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WATER RENEWAL IN THE MUNDAÚ-MANGUABA ESTUARINE-LAGOON COMPLEX (ALAGOAS, BRAZIL) UNDER DIFFERENT INLET CONFIGURATIONS

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Abstract

The present study analyzes the morphological changes that occurred in the Mundaú-Manguaba Estuarine-Lagoon Complex (MMELC), through geoprocessing techniques and computational modeling. Initially, a multitemporal analysis of the coastline variations between 1986 and 2017 was carried out using Landsat 5-TM and Landsat 8-OLI satellite images. The images were vectored in a Geographic Information System (GIS) environment for subsequent calculation of erosion and accretion rates. After that, some simulations were carried out with the Hydrodynamic Environmental System (SisBaHiA®) for residence time and water age parameters, considering three scenarios with different inlet configurations (2006, 2014 and 2017). The results indicated the predominance of sediment deposits in the inlet region, with migratory dynamics in the Southwest-Northeast direction. Residence time (RT) indicated possible stagnation areas in the Northwest region of the Manguaba Lagoon and the Northwest and Southeast portions of the Mundaú Lagoon. The 2014 scenario showed lower water ages, indicating that the different inlet configurations interfere with water renewal in the lagoon-estuarine complex.

Keywords: Coastal Monitoring; Inlet; Water Renewal.

RENOVAÇÃO DAS ÁGUAS NO COMPLEXO ESTUARINO LAGUNAR MUNDAÚ-MANGUABA (AL, BRASIL) SOB DIFERENTES CONFIGURAÇÕES DE EMBOCADURAS

Resumo

O presente trabalho analisa as alterações morfológicas ocorridas no Complexo Estuarino Lagunar Mundaú-Manguaba (CELMM), através de técnicas de geoprocessamento e da modelagem computacional. Inicialmente realizou-se uma análise multitemporal das variações das linhas de costa entre o período de 1986 até 2017 a partir de imagens dos satélites Landsat 5-TM e Landsat 8-OLI. As imagens foram vetorizadas em ambiente de Sistema de Informações Geográficas (SIG) para a posterior realização do cálculo das taxas de erosão e acreção. Após isso, algumas simulações foram realizadas com o auxílio do Sistema Base de Hidrodinâmica Ambiental (SisBaHiA®) para os parâmetros tempo de residência e idade da água, considerando três cenários com configurações de embocaduras distintas (2006, 2014 e 2017). Os resultados indicaram o predomínio da deposição de sedimentos na região da embocadura, com a dinâmica migratória no sentido Sudoeste-Nordeste. O tempo de residência apontou possíveis áreas de estagnação na região Noroeste da laguna Manguaba e nas porções Noroeste e Sudeste da laguna Mundaú. O cenário de 2014 apresentou menores idades das águas, mostrando que as diferentes configurações de embocaduras interferem na renovação das águas do complexo estuarino lagunar.

Palavras-chave: Monitoramento Costeiro; Embocadura; Renovação das Águas.

RENOVACIÓN DE AGUA EN EL COMPLEJO ESTUARINO LAGUNAR MUNDAÚ-MANGUABA (AL, BRASIL) BAJO DIFERENTES CONFIGURACIONES DE EMBOCADURAS

Resumen

El presente trabajo analiza los cambios morfológicos ocurridos en el Complejo Estuarino Lagunar Mundaú-Manguaba (MMELC), mediante técnicas de geoprocesamiento y modelación computacional. Inicialmente, se realizó un análisis multitemporal de las variaciones del litoral entre el período de 1986 a 2017 utilizando imágenes de los satélites Landsat 5-TM y Landsat 8-OLI. Las imágenes fueron vectorizadas en un entorno de Sistema de Información Geográfica (SIG) para el cálculo posterior de las tasas de erosión y acreción. Posteriormente, se realizaron algunas simulaciones con el Sistema Base de Hidrodinámica Ambiental (SisBaHiA®) para los parámetros tiempo de residencia y edad del agua, considerando tres escenarios con diferentes configuraciones de embocaduras (2006, 2014 y 2017). Los resultados indicaron el predominio de la deposición de sedimentos en la región de la embocadura, con la dinámica migratoria en dirección suroeste-noreste. El tiempo de residencia indicó posibles áreas de estancamiento en la región noroeste de la laguna Manguaba y en las porciones noroeste y sureste de la laguna Mundaú. El escenario de 2014 mostró edades del agua más bajas, mostrando que las diferentes configuraciones de embocaduras interfieren con la renovación de las aguas del complejo estuarino de la laguna.

Palabras-clave: Monitoreo Costero; Embocadura; Renovación de agua.

1. INTRODUCTION

Coastal lagoons, which occupy about 13% of coastal areas, are shallow water bodies found on all continents, parallel to the coast and connected to the ocean by one or more inlets (KJERFVE, 1994; MIRANDA *et al*., 2002). These systems exhibit a range of shapes and sizes that can be modified by erosion and sediment deposition, primarily in the region of the inlet (BIRD, 2008).

Since they are shallow environments, lagoon circulation is influenced by climate and oceanographic conditions, such as rainfall, wind, river discharge, in addition to tidal and wave action. The hydrodynamic response of each of these factors depends on the characteristics of the channel that connects to the ocean, which regulates water exchange between lagoons and the adjacent coastal region (GARCÍA-OLIVA *et al*., 2019; KJERFVE and MAGILL, 1989).

Thus, lagoon inlets are morphologically complex regions, dependent on the balance between coastal transport, river and tidal flows and the morphological characteristics of the inland water body, which promote the opening and closing of inlets (FORTUNATO *et al*., 2008; OLIVEIRA *et al*., 2006; SILVA and ROSMAN, 2016). The morphological configurations of the inlets determine the water exchange capacity of a lagoon, where size (length, width and depth) and a large number of inlets increase water exchange between the lagoon and the adjacent coastal region, significantly improving the quality and renewal of its waters (PANDA *et al*., 2013).

