EFFECTS OF STORM SURGE ON WATER LEVELS OF THE LAGOON SYSTEM OF JACAREPAGUÁ – RIO DE JANEIRO, BRAZIL

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The Lagoon System of Jacarepaguá is the most vulnerable coastal area of Brazil due to its high population density and important economic activities. Severe meteorological conditions due to climate changes are more likely to affect the lagoon system in the future, increasing the exposure of the area and the probability of flooding of the low-lying surrounding areas. To determine the vulnerability of the area to diverse agents, this work addressed the impact of different combinations of sea level rise, heavy rainfall and storm surges. The study cases considered two different bathymetry conditions, the actual silting bathymetry, and the resulting bathymetry after a planned dredging project. Tidal prism, the maximum water elevations and the time of occurrence were analyzed. The main results showed that storm surge has the most impact on the maximum water elevations, overcoming the impact of an increase in the sea level, river flow and changes in bathymetry. The results of time lags comparing the time of occurrence of maximum elevation recorded at the open sea and the time of occurrence of maximum elevation on the north margin, the most populated area, of the lagoon system showed a time lag of 13-17h. The benefits of the planned dredging project would be mostly to allow a better water renovation in the lagoons, due to a higher tidal prism.

Keywords: climate changes; flooding; storm surge; computational modelling.

INTRODUCTION

The Lagoon System of Jacarepaguá is located in the Metropolitan Region of Rio de Janeiro (22º59'11.72"S; 43º23'43.68"W). This is the most vulnerable coastal area of Brazil, due to its high population density, important economic activities, and exposure to meteorological and oceanographic events.

The Pedra Branca Massif, Tijuca Massif and the ocean, limit the 280 km² macro-drainage area of Jacarepaguá, which represents 25% of the total area of Rio de Janeiro city. Marapendi, Tijuca, Camorim and Jacarepaguá Lagoons form the Lagoon System. Jacarepaguá and Tijuca Lagoons communicate through the so-called Camorim Lagoon, which is in fact a channel. Through the Marapendi Channel, the Marapendi Lagoon interconnects to Tijuca Lagoon, which has a connection with the sea through the Joatinga Channel, as in Fig. 1.

The interconnection of the lagoons and the direct communication with the sea make brackish the lagoons water. The sea level variations generated by the tide directly influence the water levels of the lagoons. Sea level rise combined with heavy rainfall, storm surges around 80 cm, and the ongoing silting condition increase the exposure of the lagoons and the probability of flooding of the low-lying surrounding areas.

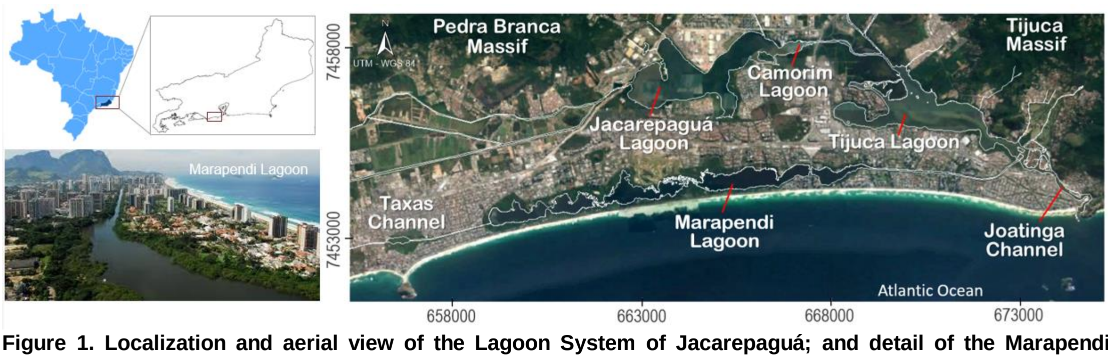

Figure 1. Localization and aerial view of the Lagoon System of Jacarepaguá; and detail of the Marapendi Lagoon and the Marapendi Channel.

