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Effect of the reduction of the outflow restriction discharge from the Xingó dam in water salinity in the lower stretch of the São Francisco River

Efeito da redução da vazão de restrição defluente da barragem de Xingó na salinidade da água no baixo trecho do Rio São Francisco

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ABSTRACT

Among the water quality parameters subjected to changes in river flow variations, salinity stands out for being intrinsically associated to ecosystem quality. Nonetheless, salinization can cause irreversible damage to the structure and functions of aquatic communities. This work evaluated the effect of successive reductions of outflow discharges from Xingó dam in water salinity in the lower stretch of the São Francisco River, Brazil. Salinity was analysed downstream of the dam, in addition to the relation between discharge reductions and salinity levels, as well as the spatial evolution of salinity in function of the distance of the sampling points from the river mouth. Secondary water quality data from 17 monitoring points were analysed, moreover, field samples and laboratory analyses were performed. With the reductions of outflow discharges, that started in 2013, there was a considerable increase in salinity in the sampling point located 9 km far from the river mouth, and with the continuation of discharge reductions, points that are farther away from the river mouth also presented high salinity values, both in the bottom and on the surface. This study indicates salinity values above the limits of fresh water (0.5 ‰), established by the CONAMA Resolution 357, for human consumption.

Keywords: Saline wedge; Estuaries; São Francisco River; Outflow discharge from dam.

RESUMO

Entre os parâmetros de qualidade da água sujeitos a alterações com mudanças no fluxo do rio, a salinidade se destaca por ser intrinsicamente associada à qualidade do ecossistema. No entanto, a salinização pode causar danos irreversíveis à estrutura e função das comunidades aquáticas. Este trabalho avaliou o efeito das sucessivas reduções de vazões defluentes da barragem de Xingó na salinidade da água, no baixo trecho do rio São Francisco, Brasil. Analisou-se a salinidade a jusante da barragem, a relação entre as reduções de vazões defluentes e a salinidade, além da evolução espacial da salinidade, em função da distância dos pontos amostrais até a foz. Dados secundários de qualidade da água de 17 pontos de monitoramento foram analisados, além da realização de coletas de campo e análises em laboratório. Com as reduções das vazões defluentes, a partir de 2013, houve considerável aumento da salinidade no ponto amostral distante da foz 9 km, e com a continuidade das reduções de vazões, pontos mais afastados da foz apresentaram valores elevados de salinidade, tanto no fundo quanto na superfície. Este estudo indica valores de salinidade acima dos limites de água doce (0,5 ‰), estabelecido pela Resolução 357 do CONAMA, para consumo humano.

Palavras-chave: Cunha salina; Estuário; Rio São Francisco; Vazão defluente de barragem.

INTRODUCTION

The alteration of river flow is the factor that most impacts ecosystems (Geddes & Butler, 1984; Attrill et al., 1996; Bunn & Arthington, 2002), since the reduction of its flow produces considerable effect on the dynamics of the estuaries, affecting large groups of organisms, from plants to fish, besides facilitating the introduction of invasive species, such as the sudden changes in the agglomeration of plants and animals (Junk et al., 1989; Poff et al., 1997; Lundqvist, 1998; Al-Taani, 2014). Among the consequences of river flow alteration, salinity is highlighted as one of the main parameters susceptible to undergo changes (Oliveira, 2003; Almeida & Silva Junior, 2007; Oliveira et al., 2008; Kingsford & Hankin, 2010; Silva et al., 2015; Khanom, 2016; Al-Nasrawi et al., 2016; Campo et al., 2016; Cheek & Taylor, 2016; Wedderburn et al., 2016).

Salinity is an abiotic component that is fundamental to all water bodies and a critical factor of the characteristics of estuaries (Miranda et al., 2002). Seasonal variation of salinity in estuaries is controlled by freshwater flow from rivers, which may cause impacts on the maintenance of ecosystem equilibrium (Alber 2002; Bate et al., 2002; Gillanders & Kingsford, 2002; Whitfield 2005; Zhang et al., 2011). The aquatic biota has differences in preference of salinity ranges, being commonly classified in these ranges (Kefford et al., 2012; Schröder et al., 2015).

Several authors have reported the negative effects of water salinization in aquatic ecosystems (Williams, 1987; Piscart et al., 2005; Whitfield, 2005; Kefford et al., 2012; Schröder et al., 2015; Wedderburn et al., 2016). The isohaline displacement, for instance, caused by alterations of freshwater flow, interferes on the distribution of rooted vegetation and sessile organisms, taking effect in the entire aquatic food chain (Alber, 2002). Studies by Dimaggio et al. (2016) show experimental results that indicates that the survival of embryos and larvae of herring from rivers may be possible in tidal influence areas, depending on the development phase and the exposure rate of salinity. Another study, developed by Cheek & Taylor (2016) on the lower stretch of the Pecos River in Texas, confirmed that temporal variation in fish groups suffered a sharp change along a time period of 24 years. The distributive changes were related to the intolerance to increasing in salinity.

According to Ghassemi et al. (1995) as cited in Blinn et al. (2004), salinization has the potential to cause irreversible damage to the structure and functioning of aquatic communities in arid regions and represents one of the major threats to rivers and wet zones. Schröder et al. (2015) affirm that some species are so sensitive to the increase in salinity levels that their population reduces and may even disappear.

Some research exemplifies the effect of alteration in salinity ranges on the aquatic biota, for instance, in macroinvertebrates. Piscart et al. (2005) verified that permanent salt contamination affects the structure of benthic macroinvertebrates communities resulting in the disappearance of many taxa considering salinity from a value higher than 1.4 g L^{-1}. Schröder et al. (2015) analyzed the effect of salt pollution on macroinvertebrates communities and diatoms from the Lippe River, Germany. Their results indicated that macroinvertebrates and diatoms suffered a distinct change in composition with conductivity between 900 and 1000 S cm^{-1}. Nevertheless, Zinchenko & Golovatyuk (2013) indicated that the critical level of salinity for the development of hydrobionts in rivers from different arid regions varies from 10 to 15 g L^{-1}.

Kefford et al. (2012) aimed to determine if salinity tolerance of macroinvertebrates communities and taxonomic groups differ between regions. They studied freshwater samples from the east of Australia, France, Israel, and South Africa by using the same method, and evidence of generalized tolerance to salinity in various taxa was not found.

There is some difficulty in stating with certainty the general salinity ranges where specific changes occur in the various species that compose the aquatic biota, because in addition to the wide variety of salinity tolerance between species (Schröder et al., 2015; Zinchenko & Golovatyuk, 2013; Kefford et al., 2012), other factors interfere, for example, the time of salinization to which the region is subjected (Kefford et al., 2012). Moreover, studies about the interference of salinity on aquatic biota are rare; thus, the effects of salinization on river ecosystems are slightly known (Piscart et al., 2005; Bailey et al., 2006; Kefford et al., 2012; Schröder et al., 2015). Kefford et al. (2012) still specify that the limited data regarding sensibility to salinity are the product of distinct methodologies, which prevents a clear comprehension of the effects of salinization on aquatic biota since salinity sensitivity also depends on the method used.

In view of the impacts on the human population, alterations on salinity ranges of waters may compromise the multiple uses, consumptive and/or non-consumptive, such as human supply and fishing by riverine communities. According to CONAMA Resolution 357 (Brasil, 2005) in terms of salinity, water is classified as: freshwater (salinity up to 0.5 ‰), brackish water (salinity between 0.5 to 30 ‰) or saline water (salinity > 30 ‰).

Salinization may happen due to the rise in evaporation rate, in the function of high environmental temperatures, waste discharge, but mainly saline intrusion caused by sea-level rise, as a result of climate change and human activities. Many authors noted that the increase of river water salinity might be related to intervention and operation of reservoirs built for electric power generation and also to supply other uses, like irrigation, human supply, and navigation (Silva et al., 2015; Al-Nasrawi et al., 2016; Campo et al., 2016; Cheek & Taylor, 2016; Khanom, 2016; Wedderburn et al., 2016).

The implantation and/or operation of reservoirs of this nature generate several impacts on the basin, for example: interference on sedimentological processes (Medeiros et al., 2007), alteration on the configuration of the dynamics and morphology of the river mouth (Oliveira 2003; Felippe et al., 2009), change of the flood pulse (Junk, et al.,1989; Poff & Ward, 1989; Callisto et al., 2009) and modification of flow regime and hydraulic behaviour (Genz, 2006; Graf, 2006).

The environmental systems downstream of the reservoirs are harmed as well in consequence of its implantation (Brandt, 2005; Genz, 2006; Graf, 2006; Bachman & Rand, 2008; Robinson & Uehlinger, 2008; Lima et al., 2010; Kingsford & Hankin, 2010), making possible to occur alterations in water quality, highlighting salinity among other parameters (Genz, 2006; Pinheiro & Morais, 2010; Rahman et al., 2011).