A number of studies have investigated the morphological variations of inlets in natural water bodies. Dias *et al*. (2009) studied the impact of Ancão inlet relocation on the hydrodynamic circulation and residence time of the Ria Formosa Lagoon. García-Oliva *et al*. (2019) analyzed the effects of different dredging scenarios on salinity and temperature parameters in the Mar Menor Lagoon. Mulligan *et al*. (2019) conducted hydrodynamic and salinity simulations in Pamlico Sound for different geomorphological conditions. Oliveira *et al*. (2006) determined the morphological changes that occurred during water renewal of the Óbidos Lagoon, in Portugal. Panda *et al*. (2013) investigated the geomorphological changes in the Chilika Lagoon, based on the analysis of satellite images, hydrodynamic simulations and salinity distribution.

With respect to water renewal, the parameters water age and residence time are essential in determining water exchange, in order to detect areas prone to pollutant accumulation and assess the transport of substances within water bodies, thereby contributing to coastal management and planning (AGUILERA *et al*., 2020).

Among the lagoon systems on the Brazilian coast is the Mandaú-Manguba Estuarine Lagoon Complex (MMELC), located in Alagoas state (Figure 1), a system of natural water bodies consisting of two lagoons, Mundaú and Manguaba, connected to the ocean by a series of mangrove-lined channels that constantly open and close, ending at an inlet exhibiting high variability (OLIVEIRA and KJERFVE, 1993).

The MMELC region has been studied by several authors. Lima (2017) calculated residence time (RT) using the Mike 21 computational model. Brito Júnior *et al*. (2018) studied different approaches to measure RT during the dry season of the Mundaú Lagoon and assessed the influence of tides and wind on water exchanges. Cunha *et al*. (2021) determined how the variations in river discharge and wind influence hydrodynamic circulation and water renewal. Nunes *et al*. (2020) developed a morphological model for inlet evolution and applied it to the Mundaú Lagoon inlet. Pinheiro (2020) calculated RT, renewal rate and water age for different inlet configurations, considering the dry and rainy seasons.

The present study proposes to broaden knowledge of the impacts of morphological variations in the inlet on the circulation and renewal of MMELC waters, in addition to using disperse information to understand the dynamics of the morphological changes that occurred in the inlet.

Therefore, the aim of this study was to describe the morphological changes that occurred at the MMELC inlet, using geoprocessing techniques, thereby assessing the effect of different inlet configurations on the water renewal of the lagoon-estuarine complex, via the SisBaHiA® modeling system.

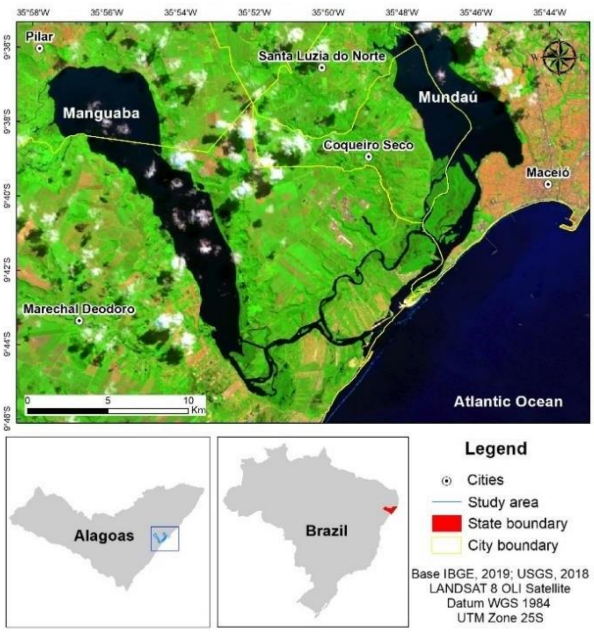


Figure 1 –Location of the Mundaú-Manguaba Estuarine Lagoon Complex. Source: Adapted from Cunha et al. (2021).

2. METHODOLOGY

2.1. Study area

The Mundaú-Manguaba Estuarine Lagoon Complex (MMELC) is located between latitudes 9°35’ and 9º45’ South and longitudes 35°44’ and 35º58’ West, in Alagoas state, including the cities of Santa Luzia do Norte, Coqueiro Seco, Marechal Deodoro, Pilar and Maceió (Figure 1).

The MMELC is a choked lagoon system, with prolonged residence times (RTs) and limited water exchanges (KJERFVE, 1986; OLIVEIRA and KJERFVE, 1993). The system also acts as an efficient filter for tidal range attenuation. Tidal dampening reached 88% and 98% in the Mundaú and Manguaba Lagoons, respectively, when compared to the amplitude in Maceió Harbor (OLIVEIRA and KJERFVE, 1993).

The Mundaú and Manguaba Lagoons are shallow water bodies, with average depths of 1.7 and 2.1 meters, respectively (COSTA *et al*., 2010; OLIVEIRA and KJERFVE, 1993). The Mundaú Lagoon covers an area of 27 km² and Mundaú River is its main source of freshwater. The area of the Manguaba Lagoon is approximately 42 km² and its primary contributor is the Paraíba do Meio river (ANA, 2006).

The rainfall regimen can be divided into two well-defined seasons, a dry season between September and March, and a rainy season from April to August, accounting for 70% of total annual rainfall (INMET, 2020). Average annual rainfall is around 1800 mm, and average air temperature varies between 24 and 26.5ºC (INMET, 2020). The lagoons are classified as As (Köppen), characterized by a tropical climate with a dry summer (ALVARES *et al*., 2013).

2.2 Morphological changes

Satellite images taken between 1986 and 2017 were used to determine the morphological changes in the region near the MMELC inlet and quantify the erosion and deposition rates. The criteria established for scene selection were cloud cover and image availability. Seven time intervals were established (1986 to 1990, 1990 to 1998, 1998 to 2003, 2003 to 2006, 2006 to 2010, 2010 to 2014, and 2014 to 2017).

The images selected were obtained from Landsat 5-TM and Landsat 8-OLI images, with 30-meter spatial resolution, path/row 214/67, WGS-1984 datum, Universal Transverse Mercator (UTM) zone 25 South, extracted from the United States Geological Service (USGS, 2018) and presented on the 1:100,000 scale in Figure 2.

