INCLUDING TIDAL WINDOWS INTO A DISCRETE EVENT TRAFFIC SIMULATION TO IMPROVE NAVIGATION

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ABSTRACT

It has been shown how traffic simulations can be used to improve trade performance of approach channels and port logistic. Two specific situations merits to be highlighted. First, in some approach channels, fluvial currents combined with tidal currents may be too strong at certain stages of the tide to allow some ships to navigate safely. Second, depending on transit times and traffic, it may be possible to use tidal windows to bring in deeper drafts ships than would normally be acceptable. This implies that there will be access downtime for which the channel will not be available for such ships. Therefore, there is a need to include theses parameters into traffic simulation in order to improve the channel navigation safety as well as the port efficiency. In order to solve this problem, a discrete-event traffic simulation combined with a 2DH hydrodynamic model is proposed in this paper. A case study of the Amazon North Channel is studied because it is considered critical for navigation due to sandy banks migration, macro tides and limited depths (lower than 10 m). Both, astronomical tides and river flow are considered to assess the currents and under keel clearance. Therefore, together with ship speed and draft, the travelling and waiting times can be assessed. The results show the influences of ship draft and speed over water on tidal windows size for both upstream and downstream travels. Finally, this study suggests that the proposed model can improve the decision making regarding acceptable tidal windows. It will lead to a better safety and better efficiency of ports and channel operations.

1 INTRODUCTION

Tides can vary in time and space and they can be derived by water level records or can be predicted by tide tables or mathematical models. In the case of meso or macrotides or long tidally influenced channels or different drafts, a decision may be made whether to use the channel throughout the tidal cycle, that is called as suitable ‘tidal windows’ (PIANC, 2014). Depending on whether a stretch is passed at high or low tide, the design can be adapted by a stepped depth profile of the channel. In addition, ship speed plays an important role in the design process since it interacts with tidal currents (during flood and ebb phases). Then, decisions regarding acceptable tidal windows should be based mainly on safety (maneuverability and squat) and secondarily on economic considerations (travel and stop time).

The Amazon estuary mouth has converging effect on the incident macro-tide causing an increase of its amplitude. Tides with height above 3 meters, flood/ebb asymmetries and seasonally modulation are observed throughout the navigation channel. Despite of that, measurements of the levels generally take place in the coastal station in Ponta do Céu (Figure 1) with a low predictability of levels over the 100 km of the approach channel (Gallo, 2004; Fernandes, 2006; Arentz, 2009). Moreover, the sediments carried by the Amazon River find ideal conditions for sedimentation at its mouth originating an extensive area of reduced depths at the inner continental shelf that can be described as problematic to navigation, restricting the draft of vessels that enters the Amazon. Pinheiro and Vinzon (2013) have demonstrated the viability to incorporate the model results – through tidal level forecasting and updating the instantaneous depth – to the 3D visualizations technics, aiding navigation safety to facilitate understanding of the scenario and rendering the decision-making faster and intuitive. Then, a methodology based on water level results from a numerical modelling is proposed to forecast the tide along the channel. This methodology will allow a continuous adjustment and it will consider the seasonal variations of the tide.

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In this way, it may be possible to use tidal windows to bring in deeper draft ships than would normally be acceptable. This implies that there will be times (access downtime) for which the channel will not be available for such ships. Therefore, there is a need to include theses parameters into traffic simulation in order to improve the channel navigation safety as well as the port efficiency. Thus, in order to contribute to the safety and efficiency of navigation, this work presents different improvements to forecast the water levels and under keel clearance, through the operation of hydrodynamic modeling and discrete-event simulations of the traffic.

2 METHODOLOGY

2.1 Hydrodynamic Model

This research used the Delft3D – FLOW, a finite differences model, to simulate the hydrodynamic conditions in region of study. The computational grid has approximately 18.000 elements, with cells varying from 0.2 to 186km², with a mean value of 30km². Its domains extend from the Cape Orange to western coast of Maranhão states in along-shore direction; and from the Amazon River, just downstream Santarém City, to the deep ocean basin, about 280 km beyond the shelf break, in cross-shore direction (Figure 1) (Molinas et al., 2014).

