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Seasonally Hypersaline Estuaries in Semiarid Climate Regions: an Example from the Northeast Brazil.

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ABSTRACT

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The Coreaú river estuary is located in Ceará state, Northeast of Brazil and it is a shallow system, dominated by meso tides and barred about 35 km upstream from its mouth. Generally, hypersaline estuaries are naturally found in arid and semi-arid regions of Brazil, but the blockage the natural flow of rivers by dam interference can also increase hypersaline conditions and residence time in these estuaries. This study examines the importance of water balance and dam interference to the circulation of the Coreaú river estuary, using observed data and Delt3D numerical simulations. Five discharge scenarios (with values from 0 to 300 m^3s^{-1}) were used in the Delft3D simulations to calculate the residence and flushing time in the estuary. Based on salinity data collected during two years the estuary was characterized as a hypersaline and well mixed system during the dry period (August to December) and a positive estuary during the wet season (January to June). The observed salinity along the estuary ranged from 37 g/kg to 44 g/kg in October, 2012 and from 37g/kg to 13g/kg in May, 2013, respectively near the mouth and 20 km upstream. Regardless of the discharge conditions and the atmospheric water balance, the estuary acquires hypersaline conditions during the dry season. Tidal circulation under all discharge conditions dominates the residence time in the first 10 km of the estuary. Water and materials from the upper region of the estuary depends on the river discharge to be transported to the shelf. Under all discharge conditions lower than 300 m^3 s^{-1} the flushing time of the upper estuary is larger than 60 days. These fact associated with the high values of evaporation during the dry season explains the hypersalinization of the Coreaú estuary.

ADDITIONAL INDEX WORDS: *Dam, Hypersalinization, Delft3D model, Coreaú estuary*

INTRODUCTION

Estuaries are coastal environments of great social, economic, ecological and environmental importance (Maia et al., 2006). However, estuaries are affected by anthropogenic actions, such as dam construction, urban supply, fish farming (e.g.: shrimp farming, oyster farming), salt industry, and water pollution from domestic, industrial and ship waste. These factors can cause serious damage to the water quality of these systems and may lead to hypersalination (Potter *et al.,* 2010).

Hypersaline estuaries are typically found in arid and semi-arid regions where evaporation exceeds precipitation rate and freshwater discharge. The intensification of saline intrusion into estuaries may alter local hydrodynamics, interfere with the development of mangrove forests, reducing nutrients and species reproduction and migration (Zampatti, 2010; Gillanders *et al.,* 2011).

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Historically, in arid and semi-arid climates, episodes of drought and the consequent water deficit led to the construction of weirs and dams for water storage and control of the natural flow of rivers, which intensified the problems of hypersalination.

The Coreaú River estuary, is a shallow (<5m deep), low influx system, dominated by a mesotidal regime (~3.2 tidal range), located in the extreme western region of the state of Ceará, in the Brazilian's Northeast Region (Figure 1). The regional climate is characterized as semi-arid hot tropical climate, with precipitation concentrated between January and June (1164.4 mm total for the period). The dry period lasts from August to December, with very low or no precipitation (22.6 mm total for period). The river discharge is intermittent and concentrated to the rainy season and is subjected to interference from a dam 35 km upstream of the mouth. The average discharge value during the peak of the rain season (March to April) is 30 m^3 s^{-1} and less than 1 m^3 s^{-1} during the peak of the dry season (September to November) (Colares *et al*., 2016)

The main goal of this paper is to characterize salt distribution along the Coreaú River estuary, considering different atmospheric water balance and discharge conditions.

