

Hydrodynamic modeling over a sand wave field at São Marcos Bay, Brazil

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Abstract

Sand wave studies indicate that flow patterns and local hydrodynamic regime are essential elements to determinate orientation, asymmetry, height and migration of subaqueous features. The goal of this work is to characterize the small scale hydrodynamics that control sediment transport at São Marcos Bay, along Ponta da Madeira Port Complex, at São Luís (Maranhão state, NE Brazil). Numerical modeling was based on bathymetric campaigns, topographic data, sediment samples and 4 velocity ADCP monitoring stations along east margin of the bay. Tidal levels reach 7.0 m high, 3.5 m being the mean value and 6.0 m the mean high water level, producing overall ebb dominated strong currents that reach up to 3 m/s on ebb spring tides. Neap currents are weaker and reach 1.9 m/s and 2.0 m/s on flood and ebb tides, respectively. Local morphology determinates the occurrence of intense gyres, which allied to absolute sediment availability, dominated by fine sand, allows 0.5 m to 6.0 m sand waves height development.

1. INTRODUCTION

Hydrodynamic structures, sediment transport patterns and bottom features migration are the subjects of innumerable studies to better understand the evolution of rhythmic features at coastal areas around the world (e.g. Allen, 1968; Allen & Collinson, 1974). Bartholomä et al. (2008) indicates various studies with two-three dimension morphodynamic models as tools to assess bed evolution at tide dominated regions (e.g. Hulscher, 1996; Nemeth et al., 2007; Soulsby & Damgaard, 2005).

Bottom features generated by currents are frequently denominated as subaqueous dunes or sand waves (Bartholdy et al. 2002), while some authors restrict the former to features generated by tide-forced flows. Linear stability analysis (Gerkema, 2000) enforced this denomination,

indicating that relevant differences are observed between features formed under tide conditions to the ones from stationary flows.

Shape, asymmetry, height and migration of sand waves provide important information about sediment dynamics and orientation of bottom transport in estuaries and coastal channels. Barnard (2012) indicates that flow structure, regional sediment transport regimes, boundary conditions and the residual hydrodynamic patterns can be described through the cited variables (e.g. Langhorne, 1982; Belderson et al., 1982; Kubo et al., 2004).

To characterize the morphodynamic behavior of sand waves, Flemming (2000) indicates that water column thickness, critical shear velocity and thus sediment granulometry are limiting factors to bottom features growth in shallow waters. Considering this, maximum potential heights tend

to occur at the presence of relative coarser sediments and intense flows, showing the importance of hydrodynamic mapping at sand waves regions. Recent study of Barnard et al. (2011) characterized the dynamics end evolution of subaqueous features at San Francisco Bay (USA) through wave parameters calculation and numerical modeling. Computational simulations described small scale bed dynamics, reinforcing the idea that modern echo sound systems allied to numerical models raise the potential to predict migration on coastal sand wave fields.

Model results generated the hypothesis that sediment transport gradients control migration patterns. Changes on tidal phases and bathymetric features also define the direction of subaqueous dunes migration.

Activities that can potentially influence the hydrodynamics of these systems, such as mineral resources exploitation, beach nourishment, aggregate mining, dredging, navigation and port operations depend on the knowledge about sedimentary budget and transport directions, making sand waves to exercise a fundamental role in this relation.

The main goal of this study is to assess the small scale hydrodynamics that control sediment transport at São Marcos Bay, along Ponta da Madeira Port Complex (São Luís, Maranhão state, Brazil), through numerical experiments of the estuarine channel hydrodynamics.

2. STUDY AREA

Ponta da Madeira Port Complex (PDM) represents one of the greatest exportation sectors of the world in terms of cargo shipping (Amaral, 2010). It is located at the coast of São Luís city, capital of the northern Brazilian state of Maranhão, representing a natural exportation corridor of the geoeconomic important region of the Oriental Amazon (Amazônia Oriental).