It is important to highlight that operating a reservoir or a set of reservoirs means to use rules based on the volume of the reservoir or the outflow discharge established for a determined time interval (Loucks et al., 1981). Those rules are specific to comply with the water levels and the release of a certain amount of water downstream in order to supply the uses and targets of the water management of the watershed. This operation faces great challenges when in periods of drought or water crisis.

In this context, the São Francisco River, a highly important river to Brazil, mainly due to energy power generation and freshwater availability for the Brazilian Northeast Region (Campos, 1995), has a cascade system of dams in order to meet water multiple uses. However, water levels in reservoirs have been suffering a reduction because of an intense drought that started in 2012 (Agência Nacional de Águas, 2017).

Rainfall levels in the region have decreased considerably in the upper and medium stretches of the São Francisco River, areas that contribute the most for water discharge in this basin. Facing this situation, it was necessary to operate the system in order to maintain the reservoirs with the water accumulation sufficient to supply the demands for water in its multiple uses. Therefore, the responsible environmental organs (ANA and IBAMA) authorized, starting in the year of 2013, successive reductions of the outflow discharge for the reservoirs of Sobradinho and Xingó, in the medium and lower stretches of the river (Agência Nacional de Águas, 2017). Since then, in the region of the lower stretch, complaints were aroused from the riverine population regarding the increase of water salinity (Comitê de Bacia Hidrográfica do Rio São Francisco, 2016).

In this sense, this study aims to evaluate the effect on the behavior of salinity downstream of Xingó's reservoir, due to the successive reductions of outflow discharges as a result of the operation of reservoirs in the São Francisco River Watershed, directing to (1) analyse the behavior of salinity during the period from 2008 to 2017, considering the quadrature and syzygy tides; (2) evaluate the influence of seasonality on salinity; (3) analyse the relationship between reduction of outflow discharge from the reservoir and salinity, making possible to notice the temporal and spatial behavior of salinity in the lower stretch of the São Francisco River.

Studies about river water salinity can aid the decision-making process on the water resources management, contributing to the protection of riverine population and ecosystem conservation.

MATERIALS AND METHODS

Study area

The study area extends from the Piranhas River Station (CHESF), downstream of the Xingó Dam, located between Sergipe and Alagoas to the São Francisco River mouth with an extension of approximately 200 km including the river and estuary sections, whose incremental area is 29866.5 km² (Figure 1). According to Oliveira et al. (2008), the estuarine stretch of the São Francisco River extends around 75 km from the river mouth.

The chosen sections along the longitudinal stretch (Figure 1a) were based upon developed researches in the lower stretch of the São Francisco River Watershed initiated with the network "Ecovazão" (Ecoflow), a research network composed by federal universities that has as main goal to establish an environmental flow regime for the lower stretch of the São Francisco River.

The same sections in the longitudinal stretch, numbered from upstream to downstream, were worked on the Project "*Hidrograma Ecológico e Modelagem Quali-Quantitativa de Bacias*" (HIDROECO), which in english is "Ecological Hydrograph and Quali-Quantitative Modelling of Watersheds", financed by Financier of Studies and Projects (FINEP). The aim of that project was to develop environmental hydrographs to different Brazilian watersheds, in it was the subproject "*Avaliação dos Impactos Hidrológicos da Implantação do Hidrograma Ambiental do baixo rio São Francisco*" (AIHA), that is "Evaluation of Hydrological Impacts on the Implantation of the Environmental Hydrograph for the Lower São Francisco River", with the participation of researchers from UFBA, and it worked on the adequacy of the Building Block Methodology (BBM) in order to evaluate the environmental hydrograph (King et al., 2008).

This present work is inserted in the subproject AIHA, adding new sampling points, SPs, in the estuary (Figure 1d) to study the salinity behavior in the context of reductions of outflow discharges in the Xingó Dam.

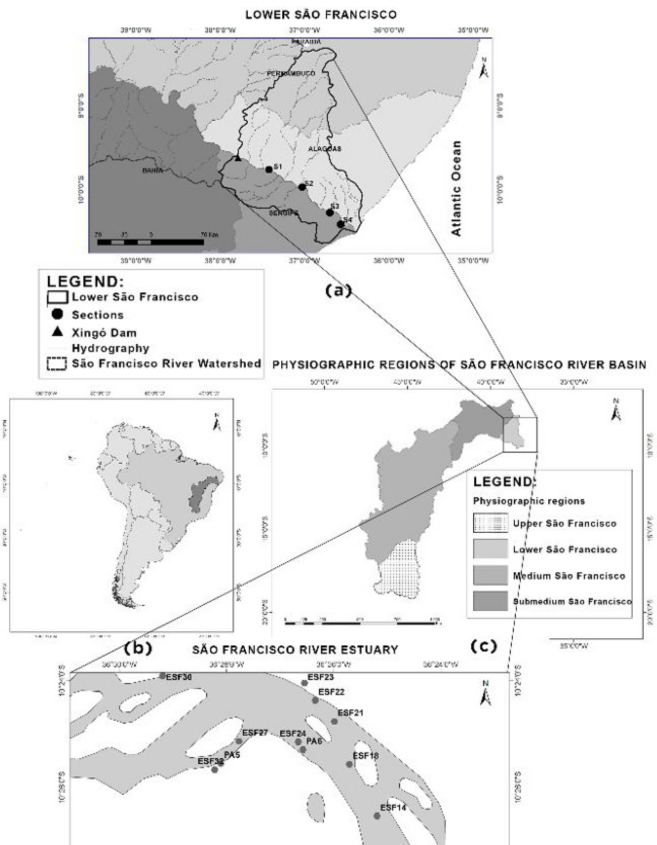

Figure 1. Location of the study area: Lower stretch of the São Francisco River with sections in the river segment (a). Lower stretch in the São Francisco River Watershed (b). São Francisco River Watershed in Brazil, South America (c). Points in the estuary (d).

On Tables 1 and 2 are presented the sections of the river stretch and the points studied from the estuary, respectively.

Analysis of the evolution of reductions of outflow discharges downstream of the Xingó reservoir

Daily discharge data were provided by CHESF, that is responsible for the maintenance and operation of the stations. The gauging station of Piranhas was selected because it was closer to Xingó, which may represent better the outflow discharges from the reservoir. The outflow discharges were presented graphically between the years of 1994 (beginning of reservoir operation) until May of 2017 (final period of this study). To understand the influence of the reservoir operation on water salinity, two periods of time were studied: before and after the consecutive reductions of outflow discharges, respectively, 2008 to 2010 and 2013 to May of 2017. And, in order to visualize the distribution of flow values used for the study period, boxplot graphs were plotted with the discharges that occurred at the period.

Analysis of temporal and spatial variation in salinity in the estuarine stretch

The secondary data used for salinity (surface and bottom) were taken from CHESF water quality monitoring reports for five measurement campaigns, distributed from 2008 to 2010 (Companhia Hidrelétrica do São Francisco, 2011), the period prior to flow reductions, and the 2013 to 2017 (Companhia Hidrelétrica do São Francisco, 2013, 2014, 2015, 2017a, 2017b, 2017c), the period for the reduction of outflow discharges.

Studying the reference stretch

Initially, the stretch in the estuary, that extends from 4.8 km to 9.3 km to the river mouth, was studied. In this stretch, there are ten sampling points (ESF09 to ESF18) monitored by CHESF. In order to represent the variation in salinity in the entire studied period, a boxplot graph was plotted with the data from all of those points, including all the values of salinity related to the quadrature and syzygy tides. After this analysis, among the ten sampling points, three sections were chosen to represent the reference stretch: section 13, where the sample point ESF10 passes, distant from the 5.3 km mouth; section 12, where the sample point ESF14 passes, distant from the mouth 7.3 km; and section 11, where the sample point ESF18 passes, far from the mouth 9.3 Km. In this stretch was developed the entire study, always comparing two periods, before and after the reduction of outflow discharges. The study in the reference stretch aided to support the evaluation of the advancement of the saline wedge on sections situated farther from the river mouth.

In the reference stretch the following analyses were developed:

- *Analysis according to the measurement period*: the data were separated by the period they were measured during the quadrature tide and the syzygy tide;
- *Analysis of the influence of seasonality*: distribution of salinity values on wet and dry periods during the high tide of syzygy;

Table 1. Information about the sections in the river stretch with their respective sampling points: Lower São Francisco River.

Section	Distance to the river mouth (km)	Location	Position	Sampling point	Coordinates	
					East	North
1	160.2	Niterói-SE – Pão de Açúcar-AL	middle of the section	PA1	672559.0	8920766.0
2	102.3	Gararu-SE – Traipu-AL		PA2	720484.0	8896277.0
3	54.6	Pindoba-SE – Xinaré-AL		PA3	750928.0	8863884.0
4	21.6	Ilha das Flores-SE – Penedo-AL		PA4	770148.0	8846167.0

Table 2. Information about the sections in the estuarine stretch, with their respective sampling points. Location Lower São Francisco River.