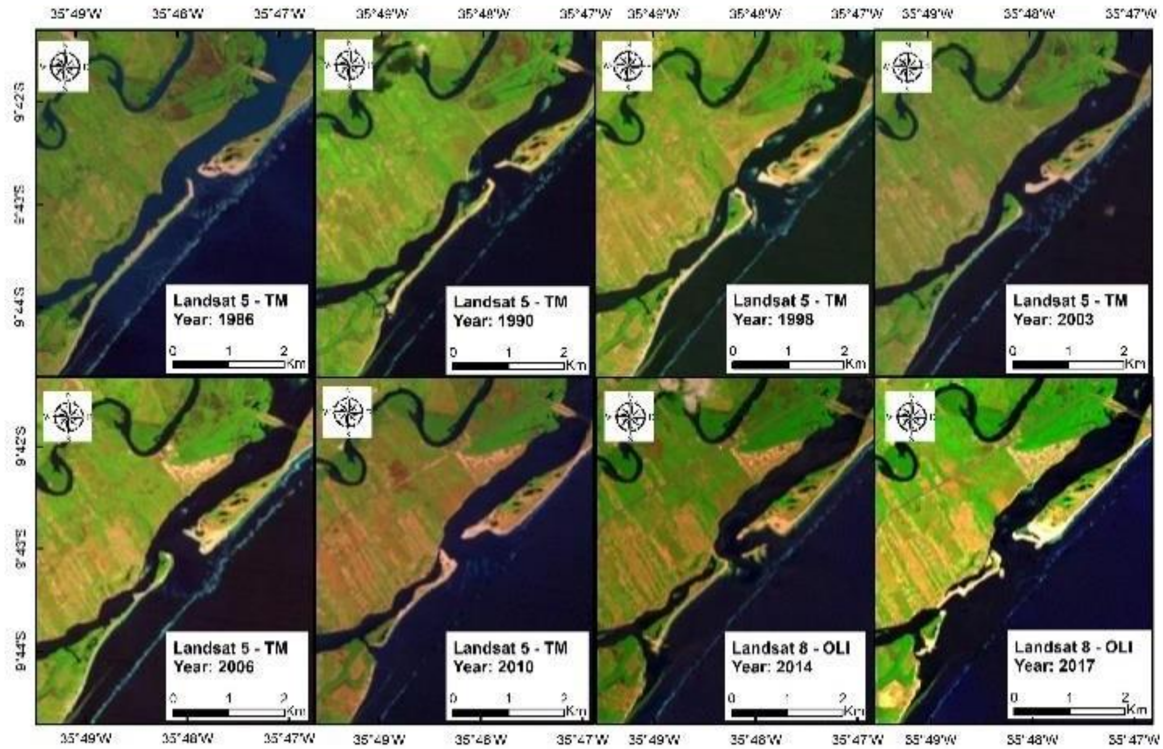


Figure 2 – Orbital images from the Landsat satellite between 1986 and 2017. Source: Adapted from Luz et al. (2021).

The spectral bands were combined in the Red-Green-Blue (RGB) color system in order to determine the differences between the water body and the immersed areas. The compositions used are depicted in Table 1.

Next, the images were stored in the Geographic Information System (GIS), using ArcGIS® software to vectorize the coastlines and subsequently analyze the erosion and deposition areas. According to Amaro *et al*. (2012), the ratios (R) between deposition and erosion in the time intervals mentioned were calculated and classified as intense deposition (ID, R>2), deposition (DP, 1.10<R<2.0), equilibrium (EQ, 0.90<R<1.10), erosion (ER, 0.70<R<0.90) and intense erosion (IE, R<0.70).

Table 1 – RGB composition of the satellite images used. Source: adapted from Luz et al. (2021).

Satellite	Sensor	Image date	Time (Brasilia)	RGB
Landsat 5	TM	06/16/1986	08:53	543
Landsat 5	TM	06/11/1990	08:50	543
Landsat 5	TM	09/21/1998	09:08	543
Landsat 5	TM	09/03/2003	09:07	543
Landsat 5	TM	08/26/2006	09:23	543
Landsat 5	TM	12/11/2010	09:19	542
Landsat 8	OLI	12/06/2014	09:30	751
Landsat 8	OLI	12/14/2017	09:30	751

2.3. Models used

The modeling system used was the Hydrodynamic Environmental System called SisBaHiA® (Portuguese acronym for Base System of Environmental Hydrodynamics), registered and developed by the Aberto Luiz Coimbra Institute of Graduate Studies and Engineering Research of the Federal University of Rio de Janeiro. The simulations of this study were conducted using the two-dimensional hydrodynamic model, the Eulerian transport model and the Lagrangean transport model of SisBaHiA®. The hydrodynamic model used a second-order numeral scheme for temporal discretization and quadratic finite elements for spatial discretization. The wind fields and bottom friction varied dynamically in time and space and multi-scale turbulence modeling is based on large eddy simulation (LES). The transport model uses the same spatial discretization and the same scheme for temporal discretization of the hydrodynamic model. The Lagrangean transport model is especially suited to determining residence time in natural water bodies, thereby obtaining isoline maps of residence time in different sectors of water bodies with complex geometry (ROSMAN, 2020).

Vertical integration, which characterized the two-dimensional model, should be applied to water bodies with horizontal dimensions predominating the vertical dimension and with non-significant vertical stratification. MMELC is a shallow water system with little vertical stratification and horizontal scales with orders of magnitude larger than those of vertical scales, making it possible to apply the two-dimensional model in this study.

Residence time is defined as the average time a fluid particle remains in a compartment, and is usually calculated by the ratio between the volume of the compartment and residual flow through the compartment (BRYE *et al*., 2013; ZIMMERMAN, 1988). This traditional calculation is adequate for well mixed water bodies, but unviable in heterogeneous water. For these heterogeneous bodies and with computational modeling, it is possible to define a function of variable residence time in space. In order to calculate this spatial distribution, the model adopted the following methodology: initially, the compartments are filled with several randomly distributed neutral particles, with the initial positions and times duly recorded. Next, the particles are advected by the currents generated in the hydrodynamic circulation model and the trajectory of each particle is monitored over time. When the particle leaves the compartment, its lifetime corresponds to the residence time (ROSMAN, 2020). At the end of the simulation, the residence time of the particles that did not leave the system is equivalent to the final simulation time.

