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A STUDY ON THE WATER EXCHANGE IN MUNDAÚ LAGOON, NORTHEASTERN BRAZIL DURING THE DRY SEASON

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Abstract

Changes in the inlet morphology of choked coastal lagoons often restrict the water exchange with the sea, making them vulnerable to pollution release and eutrophication processes. In this study, the role of tides for the water exchange was investigated in a choked lagoon for critical scenarios during the low river flow season. Both an integrated and spatially distributed approach were employed using Lagrangian tracking of particles. The spring tides were responsible for the most pronounced water exchange and the spatially distributed approach identified different zones with similar water exchange characteristics. The tide action was primarily limited to the southern portion of the lagoon presenting a zone with rapid exchange times, whereas the other parts involved lower exchange and consequently long renewal times making it a more vulnerable area to different types of pollution releases.

Key words: Choked Coastal Lagoon, Water Exchange Time Scales, Hydrodynamic Modeling, Particle Tracking, Mundaú Lagoon, Brazil

1. Introduction

Coastal lagoons are shallow water bodies that exhibit intense morphological changes that tend to evolve to other kinds of systems in geological time due to sedimentary processes (Martin and Dominguez, 1994; Adlam, 2014). Such processes, for example spit formation across the lagoon inlet, restrict the flux of water between the sea and the lagoon and reduce the efficiency of water renewal (Bird, 1982; Kennish and Paerl, 2011). Among the different classifications of coastal lagoons, the choked lagoons present the less favorable geomorphologic condition to water flux. In these lagoons the long entrance channels act as a dynamic filter, reducing tidal currents and water level fluctuations (Kjerfve, 1986; Kjerfve, 1994; Smith, 1994).

In addition to the morphological implications for the choked lagoons water exchange presented above, many of these systems are located in regions exposed to droughts or simply with marked differences between wet and dry seasons. During periods of low freshwater discharges the role of the tides is increased and often becomes the only forcing responsible to the water renewal. The limited water exchange makes these water bodies vulnerable to events of pollution and to eutrophication (Paerl et al., 2006).

Mundaú Lagoon (surface area 24 km^2) is an example of a choked coastal lagoon. It is a part of the Mundaú-Manguaba Estuarine-Lagoon System (MMELS), located in northeastern Brazil (Fig. 1), this water body with an average depth of 1.5 m receives freshwater from the Mundaú River and seawater through a 350-m wide, highly dynamic inlet (Fig. 2) linked to the lagoon through a system of channels. As observed by Oliveira and Kjerfve (1993), tides and freshwater discharge are controlling the water exchange in this lagoon. However, during the dry season, from December to March, the river flow decreases substantially and the meso-tidal sea level variation dominates the water renewal. The environmental response to these conditions is a higher algae density responsible for bloom formation (Melo-Magalhães et al., 2009).

An assessment of the water exchange is possible by applying different transport time scale concepts. These time scales can constitute integrated measures or be spatially distributed (Monsen et al., 2002). The integrated time scale is usually denoted in literature as the turnover or flushing time and is useful for a comparison between different water bodies, although potential misconception can arise from the use of this time scale since it involves an assumption of a fixed value on a quantity that varies with the environmental conditions, such as tidal flows or river discharges (Oliveira and Baptista, 1997). Spatially distributed or

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local time scales are useful for assessing the role of distinct forcing in the spatial heterogeneity of the water exchange. For the estimation of these time scales, an hydrodynamic modeling of the water body is usually performed and the estimated flow field is employed, either from an Eulerian perspective, calculating the concentration decay in the different parts of interest, or from a Lagrangian perspective, calculating the time spent by the water parcels inside a region of interest with respect to their initial position.

In the present study, the tidal exchange and water movement patterns in Mundaú Lagoon during the dry season were investigated using a Lagrangian particle-tracking approach based on a hydrodynamic model, yielding spatial patterns for the exposure and residence time scales. Information about the tidal exchange, including its spatial and temporal properties, is vital for the water quality management of the Mundaú Lagoon, which suffers from severe pollution and sedimentation problems.