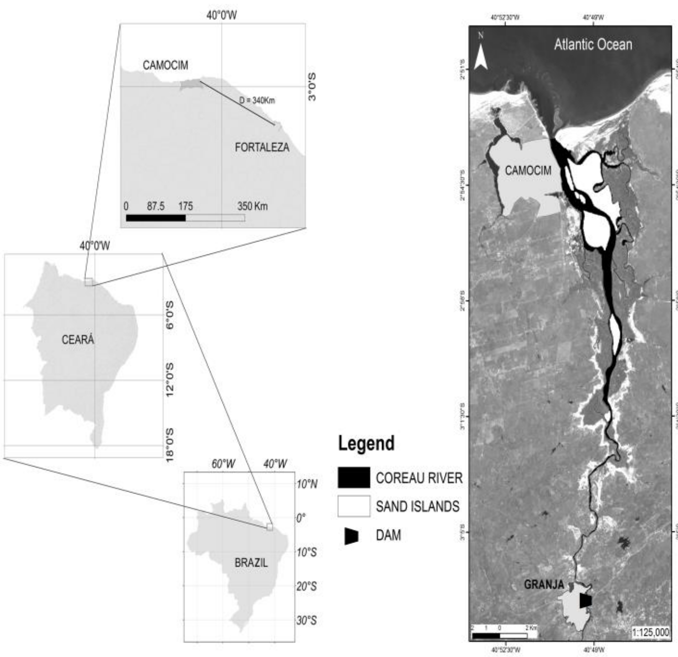

Figure 1. Location of the study area.

METHODS

The Delft3D model was used to simulate and represent the circulation and salt intrusion of the Coreaú river estuary for the period of 2008-2015 representing different climatological and hydrological conditions. After the model has been validated for the period 2008 to 2015, five discharge scenarios were simulated (0, 6, 30, 60 and 300 $m^3 s^{-1}$ from March to April using the average meteorological forcing for 2008 to 2015. These scenarios, with a controlled climatic water balance (CWB) (reference evapotranspiration *minus* precipitation) forcing, were used to understand the influence of the river discharge in the Coreaú estuary circulation during the dry season.

Particles were added to the simulations in order to estimate residence and flushing time of possible contaminants in the system.

Vertical profiles of salinity and current velocity and direction were obtained in 13-hour tidal surveys carried out on three dates (Table 1). Current data were collected with an acoustic Doppler current profiler (ADCP) (Sontek ADP 1.5 MHz) every half-hour intervals during the sampling period (13hrs). Vertical profiles of salinity and temperature data were collected every 1 km along 20 km upstream of the estuary mouth, with YSI CastAway CTD. All CTD data were collected in flood spring tidal phase due to estuary depth restrictions (Table 1). These data was used to characterize the estuary and to validate the model results.

The CWB used to force the model was calculated using precipitation data obtained with Cearense Foundation of Meteorology and Water Resources (FUNCEME) and Reference Evapotranspiration (ETo) calculated using the Penman-Monteith universal method (FAO-56).

Discharge data available on the HidroWeb/NA platform was used to force the model to the period of 2008 to 2015. The model was also forced with the four main tidal components for the region and tidal harmonics components provided by the Foundation for Sea Studies - FEMAR) were used to calibrate and validate the tidal model results.

In order calibrate and validate the simulations the root mean square error (REQM) (Equation 01) and the Skill parameter defined by Warner et al. (2005) (Equation 02) were calculated for each variable.

$$\text{REQM} = \sqrt{\frac{\sum_{i=1}^{n} |X_{modelo} - X_{obs}|^2}{N}} \quad (1)$$

$$\text{Skill} = 1 - \frac{\sum |X_{modelo} - X_{obs}|^2}{\sum \left(|X_{modelo} - X_{obs}| + \sum |X_{modelo} - X_{obs}| \right)^2} \quad (2)$$

The Skill parameter varies between zero (0) and one (1), indicating total disagreement or complete agreement between observations and model results. Allen et al. 2007 rated the Skill values> 0.65 as excellent, 0.5-0.65 as very good, 0.2-0.5 as good and <0.2 as poor.

Table 1. *Period of field works of the distribution of salinity along the estuary.*

Scenarios	**Period**	**Wet season**	**Dry season**
		Spring tide	Spring tide
Dry season	October 2012		X
Wet season	May 2013	X	
Dry season	August 2013		X

RESULTS

First, this item shows the Climatic Water Balance (CWB) that was important tool to characterize wet and dry seasons, and to give robustness to the numerical modeling. Then, the results of observational data and simulations are shown.

Climatic Water Balance (CWB)

The CWB developed for the study area characterized the local climatic conditions as semi-arid climate with two seasons along of the year. The wet season is considered in the months of January to June, with greater precipitation values in March (climatological mean: 336.4 mm) and April (climatological mean: 305.6 mm). The dry season occurs in the months August to December, with lower precipitation values in September (climatological mean: 0mm) e October (climatological mean: 1.2 mm).