At the eastern margin of São Marcos Bay, where PDM holds its port operations, shallow sandbanks are formed next to the navigation route. The sand waves assessed in this study are located in this important socioeconomic area (Fig. 1).

Despite of its great environmental relevance, there are few scientific studies available about sediment processes in São Marcos Bay. Local tide regime is

characterized by semidiurnal frequency and macrotidal heights, reaching 7 m in equinox periods. Spring tide amplitudes observed may generate strong currents (Pereira & Harari, 1995), reaching up to 3 m/s in the main channels of the bay.

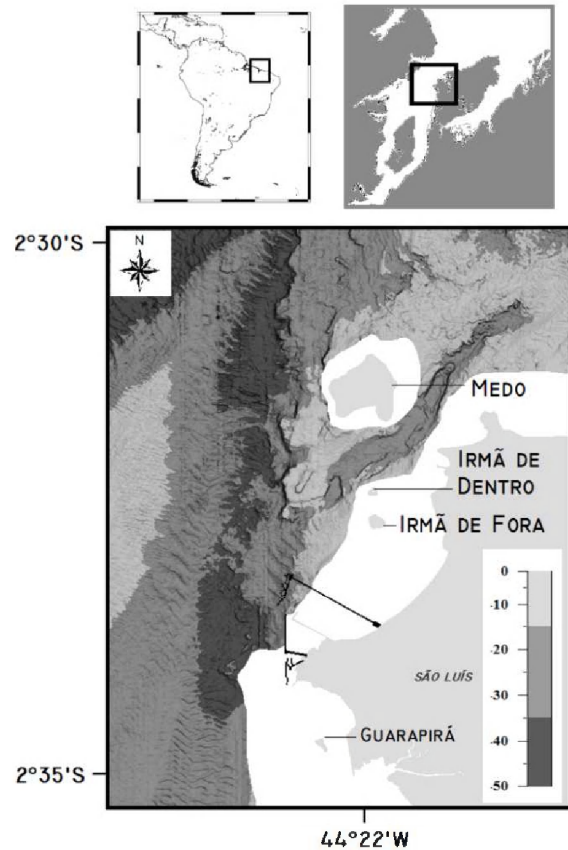


Figure 1. Hill-shaded bathymetry map of the study area, indicating the locations of Medo, Irmãs and Guarapirã Islands at São Luís city, adjacent to the east margin of São Marcos Bay.

Climatology of Maranhão state indicates two distinct stations and the important influence of the trade wind system. Rainy season in the region is from January to June, while dryer periods occur from August to December, according to the Brazilian National Institute of Meteorology (INMET).

Superficial sediments are composed by sand, covering the entire subaqueous dunes area. The dominant fraction is composed by fine to very fine sand (> 90%).

3. NUMERICAL MODELING

The applied numerical model is the hydrodynamic (HD) module of the MIKE 3 software (DHI Water & Environment). It simulates unsteady three-dimensional flows, taking into account density variations, bathymetry, tidal elevations, currents and river fluxes.

3.1 Field data

Field data set used in this study was collected from March 2011 to June 2012. Temporal series are composed by flow intensity and direction, water level, conventional and multi-beam bathymetry. Additional information of local depths and sediments at non-measured areas was taken from nautical charts of the Brazilian Navy (DHN).

Velocity data was registered each 15 minutes through the water column, divided by cells of 0.5 meters, with an Acoustic Doppler Current Profiler (ADCP) which has 600 KHz of frequency. Large mooring structures have been used to avoid burial or damage to the instruments.

Five observation points were monitored with ADCPs, distributed in two regions adjacent to PDM. Points identified as P16, P17, P18, P19 and 15H (Fig. 2) have been considered in this study.

Bathymetric surveys have been carried out from November 2011 to June 2012. The tide gauge is recording since October 2011, at a five minutes frequency. 55 superficial sediment samples have been collected with a Van Veen sampler.

