ANALYSIS OF THE DREDGING EFFECTS ON CURRENT CIRCULATION AND SALINITY OF THE ITAJAÍ-AÇÚ ESTUARY

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ABSTRACT

Pavo-Fernández, E., Pereira Filho, J., Horita, C. O. & Andrade, M. M. (2023). Analysis of the dredging effects on current circulation and salinity of the Itajaí-Açú estuary. Braz. J. Aquat. Sci. Technol. 27(1). ISSN 1983-9057. DOI: 10.14210/bjast.v27n1.19245. The Itajaí-Açú river is the largest source of drainage in the state of Santa Catarina (Brazil). At the mouth of this river is located the Itajaí-Açú estuary, which is a highly stratified estuary, dominated mainly by river discharge. The port of Itajaí is located at the mouth of this estuary, which is one of the most important Brazilian ports. Due to the presence of the port, the Itajaí-Açú estuary is constantly dredged. Therefore, the main objective of this paper is to analyse the effects of the dredging of 2011, which deepened the channel from 11 m to 14 m, on the estuary circulation of the Itajaí-Açú river in comparison to the estuary circulation in 2008. Thus, data on river discharge, recorded by a hydrometric station, and current velocity vertical profiles, recorded by an Acoustic Doppler Current Profiler (ADCP) anchored in the channel of the estuary were analysed. A salinity analysis was also performed with data recorded by a CTD to compare the salinity stratification of the water column in the study period. Results showed an increase in current velocity in the estuary after the 2011 dredging. In both study periods (2008 and 2011), currents were ebb-directed to the river mouth. Results suggest that the dredging has modified the estuarine circulation as the currents intensified. Salinity results show an increase in values after the dredging (2011), being the water column clearly stratified.

Key Words: Dredging. Highly stratified. Currents. Itajaí-Açú river.

INTRODUCTION

According to Cameron and Pritchard (1963), estuaries are defined as a semi-closed coastal water body that has a free connection to the open ocean and in which seawater is measurably diluted by the freshwater coming from the continental drainage. The definition of Kjerfve (1994) is a section of the continental shelf or the valley of a river, which the ocean flooded during the Holocene by rising sea levels, and which contains marine water in constant dilution with the continental water, affected by the tides and usually less than 20 m deep. These environments are important because they have several functions, from biological to economic for coastal communities, serving as focal points for local commerce.

The hydrodynamics of the estuary system is the result of the interaction between fluvial and marine processes, and those that occur in the inner portion of the estuary (Schettini & Truccolo, 2009). Circulation in estuaries can be modified by human activities. These modifications include direct changes in the estuary basin, such as land reclamation for urban or industrial use, channel expansion and widening by dredging, stabilization of the mouth of the estuary, and elongation by piers, among others (Eidam et al., 2020; Yuan et al., 2015). Increasing depth increases the dissipation of tidal energy, leading to changes in vertical mixing and sediment transport (Schettini et al., 2017).

Dredging for deepening estuarine channels can affect the hydrodynamic regime, physical properties of water, and geomorphology of the estuary or adjacent coastal areas. This is because deepening can increase the intrusion of the salt wedge, change the tidal range, and modify tidal currents, as well as change the suspended sediment load and its sedimentation rates. Any factor that influences the hydrodynamic regime and/or the geomorphology of the estuary can modify the natural balance, as well as the flow of sediments, and lead to changes in the location of the habitats that constitute the estuarine and coastal ecosystems (European Commission, 2011). Channel depth is one of the important parameters that control the sequence of estuarine mixing types. An increase in depth lowers the effectiveness of tidal velocities in promoting vertical mixing between lower and upper estuarine layers. Consequently, haline stratification increases and the net volume transport in each layer is reduced (Kjerfve, 1988). Greater depth would lead to stronger vertical circulation resulting in more saltwater transported upstream at the bottom (Wu et al., 2016). As dredging removes entrance shoals or bars and deepening increases the channel's volume, saltwater penetrates farther landward than its normal position (Kjerfve, 1988).

