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DISSERTAÇÃO DE MESTRADO

Cibele Rodrigues Costa

Indicadores da qualidade da água em um estuário tropical: o valor do monitoramento contínuo e seus desdobramentos para a ciência, sociedade e meio ambiente

Recife
2017

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Dissertação apresentada ao Programa de Pós-Graduação em Oceanografia do Departamento de Oceanografia da Universidade Federal de Pernambuco, como requisito para obtenção do grau de Mestre em Oceanografia.

Orientadora: Profª. Drª. Monica Ferreira da Costa
Coorientador: Prof. Dr. Mário Barletta

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Aprovada em 06 de fevereiro de 2017.

BANCA EXAMINADORA

____

Profª. Drª. Monica Ferreira da Costa
(Orientadora/Presidente/Titular Interna PPGO)

____

Prof. Dr. David Valença Dantas
(UDESC Laguna-SC/Titular externo)

____

Profª. Drª. Suzana M.G.L. Montenegro
(UFPE/DECIVIL/Titular externa)

“Resiliência é a capacidade de entender que
o caminho do sucesso é cheio de obstáculos
e não surtar por conta disso.”

Jhon Rocha

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Resumo

Há estuários na costa leste do Brasil que apresentam volume reduzido quando comparados aos grandes rios nacionais. Suportam juntamente com suas bacias uma grande pressão antrópica advinda de atividades agrícolas, agroindustriais, industriais e urbanas. No entanto, permanecem parte do principal recurso hídrico superficial disponível para o suprimento de recursos e serviços à população. O estuário do Rio Goiana é um desses casos típicos. Pode servir de modelo a muitos outros estuários do mundo tropical cujas bacias se formam e cortam áreas relativamente pequenas (~ 3000 km^2) em outras regiões do mundo com limitações hídricas sazonais (duas estações bem marcadas, uma seca e outra chuvosa) e forte interferência da sua captação devido ao desmatamento e supressão de água para abastecimento. Nesse contexto, informações sobre as variações da qualidade da água são importantes para se planejar estratégias de conservação dos recursos hídricos e dos habitats que deles dependem. Apesar da existência de programas oficiais de monitoramento da qualidade da água, há de se considerar novas estratégias amostrais que caracterizem tanto a bacia quanto o estuário em diversas escalas espaciais e temporais. Desta forma, foram abordados neste trabalho dados de diferentes origens para se fazer uma composição de seus valores como ferramentas cientificas e de gestão. Os dados indicam que no estuário do Rio Goiana, a qualidade da água é fortemente controlada pela precipitação, que na estação chuvosa (março-agosto) promove uma renovação do volume contido no sistema e consequentemente sua oxigenação. Na estação seca (setembro-fevereiro), estabelece-se um forte gradiente ambiental (ecoclina) ao longo do canal principal do rio e do estuário, estabelecendo diferentes habitats aquáticos que serão utilizados por espécies animais e pelo homem de formas diferenciadas. A descrição desse gradiente se dá pelos valores de salinidade. Os teores de oxigênio dissolvido também se distribuem espacialmente de maneira a reforçar essa ecoclina, sendo menores no interior do estuário e maiores em direção ao mar. A ocorrência de eventos de queda brusca de oxigênio (hipóxia episódica), concentrados nas estações secas, é sinal de queda da qualidade ambiental. A carga de material particulado em suspensão, expressada aqui através das medidas feitas como disco de Secchi, também varia de acordo com a precipitação, aumentando na estação chuvosa, quando todo o sistema se torna bastante turvo (limitando-se a 12,0 cm em algumas amostragens) devido ao aporte da bacia. A temperatura da água varia pouco ao longo do ano em todo o sistema (25,3 a 31,4ºC). O entendimento do funcionamento do sistema estuarino foi possível devido a um desenho amostral focado em descrever as variações da qualidade da água nos diferentes habitas do ecossistema, e não apenas no monitoramento de fontes poluidoras. Associado a ele, um esforço amostral bastante intenso possibilitou o conhecimento de variações de menor escala espacial e temporal do que programas de monitoramento oficiais. No entanto, diferentes estratégias amostrais não são de todo incompatíveis, e apesar de seguirem diretrizes muito diferentes, foi possível fazer-se com que se acoplassem e somassem seus potenciais para estender a malha amostral e descrever uma região estuarina maior do que a inicialmente prevista em cada um deles isoladamente. Nesse sentido, conclui-se que os objetivos deste trabalho foram atingidos, e recomenda-se a continuidade das tentativas de fusão de informações de redes amostrais independentes, assim como atenção aos sinais de desgaste ambiental.