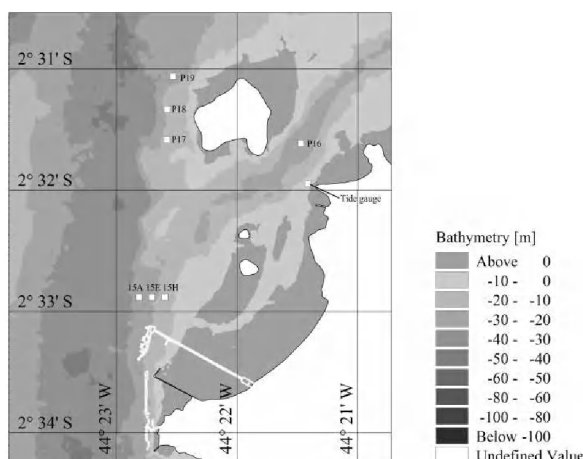


Figure 2. Location of the current monitoring points investigated with acoustic doppler current profiler.

3.1 Model calibration

Comparison between modeled results and field data has been done at four velocity observation points (P16 to P19) and tide levels were compared at the tide gauge location.

Statistical parameters have been applied to evaluate the model adjustment to in situ data. Relative Mean Absolute Error (RMAE) and Adjusted Relative Mean Absolute Error (ARMAE) parameters (Table 1 - van Rijn et al, 2003) provided a quantitative assessment of the modeled outputs.

Table 1. Qualification of agreement between field and modeled data through RMAE (Relative Mean Absolute Error) and ARMAE (Adjusted Relative Mean Absolute Error).

Classification	RMAE	ARMAE
Excelent	< 0.1	< 0.2
Good	0.1 – 0.3	0.2 – 0.4
Reasonable/fair	0.3 – 0.5	0.4 – 0.7
Poor	0.5 – 0.7	0.7 – 1.0
Bad	> 0.7	> 0.2

3.3 Numerical parameters

The present study consists of an application of the hydrodynamic module of MIKE 3 software. It simulates flow conditions discretizing momentum equations at a flexible mesh, using finite volume method.

Variables are determined in the central points of each element of the numerical mesh through semi-implicite time differencing. As bidimensional flows occur, typical of macrotidal areas, density stratification influence has been neglected, thus only barotropic effect have been taken into account in the modeling process.

Mesh elements have variable resolution, ranging from 900 m far from the area of interest to 30 m next to PDM. Figure 3 presents the numerical mesh for the entire model domain. Bed resistance varied at the model domain proportionally to depth values.

Open ocean boundary condition consisted of amplitude and phase information obtained from a gauge station located near PDM, maintained by the Brazilian Navy. Two southwestern river

boundaries were set up with constant discharges and lateral boundaries were closed considering null normal velocity. Wetting and drying were applied on the intertidal zone to adequately represent water inflow to the bay, simulating periodic changes at surface water level and its effects in the area of interest.

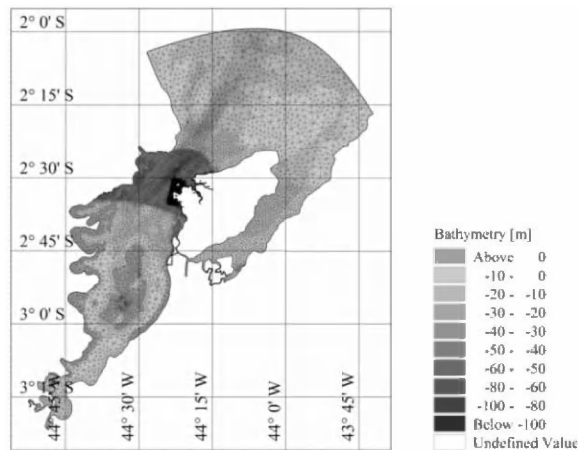


Figure 3. Computational mesh and bathymetry of the hydrodynamic model domain.