The Jacarepaguá coastal plain has undergone significant population growth since 1970. Its residents have almost triplicated, and some of the new urbanized areas have expanded without proper urban planning in some areas. The consequence of this lack of planning was the emerging of many

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communities with precarious conditions of urbanization and irregular constructions without basic sanitation, which caused an enormous environmental degradation in the lagoon system.

According to the Intergovernmental Panel on Climate Change (IPCC), by 2100 the global temperature will increase more than 1°C and, and therefore, mean sea level (MSL) can reach an elevation of 18 to 79 cm. In addition, studies show that in the last decades the average sea level has increased from 4 mm to 6 mm per year.

Considering the coastal and hydrological vulnerabilities of the studied zone, it is important to evaluate the potential effect of sea level rise in the coastal areas, since it intensifies the problems related to saline intrusion and flooding with the blockage of the drainage system.

To protect and to adapt the city to future challenges different programs were developed and this work was part of the adaptation strategies for climate changes in Rio de Janeiro, (City Council of Rio de Janeiro 2016).

Objectives

The objectives of this work are:

1. To analyze how the sea level rise added to storm surges, extreme river flows and changes in the lagoon bathymetry influence the water level of the Lagoon System of Jacarepaguá, especially near the mouth of the rivers.
2. To identify the most vulnerable areas for different scenarios of lagoon´s bathymetry.

METHODOLOGY

This section presents the different modelling scenarios and the methodology.

Scenarios

The rise in the mean sea level associated with the phenomenon of storm surge and increased rainfall will raise the water levels of the rivers that drain into the lagoons increasing the risk of flooding. To evaluate the effect of these variables in the vulnerability of the lagoon system, climate change scenarios for 2040 were established. The scenarios consider variations in the sea level rise, storm surge, rivers hydrograph and bathymetry.

According to mean sea level (MSL) rise, there are three scenarios:

- 2016 scenario, without sea level rise.
- Likely scenario with sea level elevation of 10 cm in 2040, assuming a sea level rise in a rate of 4 mm/year.
- Pessimistic scenario with 15 cm elevation, assuming a sea level rise in a rate of 6 mm/year.

For each scenario described above, the following storm surges were added:

- SS0 considers no storm surge.
- SS1 includes a synthetic storm surge with sinusoidal form and a maximum peak of 0.4 m.
- SS2 includes a synthetic storm surge with sinusoidal form and a maximum peak of 0.8 m.

Different rivers hydrographs are included for each combination represented by:

- RP25, a synthetic hydrograph for a return period of 25 year.
- 1.1 RP25 considers the hydrograph of RP25 increased 10% increased.
- 1.2 RP25 that considers the hydrograph of RP25 increased 20% respectively.

Table 1. Variables and modelling scenarios.

Scenario	Cases	Sea level rise (m)	Storm surge (m)	Rivers hydrograph	Bathymetry
2016	1	0	SS0 – 0.0	RP 25	Dredged
	2	0	SS1 – 0.4	RP 25	Dredged
	3	0	SS2 – 0.8	RP 25	Dredged
Likely 2040	4	0.10	SS0 – 0.0	1.1 RP 25	Dredged
	5	0.10	SS1 – 0.4	1.1 RP 25	Dredged
	6	0.10	SS2 – 0.8	1.1 RP 25	Dredged
Pessimistic 2040	7	0.15	SS0 – 0.0	1.2 RP 25	Dredged
	8	0.15	SS1 – 0.4	1.2 RP 25	Dredged
	9	0.15	SS2 – 0.8	1.2 RP 25	Dredged
	10	0.15	SS2 – 0.8	1.2 RP 25	Current 2014

The scenarios consider two different bathymetries: the Current 2014 case as the bathymetry measured from a field 2014 campaign and the Dredged bathymetry that considers the dredging project planned bathymetry. Table 1 summarizes all cases described.

Computational Modelling

The computational simulations were performed using SisBaHiA® (Base System of Environmental Hydrodynamics), a professional system of computer models, developed for projects, studies and environmental management of water resources, (Rosman, 2018).

The lagoons are quasi-vertically homogeneous in space over time. Therefore, it is proper to adopt a vertically integrated 2D hydrodynamic model assuming hydrostatic approximation.