The Eulerian transport model was used to calculate water age. Water age is used to calculate the decay time of a passive substance and age marker in the water. In order to estimate decay time, the substance must undergo a first-order kinetic decay reaction, with no additional effects from mass losses or gains (ROSMAN, 2020). The water age model uses the following methodology: it is assumed that the initial concentration is equal to one in all the domain, resulting in a water age of zero. The new water that enters the system from the tides and river flow also has a water age of zero. As the initial and new water mix and are transported, substance concentration declines as a function of the substance decay process (ROSMAN, 2020).

2.4. Hydrodynamic model data

The orbital images from 1986 to 2017 (Figure 2) showed the formation of a new connecting channel in 2010. In order to determine the effects of different inlet configurations, the contours of 2006, 2014 and 2017 were analyzed.

The image from 2006 was used to portray the situation prior to the opening of this new connecting channel, that is, it represents the situation with a single outlet to the ocean. The 2017 image was selected to depict the configuration that most closely resembles the current situation, with two outlets to the ocean. Finally, 2014 was used to calibrate the hydrodynamic model with water level data measured by Brito Júnior *et al*. (2018).

In order to analyze only the influence of inlets on water renewal, bathymetry, bottom roughness, tidal, river discharge and wind data were the same for all the simulations. To that end, the simulations of 2006, 2014 and 2017 were conducted using the average flow rate and wind values.

Cunha *et al*. (2021) compared the hydrodynamic results from 2014 with average freshwater discharge and wind values, but found no relevant differences. Thus, the use of average values without the influence of extreme events does not cause a significant variation in the results.

The finite element grid used in discretization was created to encompass the three inlet configurations analyzed, with changes only at the land boundaries. Figure 3 shows the discretization grid used and the insets of the grids in the inlet region from 2006, 2014 and 2017.

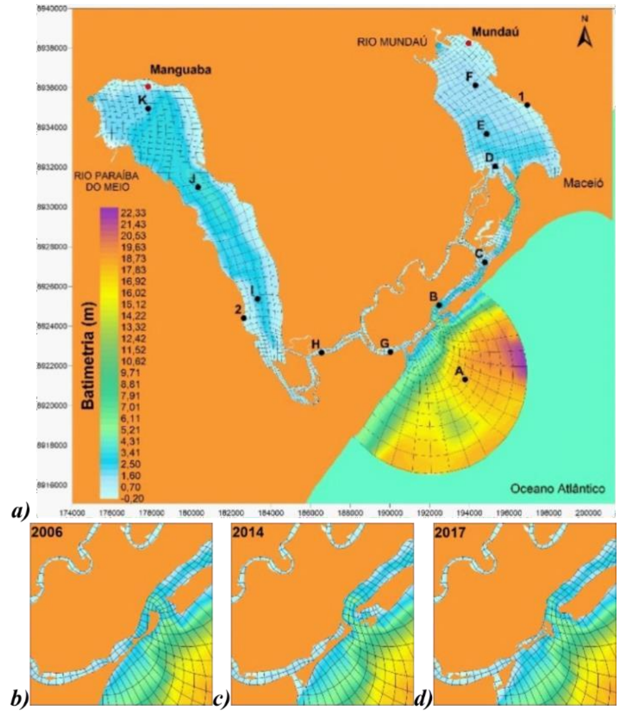


Figure 3 – a) Modeling domain of the MMELC, with a finite element grid, bathymetry, and location of stations 1 and 2, where water level was measured in 2014 and used to calibrate the model, and the other stations (A to K) used to analyze the hydrodynamic and water age results, b) Details of the inlet regions in 2006, c) 2014 and d) 2017.

Bathymetry was extracted from nautical chart number 901 of the port of Maceió, created in 1977 by the Hydrography and Navegation Division of the Brazilian Navy, based on the measurements of the National Water Agency (ANA) in 2012 and those conducted by PORTOBRÁS in 1984. Figure 3 shows that the lagoons and channels are up to four and seven meters deep, respectively.

The equivalent bottom roughness of the domain was obtained from the correlation of the data reported by Alves (2010) and the roughness values suggested by Abbott and Basco (1989). Silt predominates in the Mundaú and Manguaba Lagoons. Medium sand is prevalent in the channels and coarse sand along the coast.

The river discharge data between 1974 and 2018 at the automatic stations closest to the mouths of the Paraíba do Meio and Mundaú Rivers were acquired from HidroWeb (ANA, 2019). For the Manguaba Lagoon, the station is under code 39870000 (09º30’24.0”S and 36º01’22.0”W). In the Mundaú Lagoon, the station is in the municipality of Rio Largo, code 39770000 (09°28’02.0”S and 35º51’35.0”W).

Figure 4 shows the average daily values of the Paraíba do Meio and Mundaú Rivers, used in the hydrodynamic circulation model. The dry season occurs between October and March and the rainy season from April to September.

Peak flows take place in July for both rivers, higher in the Mundaú than the Paraíba do Meio River.

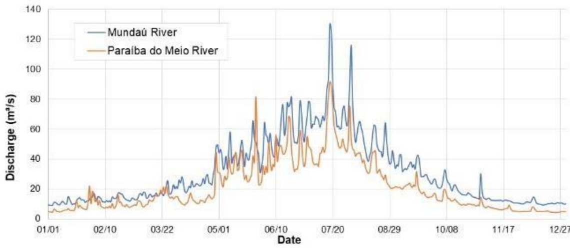


Figure 4 – Average discharge of the Mundaú and Paraíba do Meio Rivers between 1974 and 2018.

Wind direction and velocity data were obtained from the National Institute of Meteorology (INMET, 2020) for the Maceió-A303 station, under code OMM 81998 (9º33'04.2"S; 35º46'12.7"W). For hydrodynamic simulations, the average hourly data of the time series between 2004 and 2018 were used. The values for the years 2007 and 2008 were disregarded due to failures at the meterorological station. Figure 5 contains the wind regime, demonstrating a predominance of winds from the East quadrant with intensities between 0.5 and 8.0 m/s and average velocity of 2.68 m/s.

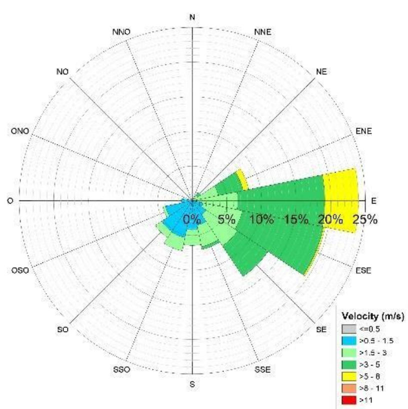


Figure 5 – Wind regime between 2004 and 2018 at the Maceió A-303 station.