Open ocean boundary condition consisted of amplitude and phase information obtained from a gauge station located near PDM, maintained by the Brazilian Navy. Two southwestern river boundaries were set up with constant discharges and lateral boundaries were closed considering null normal velocity. Wetting and drying was considered on the intertidal zone to adequately represent water inflow to the bay, simulating periodic changes at surface water level and its effects in the area of interest.

Horizontal viscosity was considered constant (0.28) and its effect calculated following Smagorinski formula. Vertical viscosity was variable ($0.4 \text{ m}^2/\text{s}$ to $1.8 \times 10^{-6} \text{ m}^2/\text{s}$) following the logarithmic law.

Final output results were obtained after a series of simulations, varying input data to assess the model sensitivity and output quality.

4. RESULTS AND DISCUSSION

Field data and model output analysis have been used to properly assess the hydrodynamics of São Marcos Bay.

4.1 Measured velocities

Intensity and direction of ADCP data have been processed to obtain temporal series of velocity at the observation points. Tide level reached 6.3 m at the period considered in this study (Fig. 4), where diurnal inequalities and high amplitudes, even at neap tides, can be observed.

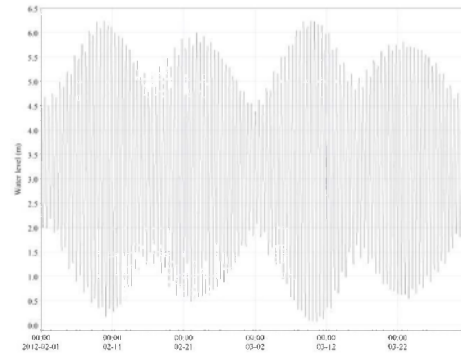


Figure 4. Water level time series registered in the coastal tide gauge.

Figure 5 presents real field data, measured at the points used to calibrate the model in terms of depth-averaged velocity.

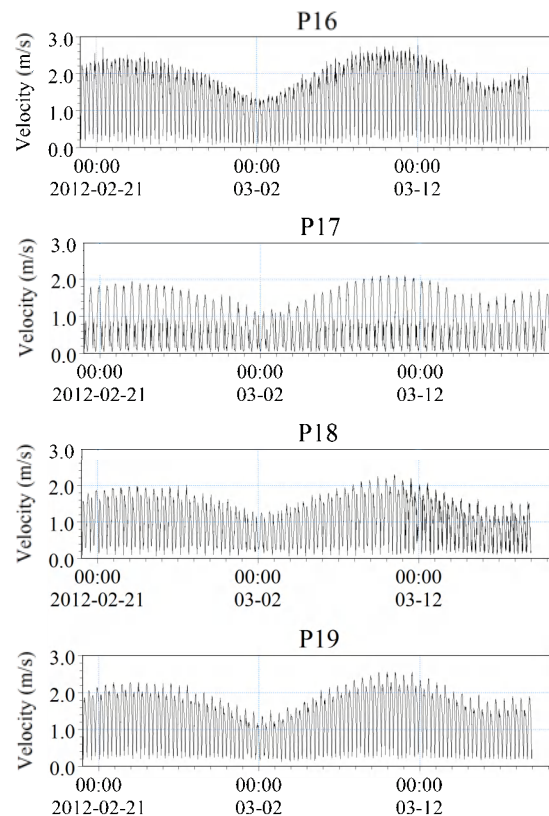


Figure 5. Depth-averaged velocity measured at the observation points P16, P17, P18 and P19.

Maximum flow intensity values are of up to 2.75 m/s at the observed sites, while to southeastern direction these values decrease. In terms of comparison, maximum intensities at point 15H are of 1,86 m/s, showing that the center channel of São Marcos Bay presents higher velocities. Jetties along the east coast of the bay are certainly influencing this hydrodynamic pattern and, consequently, sand waves migration in this area.

Different intensities are observed between ebb and flood tides, where the latter is dominant near the margin. In some areas, such as point P17, ebb currents are much stronger and may double the flood currents. River discharge system and the presence of Medo Island probably act decreasing flood currents that are only forced by periodic changes of water level.