It was used the Hydrodynamic 2DH Model, a hydrodynamic model of the FIST (Filtered in Space and Time) line, optimized for natural water bodies with a flow that is not sensitive to vertical baroclinicity (Rosman, 2018). Within the mathematical formulation used the following characteristics stand out:

• Solve the complete Navier-Stokes equations, considering the approach of shallow water (approximation of hydrostatic pressure) and the Boussinesq approximation.

• Apply turbulence modeling based on techniques similar to those employed in Simulation of Large Vortexes (LES - Large Eddy Simulation), (Smagorinsky 1963, Aldama 1985, Rosman 1987).

• It uses the State Equation, according to the Eckart formula.

• In Module 2DH, the quantity conservation equations motion and the continuity equation are averaged in vertical (two-dimensional flow).

The spatial discretization is optimized for natural water bodies and uses mostly biquadratic quadrilateral finite elements with nine nodes but can also include quadratic triangular finite elements with six nodes. The spatial discretization is up to fourth order, depending on the mesh irregularity. The temporal discretization uses second order implicit finite differences scheme, mixing Crank-Nicolson (Crank and Nicolson 1947) and Implicit Factored schemes (Beam and Warming 1978). The Porous-Rough Method (Rosman, 2018) modeled the effects flooding and drying of the domain.

Finite Element Mesh

The work obtained the contour of the lagoons from Google Earth 2015 satellite imagery. The discretization of the domain used 2514 quadratic finite elements, being 2359 quadrangular and 155 triangular elements, containing 11436 calculation nodes, see Fig. 2.

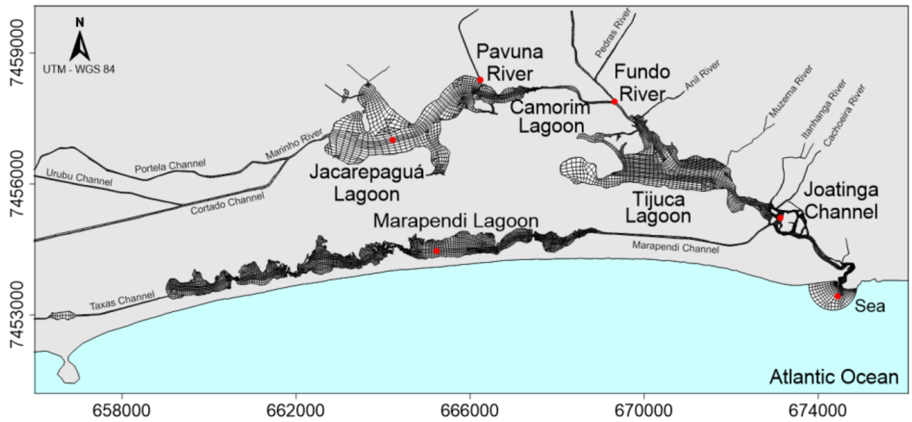

Figure 2. Quadratic finite element mesh implemented in SisBaHiA® and location of the stations.

Bathymetry

(INEA 2015) provided the bathymetry data of the lagoon system considered for the modelling domain, including the projected dredging channels, as in Fig. 3. The sea data bathymetry corresponds to the nautical chart 1506 (1:75.000), of the Directorate of Hydrography and Navigation of the Navy of Brazil. Bathymetry data refers to mean sea level of -0.2 m, corresponding to the IBGE Datum Imbituba.