The bathymetric data used for this model were from about 30 nautical charts published by Brazilian Navy. The boundary conditions considered were tide (FES2004), a monthly climatology discharge of rivers that most contributes to this estuarine complex (elaborated from ANA data base) and, the wind velocity and sea level pressure (European Centre for Medium-Range Weather Forecast – ECMWF, and ERA-Interim product). The model calibration was based on the comparison of harmonic constants in three tide gauge stations: G1, G2, and G3. Phase data at station Penrod Platform (G1) were considered for adjusting the boundary phases. Using the 2DH barotropic model, the friction factors were tuned in order to fit the amplitude and phase at the other two tidal inner stations, Ponta do Céu (G2) and Salinópolis (G3). More information about the configuration and calibration of the model is available in Molinas et. al., 2014.

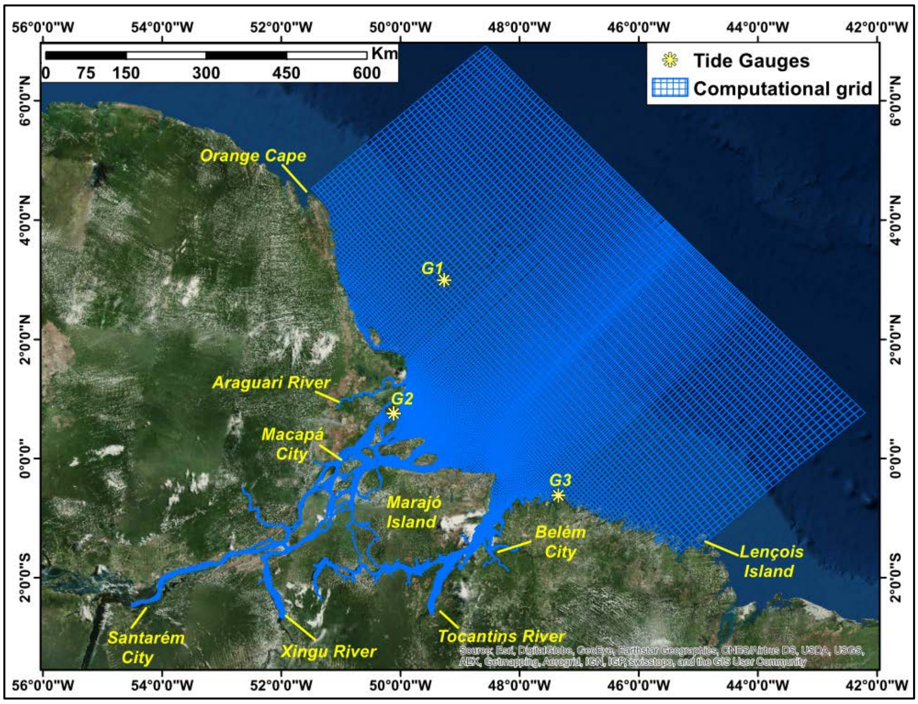


Figure 1: Model domain, numerical grid and location of the main tidal gauge stations (G1, G2, and G3). Source: Adapted from Molinas, 2014

The water level and current results from model simulation were analyzed in 10 (ten) stations distributed along approximately 350 km in the navigation channel, from nearby Santana Port (P1) to offshore at the inner shelf (PC) (Figure 2). The maximum distance between two station is ≈40.3 km (P8 – P9) and the minimum is ≈32.8km (P9 – PC), with a mean distance of ≈39 km between the stations. The bathymetry of the corresponding stations is presented in Table 1 where the minimum of 11.1 meters is observed for P8 due to the presence of a fluid mud suspension. Compared with water, such a 'black water' layer is characterized by a density that is somewhat higher (1050-1300 kg/m^3), but has comparable rheological properties. Therefore, contact between the ship's keel and the upper part of the fluid mud layer will most likely not damage the ship. In this paper, the water-mud interface is considered as the bottom level. Therefore, the minimum under keel clearance has been set to zero. In that way, the keel of the ship will just touch the surface of the mud layer without entering inside.

PC	P9	**P8**	P7	P6	P5	P4	P3	P2	P1
22.1	13.6	**11.1**	15.3	16.1	26.1	25.1	23.6	42	17.5

Table 1: Bathymetry of the region at the references stations points measured in meters.