The average daily wind direction and intensity values show that the wind was from the East during the dry season (41% of the time), with an average velocity of 2.85 m/s, while in the rainy season it was from the Southeast (21% of the time), with an average velocity of 2.25 m/s (CUNHA *et al*., 2021). In regard to lagoon alignment, Southeast wind has more influence on hydrodynamic circulation than the East, which predominates in the dry season.

The astronomical tide was determined by inserting the harmonic constants from the Brazilian catalog of tide stations, obtained from the Foundation for Sea Studies (FEMAR, 2000) for the Maceió Harbor (9º40.9'S and 35º43.5'W). The tidal curves observed in 2006, 2014 and 2017 were similar in amplitude, with few phase differences. Thus, in order to facilitate analysis of the results, the tidal curve for 2014 was used in all the simulations.

Figure 6 shows the tidal curve used in the sea level boundary condition. The tide exhibits a semidiurnal tidal regime, with a maximum range of 2.61 m and maximum tide height of 1.39 m.

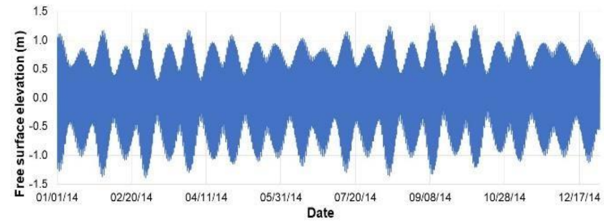


Figure 6 – Tidal curve of 2014, obtained from the harmonic constants for the Maceió harbor.

2.5. Initial and boundary conditions of the models

For the hydrodynamic circulation model as initial condition, free surface elevation and the velocities of all the nodes of the domain are required. Since no previous results were available, simulations were conducted in December for the three configurations analyzed (2006, 2014 and 2017), with null elevation and velocity values. The results of these simulations generated the initial conditions of the hydrodynamic model.

The boundary conditions for velocities and free surface elevation are needed. Except for the nodes corresponding to the rivers (Mundaú and Paraíba do Meio), all the boundary nodes were considered impermeable, with zero normal discharge.

In order to use the Lagrangean transport model, two boundary conditions are needed. The first stipulates that when a particle crosses the boundary segment, it leaves the domain and is lost. The second condition occurs along the land boundaries and two situations can be considered: the particle reaches the boundary and returns to the domain without a change in its mass or the particle returns to the domain with a fraction of its mass absorbed. This fraction is given by the absorption coefficient, which varies from zero to one. In the present study, the absorption coefficient was considered to be one, indicating total particle absorption along the part of boundary affected.

To calculate water age, a concentration of one was established in the modeling domain, the open boundaries and the nodes corresponding to the rivers.

The results of the stations located in Figure 3 were analyzed. Stations 1 and 2 indicate the sites where Brito Júnior *et al*. (2018) measured water levels. Station A corresponds to the adjacent coastal region.

Stations B and G indicate the regions closest to the inlets of the Mundaú and Manguaba Lagoons, respectively. Stations C and H are located in the intermediate regions of the access channels of the Mundaú and Manguaba Lagoons, respectively.

Stations D, E and F are located in the Mundaú Lagoon and characterize the three compartments: the region near the connecting channel, the central region and the back area of the lagoon. Similarly, stations I, J and K, located in the Manguaba Lagoon, describe the three compartments: the region nearest the access channel, the central region and the back area of the lagoon.

3. RESULTS AND DISCUSSION

3.1. Coastline evolution

Figure 7 shows the coastline evolution between 1986 and 2017, classifying and quantifying the areas eroded and added.

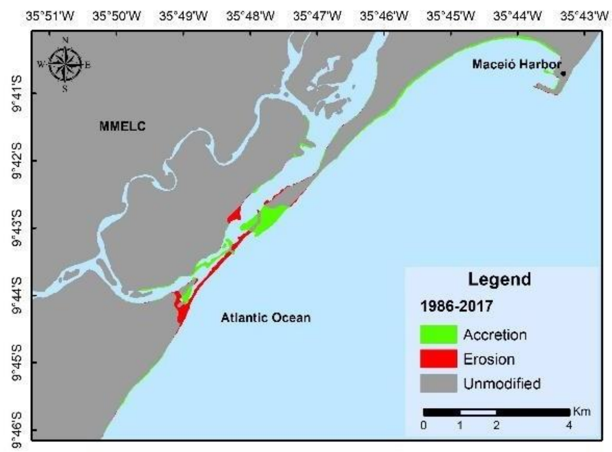


Figure 7 – Erosion and accretion zones between 1986 and 2017.

Figure 2 shows that in 1986 the MMELC had only one outlet to the ocean. Between 1986 and 1990 intense erosion occurred in the Southwest portion of the inlet, causing an access channel to open to the Manguaba Lagoon. The floods that occurred in the Paraíba do Meio and Mundaú River basins in 1988 and 1989 may have been due to this new opening in the lagoon complex (FRAGOSO JR. *et al*., 2010).

Sediments were deposited in the same region between 1990 and 1998, with the consequent closing of the access channel between the Manguaba Lagoon and the sea. Between 2003 and 2006, this region of the MMELC had only one ocean inlet.

Once again, between 2006 and 2010, erosion occurred in the Southwest portion of the inlet, with the opening of the access channel to the Manguaba Lagoon, and sediment deposition in the Northeast portion, in the connecting channel between the Mundaú Lagoon and the ocean. The Paraíba do Meio and Mundaú River floods in June 2010 may explain this occurrence (OLIVEIRA *et al*., 2014).

The connecting channel between the Manguaba Lagoon and the ocean was closed in the ensuing years (2010, 2014 and 2017). Between 2010 and 2014, sediments were deposited in the portion of the access channel to the Mundaú Lagoon, with the formation of a barrier island in the region. Sediment erosion was observed in the connecting channel to the Manguaba Lagoon between 2014 and 2017, with the formation of a barrier island in the region of the inlet, due to intense discharges from the Paraíba do Meio and Mundaú rivers in the rainy season of 2017 (NUNES *et al*., 2020).