The Itajaí-Açú estuary is an example of an environment constantly altered by deepening and maintenance dredging. This estuary has great economic importance due to the presence of the Itajaí port. This port is one of the main ports in southern Brazil, representing the largest national fish landing point (Pereira-Filho et al., 2003). Being a fluvial harbour, it needs constant dredging services and improved access to its maritime connection channels (Luz, 2014). In 2008, the port authorities intended to deepen the access channel to the port, which was between 11 m and 12 m deep, to facilitate access to larger ships. Due to the torrential rains that occurred in November 2008 in the Itajaí-Açú River valley, the navigation channel became shallower, resulting in a need for emergency dredging to deepen the channel (Antunes, 2010). In 2011 (March to December) took place one of the main alterations in the estuarine channel, deepening the channel from 11 m to 14 m. Currently, the port region is constantly dredged to maintain the navigation channel at the depth of 14 m.

This study aims to analyse the variations in current circulation and salinity stratification, through data collected in the Itajaí-Açú estuary, before and after the deepening caused by the dredging carried out in 2011 compared to circulation in 2008. Since the dredging activities in the navigation channel took place, no study has been carried out relating hydrodynamics to verify such alterations. This knowledge gap still persists in the case of this estuary and may be used in other estuaries. It is also remarkable the importance of studies concerning circulation and mixture processes in estuaries.

MATERIAL AND METHODS

Study area

The study area is the Itajaí-Açú estuary, which is a highly stratified estuary (Schettini et al., 2005). This estuary is located on the north-central coast of Santa Catarina (Brazil), approximately 80 km north of Florianópolis, between the cities of Itajaí and Navegantes (Figure 1).

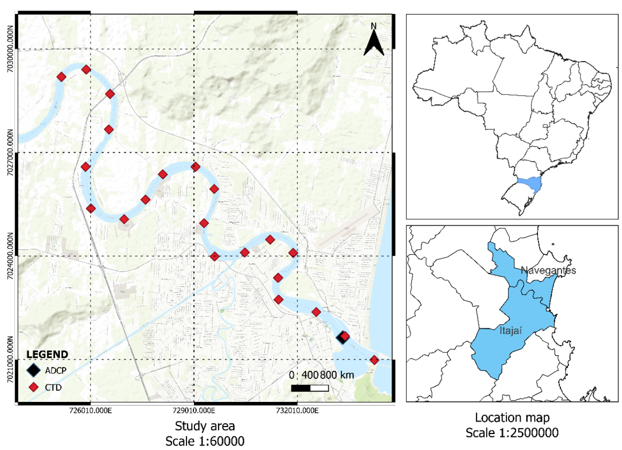

Figure 1 – Localization of the study area in Brazil.

Its waters flow into the Atlantic Ocean at 26º 54,7' S, 48º 38,1' W. The estuary is narrow (~ 200 m), long (~ 70 km), and deep (~ 14 m) (Schettini & Toldo Jr., 2006). The Itajaí-Açú river is the largest drainage in the state of Santa Catarina, draining an area of approximately 15500 km^2 in a triangular shape (Schettini & Toldo Jr., 2006), representing almost 16% of the state area (Pereira-Filho et al., 2010).

The estuary is located on a coastal plain and it is classified as a coastal plain estuary, according to the classification of Fairbridge (1980). In terms of salinity, the Itajaí-Açú river estuary is highly stratified. The main force in estuarine processes is the river discharge, so that level variations due to tides play a secondary role. River discharge can explain approximately 70% of the variability in the position of the wedge end of the Itajaí-Açú river estuary (Zaleski & Schettini, 2010). The discharge of the Itajaí-Açú river is relatively low most of the time and sporadic pulses of high discharge (5390 m^3/s) can be observed as a function of rains in the river basin, which is confirmed by the temporal evolution of average monthly discharge (Schettini, 2001). The annual river discharge average is 228 m^3/s (Schettini & Toldo Jr., 2006).