With the results of a year of simulation, were realized the extracted of water levels and depth-averaged currents and its harmonic analysis. The currents was extracted as U and V components and to build a harmonic series data, the resultant was considered as positive when ebb flow (NE) (inner the intervals 0°-150° and 330°-360º) and as negative when flood flow (SW) (inner the interval 150º-330°), with the 0º pointing to the East (Figure 2:). Moreover, to apply the harmonic analysis the water level and currents had its respective mean value subtracted of its series.

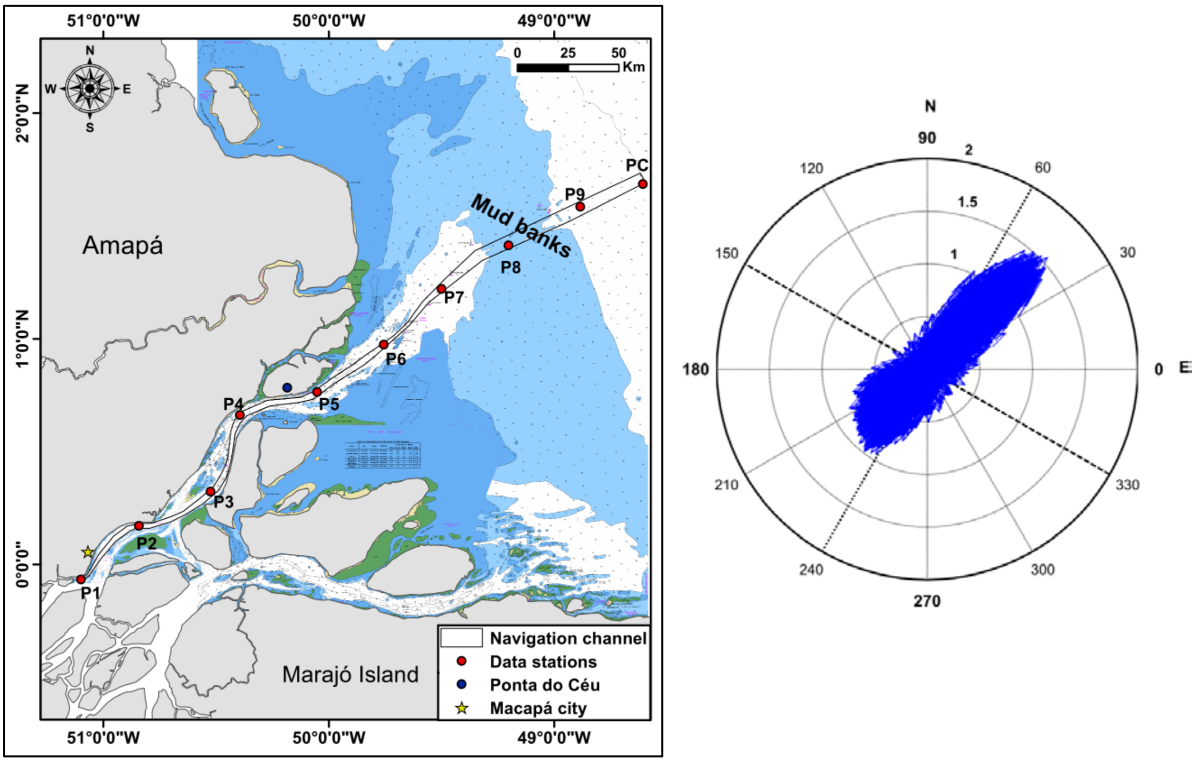


Figure 2: Localization of data stations along navigation channel (red) and the Ponta do Céu tide station (blue) in Curuá Island, at the left; and the velocities arrow graphic showing an example (PC station) of the flow predominant directions (SW-NE), at the right

The harmonic analysis is essentially a mathematical method for processing sampled data of tide for determining the harmonic constants of the various components. This method is based on the different variations of the components phases, arising from differences in their angular frequencies. It is used the Fourier analysis as a filter to separate the components and it considers that a sign is represented by a finite sum of terms in sines and cosines (Equation 1). The application of the Fourier transform in some signal creates conceptually two domains, the time domain and the frequency domain, where functions are rewritten as periodic functions using as parameters the phase, the amplitude and frequency (FRANCO, 1997; Ribeiro, 2013).

$$\eta(t) = a_0 + \sum_{n=1}^{k} an \times \cos(\omega_n t + \alpha_n) \quad (1)$$

$$V(t) = v_0 + \sum_{n=1}^{k} vn \times \cos(\omega_n t + \alpha_n) \quad (2)$$

Where: $\eta(t)/V(t)$ is signal; an/vn is amplitude of water level/currents; a_0/v_0 is the mean level of reference established; k is harmonic components considered; α_n is the phase and; ω_n is the angular frequencies correspondents.