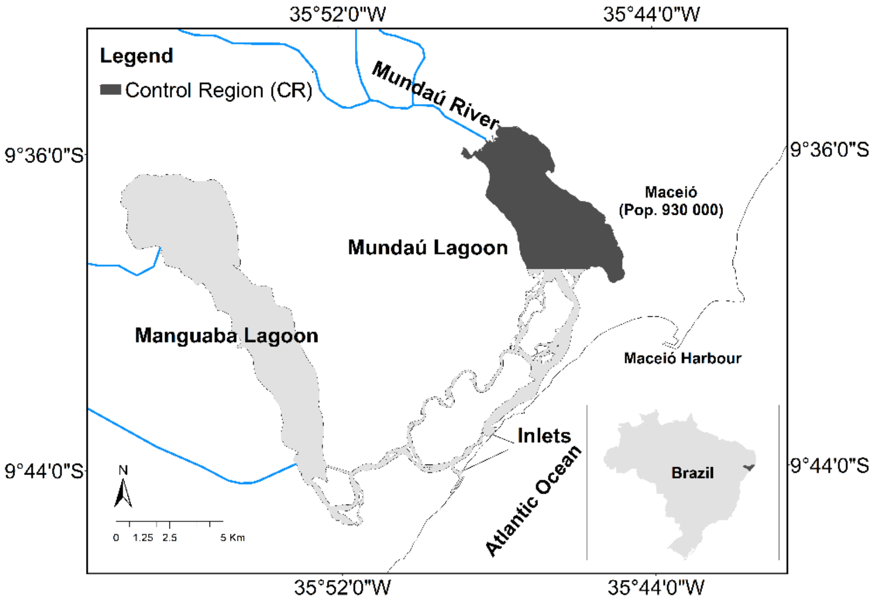

Fig. 1. MMELS with Mundaú Lagoon. Highlighted is the employed control region (CR) referred to in the subsequent modeling.

Fig. 2. Inlet system at MMELS.

2. Hydrodynamic Modeling

The hydrodynamic simulation was used to track the movement of particles released in a Control Region (CR) corresponding to Mundaú Lagoon (Fig. 1). A hydrodynamic 2D model based on TRIM3D (Casulli and Cattani, 1994), the IPH-TRIM3D-PCLake model (Fragoso et al., 2009), was implemented with depth-averaged velocities. This model uses a semi-implicit Eulerian-Lagrangian finite-element scheme to assure stability independent of the celerity while solving the shallow water equations, given by:

$$\frac{\partial \eta}{\partial t}+\frac{\partial[(h+\eta)u]}{\partial x}+\frac{\partial[(h+\eta)v]}{\partial y}=0 \tag{1}$$

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-g\frac{\partial \eta}{\partial x}-\gamma u+\tau_x+A_h\nabla^2 u+fv \tag{2}$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=-g\frac{\partial \eta}{\partial y}-\gamma v+\tau_y+A_h\nabla^2 v-fu \tag{3}$$

where t is time; $u(x,y,t)$ and $v(x,y,t)$ are the water velocity components in the horizontal x and y directions, respectively; the water depth from the bottom to the undisturbed level is $h(x,y)$ and from the undisturbed level to the free surface is $\eta(x,y,t)$; f is the Coriolis parameter; A_h is the coefficient of horizontal eddy viscosity; ; τ_x and τ_y are the wind stresses in the horizontal directions; and γ is a bottom friction term, calculated through the Chézy formula. The wind shear stress at the free surface and the bottom friction at bed are the input required for solving the equations.

The hydrodynamic simulation corresponded to a period of 27 days, from February 15 to March 14 of 2014, and a numerical time step of 30 seconds was adopted. The MMELS were spatially discretized through a regular grid with 68678 nodes and 32108 squared elements, each having 50 m width. The wind stress coefficient was chosen to $1.0 \cdot 10^{-3}$ as suggested by Hicks et al. (1974) for shallow water bodies under different wind speed conditions. A total of 10073 particles distributed in the center of the grid cells were released and their positions recorded every time step, whereas the number of remaining particles inside the CR was recorded every 30 minutes. As the tidal exchange of water depends on the tidal phase at which the particles were released (Ridderinkhof et al., 1990), the model was run 12 times with one hour of difference in release time, covering the entire ebb and flood cycle (Fig. 3), and the average rate of particle exits in time was estimated. The particle tracking method of Euler was applied with each simulation time step further divided into 10 steps to guarantee the accuracy.