Sampling

To determine the river discharge, it was used river discharge data measured by the limnimetric station of the National Water Agency (ANA for Agência Nacional de Águas e Saneamento Básico), located in the municipality of Indaial, Santa Catarina. This station measures the discharge daily and it is located around 90 km inland from the river mouth.

Current data used was recorded using an Acoustic Doppler Current Profiler (ADCP) of NortekTM brand; model Aquadopp® 1 MHz, bottom moored in a stainless-steel structure, at the edge of the main channel of the estuary, at a depth of approximately 6 m. This equipment measures vertical profiles of speed and direction of the current through the three acoustic beams it presents. In addition, it measures water level fluctuations through a pressure sensor. The ADCP was programmed to collect one profile every 10 minutes, divided into 0,5 m cells. The number of cells was set to cover the entire water column and it was constant. Data were recorded from 30/11/2007 to 17/06/2008, and 23/03/2011 to 01/10/2011, but neither of both periods was constant in measurements. Selected periods to study current behaviour were May 2008 and November 2011, as they had similar river discharge conditions (May 2008 = 230,98 m^3/s; November 2011 = 227,15 m^3/s).

Salinity data was collected by the Physical Oceanography Laboratory of the Universidade do Vale do Itajaí (UNIVALI) using multiparameter probe YSI, model EXO in surface and bottom, every km along 20 km. Sampling periods were chosen considering the availability of current and salinity data simultaneously, resulting in periods from April to August 2008 and 2011. Sampling was conducted during neap and spring tides, twice a month during the whole year.

Data analysis

To compare the behaviour of currents under similar river discharge conditions (study period), it was calculated a monthly average of the river discharge data for 2008 (before the dredging) and 2011 (after the dredging). This average was calculated using MATLAB (MATLAB and Statistics Toolbox, 2018). Study periods were chosen considering that the mean river discharge is 228 m^3/s (Schettini & Toldo Jr., 2006). Consequently, chosen study periods were May 2008 (before dredging) and November 2011 (after dredging) for having similar mean river discharge values. Overall, the current data to be analysed were 30 days of recording. Salinity data were studied ranging from April to August (2008 and 2011), as data was only available for this period. In order to check if the chosen periods were significantly similar, it was applied a t-test with a confidence interval of 95% through R software (R Core Team, 2020).

It was calculated the mean velocity values of currents in the periods before and after dredging in MATLAB R2018b software. Average velocity values were plotted in velocity profiles for the 30-day selected periods. The same procedure was applied to calculate and plot the behaviour of currents in neap and spring tides. So as to set when neap and spring tides occurred, it was consulted a lunar calendar (Table 1).

Table 1. Dates for neap and spring tides in both study periods.

Year	Spring tides	Neap tides
2008	07/05	12/05
	20/05	28/05
2011	10/11	02/11
	25/11	18/11

So as to compare salinity data in the study period, surface and bottom salinity records were analysed. It was calculated surface and bottom monthly mean from April to August, both 2008 and 2011. It was then plotted to illustrate the differences between both layers and periods.

RESULTS

River discharge

The following table (Table 2) shows mean values for the river discharge in May 2008 and November 2011, as well as the standard deviation for each month, respectively. Mean river discharge in May 2008 was 231 ± 18 m^3/s, while in November 2011 mean values for river discharge were 227 ± 9 m^3/s. It could be assured with 95% confidence that river discharge for both periods was significantly similar, with almost the same river discharge value in both 2008 and 2011, as the p-value resulted in 0,85 (being p-value > α= 0,05). It is also shown the mean values for the river discharge for April to August 2008 and 2011, as well as the standard deviation for each year, respectively. Mean river discharge in April – August 2008 was 173 ± 117 m^3/s, while in the same months in 2011, mean values for river discharge were 454 ± 409 m^3/s. Itajaí-Açú River presented high variability in the river discharge mean values. Rainfall registered in May 2008 was 63 mm, while in November 2011 was 99,6 mm. Rainfall in April – August 2008 was 517 mm. Meanwhile, rainfall registered in April – August 2011 was 917 mm. This data was obtained from the National Hydrometric Web.