Section	Distance to the river mouth (km)	Location	Position (bank)	Sampling point	Coordinates	
					East	North
5	15.5	Brejo Grande-SE-Piaçabuçu-AL	left	ESF32	776957.0	8846188.0
			right	ESF30	775210.2	8849445.5
6	15.2		left	PA5	777165.0	8846404.0
7	14.4		left	ESF27	777790.5	8847161.2
8	11.8		right	ESF23	780041.1	8849149.3
9	11.0		left	ESF24	779811.0	8847124.0
			right	ESF22	780404.0	8848550.0
10	10.5		left	PA6	779969.0	8846856.0
			right	ESF21	781052.0	8847816.0
11	9.3		middle of the section	ESF18	781549.0	8846336.0
12	7.3			ESF14	782474.0	8844550.0
13	5.3			ESF10	783580.0	8842864.0
14	4.3			ESF09	783816.0	8842421.0

- *Analysis of the relation between the reductions of outflow discharges and water salinity in the reference stretch:* for this, salinity data from the high tide of syzygy were related to the flow measured at the gauging station of Piranhas. It was applied the significance test over the r_s value, Spearman's coefficient of determination, to verify if there was a significative correlation with confidence level of 95% ($p < 5\%$) between daily outflow discharges and salinity values (surface and bottom) on points ESF10, ESF14, and ESF18;
- *Analysis of the behavior and advancement of the saline wedge in the estuarine stretch:* therefore, it was considered the numbered sections on the respective points of reference ESF 10, ESF 14 and ESF 18, following from here, every salinity analysis, to be developed by section; in this case, sections 11, 12 and 13 were used, representing the sections that pass by points ESF 18, ESF 14 and ESF 10, respectively. A line graph was plotted for surface salinity of the three sections, before and after the reductions of outflow, coming to the extension of the advancement of the saline wedge. A salinity analysis on section 11 (ESF18) was also made, in order to reference the study for the sections situated farther from the river mouth.

Acquiring primary data

The campaign in the estuary happened on May 27th and 28th of 2017, when fixed measurements were made from 10 to 12 hours in sections 6 and 10.

The parameters measured were total dissolved solids (mg L^{-1}), conductivity (μS cm^{-1}), salinity (‰), pH and temperature (°C) with a multiparameter sensor. The depth was estimated using a measuring tape and a rope tied to an anchor.

Aiming to validate the field measurements, in every hour samples – from the surface, middle and bottom – were collected and conditioned, in addition to *in loco* measurements of the parameters previously mentioned. The samples were taken to the laboratory and analyzed for conductivity and total dissolved solids randomly, for the purpose of comparing with the measures developed *in loco*.

In possession of the results, salinity was calculated using the following equation, obtained by the investigation done by Williams (1986) in 109 samples from a salty Australian lake and its application with the data of this work presented good results:

$$S = \left(C^{1.0878}\right) * 0.4665 \tag{1}$$

Where:

$$S = \text{salinity in g } L^{-1} (‰) \tag{2}$$

$$C = \text{conductivity in mS } cm^{-1} \text{ in } 25\ ºC \tag{3}$$

In order to check the measurements in the conductivity meter, random measures were made for total dissolved solids (TDS) in samples from sampling points PA5 and PA6. In this case, salinity was obtained exactly, in parts per thousand (‰ or g L^{-1}), dividing the value of TDS by one thousand:

$$S = TDS\left(\text{mg } L^{-1}\right) / 1000 \tag{4}$$

A correlation was made with the salinity data that were obtained with the measures of conductivity and of total dissolved solids and the results for conductivity obtained in the laboratory and on the field and it was applied the significance test over the Spearman's coefficient (r_s). The conductivity from the lab bench and *in loco* resulted in a significant positive correlation ($p < 0.05$) with R equals to 0.97.

Analysis of temporal and spatial variation in salinity in the river stretch

In this stretch, it was only developed an analysis of primary data. The campaign occurred on the days of 25/04 to 28/04 of 2017. Measurements were made twice a day (low tide and high tide) in three depths (surface, medium, and bottom) in the middle of the four sections defined in the project AIHA, Sections 4, 3, 2 and 1, downstream to upstream, and sample points PA4, PA3, PA2 and PA1 at the locations shown in Table 1 comprised the longitudinal section.

The parameters were measured using a multiparameter sensor and they were: total dissolved solids (mg L^{-1}), conductivity (μS cm^{-1}), salinity (‰), pH and temperature (°C). The depth was estimated with a rope that was tied to an anchor and a measuring tape.

Salinity results are presented from downstream to upstream, that is, from the points that are closer to the river mouth to the ones that are farther from it in the estuarine stretch.

RESULTS AND DISCUSSION

Analysis of the evolution of outflow discharges downstream of the Xingó reservoir

Before the construction of the reservoirs in the São Francisco River Watershed, the natural river flow used to reach lower limits within a range of 900 m^3 s^{-1}, in the dry period, to 8000 m^3 s^{-1}, in the wet period, achieving maximum peaks of 15000 m^3 s^{-1}. The river already being regulated, prior to the building of Xingó Dam (the last one in the system), the monthly average natural river discharge was reduced to 2980 m^3 s^{-1} (Companhia Hidrelétrica do São Francisco, 1992). Beginning the operation of the Xingó reservoir in December 16th of 1994, the minimum outflow discharge was 1300 m^3 s^{-1}.

In order to clearly examine the dimension of the flow variation before and after the reduction of discharges, a boxplot graph was created to show the distribution of daily outflow discharges along the years covered by the period of this study (Figure 2).

As it is possible to notice in Figure 2, the median discharge values are concentrated between 1200 and 2400 m^3 s^{-1}, in the years from 2008 to 2012, years of operation without the reduction of the minimum restricted flow; and from 600 to 800 m^3 s^{-1} in the years of 2013 to May of 2017, the period that it was operating with the reduced discharges (Figure 2). Thus, the median values of the effluent flow decreased by almost 50% in the period from 2008 to 2017, considerably reducing the river forcing, which is an important factor in the saline balance in the estuary and its reduction makes the forcing of the river prevail, which favors the advance of the saline wedge. The operation with the reduced outflow discharge of Xingó was maintained until the end of 2018. According to developed studies, changes in the river flow discharge can result in alterations in water quality, especially salinity (Genz, 2006; Pinheiro & Morais, 2010; Rahman et al., 2011).

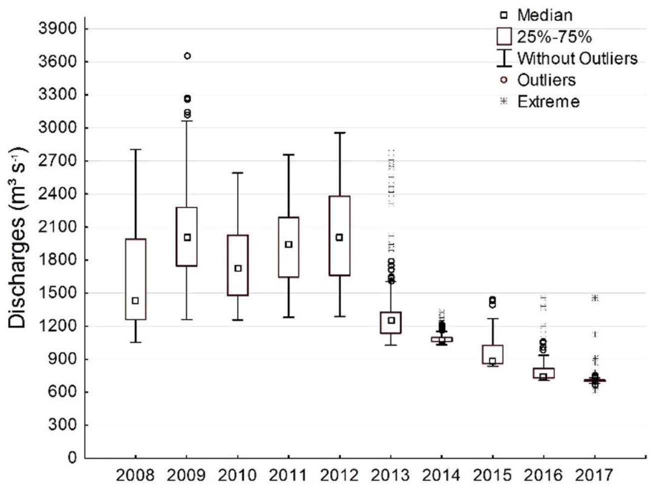

Figure 2. Distribution of daily outflow discharge ($m^3\ s^{-1}$) at Piranhas gauging station during the period of the study. São Francisco River, January of 2008 to May of 2017.

Analysis of temporal and spatial variation in salinity in the estuarine stretch

Distribution of salinity in the periods 2008-2014 and 2013-2017

Aiming to understand the distribution of surface and bottom salinity in the periods of 2008 to 2010 and 2013 to 2017, in all monitored points, along the reference section of the study (from point ESF09, distant 4.8 km from the mouth, at point ESF18, 9.3 km from the mouth), the boxplot diagram presented in Figure 3 was made.

It is possible to notice from Figure 3 that the points ESF15 to ESF18 present less variation in salinity, justified by their distance from the river mouth (7.8 km to 9.3 km respectively). On the other hand, the points ESF09 to ESF14, distant from the river mouth in 4.8 km and 7.3 km, respectively, presented the higher variation in salinity distribution, being highlighted the points ESF09 and ESF10, having their salinity levels varying between 0.03 and 36‰ in the bottom and 0.03 to 12‰ on the surface. These results are compatible with the ones obtained by Cavalcante et al. (2014, 2017) and Melo (2017), that found a large variation in salinity in the São Francisco River Estuary.