Table 2 shows the annual accumulated precipitation and Reference Evapotranspiration (ETo) and respective CWB for each year of the period of 2008 to 2015. Note that in 2012 the CWB shows a strong drought scenario, in which the annual volume of precipitation was 450.8 mm, more than 60% below the annual average for the Camocim region (annual mean: 1200 mm). The year 2012 was the beginning of the strongest drought period recorded in the Ceará state since 1911 (Martins *et al*., 2015). The period from 2012-2015 represented four years of accumulated water deficit reaching more than 2 meters of water loss to the atmosphere.

Table 2. *Accumulated yearly Precipitation, Reference Evapotranspiration (ETo) and the CWB for the analyzed period (mm).*

Year	Precipitation (mm)	ETo (mm)	Composition
2008	1392.8	1364.6	28.2
2009	1955.8	1187	768.8
2010	552.3	1259.6	-707.2
2011	1410.8	1182.1	228.8
2012	450.8	1410.6	-959.8
2013	885.4	1238.3	-352.9
2014	850.3	1339.9	-489.6
2015	753.4	1124.4	-371
Sum	**8251.6**	**-10106.5**	**-1854.9**
Mean	**1031.4**	**-1263.3**	

Observational data and simulations

Water level

Table 3 presents the results of the comparison of the FEMAR observed and simulated tidal harmonic of the region. The REQM between the observed and modeled level data was 0.03, with a Skill statistical parameter of 0.99, indicating that the model was able to reproduce the tides in the region.

Average current velocity

The observed longitudinal velocities showed a slightly larger maximum magnitude (~0.80 m.s¹) in the ebb phase than in the flood phase (~0.67 m.s¹). The modeled current velocities presented close values, with a maximum magnitude of 0.74 m.s¹ in the ebb phase and 0.73 m.s¹ in the flood phase. The Skill parameter for the current velocity data was 0.99 and the REQM 0.04 indicating an excellent agreement between the modeled and observed results.

Observed Longitudinal Distribution of Salinity

The first field campaign (October 2012) occurred in the driest year in the region since 1911. The CWB was negative and no river discharge was present due to the dam. Hypersaline conditions were observed along the longitudinal section of the Coreaú river estuary with a variation from 37 g/kg near the mouth to 44 g/kg about 20 km upstream. The Skill parameter between the observed and modeled longitudinal distribution of salinity for this period was 0.966. In May 2013 a wet month in the region with positive CWB and river discharge (~ 8 $m^3.s^{-1}$) the estuary do not showed hypersaline conditions and the values ranged from 37g/kg at the mouth to 13g/kg about 20 km upstream. The Skill parameter for this period was 0.978. In August 2013 a dry period with no river discharge but a less dry year compared with 2012, hypersaline conditions were observed again. The salinity values ranged from 37.5 g/kg near the mouth to 40 g/kg about 20 km upstream. The Skill parameter between modeled and observed salinity was 0.76.

Table 3: *Statistical comparison between modeled and observed data water level (m), mean stream velocity (m.s-¹) and longitudinal salinity.*

Methods	Level	Velocity	Longitudinal salinity		
			Oct/2012	May/2013	August/2013
REQM	0.03	0.04	0.3313	1.058	0.5976
SKILL	0.99	0.99	0.966	0.978	0.7620

Modeled Salt distribution

For the period between March and April, the first modeled scenario (Q0) showed that the estuary remains with hypersaline conditions like the observed data during dry season even with the precipitation exceeding the evaporation rates. In the other modeled scenarios (Q6, Q30, Q60 e Q300) the estuary became positive between March and April, with the higher values of salinity close to the mouth. In general, with the contribution of river discharge, the estuary is characterized in poorly stratified, with the mixing zone presenting the greatest difference between surface and bottom salinity.

In order to represent an atypical high discharge scenario, a simulation as carried out for the period from March to October with the discharge value of 300 $m^3.s^{-1}$. For March to April, the estuary presents a positive condition with salinity values below 10 in most of the system. During May to June, the same positive orientation was observed with the salinity gradually decreasing along the estuary. In terms of stratification, the estuary became well mixed.

The period of July and August mark the transition from wet to dry conditions. Positive conditions are still observed in July, but in August, the estuary acquired hypersaline conditions. In September and October, the estuary remains hypersaline with values around 41 upstream. These results show that the Coreaú estuary will always became hypersaline during the dry season even with a much stronger river discharge during the previous wet season.