Table 2 – Mean values for river discharge (m^3/s) in May 2008, April to August 2008, April to August 2011 and November 2011, as well as their respective values for standard deviation, σ (m^3/s).

Period	Mean ($\bar{x}$)	Standard deviation (σ)
May 2008	231	18
November 2011	227	9
April – August 2008	173	117
April – August 2011	454	409

In Figure 2 is shown the time series of river discharge (black solid line) for 2008 and 2011. The blue dotted line represents the mean annual value for the river discharge for each year. Selected periods for the study of the behaviour of estuarine circulation are marked in black dotted rectangles. The black arrow indicates the beginning of the dredging (28/03/2011). It can be observed that, in 2008, the maximum river discharge values were found in the last months of the year, from October to December, with values reaching 1938 m^3/s. The rest of the year, during January, February, April, and May, values were below 1000 m^3/s. Most of the time (March, June, July, August, and September) values were even below 500 m^3/s. Maximum monthly mean values were 935,56 m^3/s reached in November, and minimum monthly mean values of 124,08 m^3/s were reached in July. On the other hand, in 2011, the maximum peak doubled in value the maximum of 2008, being 4597 m^3/s. It should be noted that this maximum was a sporadic pulse, as the rest of the year presented much lower river discharge values. For most of the year, river discharge did not reach 1000 m^3/s. From January to

April, river discharge was greater, approaching, or even exceeding 1000 m³/s. From April to July, discharge was half that of previous months (500 m³/s). From then on, until October, it increased considerably, reaching values of 2000 m³/s. In October, values decreased to 500 m³/s, with some pulses of 1000m³/s. Maximum monthly mean values were reached in September, with values of 1214,70 m³/s. Minimum monthly mean values were reached in December with values of 158,38 m³/s. These results highlight the seasonal variability of river discharge previously characterized by Pereira Filho et al. (2003), and the non-homogeneity of the rainfall distribution in the region, pointed out by Murara et al. (2018).

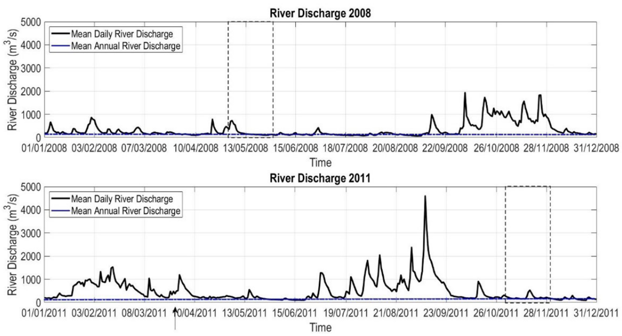

Figure 2 – Time series of river discharge (black solid line) in 2008 (top) and 2011 (bottom). The blue dotted line represents the mean annual value for the river discharge for each year. Selected periods for the study of the behaviour of estuarine circulation are marked in black dotted rectangles. The black arrow indicates the beginning of the dredging (28/03/2011).

Currents

In May 2008 current data analysed reached maximum flood peaks of 0,76 m/s, and maximum ebb peaks of 0,99 m/s. The average speed of the currents for this period was - 0,22 m/s. The negative sign indicates residual currents were predominantly ebb-directed. Results found in the analysis of current data for 2011 showed that the maximum flood speed reached was 0,48 m/s, maximum ebb values were 0,86 m/s, and the average current speed value was - 0,24 m/s. Again, residual currents were ebb-directed. The average speed profiles for both periods are shown in Figure 3.

There are visual differences in profile shape for both periods, but both were ebb unidirectional. While the expected shape was the one found in 2008, in 2011 there was a sharp reduction in the first meters of the water column. The lowest speeds at the bottom were expected in estuaries, since flood currents (positive values) occur at the bottom, causing lower values on average over time. However, the lower values of surface current when compared to the middle of the water column may have occurred due to a sampling failure.