However, it is noted that the point ESF18, although it is the farthest one from the river mouth, presented elevated salinity values, closer to 5‰ on the surface and to 16 ‰ in the bottom, which may evidence the occurrence of the advancement of the saline wedge in the river. Although salinity levels in estuaries depend on tidal action (Miranda et al., 2002), circulation patterns, and forcing associated with daily, weekly, and semi-annual tidal fluctuations

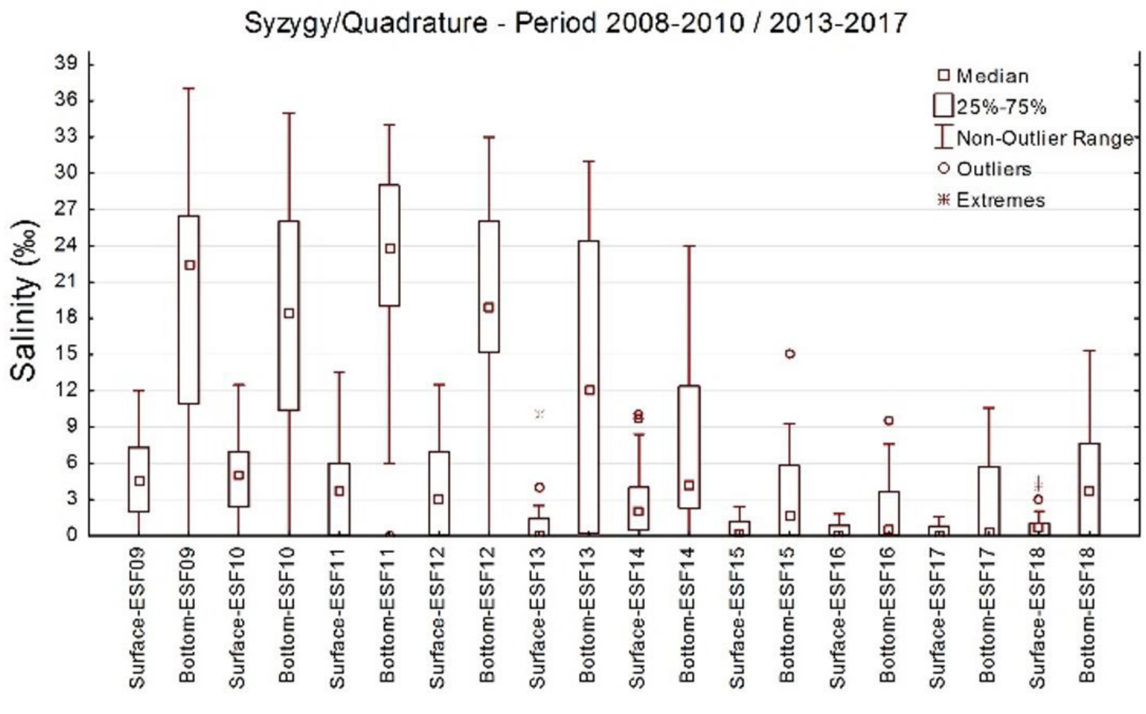

Figure 3. Distribution of salinity (‰) on the surface and in the bottom during the quadrature and syzygy tides along the reference stretch. São Francisco River, 2008-2010 and 2013-2017.

(Fettweis et al., 1998), It can be seen from Figure 3 that there was a wide variation in salinity values at all points, causing the water to vary from fresh (salinity up to 0.5 ‰) to saline (salinity > 30 ‰) at the points closest to the mouth and sweet to brackish (salinity between 0.5 and 30 ‰) at the furthest points.

Distribution of salinity in the quadrature and the syzygy tides in the reference stretch

In order to verify if there were significative differences in the values of salinity in the different kinds of tides, quadrature and syzygy, two boxplot diagrams were plotted for points ESF10, ESF14, and ESF18 – selected as representative spots of the reference stretch –, for the surface and the bottom: one for the period of the high tide of quadrature and other one for the period of high tide of syzygy (Figure 4).

It was observed that the influence of salinity during the quadrature tide is only accentuated in the points located near the river mouth. The elevated values of salinity occurred during the high tide of syzygy (Figure 5b), behavior already verified by Oliveira et al. (2008) and Frota et al. (2013). As expected, during syzygy periods, the strength of the tide is greater, increasing salinity, this being the most critical period for the analysis of the advancement of the saline wedge in the study region. Therefore,

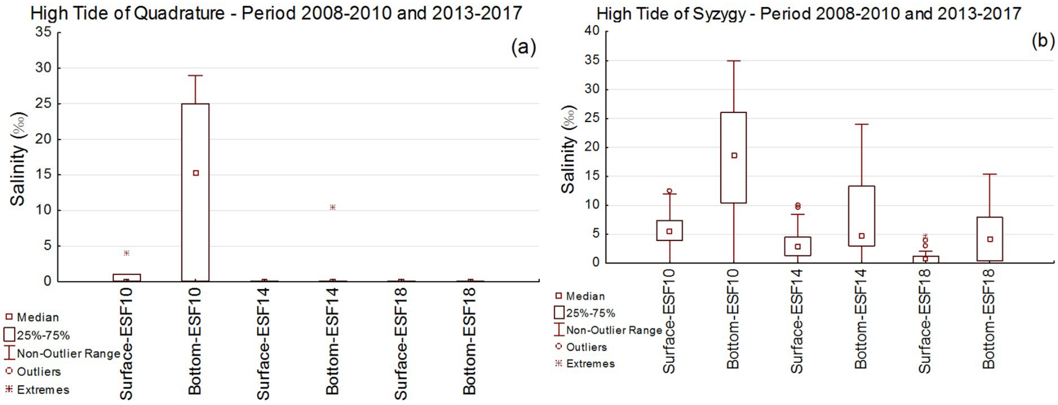

Figure 4. Distribution of salinity on the surface and in the bottom at points ESF10, ESF14 and ESF18, during the high tide of quadrature (a) and of syzygy (b). São Francisco River, 2008-2010 and 2013-2017.

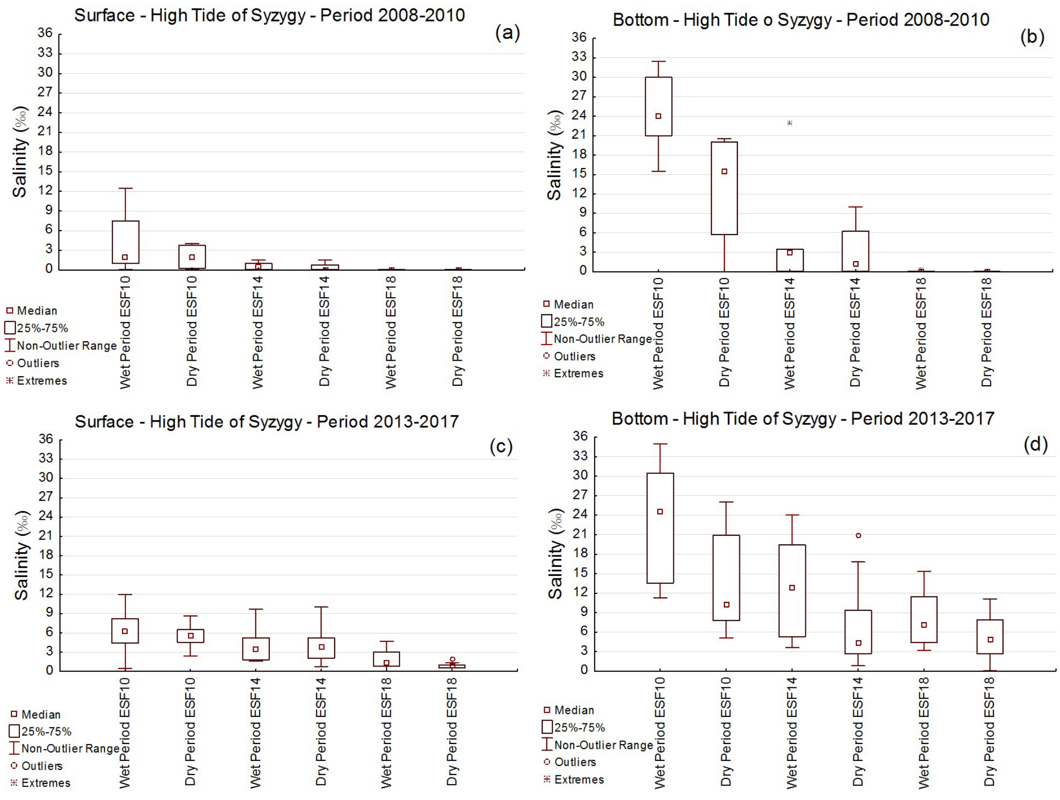

Figure 5. Distribution of salinity in wet and dry periods for the reference stretch (points ESF10, ESF14 and ESF18), during the high tide of syzygy, on the surface and in the bottom before (a, b) and after (c, d) discharge reductions. São Francisco River, 2013-2017.

from 2013, the campaigns developed by CHESF were made only in conditions of syzygy tide; then, the next topics presented by this work refer to analyses of data collected in those conditions.