Residence and flushing time.

Ten particles were inserted in the five scenario simulations approximately every 2k from the estuary mouth in order to estimate the residence and flushing time for the different sections of the estuary. The residence time is the time need by a particle to move from it original point and cross the estuary entrance for the first time (been allowed to enter the estuary again) and the flushing time is the time need by a particle to leave the estuary forever. The first four particles (close to the mouth) or approximately the first 10 km of the estuary entrance were transported outside the estuary in a period shorter than a tidal cycle (12.24 h) showing that the transport in this region of the Coreaú estuary is dominated by tides in all discharge conditions. The particles in the upper regions of the estuary depend on the river discharge to be transported to the shelf. As expected the residence time increases upstream and decrease in higher discharge conditions. Under lower than average discharge conditions (<30 $m^3 s^{-1}$) the upper 5 km of the estuary is not transported to the shelf. Since the cyclic regime of the tidal circulation, most of particles return to the estuary in flood tides and the flushing time are always larger than 1 day. The river discharge is the main responsible for flushing the estuary and the flush time decrease under higher discharge values. Even under average discharge conditions (Q30) most of the estuary is not flushed in 60 days. This characteristic of the Coreaú estuary and the high values of evaporation during the dry season explains the hypersalinity observed under all the discharge conditions.

Table 4. *Residence time (RT) and Flushing time (FT) calculated by Langragian particle method for each scenario simulations (Q0 to Q300). RT and FT units are in days. Particle P1 is located at the entrance of the estuary and P10 approximately 20 km upstream. The scenario number represents the river discharge (ex.: Q300 = 300 $m^3 s^{-1}$)*

Particle	Q0		Q6		Q30		Q60		Q300	
	RT	FT	RT	FT	RT	FT	RT	FT	RT	FT
P1	0.02	**3.84**	0.02	1.31	0.02	1.36	0.02	0.84	**0.02**	**0.33**
P2	0.04	> 60	0.04	1.32	0.04	1.92	0.04	0.86	**0.04**	**0.33**
P3	0.44	> 60	0.44	1.36	0.44	> 60	0.44	1.85	**0.38**	**0.38**
P4	0.51	> 60	0.46	1.87	0.46	> 60	0.46	1.85	**0.41**	**0.41**
P5	> 60	> 60	0.50	> 60	1.02	> 60	0.50	1.85	**0.41**	**0.41**
P6	> 60	> 60	0.99	> 60	1.50	> 60	0.98	1.91	**0.42**	**0.42**
P7	> 60	> 60	> 60	> 60	1.50	> 60	> 60	> 60	**0.42**	**0.42**
P8	> 60	> 60	> 60	> 60	> 60	> 60	> 60	> 60	**0.46**	**0.46**
P9	> 60	> 60	> 60	> 60	> 60	> 60	> 60	> 60	**0.46**	**0.46**
P10	> 60	> 60	> 60	> 60	> 60	> 60	> 60	> 60	**0.82**	**0.82**

CONCLUSIONS

The Coreaú River estuary was characterized as a hypersaline and well mixed system during the dry period and a positive estuary during the wet season. Dam interference in the drainage area of the Coreaú River in the Granja region (CE) blocks the natural flow of the river and the river discharge records are restricted to the rainy season. During the dry period rainfall volumes are insignificant (<5% of the annual total) and consequently there are no records of river discharge in the system due to the impossibility of filling the volumetric demand of the reservoir. The results of the vertical and longitudinal profiles of salinity shows an intensification in the saline intrusion in the dry period and the rising of hypersaline condition with values observed being close to 50 g/kg at the most upstream point.

Regardless of the discharge conditions and the atmospheric water balance during the wet season, the estuary acquires hypersaline conditions during the dry season.

The residence time of the first 10 km of the entrance of the estuary ranged from 48 minutes to 12.24 hours showing that the transport in this region is dominated by tides. The upper regions of the estuary depend on the river discharge to be transported to the shelf and under lower than average discharge conditions the upper 5 km is not transported to the shelf. The flushing times are always larger than 1 day and even under average discharge conditions most of the estuary is not flushed in 60 days. This characteristic of the Coreaú estuary and the high values of evaporation during the dry season explains the hypersalinity observed in this system.

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