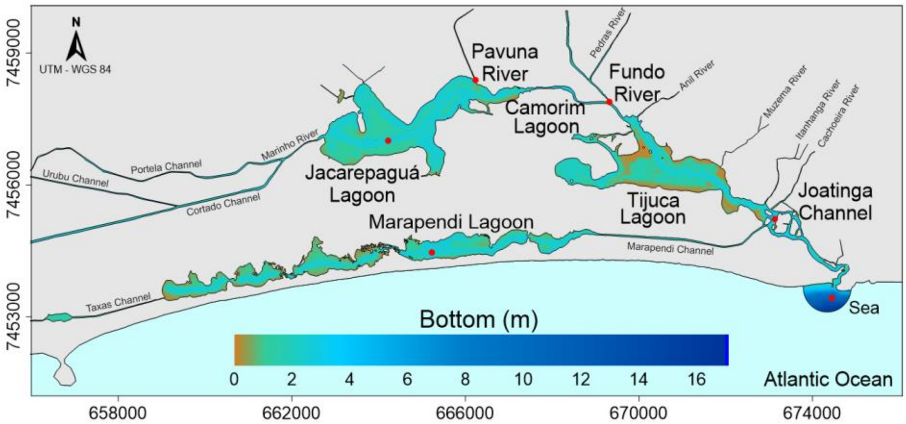

Figure 3. Dredged bathymetry referred to the IBGE Datum Imbituba.

Equivalent bottom roughness

The equivalent roughness of the bottom relates to the type of bed sediment present in the body of water and at the same time to the bottom forms molded by the flow. According to (Masterplan 2013), the bottom of the Lagoon System consists of silt in Tijuca Lagoon and average sand in the other lagoons and canals. (Rosman 2018) recommends a value of 0.001m to represent the equivalent roughness of the silt bed, and 0.020m to represent average sand. Fig. 4 shows the spatial variation of roughness adopted in the modelling.

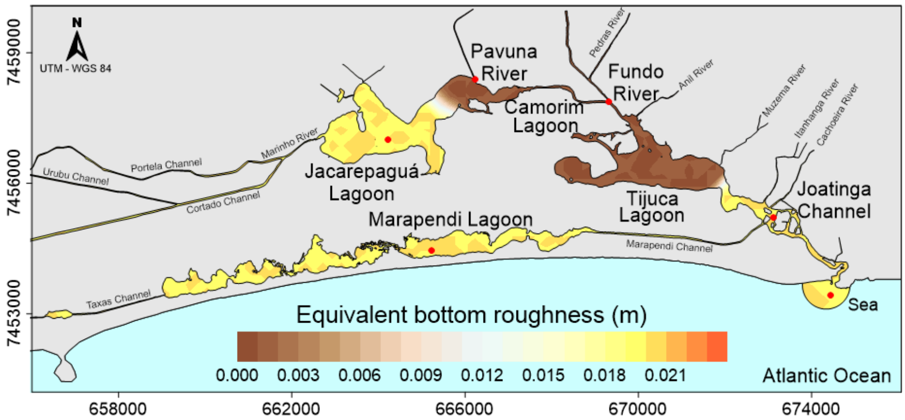

Figure 4. Distribution of equivalent bottom roughness used in the modelling.

Tides

The tide curves imposed at the open boundary were determined from the addition of the predicted astronomical tide and a synthetic upwelling sinusoidal form wave. The storm surge rises and falls above mean sea level (MSL) in approximately 8 days with maximum peak of 0.4 m and 0.8 m. These cases represent the passage of a storm surge coinciding with an equinox syzygy.

Fig. 5 shows an example of the simulated tide used for the Case 9. This curve is the boundary condition for the open frontier in the sea (red line). The dark blue line indicates the synthetic storm surge of 0.8 m of maximum peak, and the light blue line represents the astronomical tide. The value of the sea level rise considered in this scenario was 0.15 m.

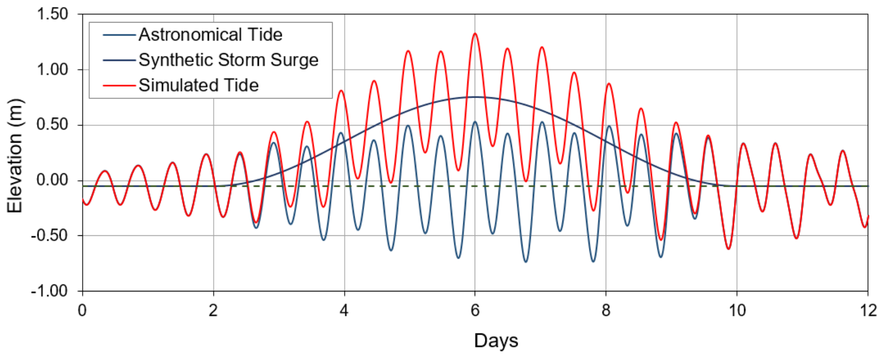

Figure 5. Sea level boundary condition used for Case 9 and Case 10.