To evaluate the representativeness of the harmonic components resulting from analysis was made the tide forecast for the same year of data. It was using the tools “t_tide” and “t_predic”, of MatLab program, to proceed the harmonic analysis and tide forecast, respectively. The following figure of PC station (Figure 3) show an example of the comparison between the series resultant of model simulation and the forecast made with the components resultant of harmonic analysis. Water level and currents had the representation of amplitude/phases varying in the stations, with a maximum - minimum mean error of 6.10×10^{-4} (P9) and -5.92×10^{-6} (P7) for water level, and of 9.13×10^{-4} (P9) and -9.61×10^{-4} (P6) for currents.

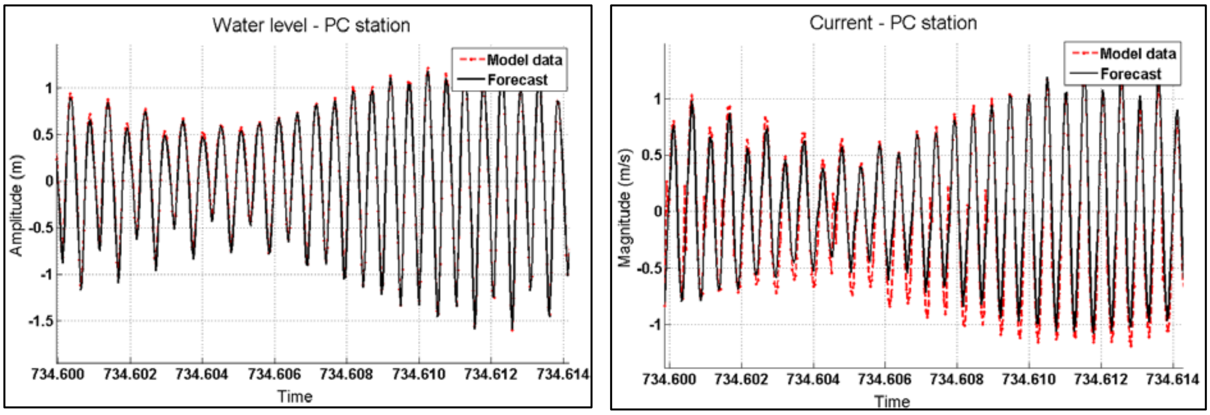


Figure 3: Graphics with the model data and forecast for PC station. Time indicated in Julian days

2.2 Traffic Simulation

The traffic simulations were realized with all the components resultants of harmonic analysis to represent the tidal window. Two intervals of 3 days were taken to make the traffic simulation: the higher spring tide and the smaller neap tide, as shown in Figure 4.