There was high variability in the region of the MMELC and a predominance of sediment deposition with the migratory dynamics of sediments occurring in the Southwest-Northeast direction. Erosive processes predominate in the Southwest portion of the inlet and sediment deposition in the Northeast region.

Table 2 shows the quantitative results of the sedimentary balance between 1986-1990, 1990-1998, 2003-2006, 2006-2010, 2010-2014 and 2014-2017. Sediment deposition prevailed between 1986-1998 and 2003-2010. Between 1998-2003, the ratio was less than 0.7, indicating intense erosion in the region. Finally, the period between 2014-2017 indicated a sediment deposition process, according to the methodology developed by Amaro *et al*. (2012).

*Table 2 – Erosion and accretion areas in km², classified into intense deposition (*ID*, $R>2$), deposition (*DP*, $1.10<R<2.0$), equilibrium (*EQ*, $0.90<R<1.10$), erosion (*ER*, $0.70<R<0.90$) and intense erosion (*IE*, $R<0.70$).*

Period	Acretion (A)	Erosion (E)	Ratio R =A/E	Classification
1986-1990	0.4613	0.2445	1.8872	DP
1990-1998	0.6198	0.4299	1.4416	DP
1998-2003	0.1900	0.4792	0.3965	IE
2003-2006	0.4889	0.3149	1.5527	DP
2006-2010	0.5805	0.4291	1.3527	DP
2010-2014	0.2879	0.4110	0.7005	ER
2014-2017	0.7014	0.3599	1.9487	DP
1986-2017	1.2822	0.6209	2.0650	ID

3.2. Calibration and hydrodynamic results

The model was calibrated by comparing the water levels measured by Brito Júnior *et al*. (2018) between 02/15/2014 and 02/24/2014 and the data computed by SisBaHiA® at two points of the MMELC: station 1 in the Mundaú Lagoon and station 2 in the Manguaba Lagoon. The calibration results can be seen in Cunha *et al*. (2021). Water level calibration was satisfactory, indicating good model representativeness.

Three hydrodynamic simulations were performed for 2006, 2014 and 2017, with average and maximum Courant numbers of 0.7 and 2.7, respectively. The hydrodynamic results indicate that the stations near the inlet (stations B and G) exhibit relatively higher tidal current speeds and amplitudes than those of the other stations, due to the predominant influence of the tides.

With respect to the differences between the simulations, the Manguaba Lagoon had higher velocities and elevations between 2014 and 2017. Given that the region near the inlet of the Manguaba Lagoon was closed in 2006, water exchanges occured only through the inlet near the Mundaú Lagoon. In 2014 and 2017, the inlets were branched, favoring water exchanges and causing an increase in tidal amplitude and velocity. Tidal amplitudes in the Mundaú Lagoon were higher in 2006 due to the inlet configuration, favoring on water mass exchanges between the lagoon and the adjacent coastal region.

3.3. Residence time

Simulations were performed for the rainy and dry seasons of 2006, 2014 and 2017. For the dry season, January, February and March (01/01 to 03/31) were used, and June, July and August (06/01 to 08/29) for the rainy season. The particles were arranged with a spacing of 100 x 100 meters.

Figure 8 shows the RTs for the dry seasons of 2006, 2014 and 2017. The particles that did not leave the system after the 90-day simulation were assigned an RT corresponding to 90 days.

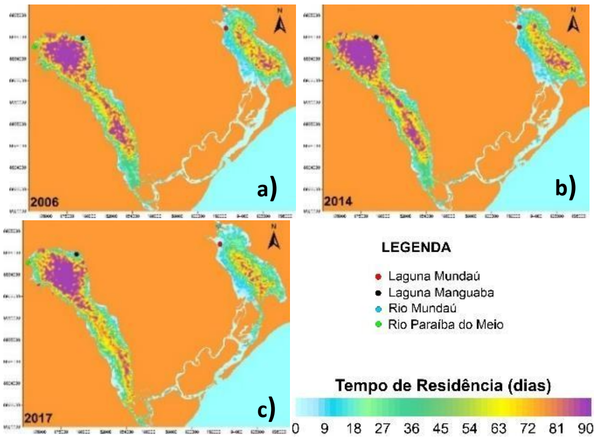


Figura 8 – a) Tempo de residência após 90 dias de simulação no período seco para os cenários de 2006, b) 2014 e c) 2017.

In general, the Mundaú Lagoon has higher RTs in the Southeast portion, with values between 63 and 90 days. The RTs are lower in the areas near the margins (less than 20 days). The study considered the total particle absorption at the margins of the lagoons and in the channels, which may explain the shorter residence times in these regions.

There are three compartments in the lagoon: the region near the Mundaú River mouth, with RTs of up to 20 days, where water exchanges are favored by the river discharge; the central portion, with RTs between 50 and 80 days; and the region near the entrance of the connecting channel, with RTs of up to 40 days, where water exchanges are favored by the tides.

RTs are high along the entire length of the Manguaba Lagoon, with values varying between 63 and 90 days. These results are similar to those reported by Lima (2017), who identified the regions to the east of the Mundaú Lagoon and the entire Manguaba Lagoon as susceptible to water quality problems.

Two compartments were found for the Manguaga Lagoon: the region near the connecting channel, with relative tidal influence and RT between 25 and 70 days; and the portion near the Paraíba do Meio River mouth, with times ranging from 60 to 90 days; in this region, the freshwater discharge is dominant and the Paraíba do Meio discharges are insufficient to generate significant water exchanges.

Figure 9 presents the RTs for the rainy season, after 90 days' simulation, for 2006, 2014 and 2017. In the Mundaú Lagoon, the particles are retained in the Northwest and Southeast portions of the lagoon, with higher RTs of 30 to 72 days. The Western region of the lagoon shows values of less than 15 days.