Hydrographs of tributaries

The main contributory rivers of the drainage basin of the Jacarepaguá Lagoon Complex have their sources from the slopes of the Pedra Branca and Tijuca Massifs. The list below describes these rivers according to the respective receiving lagoon.

1. Jacarepaguá/Camorim Lagoons: Portela Channel, Urubu Chanel, Cortado Channel, Vargem Pequena, Cancela, Calembá, Marinho, Camorim, Caçambê, Pavuninha and Pavuna Rivers.
2. Tijuca Lagoon: Fundo, Anil, Rio das Pedras, Muzema, Itanhangá, Cachoeira Rivers.
3. Marapendi Lagoon: Taxas Channel.

The hydrographs of the main tributaries considered a 12 days period with the peak of the flood coinciding with the higher elevations of the final tide of each case. They are synthetic hydrographs for a return period of 25 year increased 10% in the Likely scenario and 20% in the Pessimistic scenario.

For Portela, Cortado and Urubu Channels were adopted 70%, 20% and 10% of Marinho River hydrograph respectively. Based on (Masterplan 2013) for Itanhangá River, the average rainfall considered was 0.0693 m^3/s and for Taxas Channel was 0.0046 m^3/s. These values are average rainfall period flows calculated by a Rational Method. Fig. 6 shows the principal tributaries of the lagoon system, with peaks coinciding with the time of occurrence of maximum elevations at each lagoon.

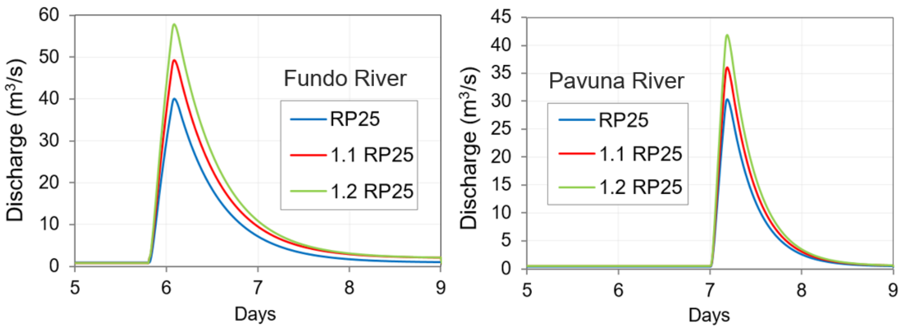

Figure 6. Hydrographs of the principal tributaries of the lagoon system, with peaks coinciding with the time of occurrence of maximum elevations at each lagoon.

RESULTS

The hydrodynamic study computed the tidal prism and investigated the maximum water elevations and the time of occurrence at the selected stations. Fig. 2 shows the location of the result stations.

Fig. 7 represents the maximum water elevations in the stations for all cases. The maximum elevations occurred in cases 9 and 10. The storm surge produced the higher maximum water elevations, with a mean rise of 0.73 m when the storm surge increased from 0 m to 0.8 m. The present silting situation, represented by Case 10, produces higher water elevations in the innermost lagoon.

The City Council established the level of the mouth of the urban drainage system near the Jacarepaguá Lagoon System as 0.92 m above MSL (Rio Águas 2010). The dashed line in Fig. 7 represents this inferior limit of the drainage system for the Jacarepaguá lagoon. Areas near the stations where computed water level stays above 0.92 m are potentially vulnerable to suffer problems due to inundation. Twenty-three stations of Cases 3, 6, 9 and 10 showed maximum water elevation higher than 0.92 m.