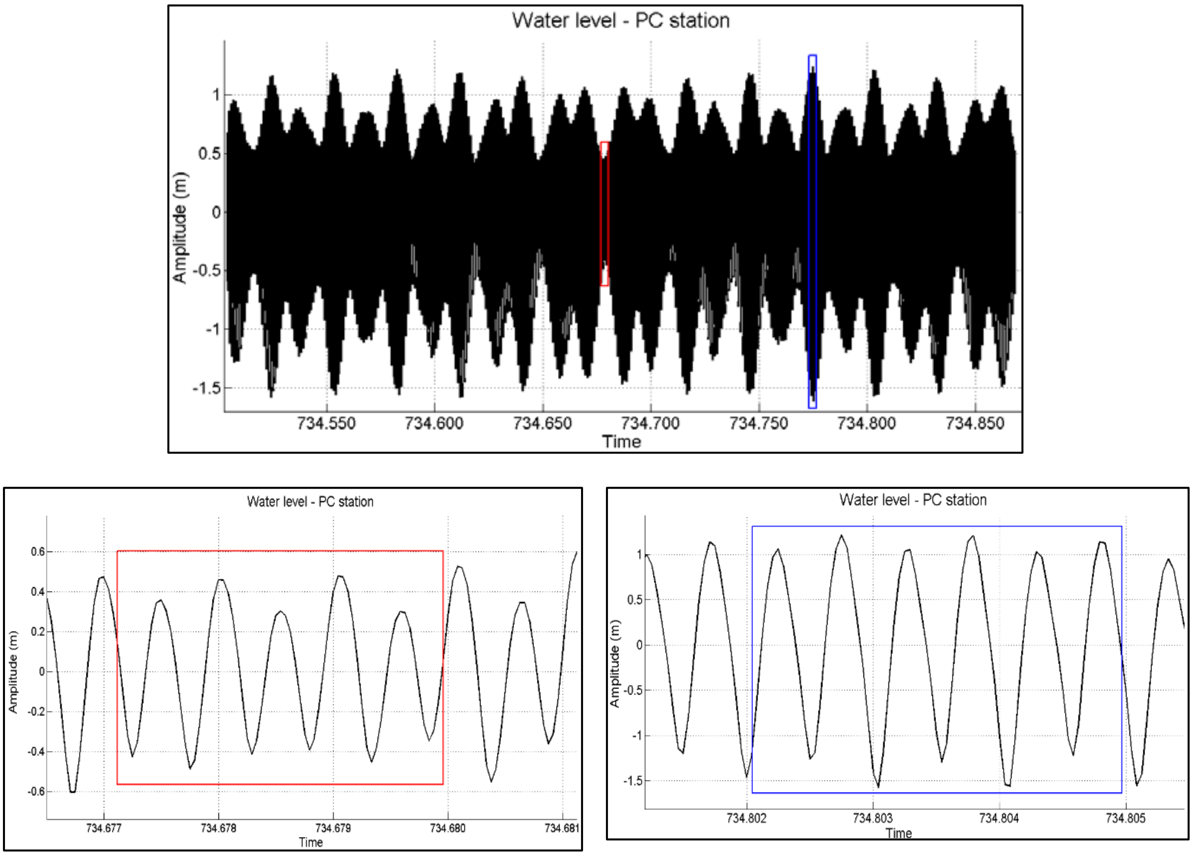


Figure 4: The tidal data from model simulation, showing the whole in top, and the intervals selected for traffic simulation: the neap tide in down left and the spring tide in down right

As an example for the simulations, five different drafts were considered, from 11 to 12 m at a constant speed over water of 12 knots. Speed plays an important role as it interacts with tidal limits. The reference case used in this paper corresponds to a ship of 11.5 meters draft navigating. The simulation model has been sliced in nine sections where the bathymetry was considered constant, see Figure 2. At each section is corresponding a reference point (P1-9 and PC) to assess the water level as well as the currents due to the tide (see equations (1) and (2), respectively). Both under keel clearance and ship speed over ground has been re-calculated every hour of the simulation. However, these values are considered constant during this interval. If the under keel clearance has been inferior to zero at least once in the simulation, a trigger is set to true in order to identify that the ship has been in front of a grounding issue, e.g. the bottom of the ship touched the muddy layer of the channel bed. Squat effect, heel due to wind and ship motions due to waves has not been considered in this study.

The traffic simulations were realized for both entrance, from shelf to Santana port (PC to P1) and exit from port to shelf (P1 to PC). In each case, a departure of the ship is considered each hour during 48 hours.

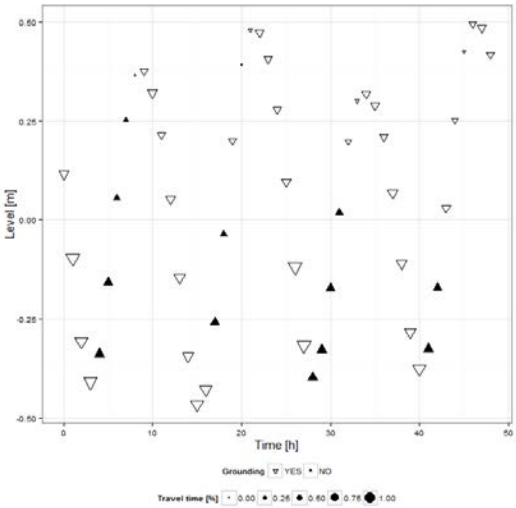
3 RESULTS

Figure 5 presents the results of the simulations on a scatter plot considering the tide level at the departure point. Each point corresponds to the result of one traffic simulation. The downward white triangles indicate that the ship has been in front of grounding issue in P8 due to the presence of mud banks while the upward black triangle indicate that the ship passed through the approach canal without any problems. The size of the point corresponds to the total travel time of the ship. This value has been normalized between 0 and 1, where 0 corresponds to the minimum travel time and 1 represents the maximum in this condition. The average travel time results in 15.7 hours.