The bathymetry data used correspond to the most recent surveys carried out in MMELS at different occasions. For Mundaú Lagoon the depth information is from 2012 and was provided by the Agência Nacional de Águas (ANA), Manguaba bathymetry was surveyed in 2011 by PETROBRAS, while the channel data are from 1985 and the Instituto de Pesquisas Hidroviárias (INPH) was the responsible for the measurements. Tidal levels in the period of simulation were obtained from a harmonic tidal prediction utilizing the constituents provided by the Centro de Hidrografia da Marinha (CHN) for the Maceio Harbor, 9 km from Mundaú Lagoon inlet. The river flow data utilized correspond to measurements at a flow gauging station located in Mundaú river, 24 km upstream the CR. The wind data employed for the period of simulations were measured at a meteorological station located 7.5 km northeast of Mundaú Lagoon.

Water level data were utilized for calibration and validation of the simulations. These data were obtained from a water level gauge (In-Situ Aqua Troll 200) installed inside the CR in the southeasthern portion of Mundaú Lagoon with a 15-min sampling frequency and encompassing approximately 52 tidal cycles. After calibration a value on the adjusted Chézy bottom friction coefficient of 48 $m^{1/2}s^{-1}$ was obtained. The model was verified by comparison with the measured data set (Fig 4a), where a Mean Absolute Error (MAE) of 0.019 was obtained and a Root-Mean-Square Error (RMSE) of 0.021 m. An R^2 of 0.97 was obtained from the linear regression analysis applied for the model outcome (Fig 4b). No systematic residual errors were observed.

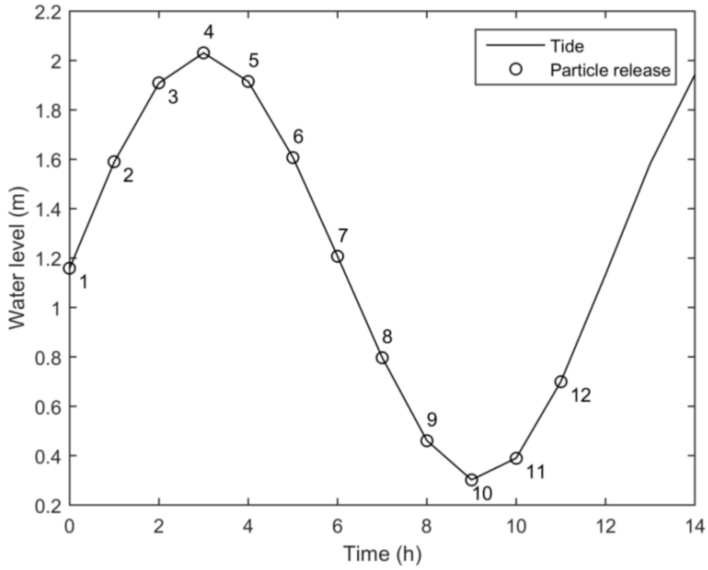

Fig. 3 - The particle release time for each simulation in the first tidal cycle.