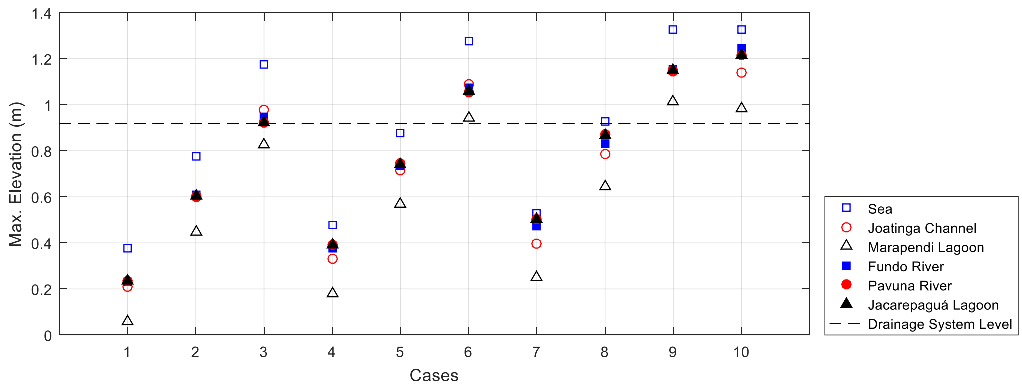

Figure 7. Maximum elevations at the specified stations for each modelling cases.

Time lags between the occurrence of the maximum elevation at each station and the maximum elevation at Sea station were computed and are shown in Fig. 8. Note that time lag refers to the time of the maximum water elevation at Sea Station implying that a time lag of 0 h is equivalent to 6 days of simulation time.

The time lags occurred on the north margins of the lagoon system, the most populated area near the water, varying from 13 to 17 hours, in Cases 3, 6, 9 and 10. Hence, there would be enough time to warn the population, to take actions to avoid flooding, and to control the blockage of the drainage system. Therefore, for warning purposes, a real-time water level monitoring system should be installed near the Sea station.

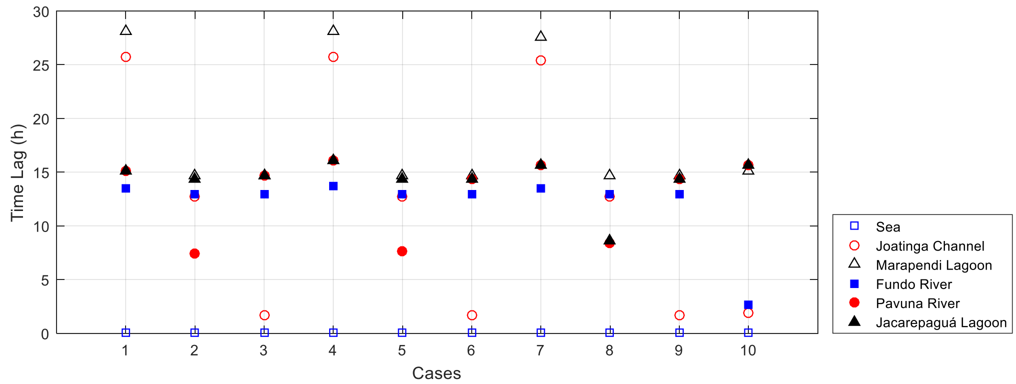

Figure 8. Time lag for the maximum elevations, comparing with the time of the maximum water elevation at Sea Station (Time Lag=0h is equivalent to t=6d of simulation time).

The maximum elevations are reached at different stations and at different times depending on the case. Therefore, the surface elevation isolines maps calculated at the time of the maximum elevation at each case are different. Fig. 9 represents the isolines maps for three instant times: (1) before the storm surge; (2) when the maximum elevation at Sea station of each case is recorded, and; (3) when the maximum elevation at any of the other five stations is reached. As shows Fig. 9, the surface elevation in Jacarepaguá Lagoon, Tijuca Lagoon and Marapendi Lagoon, v. Fig. 1, at the time of maximum elevation in the modelling domain differs significantly from Cases 6, 9 and 10.