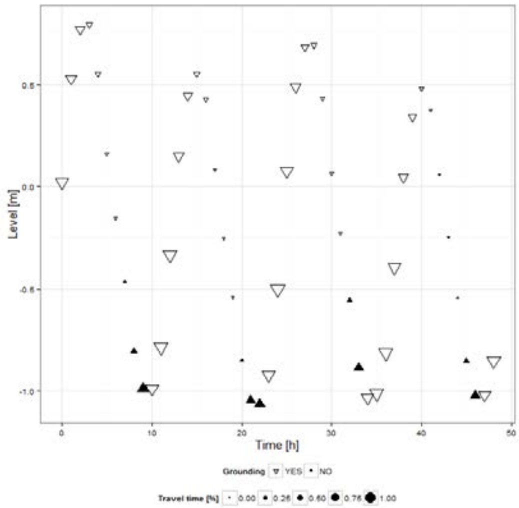
Moreover, it is observed that in the case of ship entrance (PC to P1) the total travel time is minimized if the ship starts as late as possible at the rising tide, for neap (a) and spring (c) cases. This is explained by two factors: first as shown in Figure 6, there are approximately 3 hours of difference between PC and P8 which allows the ship to enjoy the entire flood tide with favorable depths; second, at the end of the rising tide at PC is still ebb at P1, and in this way, the vessel is able to enjoy the flood currents along the channel.

When the ship is traveling from port to sea (P1 to PC), the total travel time is minimized if the ship start at the beginning of the falling tide (cases b and d). Thus, the ship takes the favor ebb currents, and arriving at P8 point near the high tide and so on favorable depths.

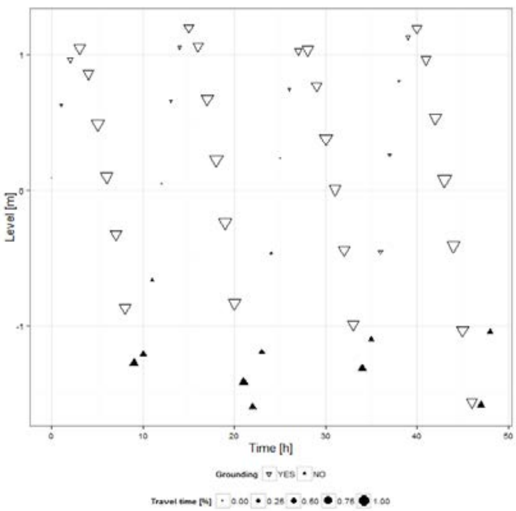
For example, the maximum gain of travel time observed between an early and a late departure of the ship correspond respectively to 0.83, 2.44, 0.94 and 2.00 hours for cases (a), (b), (c) and (d). Considering an average consumption of 30 tons per day and a bunker price of 250 USD/tons, each hour saved on the travel costs 312 USD to ship owner.



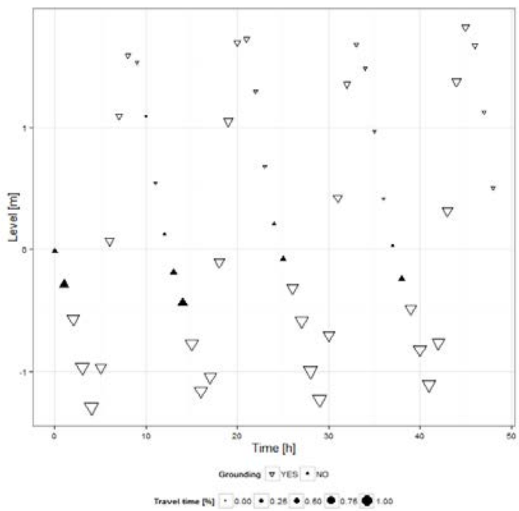
(a) Neap tide from PC to P1



(b) Neap tide from P1 to PC



(c) Spring tide from PC to P1



(d) Spring tide from P1 to PC

Figure 5: Results of the traffic simulation for a ship of 11.5 m draft at 12 knots over water considering a ship departure every hour in the two navigation directions