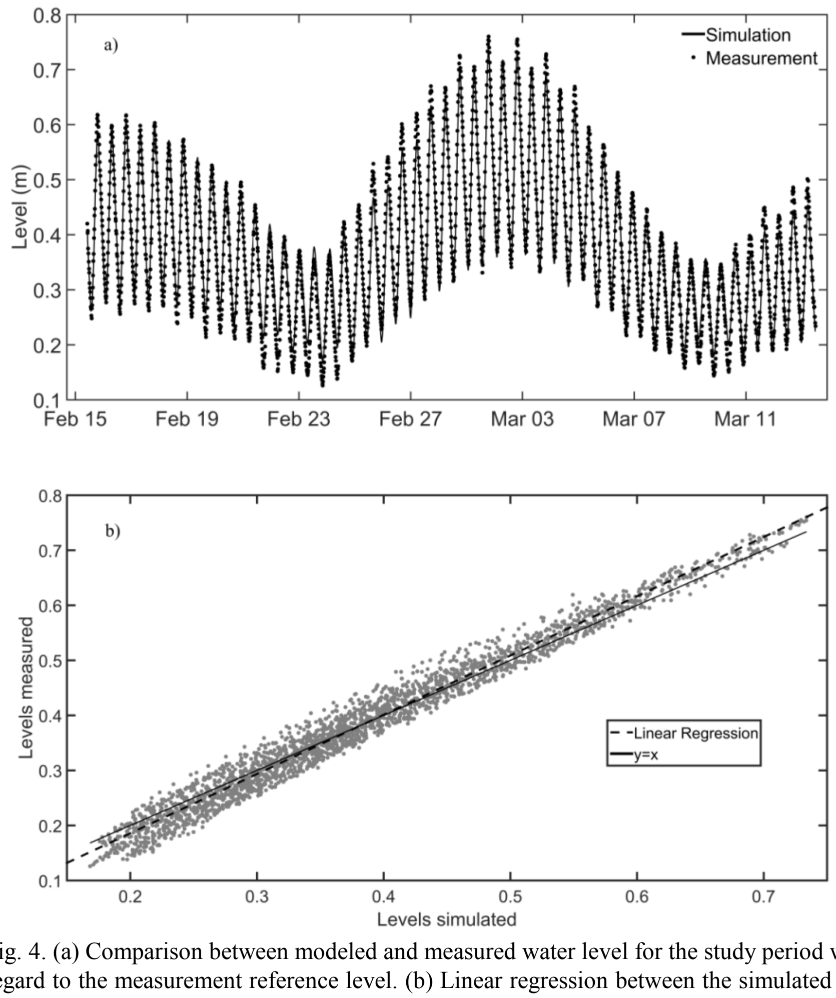

Fig. 4. (a) Comparison between modeled and measured water level for the study period with regard to the measurement reference level. (b) Linear regression between the simulated and measured water levels.

3. Water exchange time scales

Exchange times for the lagoon were estimated through the Lagrangian tracking of neutrally buoyant particles. From this particle tracking, two approaches were applied: (1) an estimate for the entire lagoon, using a e-folding approximation, where the number of remaining particles inside the domain in time was approximated with a continuously stirred tank reactor (CSTR) model; and (2) a spatially distributed estimate, using the particle movement inside, outwards, and inwards the domain to identify local differences in the water exchange, through the concepts of residence and exposure time.

The entire lagoon approach through the CSTR model assumes that at t = 0, a conservative tracer of a known quantity is introduced into the CR and a homogeneous concentration C_0 is established through instantaneous and complete mixing. The flow and volume of the region are constant and no further load of tracer is introduced. Thus, the concentration (C) decay is governed by (Ridderinkhof *et al*., 1990; Monsen et al., 2002):

$$C(t) = C_o e^{-t/T_f} \tag{4}$$

The so-called e-folding flushing time (T_f) is calculated as the time for the average tracer concentration to decrease to e^{-1} (37%).

For the spatially distributed estimate of the water exchange, also called the local time scale, the concepts of residence and exposure time were applied. The residence time is defined by Delhez *et al*. (2014) as the time the water parcel takes from its initial position until leaving the CR for the first time. However, for tidal systems, the particles can re-enter the CR depending on the tidal cycle; thus, the exposure time was also applied and is defined as the cumulative time each parcel spends inside the CR (Delhez, 2013). The open boundary of the hydrodynamic model domain was defined as the inlet of MMELS. Here, it was assumed that once the particles reach the inlet they leave the system permanently.

4. Results

Comparisons between measurements and calculations by the hydrodynamic model during the validation phase resulted in a high value on R^2, indicating an accurate reproduction of the observed water level variation in the lagoon. For the maximum level values the model was less accurate, tending to underestimate these values during the transition from neap to spring tides.