Since the ADCP is at the bottom, sometimes at lower levels, measuring cells at the interface between water and air does not perform measurements. Thus, just at these times, speeds were less intense, which generated less intense average current values in the analysed period. Even though it is real data, data that was not collected by ADCP in these low-level moments could compromise the results. However, the average speed of currents in 2008 was less intense than currents in 2011, as can be seen in Figure 3. There is a slight difference in the average speeds of the two periods. However, this difference shows that there was a change in the speed of the currents since an average was made for a long period (30 days).

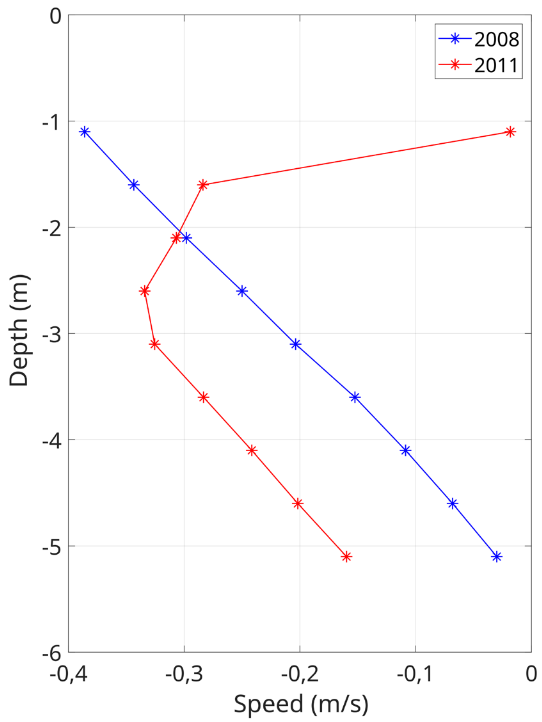

Figure 3 – Mean speed profiles in 2008 (blue solid line) and 2011 (red solid line).

The mean profile of currents in spring tide (Figure 4) appeared to be an ebb profile. Currents before dredging (2008) reached mean values of 0,17 m/s, while in 2011 mean speed values were 0,23 m/s. Maximum ebb values in 2008 were 0,97 m/s and maximum flood values were 0,76 m/s. Velocities in the maximum ebb peak in 2011 were reached at 0,79 m/s and minimum values were reached at 0,48 m/s.

In neap tides (Figure 5), the mean profile of currents appeared, once again, to be an ebb profile. Currents in neap tide showed mean speed values of 0,20 m/s in 2008 and 0,19 m/s in 2011. In this case, values were almost the same. Velocities in the maximum flood peak in 2008 were reached at 0,96 m/s and minimum values were reached at

0,76 m/s. The maximum flood peak in 2011 reached values of 0,86 m/s, while the minimum flood values registered were 0,41 m/s.

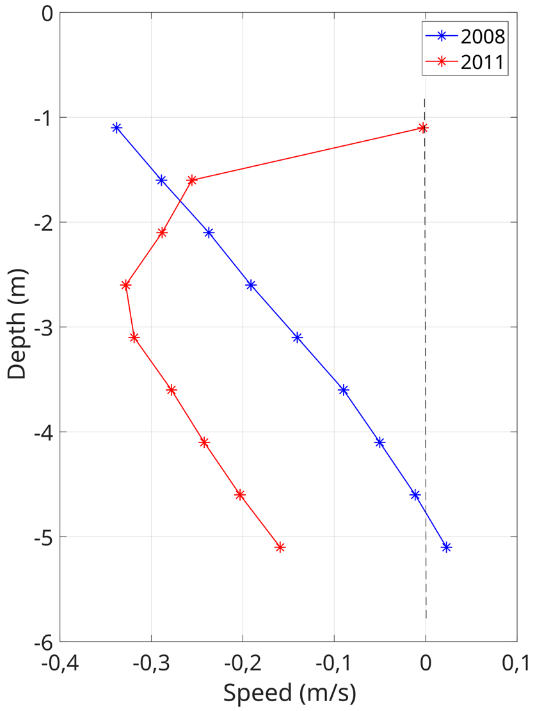

Figure 4 – Spring tide speed profile in 2008 (blue solid line) and 2011 (red solid line).