Influence of seasonality in the behaviour of salinity in the reference stretch

In the region of the lower São Francisco, the rainy period corresponds to the months from December to April; and the dry period to the months from May to November (Companhia Hidrelétrica do São Francisco, 1992). For a better understanding of the distribution of salinity in the periods of 2008 to 2010 and 2013 to 2017, that encompass the years with and without the reductions of outflow discharges, four boxplot diagrams were made, one for the surface and one for the bottom, considering wet and dry periods, before (Figures 5a and 5b) and after (Figures 5c and 5d) the reductions of discharges.

It is important to point out that the variation in salinity observed in points ESF10 and ESF14 occurred naturally in the period from 2008 to 2010, in the function of the natural characteristics that classify the estuary: lower estuary, also named, marine estuary, it has a free connection with the open sea; the *medium estuary*, where occurs intense mixture of freshwater with salty water; and, the *upper estuary*, named riverine estuary, an area subjected to the action of tides, but there is not saline water in it (Dionne 1963 in Fairbridge 1980 as cited in Perillo, 1995, p. 25). This classification can be related with the one of Miranda et al. (2002) that subdivides the estuary into salinity zones, and then relate with the observations obtained in the lower São Francisco River: when salinity is above 35 ‰, it means that the strength of the tide is outstanding. This region is located at the mouth of the estuary and extends until the limit of the estuarine plume named *Oceanic Tide Zone* or *Coastal Zone,* which is equivalent to the *lower estuary*. It is possible to observe that the point ESF9, distant 4.3 km from the river mouth (Figure 3), presents those characteristics.

The point ESF10, distant from the river mouth in 5.3 km, presents salinity varying up to 35 ‰, where the mixtures of water masses and the equivalence of river and tidal forcings happen, corresponding to the *Mixture Zone* (Miranda et al., 2002) and is equal to the *medium estuary*. It is observed that the point ESF14, 7.3 km far from the river mouth, also belongs to this zone, but it has suffered an accentuated increase in salinity, on the surface and in the bottom with the reductions of discharges (Figure 5).

On the other hand, the point ESF18, located 7.3 km from the river mouth, presented salinity values with characteristics of freshwater (up to 0.5 ‰) before the reduction of discharges (Figure 5a, b), characteristic of River Tide Zone (riverine estuary), where salinity varies to 1 ‰. In this zone happens the influence of tides, however with the dominance of the river forcing (Miranda et al., 2002). After discharge reductions (Figure 5c, d), this point in the estuary lost its characteristics of the *riverine estuary* and has begun to present characteristics of the *Mixture Zone* with salinity reaching 5 ‰ on the surface and 15 ‰ in the bottom.

Another observation that can be made from the evaluation of data is related to the vertical variation patterns of salinity in the water column. It is observed that the São Francisco River estuary is *stratified, that is, a shaped saline wedge*. In this type of estuary, the river force prevails over the tide one, thus, on the surface, the salinity values are lower when compared to the bottom, and in the profile of the vertical water column occurs high saline variation (Pritchard, 1955; Dyer, 1997). Thus, it is assumed that although the tidal force has increased with the reductions in flow rates from 2013 to 2017, changing the salinity values in the estuary, the river forcing still prevails, preventing the estuary from becoming homogeneous. In other words, when tidal strength is predominant over river strength, the bottom and surface salinity values are similar, with no significant vertical variation along the water column, although there may be variation in the direction longitudinal (Pritchard, 1955; Dyer, 1997).

Regarding the influence of seasonality, in the nearest point (ESF10) to the river mouth and the farthest one (ESF18), the values of salinity are more elevated during wet periods, wherein that last point this observation can only be developed in periods of discharge reductions (Figure 5c,d). In the intermediary point (ESF24), 7.3 km distant from the river mouth, salinity, before the reductions of discharge, presented more elevated values during the dry period than in the wet period. However, after discharge reductions, it began to be more elevated during the wet period.

There is not only one cause for the increase in salinity in the river. For instance, in the wet period, it is likely expected an increase in salinity due to the carrying of dissolved solids to the river channel, in the function of the increase in rainfall and land management in the watershed. On the other hand, it could be expected that in the dry season there would be a concentration of salts in the river due to the higher probability of water evaporation due to higher temperatures. With the reductions of outflow discharges, it would be expected that there would be an imbalance between the river and ocean forces, with greater salt input in the estuary, and there may be considerable advance of the saline wedge in stretches that previously did not have saline history above certain limits, which would increase salinity in both periods (Knoppers et al., 2005; Oliveira et al., 2008), of currents, Souza (2015).

Analysis of the relation between the reductions of outflow discharges and water salinity in the reference stretch

For the purpose of visualizing graphically the existing relations between daily outflow discharges and salinity values on the surface and in the bottom of the reference stretch (points ESF10, ESF14 and ESF18), scatter graphs were plotted for the periods of 2008 to 2010 and 2013 to 2017 (Figure 6). Additionally, it was developed the Spearman's correlation analysis to identify significative relations between those parameters.

The scatter graphs presented in Figure 6 show that the values of salinity on the surface on point ESF10 (5.3 km from the river mouth), present negative relation along with the outflow discharges, even though the Spearman's correlation has not been significant (n= 45; r_s = -0.2757; $p > 0.05$). However, in the bottom, salinity values were significantly correlated to discharge values (n = 45, r_s = 0.4187; $p < 0.05$), indicating that in this depth the values of salinity are may be affected positively by discharges. Thus, even at

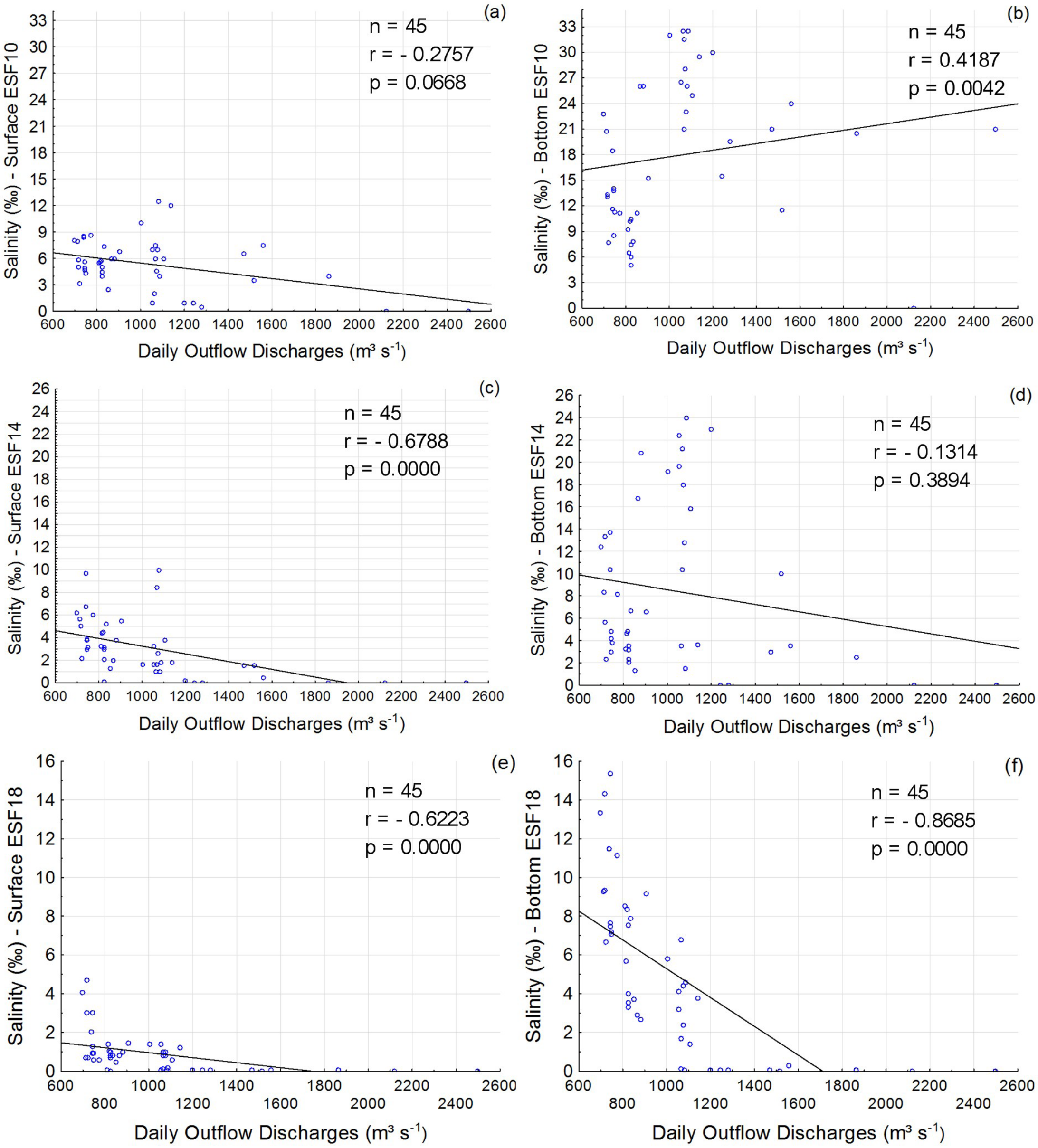

Figure 6. Linear relations between daily outflow discharges (m^3 s-1) and salinity (‰) on the surface and at the bottom, respectively, at the reference stretch: point ESF10 at 5.3 km from the river mouth (a, b); point ESF14, 7.3 km from the river mouth (c, d); point ESF18, 9.3 km from the river mouth (e, f). São Francisco River, 2008-2010 and 2013-2017.