The relative number of particles (N/N_{total}) inside the CR in time, obtained for the 12 different release times, is present in Fig. 5a considering only the first exit of the particles and in Fig. 5b accounting also for particle reentrance to the CR. For both situations, the particles with release times during ebb tide exhibited lower flushing times, *i.e.*, the particles exited the CR quicker than those released during flood tide. Still, with regard to the tidal cycle effects on the particle flushing, the spring cycle was responsible for a higher net exit of the reentrant particles, while this effect was not observed during the neap tidal cycle; neither for the situation when only the first exit was taken into account. The average fraction of particles in time inside the CR was used to fit an exponential curve with an optimized initial value. The R^2 values of 0.997 and 0.946 were obtained for the non-reentrant and reentrant particles situations, respectively. The e-folding flushing time was then calculated to be 56.5 days for one exit particles and 64.4 days for particles free to return to the CR.

The analysis of the particle movement made it possible to identify four patterns in the CR: (a) the particle directly went out of the CR reaching the open boundary and exiting the MMELS (Fig. 6a.); (b) the particle followed a circular trajectory ending up near its initial location (Fig. 6b.); (c) the particle rapidly exited the CR, but returned and remained inside the CR in the subsequent tidal cycles (Fig. 6c.); and (d) the particle was flushed out of the CR without leaving the MMELS (Fig. 6d.).

Maps corresponding to the residence time and the exposure time were obtained by associating the values of these time scales for each cell with the original position of the particle (Fig. 7a and Fig. 7b). Three zones could be specified from this results: (1) the southern zone of the lagoon with the smallest residence time, from 6 hours to 8.6 days, indicating higher exchange values in the proximity of the channels - however, in this zone differences between the time scales were observed, where a well-defined zone of small residence time values was obtained and highly variable values for the exposure time; (2) the northern and western zones with values from 3.5 to 23 days for both time scales; and (3) the central and the eastern portion of the lagoon with values higher than 23 days.