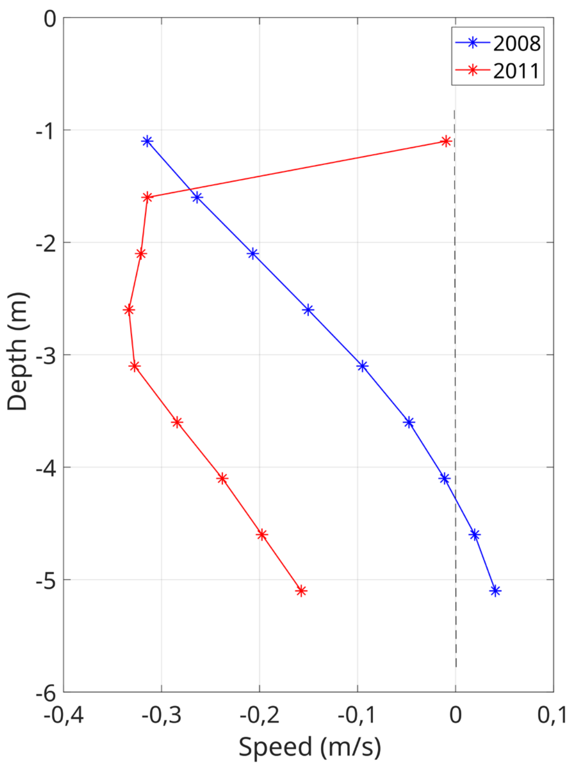

Figure 5 – Neap tide speed profile in 2008 (blue solid line) and 2011 (red solid line).

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Salinity

Surface mean salinity between April and August 2008 showed values of 4,57, while in the same months in 2011 values were 5,82, as shown in Figure 6. Bottom salinity before dredging presented values of 12,80, whereas in 2011 values of 33,61 were reached. There was a clear increase in salinity both on the surface and at he bottom, in mean terms.

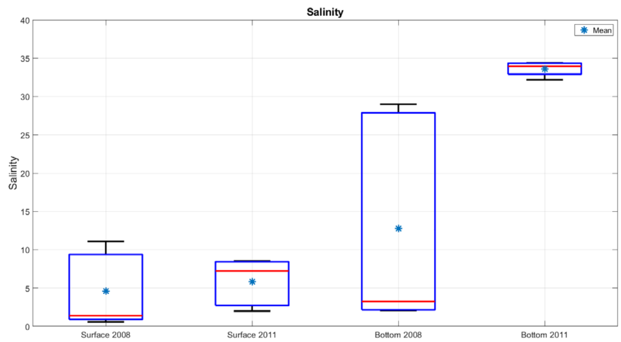

Figure 6 – Surface and bottom April-August salinity boxplot. The red line indiates the median, and the blue star indicates the average. Whiskers indicate maximum and minimum values not considered outliers.

In Figure 7, one can observe that, during the first three months of study (April, May, and June) in 2008, the water column was homogeneous with values ranging from 2,06 to 3,25 in the bottom, and from 0,59 to 1,39 in the surface. These values indicate that the entire water column was almost freshwater. In July and August 2008 values increased exponentially, with values ranging from 27,50 (August) to 29 (July) at the bottom, and 8,81 (August) to 11,10 (July) on the surface. Southern winds cause the increase in salinity, which push the seawater into the estuary at the subsurface. In 2011, the water column was clearly stratified, as salinity on the surface ranged from 1,99 to 8,51. Salinity values in the bottom ranged from 32,2 to 34,33. It can be assured with 95% confidence that salinity increased after the dredging, as the p-value resulted in 0,99.