points near the mouth, the outflow discharges may be influencing the salinity values at the bottom although they may also be under the influence of saline wedge formation. Since seawater is denser, the bottom of the river is subjected for a longer time to higher salinity values especially in sections closer to the mouth, it is natural that there is greater permanence of salts at the bottom.

Figure 6c-f, referent to the points farther the river mouth (ESF14 and ESF18, respectively, 7.3 and 9.3 km distant from the river mouth), show that there is an inverse linear tendency between discharge and salinity, both on the surface and in the bottom, indicating that the reductions of discharges have a strong influence on the increase of salinity levels in those sections. In point ESF10, intermediary in the reference area, the negative correlation between discharge and salinity was significant only on the surface ($n = 45$, $r_s = -0.6788$; $p < 0.05$); then, in the point farther from the river mouth (ESF18) the negative correlation exhibited to be more significant, both on the surface ($n = 45$, $r_s = -0.6223$; $p < 0.05$) and in the bottom ($n = 45$, $r_s = -0.8685$; $p < 0.05$), respectively, evidencing, as expected, a stronger influence of the reductions of outflow discharges in this section located more distant from the river mouth.

Analysis of the advancement of the saline wedge in the reference stretch

The behavior of salinity on the surface, in the three sections that are part of the reference stretch, corresponding to the point previously studied, ESF10, ESF14, and ESF18 (Table 2), is represented in Figure 7.

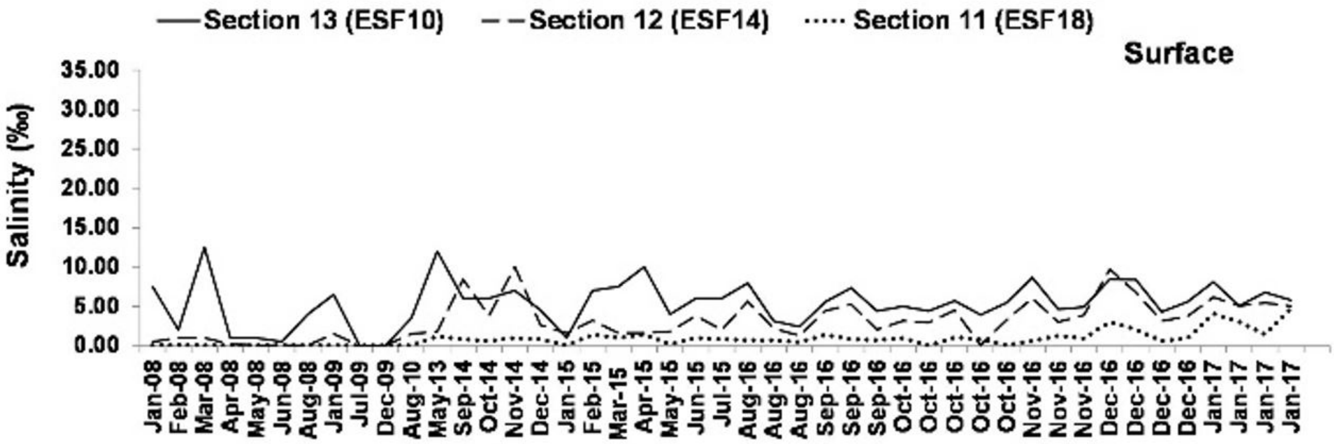

Figure 7. Distribution of salinity on the surface during the high tide of syzygy, respectively, on sections 13 (point ESF10), 12 (point ESF14) and 11 (point ESF18) during the periods São Francisco River, 2008-2010 and 2013-2017.

The salinity values for section 13 (ESF10), distant from the river mouth in 5.3 km, present oscillation in the period of January of 2008 to May of 2013. This result is corroborated by Barbosa (2011), who studied the salinity in a spot closer to this one, 5.1 km far from the river mouth, and found salinity below 0.1 ‰ in March, July and October of 2008, April and July of 2009; in January of 2009, he found values equal to 5‰ on the surface and 10‰ in the bottom. In the case of this study, it is observed in Figure 7 that at the beginning of discharge reductions, there was a tendency in salinity to oscillate between 5 to 10‰.

In section 12 (ESF14), 7.3 km distant from the river mouth, the salinity values in the period from 2008 to 2010 (before discharge reductions) prevailed below 1 ‰; however, in the period of 2013 to 2017 (after discharge reductions), the values were higher than 5 ‰ (Figure 7). In section 11 (ESF18), farther from the river mouth (9.3 km), the values were low and less than 0.05 ‰ for the period without the reductions in discharge (2008 to 2013), results that are compatible to Barbosa (2011), that also studied salinity from 8.1 km far the river mouth and found results below 0,1 ‰, both on the surface and in the bottom, in the years of 2008 and 2009.

However, with the flow reductions, it is possible to notice an increase in salinity values in the years 2016 and 2017, in the same sections previously analyzed. It is observed that, in section 11, as discharges were reduced (2013 to 2017) the behavior of salinity was gradually becoming similar to the one from the other sections located nearer the river mouth, mostly from August of 2016, with the intensification of discharge reduction.

It is also possible to verify that the section 12, which is 7.3 km far from the river mouth, after the beginning of reductions in discharge, in Xingo, in 2013, started to present a similar salinity behavior as section 13. This indicates that after the discharge reductions, there was a significant increase in salinity in sections 12 and 11, reaching the surface of the estuary, highlighting the saline wedge advance in the reference stretch in approximately 4 km from section 13.

Additionally, section 11, situated farther the river mouth, 5.5 km downstream of the city of Brejo Grande-SE and 2.3 km from the city of Piaçabuçu-AL, consists in a strategic section for the evaluation of the advancement of the saline wedge in the sections located farther from the river mouth. Thus, Figure 8 presents the evolution in salinity in section 11, where the data of salinity for the sampling point ESF18 were collected, inserted in the reference stretch, and they were related to the outflow discharges in Xingó.

It is observed in Figure 8 that in the period from 2008 to 2010 the values of salinity in section 11, both on the surface and in the bottom were below 0.1‰, within the limit for freshwater, results that corroborate Barbosa (2011). After the beginning of reductions of outflow discharges in Xingó (the year 2013), salinity values in the bottom of section 11 were about 8 to 64 times higher than the period without discharge reduction (2008 to 2010). Within the period when there was discharge reduction (2013 to 2017), salinity in the bottom varied from 1.4 ‰, for the discharge of 1105 $m^3 s^{-1}$ in October of 2014, to 15.4 ‰ for the discharge of 741 $m^3 s^{-1}$ in December of 2016.

On the surface, salinity started to present values above 0.5 ‰ from 2014 with the minimum restriction discharge of 1100 $m^3 s^{-1}$, reaching 4.7 ‰, with outflow discharge of 717 $m^3 s^{-1}$. In the period without reductions of discharge, salinity used to remain, approximately, 0.03‰. It was still noted that despite practically stable discharges (about 700 $m^3 s^{-1}$), in the year of 2016, even so salinity tended to increase, probably causing, besides the advancement of the saline wedge, salt accumulation in this section, intensifying, even more, the impacts provoked by flow alteration in the immediate vicinity of this location.

Analysis of the advancement of the saline wedge in the estuarine stretch

For the purpose of evaluating the reductions of outflow discharges, negative effects were presented in the points more distant from the river mouth, secondary data regarding salinity were analyzed that were available for the sections upstream, followed by the location of Brejo Grande-SE (right bank) and Piaçabuçu-AL (left bank), besides acquiring primary data in two sampling points in Brejo Grande-SE.