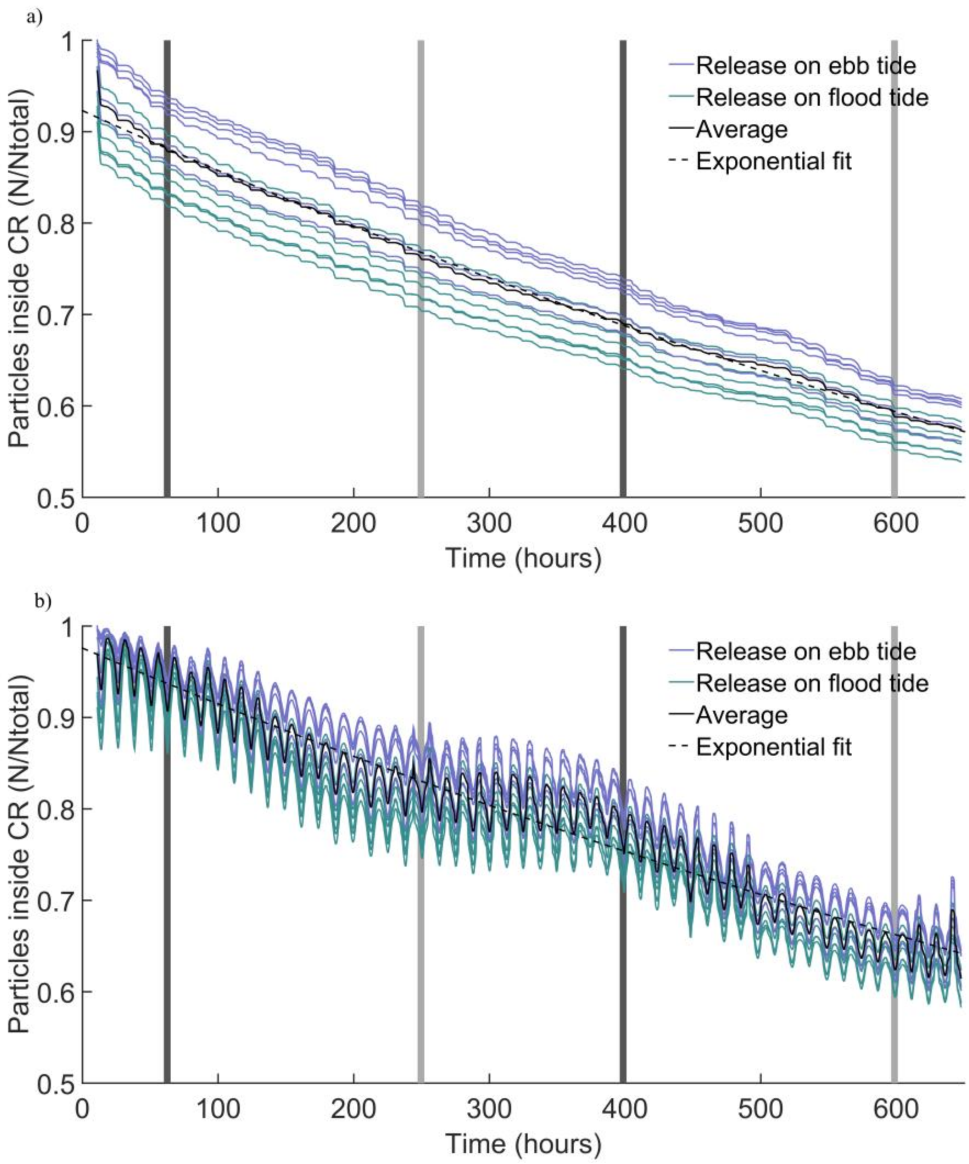

Fig. 5. Fraction of particles inside the CR for the situations: (a) without particle re-entrance, and (b) with particle re-entrance. The vertical shaded periods are the spring (dark grey) and neap (light grey) tidal cycles.