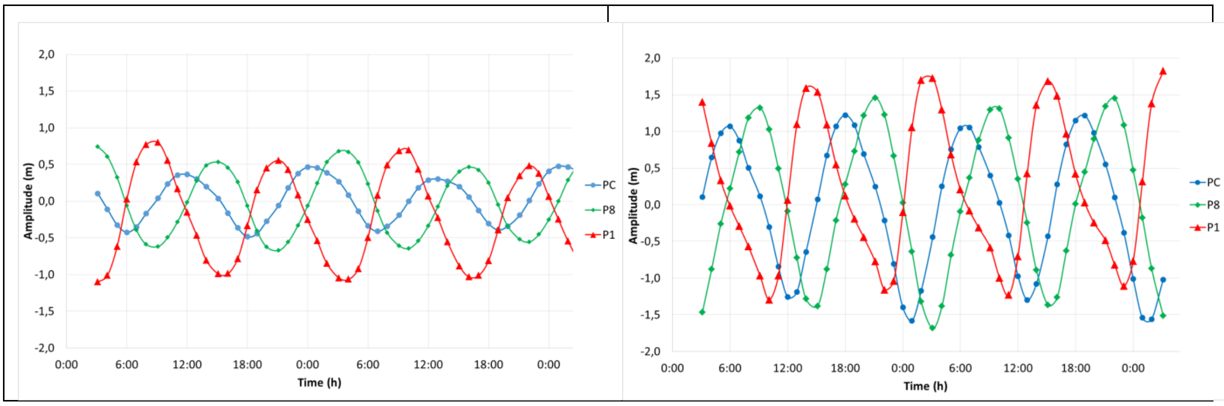


Figure 6: Tidal levels comparison for 3 stations: PC (at the shelf entrance), P8 (at the possible grounding point) and P1 (near Santana port). Neap period is on the left and spring ones at the right

Table 1 shows the effect of ship draft on the average tide window considering a constant ship speed over water of 12 knots. The average tide windows is presented for neap tide and spring tide while the traffic simulation has been realized with a resolution of 1 hour. It can be observed that the de window decrease linearly from 5.81 hours to 0.87 hours when the draft is raised by one meter. Since squat effect, angle of list due to wind and ship motions due to waves are not considered in this simulation, it is recommended to limit the maximum draft of the ships to 11.5 meters. Indeed, the tide window of 3 hours is still comfortable even if no above-mentioned effects are considered.

	Neap tide		Spring tide		Total
Draft [m]	PC to P1	P1 to PC	PC to P1	P1 to PC	Average
11.00	6.75	5	6.25	5.25	5.81
11.25	4.25	5.5	3.75	4.75	4.56
11.50	**3.25**	**2.75**	**3.5**	**2.25**	**2.93**
11.75	1.75	1.75	2.25	1.75	1.87
12.00	1.25	0.5	0.75	1	0.87

Table 2: Effect of ship draft on average tide window measured in hours considering a constant ship speed over water of 12 knots

4 CONCLUSIONS

This study suggests that the proposed model can improve the decision making regarding acceptable tidal windows. It has been shown that the combination of hydrodynamic model and traffic simulations can be used to improve trade performance of approach channels, mainly where low predictability of levels exists.

Simulations for the case of the Amazon North channel showed that the total travel time is minimized if the ship starts at the final of the rising tide and at the beginning of the falling tide, in the case of ship entrance at the shelf (upstream travel) or at the port (downstream travel), respectively.

This analysis will lead to a better safety and better efficiency of ports and channel operations. Indeed, the methodology allow the calculation of a timetable on a year period showing the tide window for a specific draft and a specific ship speed over water. High-tide windows can be used to allow deep-draft vessels to sail in the channel with the tide. Although, there is a need to include other effects and parameters into traffic simulation in order to improve the channel navigation, such as, seasonal river flows.

Other considerations such the squat effect, the heel due to wind or the ship motions due to waves might be included in the model in a future work. However, in the present case study, these effects are considered secondary as the limited depth of the approach channel present a small extension and the sea bottom presents a soft mud in suspension.

Although the probabilistic aspects are not included in this study, future enhancements will include uncertainties for ship draft, bottom level fluctuations, tidal prediction errors and wave forecast.

5 ACKNOWLEDGMENTS

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