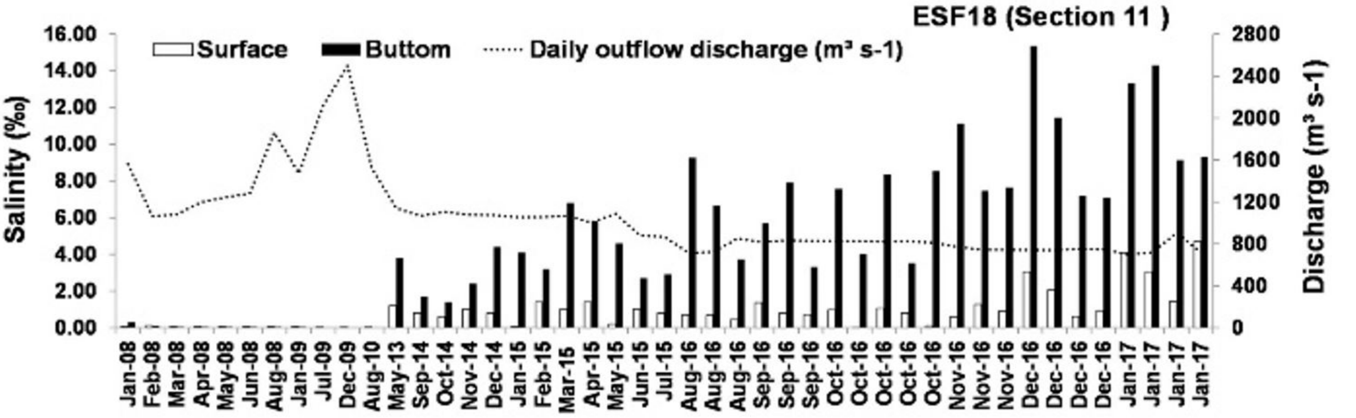

Figure 8. Relation between salinity on the surface and at the bottom and outflow discharges at point ESF18, located in Piranhas, 9.3 km far from the river mouth and component of section 11 (between Brejo Grande-SE and Piaçabuçu-AL).

Figure 9 presents the acquirement of secondary data for the sampling point ESF 21, from which the measurements made by CHESF were initiated in 2014, aiming to monitor salinity during the period of discharge reduction. This point is located on the left bank of section 10, at the beginning of the town of Piaçabuçu, downstream of Brejo Grande-SE.

It is observed from Figure 9 that with the maintenance of the minimum restriction discharge between 1100 $m^3 s^{-1}$, that was in force in September of 2014 to March of 2015, and 1000 $m^3 s^{-1}$, in force from March to June of 2015, the salinity in the bottom varied from 0.5 to 4 ‰. Nonetheless, with the continuity of discharge reductions with discharges between 900 to 700 $m^3 s^{-1}$ between July of 2015 to January of 2017, the salinity in the bottom started to vary for values closer to 3 to 25 ‰.

On the surface, where salinity, with discharges around 1000 $m^3 s^{-1}$, reached to 0.2 ‰, started to reach values above the threshold for freshwater, achieving 2.3 ‰ in January of 2017, with the outflow discharge in about 700 $m^3 s^{-1}$. Despite the fact of not having measurements for this section before outflow discharge reductions (period from 2008 to 2010), it is possible to infer that if section 11, which is 9.3 km from the river mouth, the water presented salinity both on the surface and in the bottom in about 0.05 ‰, section 10, that is distant from the river mouth in 10.5 km, should have also presented low salinity values for the same period. Thus, it can be concluded that the saline wedge may have advanced from section 11, more 1.6 km to section 10, through the left bank, after discharge reductions.

In the right bank, primary data of the salinity profile were obtained in the sampling point PA6, 10.6 km from the river mouth. The salinity profile presented elevated values, above the threshold for freshwater on the surface, in the middle and in the bottom, where the values reached 1.7 ‰ and on the surface 0.7 ‰ during the high tide. In the low tide, salinity values were maintained around 0.1 ‰. These results indicate that the saline wedge advanced approximately 1.4 km by the right bank from section 11 to 10.

Section 9, 11 km from the river mouth, presents as the nearer sampling point the ESF22, located in the left bank in

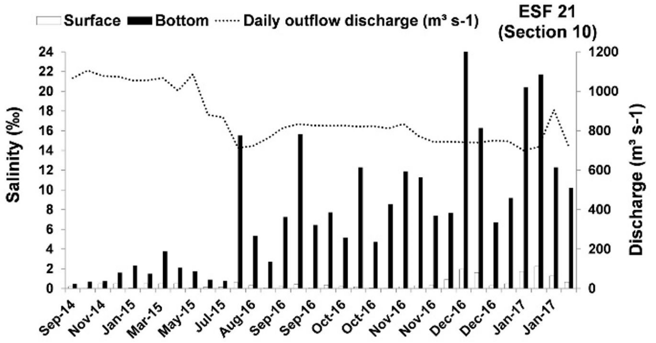

Figure 9. Relation between salinity on the surface and at the bottom and outflow discharges at point ESF21 in Piaçabuçu-AL, left bank of section 10, 10.6 km far from the river mouth. Rio São Francisco, 2014 to 2017.

Piaçabuçu-AL, and the sampling point ESF24 in the right bank in Brejo Grande-SE. Figure 10 presents the values for salinity obtained by CHESF in the period from September of 2014 to January of 2017 in the point ESF22.

Figure 10 exhibits the highest values reached, both in the bottom and on the surface, occurring in December of 2016 to January of 2017, with an outflow discharge in about 700 to 800 $m^3 s^{-1}$. The oscillation that was observed in salinity is probably justified by the measurement procedure: the data from sampling point ESF22 were obtained via mobile monitoring; thus, not always, the measurements were taken at the best time during the high tide. Even so, it is possible to verify that there was a considerable increase in salinity, intensifying the saline wedge in relation to the reference section 11, around 2.7 km by the left bank.

Salinity values of the sampling point ESF24 are shown in Figure 11.

Similarly, the analyses developed for the other sections, it is noted that, before discharge reductions, salinity values above 0.5 ‰ were not found, meaning that the water was always freshwater. During salinity monitoring in the discharge reduction period, however, in the year of 2015, with outflow discharges around

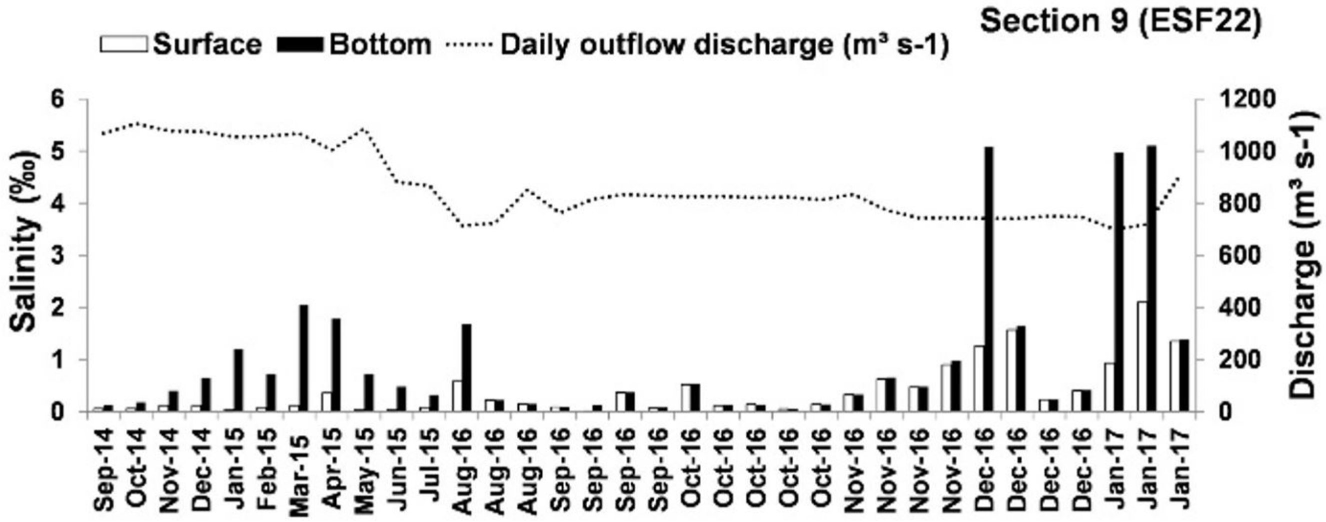

Figure 10. Relation between salinity on the surface and at the bottom and outflow discharges at point ESF21 in Piaçabuçu-AL, left bank of section 9.11 km far from the river mouth. Rio São Francisco, 2014 to 2017.