4.2 Model calibration

Sensitivity analysis of the model has been done through changes in key parameters such as bed resistance, time step, mesh element size, horizontal and vertical viscosity.

Comparison of the model and field data through RMAE and ARMAE shows the statistic calculation, assessed at the points P16, P17, P18 and P19 (Tab. 2).

Table 2. Statistical classification of model calibration. U indicates the east-west velocity component and V indicates the north-south velocity component. Mod is the resulting vector.

	P16		P17		Mod	U	V
	U	V	U	V			
RMAE	0.6	0.6	0.4	1	0.6		
ARMAE	0.6	0.6	0.4	0.2	0.6		

	P18		P19		Mod	U	V
	U	V	U	V			
RMAE	0.8	0.5	0.4	0.5	0.5		
ARMAE	0.6	0.5	0.3	0.4	0.4		

Statistical parameters RMAE and ARMAE show good to fair agreement between model results and field data. The numerical model can be considered

well calibrated, mainly near Medo Island, thus able to help in the better understanding of the flood and ebb currents that flow above sand waves next to the eastern margin of the bay.

A comparison between modeled and measured flow velocity time series at four observation points are shown in Figure 6, showing the overall good agreement in the compared series.

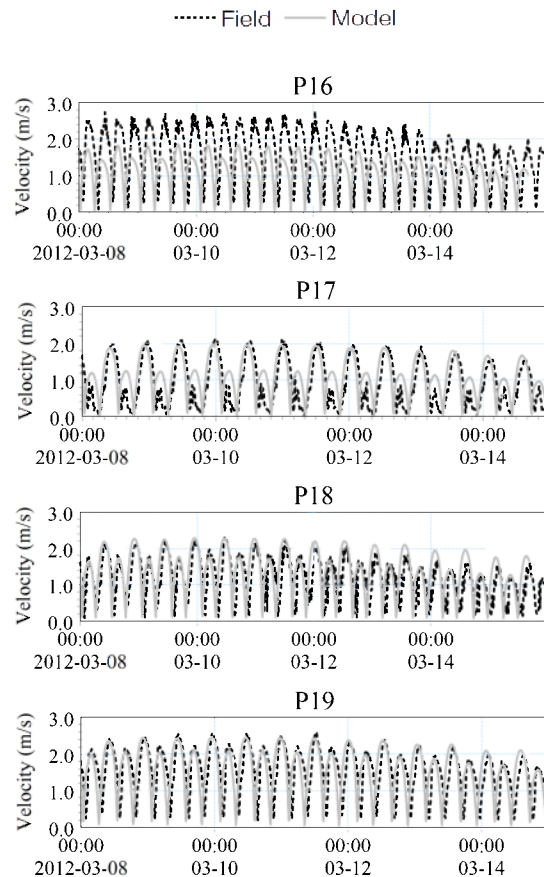


Figure 6. Comparison between modeled results (continuous line) and field data (dashed line).

4.3 Currents vector field

Numerical simulations are an important tool to better understand the overall hydrodynamic process that control sand wave fields, mainly in macrotidal areas. In this study, 6.0 m height tides were simulated generating strong currents that reach up to 3.0 m/s in spring tides. Neap velocities are weaker, although reaching up to 1.9 m/s and 2.0 m/s at flood and ebb tides, respectively.

Regions adjacent to the jetties present intermittent gyres and recirculation forms between the small embayment formed by Irmãs Islands and the harbor structures (Fig. 7).

These specific gyres migrate, weakening and strengthening along the year due to changes in tidal currents. As important hydrodynamic features these fluxes play an essential role on the migration of sand waves, mainly to the north at areas where ebb flux dominate (center channel of Sao Marcos Bay) and to the south where flood currents are stronger, as in the Boqueirão Channel between Medo Island and Irmã de Fora Island.

