Another interesting continuation would be investigating the effects of sea level rise, as it could effectively change the tidal prism of the lagoon, change water circulation, and alter the balance between the volumes of water inside the ponds and in the lagoon. Alternatively, if the shrimp ponds advance towards the lagoon, its water surface would reduce, and the tidal prism would decrease. Aquaculture ponds constructed around estuaries or coastal lagoons also produce a physical barrier that would hinder intertidal zone expansion and migration of mangroves (as found in the Guaraíras Lagoon) or other vegetation species to upper areas, reducing the capacity of these ecosystems to adapt to higher sea-level conditions (Schuerch et al. 2018). A numerical modeling analysis accounting for the effects of ponds in conjunction with sea level rise could provide a more holistic assessment on the ability of such wetlands to keep up with rising sea levels, ultimately supporting novel regulations for the conservation of coastal habitats.

5. CONCLUSIONS

In this study it was demonstrated that water management operations performed by marine shrimp farming in excavated ponds have the capacity to modify hydro-sedimentary processes and decadal-scale morphological evolution of coastal lagoon systems. Main findings can be summarized as:

- long-term morphodynamic behavior of a coastal lagoon can be disturbed by shrimp farming in two main ways: (i) regular water intake operations increase sediment import, whereas, (ii) water exchange operations reduce sediment import and attenuate tidal basin morphology development;
- the larger the pond occupation, the larger the effects on hydro-morphological processes;
- depth and configuration of tidal channels are modified when shrimp farming is present;
- water exchange operations are capable of modifying the morphological equilibrium state of a coastal lagoon system, especially if carried out synchronously to the local tidal oscillation;
- the modelling approach presented here can be extended to other comparable systems and provide environmental impact prognostics for a wide variety of designed scenarios, supporting coastal planning and enhancing the sustainability of land-based ponds for marine aquaculture in the long-term

Acknowledgements

This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brazil (CAPES) - Finance Code 001.

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