Palavras-chaves: Conservação aquática. Impactos antrópicos. Recursos hídricos

Abstract

There are estuaries on the east coast of Brazil that present reduced volume when compared to the great national rivers. Together with their basins, they support great anthropogenic pressure from agricultural, agroindustrial, industrial and urban activities. However, they remain part of the main surface water resource available for the supply of resources and services to the population.The estuary of the Goiana River is these typical cases. It can serve as a model for many other estuaries in the tropical world whose basins form and cut relatively small areas (~ 3000 km2) in other regions of world with seasonal water limitations (two well-marked seasons, one dry and one rainy season) and strong interference from its capture due to deforestation and water suppression for water supply.In this context, information on changes in water quality is important in planning strategies for conservation of water resources and habitats that depend on them. Despite the existence of official water quality monitoring programs, new sampling strategies that characterize both the basin and the estuary at various spatial and temporal scales should be considered. In this way, data from different origins were approached in order to make a composition of their values as scientific and management tools. The data indicates that in the Goiana estuary the water quality is strongly controlled by precipitation, which in the rainy season (March-August) promotes a renewal of the volume contained in the system and consequently its oxygenation. The description of this gradient is given by the values of salinity. The dissolved oxygen contents are also spatially distributed in order to reinforce this ecoclimate, being smaller in the estuary and larger in the direction of the sea. The occurrence of sudden drops of oxygen (episodic hypoxia), concentrated in the dry seasons, is a sign of a decline in environmental quality.The load of suspended particulate matter, expressed here by the measurements made as a Secchi disk, also varies according to the precipitation, increasing in the rainy season, when the whole system becomes very turbid (being limited to 12.0 cm in some sampling) due to the contribution of the basin. The water temperature varies little throughout the year throughout the system (25.3 to 31.4 °C).Understanding the operation of the estuarine system was possible due to a sampling design focused on describing the variations of water quality in the different habitats of the ecosystem, and not only in the monitoring of polluting sources. Associated with it, a very intense sampling effort allowed the knowledge of variations of smaller spatial and temporal scale than official monitoring programs. However, different sample strategies are not at all incompatible, and although they follow very different guidelines, it was possible to have them couple and add their potentials to extend the sample mesh and to describe a larger estuarine region than initially foreseen in Each in isolation. In this sense, it is concluded that the objectives of this work have been achieved, and it is recommended the continuation of the attempts to merge information from independent sample networks, as well as attention to signs of environmental degradation.

Keywords: Aquatic conservation. Anthropogenic impacts. Water resources

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Sumário

1 APRESENTAÇÃO

Este documento de dissertação além de possuir introdução e conclusão gerais, está dividido em 4 capítulos, os quais:

O capitulo 1, intitulado "Interannual water quality changes at the head of a tropical estuary", trata sobre a qualidade das águas na cabeça do estuário do Rio Goiana, baseado em dados obtidos a partir de um banco de dados público, pertencente a CPRH – Agência Estadual de Meio Ambiente de Pernambuco, durante o período de 4 anos (2006 a 2009);

O capitulo 2, intitulado "Seasonality-driven changes in water quality in a tropical estuary", trata sobre a qualidade das águas no canal estuarino do Rio Goiana, levando em consideração amostragens realizadas durante o período completo de um ano (2006), desde sua porção superior até a sua porção inferior;

O capítulo 3, intitulado "Interannual and seasonal variations in water quality of a tropical estuary", que trata também sobre a qualidade das águas a partir do monitoramento realizado durante um período de 4 anos (2006 a 2009), em toda a extensão do estuário;

Por fim, o capítulo 4, "Análise integrada da qualidade da água na bacia e no complexo estuarino do Rio Goiana" que realizou o acoplamento dos dados obtidos, dos parâmetros coincidentes as duas formas de coleta, no período de 2006 a 2009.