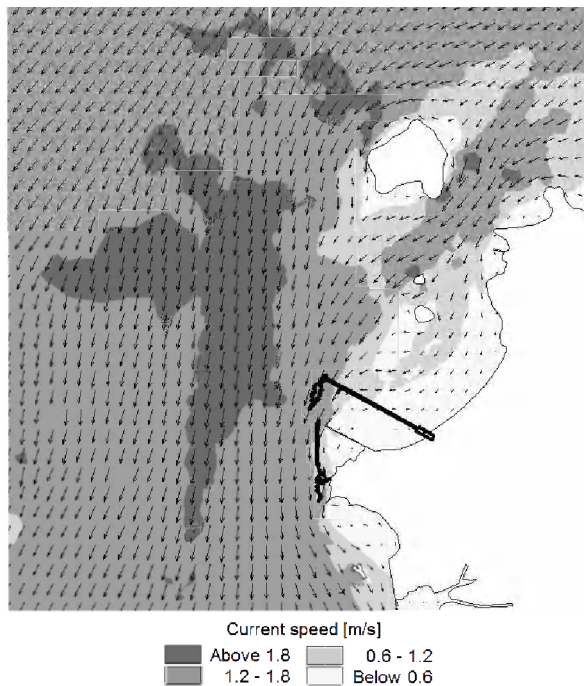


Figure 7. Typical maximum flood currents at São Marcos Bay.

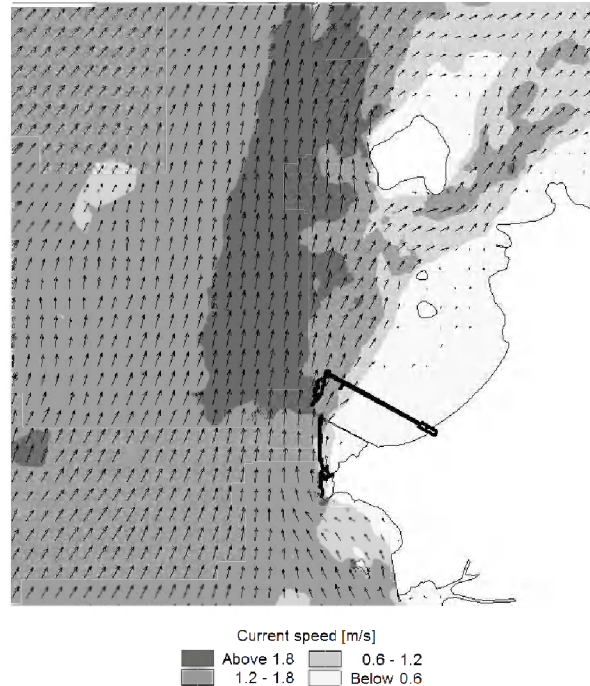


Figure 8 . Typical maximum ebb currents at São Marcos Bay.

5. CONCLUSIONS

Field data analysis and hydrodynamic modeling experiments provide essential information to build up the knowledge about sand waves migration at São Marcos Bay. As indicated in previous studies, tidal forcings are the main hydrodynamic controls in the estuary, where intense currents observed at the numerical model reached 3.0 m/s during spring tides.

Simulations show interesting features near the coast, which are characterized by gyres and recirculation patterns between Irmãs Islands and the port structures. East margin geomorphology and jetties control the development of circular flows.

These important dynamic features play an essential role to the systems residual bottom movement, as indicated by the vector fields. The transport is mainly to the north at ebb dominated flows, for instance at the center channel of Sao Marcos Bay, and to the south where flood currents are stronger, as at the Boqueirão Channel between Medo Island and Irmã de Fora Island.

The gyres move along the year due to tidal variations, thus the understanding of long time sand waves migration is extremely dependent on the residual flows present in the bay. Currents are also sufficient to transport the local sediment as bed and suspended load, influencing greatly the formation, amalgamation and dissipation of sand waves.

6. ACKNOWLEDGMENTS

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