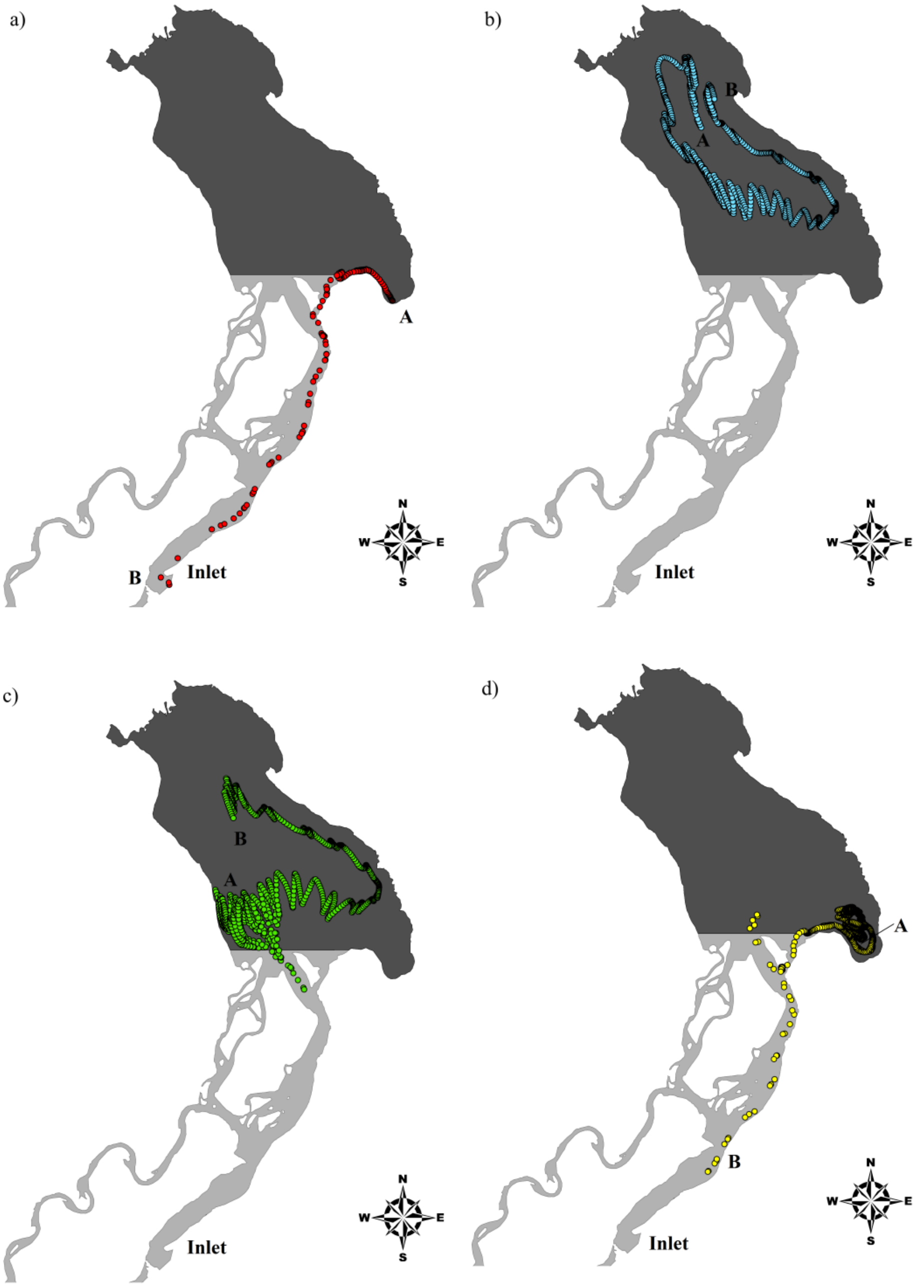

Fig. 6 – The four identified particle behaviors (the colored points represent all recorded particle positions from A to B): (a) Particle exits MMELS. (b) Particle finishes the simulation without exiting the CR. (c) Particle exits the CR but returns and ends up inside the lagoon. (d) Particle finishes the simulation outside the CR but without exiting MMELS.