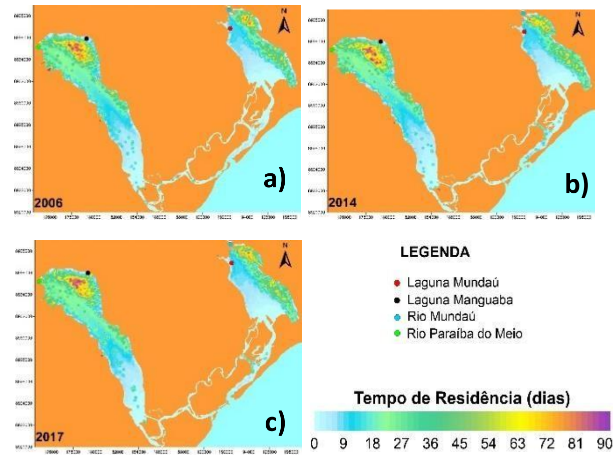


Figure 9 – a) Residence time after 90 days' simulation in the rainy season for 2006, b) 2014 and c) 2017.

In the Manguaba Lagoon, the central and Southeast portions, closest to the channel, have RTs of around 20 days; the Northwest region exhibits values between 36 and 90 days, due to the higher freshwater discharge of the Paraíba do Meio River.

A comparison between the dry and rainy seasons reveals a marked decline in values, indicating that the freshwater discharge interferes significantly in water exchanges in the MMELC. In relation to the scenarios analyzed, no significant differences were found between 2006, 2014 and 2017.

3.4. Water age

Simulations were performed for the three scenarios analyzed, considering the dry (01/01 to 04/30) and rainy seasons (06/01 to 09/28). Figure 10 and Figure 11 show the water age time series at stations D, E, F, I, J and K, located in the interior of the Mundaú and Manguaba Lagoons. The time series show the maximum age found and were filtered with the moving average for a 24-hour window.

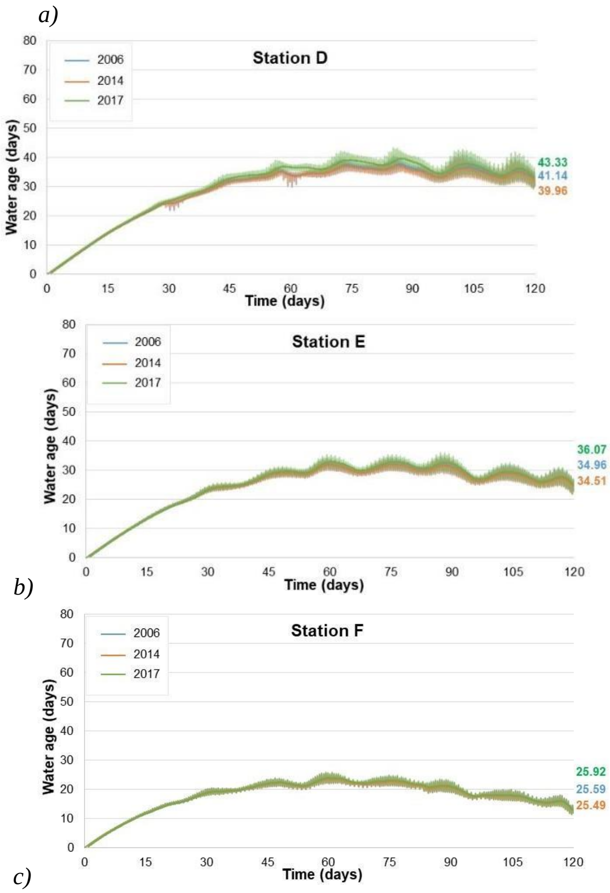


Figure 10 – a) Water age time series for 120 days' simulation at stations D, b) E and c) F, in the Mundaú Lagoon during the dry season.

The Northwest regions of the Mundaú (station F) and Manguaba Lagoons (station K) have lower water ages, with a maximum of 26 and 32 days, respectively. These stations are near the mouths of Mundaú and Paraíba do Meio Rivers. A comparison of the simulations performed reveals that 2014 has lower ages than in the other scenarios.

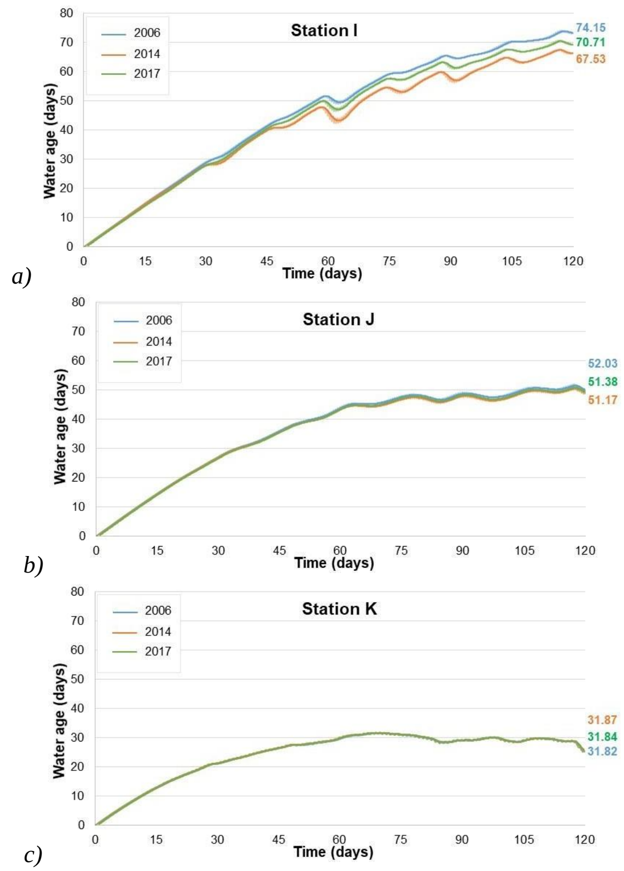


Figure 11 – a) Water age time series for 120 days' simulation at stations I, b) J and c) K, in the Manguaba Lagoon during the dry season.