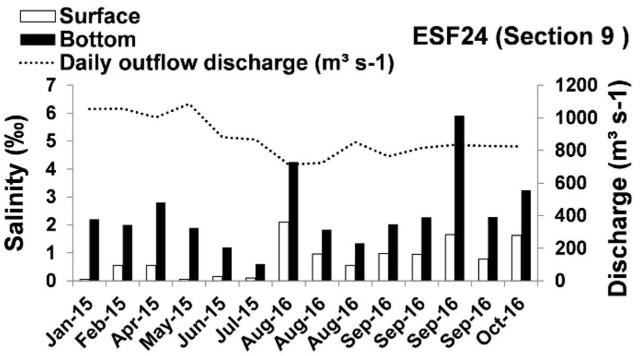

Figure 11. Relation between salinity on the surface and at the bottom and outflow discharges at point ESF24 in Brejo Grande-SE, 11 km far from the river mouth, left bank of section 9. Rio São Francisco, 2014 to 2017.

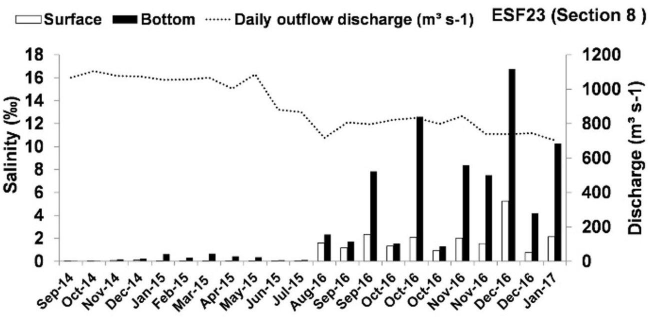

Figure 12. Relation between salinity on the surface and at the bottom and outflow discharges at point ESF23 in Brejo Grande-SE, Piaçabuçu-AL, 12.4 km far from the river mouth, left bank of section 8. Rio São Francisco, 2014 to 2017.

1000 $m^3 s^{-1}$, values higher than 0.5 ‰ were verified in the bottom, although the values on the surface had remained inside the limit for freshwater. On the other hand, in 2016, with discharge reduction to 800 $m^3 s^{-1}$, high salinity values were found on the surface and in the bottom, reaching 6 ‰ in the bottom and above 2 ‰ on the surface. In relation to the reference section 11, there was an advance of the saline wedge by the right bank around 2.1 km.

Concerning section 8, 11.8 km from the river mouth, via the left bank in front of the water catchment location for human supply in Piaçabuçu-AL and transversely following to the right bank in Brejo Grande-SE, only the salinity data from the left bank were analyzed. Salinity values in section 8 were obtained in the sampling point ESF23, the nearest one from the water catchment. Figure 12 exhibits the most critical results of the fixed monitoring during the high tide of syzygy in the point ESF23.

Figure 12 exhibits salinity results for the year of 2014, agreeing with Barbosa (2011), that presented values below 0.05 ‰, both on the surface and in the bottom for the same study period. It is noted that with the outflow discharge around 1000 to 1100 $m^3 s^{-1}$, salinity values are kept below 0.5 ‰ in most of the time, for the two positions, with the possibility to reach 1 ‰ at the bottom; however, from November of 2016, having the outflow discharge in about 700 to 800 $m^3 s^{-1}$, salinity peaks were observed achieving approximately 18 ‰ in the bottom and above 0.5 ‰ on the surface (Figure 12).

The sections 7, 6 and 5 passes by near Brejo Grande-SE downtown area and arrive in Piaçabuçu-AL on the left bank. In section 7, 14.4 km far from the river mouth, secondary data were evaluated in the sampling point ESF27, right bank. The values of water salinity were kept within the limit of freshwater. In section 6, that is located 15.2 km distant from the river mouth, primary data were acquired only in the sampling point PA5, in the right bank. The values in the salinity profile remained below 0.5‰, both in the low tide and in the high tide, indicating characteristics of freshwater.

In section 5, far from the river mouth in 15.5 Km, the analysis for the left bank was developed with data available in the sampling point ESF30. Salinity values remained around 0.05 ‰,

Table 3. Results of the longitudinal monitoring of salinity (‰) during low and high tides of syzygy in sections PA4, PA3, PA2 and P1, far from the river mouth, respectively, 21.6 km, 54.6 km, 102.3 km and 160.2 km.

Section	Sampling point	Location (middle of the channel)	Date of measurement	High tide			Low tide		
				Surface	Middle	Bottom	Surface	Middle	Bottom
4	PA4	Ilha das Flores-SE -Penedo-AL	28/04/2017	0.030	0.032	0.037	0.030	0.030	0.031
3	PA3	Pindoba-SE - Xinaré-AL	27/04/2017	0.029	0.033	0.032	0.032	0.031	0.031
2	PA2	Gararu-SE- Traipu-AL	26/04/2017	0.035	0.031	0.032	0.030	0.030	0.030
1	PA1	Niterói-SE-Pão de Açúcar-AL	25/04/2017	0.029	0.033	0.033	0.030	0.030	0.030

which evidences that the tide does not have strength, up to the moment, to reach the left bank of the section. The point ESF32, near the water catchment, was used to study the right bank of the section. The values for salinity in this point are also below the threshold of freshwater, even though the stretch suffers the influence of the tide. This behavior was verified for both periods, dry and wet.

Analysis of the spatial variation in salinity in the river stretch

Upstream of the river, the sections with the respective sampling points located in the middle of the river channel are from PA4 to PA1 (Table 1).

The results obtained in this campaign did not indicate high salinity values in any of the analyzed sections, which remained below 0.05 ‰, about ten times lower than the salinity limit (0.5 ‰) established for freshwater.

The results indicate that in the river stretch there was not tidal influence during the period in which the samples were collected, in April of 2017 (Table 3); however, it would be necessary to do fixed monitoring on section 4; that is, measurements of 13 hours on the surface, in the middle and in the bottom on syzygy tides, in order to validate these results. The results from secondary data obtained in the upper estuary indicate that the saline wedge still has not reached section 5, implying that section 4 and subsequent sections probably do not suffer from saline wedge advancement.

CONCLUSIONS

After reductions of outflow discharges, in 2013, the points located farther from the river mouth, in the reference stretch, ES14 and ESF18, 7.3 and 9.3 km distant, respectively, started to present the same behaviour as point ESF10, located closer to the river mouth, exhibiting both on the surface and in the bottom of the river a strong influence of the reduction of those discharges, evidencing the advancement of the saline wedge in around 4 km.

At the nearest point from the river mouth (ESF10), the values of salinity, in general, were higher during wet periods, which can be explained due to the proximity of the point to the banks, influenced by rainfall, that carries sediment and total dissolved solids to the river channel. Another possibility is that the management and use of the land are influencing those values, besides the potential to accumulate salts in the medium estuary.

The correlations found between outflow discharges and salinity in the estuary show that reductions of outflow discharges exert a strong influence on the increase in salinity in the stretch situated between sections 12 and 11, respectively, 7.3 and 9.3 km distant from the river mouth. With the continuing reductions of discharges, points that are farther from the river mouth began to present high salinity levels, both in the bottom and on the surface, demonstrating that the reductions of outflow discharges, that started from the year 2013, contributed to the increase in salinity on section 11, which is 9.3 km far from the river mouth.

In the immediate vicinity of the town of Piaçabuçu-AL, it can be inferred by the previous results the reductions of discharges, among which there were not values of salinity higher than 0.5 ‰, as it was always freshwater. After the reductions of discharges, that began in 2013, although salinity values oscillated between characteristics from freshwater to brackish water, elevated values of salinity occurred not only in the bottom, reaching 18 ‰, but also on the surface, reaching 13 ‰. On the dry period, the values stood above 0.5 ‰ as well, mainly on the high tide of syzygy, being more elevated during the wet period in the years of 2016 and 2017. During low tide hours, the characteristics of the river in the vicinity of Piaçabuçu (11.8 km far from the river mouth) are those of freshwater.

It is evidenced that the water drought situation that led to changes in the operational rules of the dam has as consequence the advancement of the saline wedge with strong impact on water quality in terms of salinity, modifying the characteristics of the estuary, causing part of the stretch to acquire characteristics of Upper Estuary, that is, River Tidal Zone (from 9.3 to 11.8 km) to Medium Estuary (Mixture Zone).

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Authors contributions

Sândira Lívia Moraes Fonseca: Analysis of salinity variation in the lower stretch of the São Francisco River, literature review, determination of study methodology, elaboration of graphs, and analysis and discussion of results.

Aline Almeida de Jesus Magalhães: Statistical analysis of data, support in methodology, elaboration in graphs, and analysis and discussion of results.

Vânia Palmeira Campos: Support for water quality analysis, support in determining the methodology, analysis and discussion of results, and research advisor.

Yvonilde Dantas Pinto Medeiros: Analysis and discussion of results, support coordination, and research advisor.