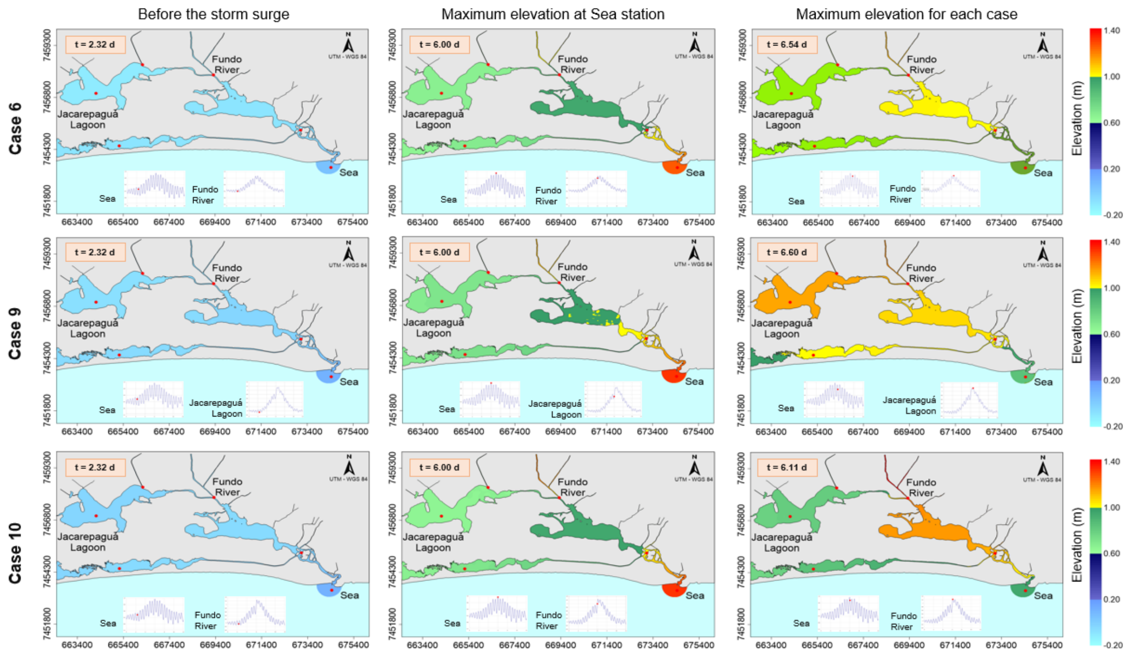

Figure 9. Isolines maps for Case 6, Case 9 and Case 10 for three instant times: before the storm surge, when the maximum elevation at Sea station of each case is recorded, and when the maximum elevation at any station for each case is recorded.

The results of the tidal prism of the lagoon system for all cases, as in Fig. 10, indicate that the tidal prism is more sensitive to storm surges and the river discharge than to changes in mean sea level. This conclusion follows from the variation of flow resistance due to bottom roughness. The tidal prism, as expected, is incremented when storm surge increases and is reduced when river flow increase.

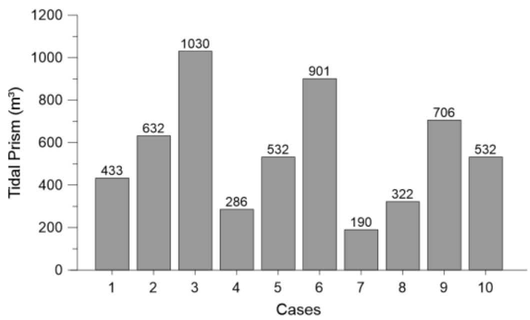

Figure 10. Tidal Prism for each modelling cases calculated at Joatinga Channel.

CONCLUSIONS

Considering different scenarios of hydrological, meteorological and oceanographic agents on the Lagoon System of Jacarepaguá, the storm surge has the most impact on the maximum water elevations inside the lagoons, overcoming the impact of increases in mean sea level, river flow and changes in bathymetry. The planned dredging project would allow a better water renovation in the lagoons, due to a higher tidal prism, and reduce about 7.3 cm the maximum elevation in the north and most populated part of the system.

The time lags on the north margins of the lagoon system, the most vulnerable area for flooding, varied from 13 to 17 hours. This result would give the authorities enough time to take actions to alert the population and to control flooding in critical areas.

Finally, future climate changes that involve sea level rise, higher storm surges and stronger river flows, will make the Lagoon System of Jacarepaguá more vulnerable in terms of potential floodings, but they will improve the water quality of the system.

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