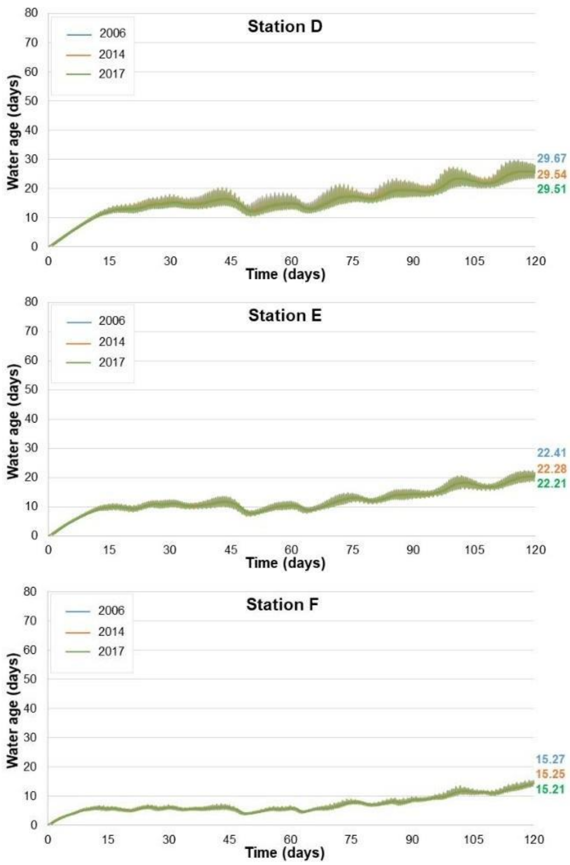
A similar behavior, identified in the hydrodynamic results, was found in the Manguaba Lagoon, with the lowest water ages occurring in 2014, followed by 2017 and 2006, due to branched inlets. In the region near the connecting channel (station I), the 2006 scenario has a water age of up to 74.15 days, representing a difference of 6.6 days between 2006 and 2014.

In general, the water ages of the Southeast portion of Mundaú Lagoon and the central and Southeast regions of Manguaba Lagoon are higher, compatible with the RT results. Differences are found between the results in the Northwest portion of the lagoon, with high RT and low water age.

RT is calculated from the trajectory of particles that are advected by the currents, using a Lagrangean approach. Given that the Northwest exhibits lower velocities, RT is high.

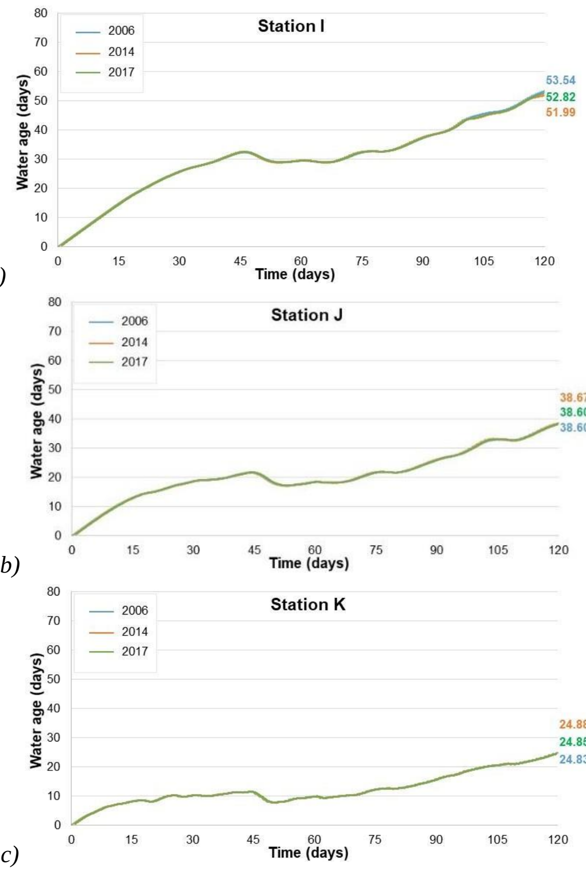
Water age is calculated using a Eulerian approach, related to the concentration of the substances found in the water body. The Northwest region is near the Paraíba do Meio River, which has high concentrations, making water age lower in this location.

Figures 12 and 13 show the water age time series for the rainy season at the stations within the Mundaú and Manguaba Lagoons, considering the 120 days simulation. The images are also filtered using the moving average for a 24-hour window.



a)
b)
c)

Figure 12 – a) Water age time series for 120 days' simulation at stations D, b) E and c) F,in the Mundaú lagoon during the rainy season.



a)
b)
c)

Figure 13 – a) Water age time series for 120 days' simulation at stations I, b) J and c) K, in the Manguaba Lagoon during the rainy season.

The Southeast portion of the Mundaú Lagoon (station D) exhibits a maximum age of 29.67 days, declining to 15.27 days in the Northwest portion (station F), due to the significant influence of the freshwater discharge.

A comparison of the dry and rainy seasons demonstrates the importance of river discharge in the region, which decreased water age in the lagoon by up to 14 days.

In the Manguaba Lagoon (Figure 13), only the Southeast portion (station I) exhibits significant differences between the scenarios analyzed. The behavior assessed is similar to that found in the dry season, in which the 2006 scenario has the highest water ages and 2014 the lowest. Water ages are also high in the rainy season, representing a region more susceptible to environmental problems.

Since the discharges of the Mundaú River are higher than those of the Paraíba do Meio River and the tide penetrates the Mundaú Lagoon more easily and with less tidal dampening (88%), the water ages found in the Mundaú Lagoon are lower compared with the Manguaba Lagoon.

How seasonality influences water renewal in the MMELC can also be determined. In the rainy season, with Southeast winds and higher river discarges, water ages are lower throughout the complex than in the dry season, characterized by low water discharges and more intense winds in the East direction

4. FINAL CONSIDERATIONS

The historical analysis of the MMELC coastlines based on Landsat 5-TM and Landsat 8-OLI satellite images shows that the MMELC exhibits high variability in the inlet region, with a predominance of sediment deposition and migratory dynamics occurring in a Southwest-Northeast direction.

Spatial distribution of RTs in the MMELC region identified areas of stagnation, potentially susceptible to pollutant accumulation in the Northwest region of the Manguaba Lagoon and Northwest-Southeast axis of the Mundaú Lagoon.

The simulations for water age and residence time indicated that the MMELC is strongly influenced by the discharge of its main river tributaries, the Mundaú and Paraíba do Meio Rivers, lowering water age and RT. The tides also play an essential role in water renewal, primarily in the channels and regions Southeast of the lagoons.

The central and Southeast regions of the Manguaba Lagoon had higher water ages, due to less influence from the Paraíba do Meio River. Thus, these areas are more vulnerable to pollution caused by the discharge of untreated waste.

With respect to the different scenarios, the inlet configuration of 2014 showed the lowest water ages, demonstrating that branched inlets significantly improved water mixture.

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