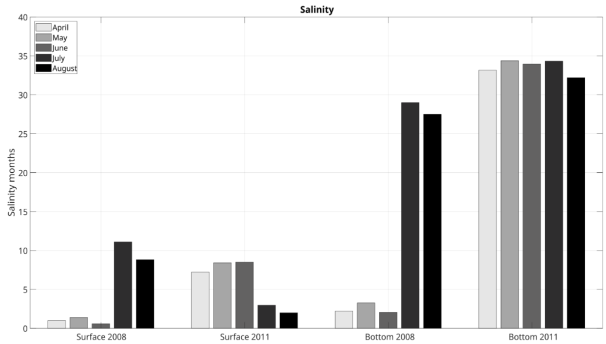

Figure 7 – Monthly average of the surface and bottom salinity in the study period in 2008 and 2011.

As the population continues to grow in areas where they can obtain resources and settle, it is obvious that environmental alteration is due to human interference. A clear example is the study area presented in this paper. The Itajaí port is one of the most important ports in south Brazil. Consequently, bigger vessels dock at this port. This could only be possible if the navigation channel presented enough depth, which is feasible as long as dredging is undertaken.

Current speed presented a small increase in the Itajaí-Açú estuary after dredging took place. These results agree with those obtained by Jeuken & Wang (2009) in Schelde Estuary (The Netherlands), which is a tide-dominated estuary and is of large economic importance. They also conceded with results obtained by Van Maren et al. (2014) in Escalda Estuary (The Netherlands), as well as Chant et al. (2018) in Modaomen Estuary under similar conditions. This estuarine circulation intensification because of dredging could be due to a reduction in vertical mixing or an increase in salinity gradient, as suggested by Chant et al. (2018).

In the present study, an intense variation in the vertical gradient of salinity was also observed. After dredging, salinity stratification, under the same hydrological conditions, increased. Richards and Granat (1986) used a physical model to determine the effect of deepening the Norfolk harbour on salinity distributions in the lower bay. Channel deepening resulted in increased salinity intrusion and vertical stratification, the same observed in the Itajaí-Açú River. In Richards & Granat (1986) study, the increased intrusion was confined largely to the deepened channel areas. Chubarenko & Tchepikova (2001) studied the implications of salinity of man-made contributions in the Vistula Lagoon (south-eastern Baltic) during the last century. They used a numerical model to study the dynamics of salinity fields in the whole lagoon. The model resulted in an increase in salinity due to man-made interventions that changed the morphology of the lagoon. One of the reasons for the increase in salinity was the deepening of the Baltiysk Strait, which caused the intensification of water exchange and, correspondingly, the increase of the salinity in the lagoon. A study at the Ems estuary, carried out by Van Maren et al. (2015), used numerical modelling of suspended sediment transport for forcing such as tides, waves, and salinity. The result demonstrated that the deepening of the channel seems to be an important factor for the increase in the transport of sediments above the estuary, due to the increase in estuarine circulation driven by the salinity gradient. Ralston and Geyer (2019) observed that modifications for navigation increased channel depth by 10 – 30% leading to an increase in both salinity and stratification over the past century. Model results showed an increase of about 30%.

CONCLUSION

Current circulation in the Itajaí-Açú estuary was altered by dredging carried out in March 2011, since, in average terms, the current speed after dredging appeared to be more intense. Currents under similar river discharge conditions were predominantly ebb, being more intense (- 0,24 m/s) after dredging (2011) than before (- 0,22 m/s) the dredging (2008). Itajaí-Mirim influence is not noticeable as the mean river discharge in May 2008 was 16,63 m^3/s and in November 2011 was 28,62 m^3/s. Therefore, the speed increase cannot be attributed to the Itajaí-Mirim river discharge.

The pattern of current circulation in the Itajaí-Açú estuary under the same river discharge and the same lunar phase showed changes in speed after dredging compared to speed before dredging, being more intense in 2011 than in 2008. Salinity data showed that there was an increase after the dredging. During the first three months of 2008, the water column was homogeneous. After that, salinity values increased exponentially. In 2011, the water column was clearly stratified. The analyses carried out in the present work were part of the author's degree thesis. It is suggested future studies to be conducted including numerical modelling to better understand the physical processes identified.

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