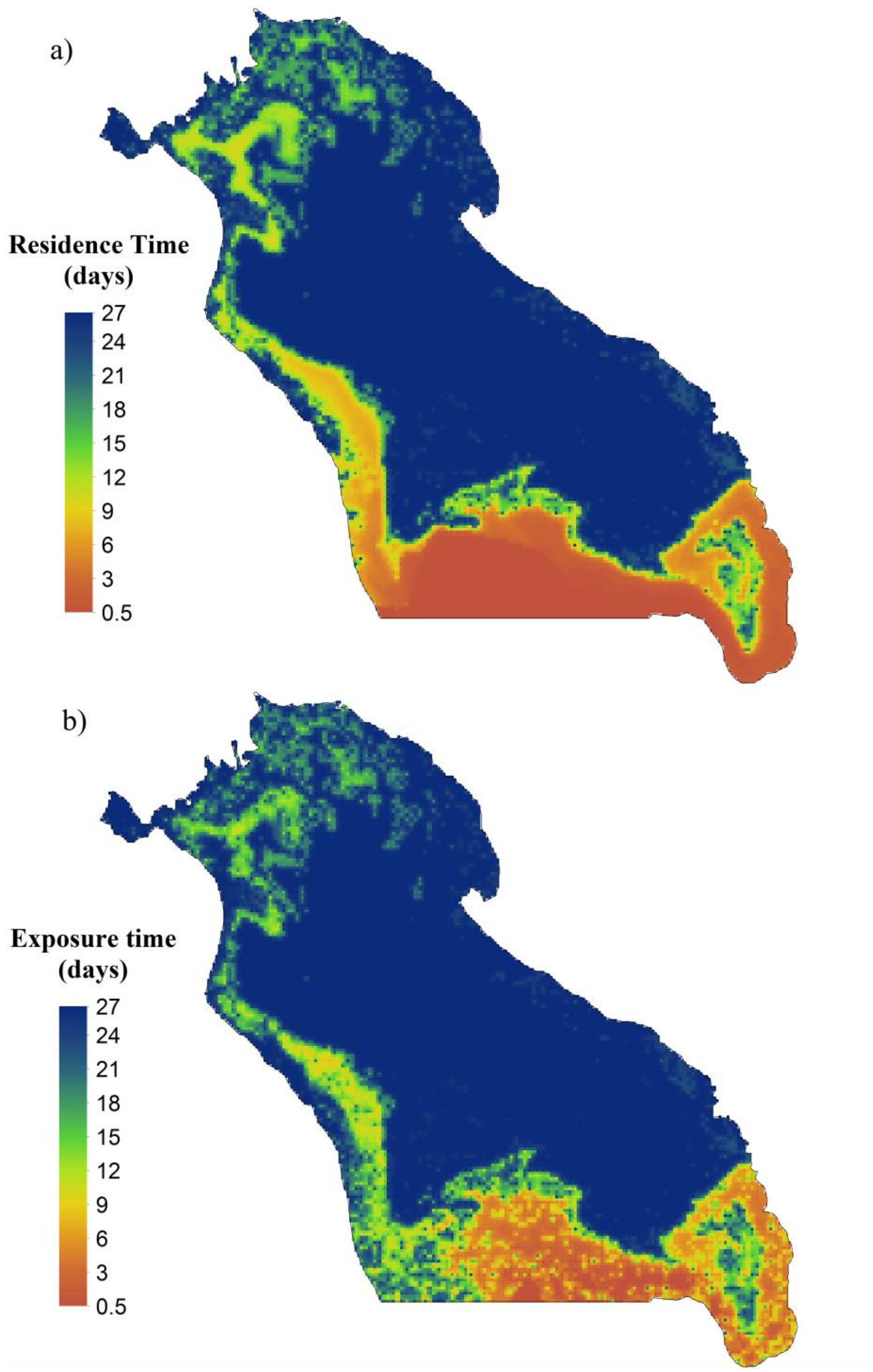

Fig. 7. The spatial distribution of residence and exposure time.

5. Discussion

The effects of ebb and flood tidal cycles for the whole lagoon water exchange was assessed through the e-folding flushing time for different particle releases in time during these cycles. The release during ebb tide resulted in the smallest values for both returning particles and particles not returning, whereas the release during the flood tide yielded the opposite behavior. However, the differences in final flushing time values between the ebb and flood were small.

The allowance for the particles to return to the CR caused a fraction of the particles to keep returning, some of them until the end of the simulation; thus, the estimated exposure time was larger than the residence time. The simulation period comprised two neap and two spring tides. Differences in the behavior of the particles, and consequently in the water exchange for the CR between these cycles were visible through the use of the exposure time concept. During the neap tide the net exit of particles is small compared to the net exit flux during the spring tides. Thus, the tides during the period of higher amplitudes can be considered the most important factor in renewing the Mundaú Lagoon water during the dry season.

The effects of the considered forcing (tides, river discharge, and wind) varied markedly in space. Based on the analysis of the particle fate with regard to the initial position, the influence of the forces acting in Mundaú Lagoon was divided into different zones. The moderate time scale values on a preferential pathway obtained in the northern and western parts of the lagoon were caused by the influence of the Mundaú River discharge. From the central to the eastern parts of the lagoon the wind is the main factor promoting transport and mixing; however, the wind was not strong enough for an efficient water exchange with other parts of the Lagoon.

Both the residence and exposure times indicated that the tides, the forcing of primary interest in this study, influenced only in a limited region in the southern part of the CR. It was observed that, although the residence time yielded a well-defined zone of short permanence of water particles, the exposure time approach indicated that most of these particles that initially left the CR returned during the next tidal cycle, in this way limiting the effective water renewal promoted by tides to a smaller area.

6. Conclusions

In this study, the water exchange in Mundaú Lagoon, located in northeastern Brazil, was investigated and quantified for different scenarios during the dry season. The water exchange promoted by the tides is the most effective mechanism during this season, varying with the different tidal cycles. The spring tides contributed to a more accentuated net exit of water particles than the neap tide. Although particles released during ebb tide yielded exchange times lower than for those released on the flood tide, the overall particle presence in the lagoon exhibited a limited dependence on the release time on the ebb and flood cycles.

The eastern zone of the lagoon had the lowest values for the water exchange; the wind is the main forcing acting in this region but it does not contribute to the transport of particles out of the lagoon. Thus, this zone has the highest potential risk of pollutant accumulation for the environmental conditions analyzed. The water in the northern and western zones is first transported by the river discharge and finally by the tidal flow. This flow is limited to the southern zone, where faster water renewal occurs. However, when considering the possibility of the water parcels to renter the lagoon during subsequent tidal cycles, this zone of active exchange is even more limited. Thus, the overall water exchange of Mundaú Lagoon is small during the dry season and the lagoon is sensitive to pollution releases.

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