Os capítulos foram escritos em forma de artigos científicos, em processo de preparação para submissão em diferentes periódicos.

2 INTRODUÇÃO GERAL

Estuários são corpos d'água semiconfinados, onde ocorre a mistura de água doce, proveniente do continente, com água salgada do oceano (Eyre, 1997; Kennish, 1991; Schaeffer-Novelli et al., 1990). São ambientes transicionais costeiros que ocorrem em todo o mundo, cujo papel ecológico em áreas tropicais e subtropicais gera grande interesse. Entre suas particularidades, apresentam uma combinação única de características ambientais e alta produtividade biológica, ligada ao grande aporte de nutrientes inorgânicos e matéria orgânica provenientes da bacia de drenagem (Eyre, 1997; Harrison and Whitfield, 2006; Telesh and Khlebovich, 2010). Ao considerar qualquer estuário do mundo, podem ser aplicadas algumas generalizações, entre as quais a existência de um gradiente de condições ambientais é a principal característica comum (Kennish, 1991; Telesh and Khlebovich, 2010). A salinidade da água é um dos principais fatores que definem a direção, intensidade e duração desse gradiente, e logo as propriedades estruturais e funcionais deste ambiente, principalmente ligado à distribuição dos organismos (Attrill and Rundle, 2002; Barletta and Dantas, 2016) e consequentemente muito dos seus usos pelo homem. Os estuários são ecossistemas muito dinâmicos e de grande relevância ecológica, devido às flutuações das características da água em diferentes períodos do ano, resultante das constantes variações quali-quantitativas que correm nas águas doces e salgadas (Kennish, 1991; Schaeffer-Novelli et al., 1990). Além da significativa importância ecológica, através do oferecimento de oportunidades de abrigo, alimentação, e espaço para o desenvolvimento de espécies biológicas, estuários são de grande valor para a população humana face aos recursos naturais que guardam e serviços ecossistêmicos que prestam (abastecimento de água, diluição de efluentes, rcursos, pesqueiros etc). Recursos hídricos e pesqueiros são consideráveis, destacando-se as comunidades ribeirinhas instaladas as margens do estuário, trazendo grandes benefícios socioeconômicos locais (Barletta and Costa, 2009; Barletta and Dantas, 2016; WHO, 2014, 1996). Os estuários são importantes reservatórios biogeoquímicos temporários de material dissolvido e particulado, bem como para substâncias a eles associadas, tornando-os suscetíveis a impactos oriundos de toda a bacia de drenagem, como poluentes orgânicos e inorgânicos, além dos impactos provenientes de áreas marinhas, que podem adentrar o sistema com a maré (Mérigot et al., 2016; Statham, 2012; Zhao et al., 2015). Diversas atividades humanas têm gerado grandes perturbações em sistemas estuarinos, principalmente alterando a qualidade das suas águas. Desmatamento da bacia e das margens do estuário, erosão, subtração de água para o abastecimento público, agricultura, aquicultura, lançamento de efluentes domésticos, agrícolas e industriais, recepção de resíduos sólidos, pesca predatória e dragagem são exemplos destas atividades (Barletta et al., 2016; Gurgel et al., 2016; Hatje and Barros, 2012; Li et al., 2015; Lucena-Moya and Duggan, 2017; Mérigot et al., 2016; Statham, 2012). A qualidade da água é dependente de suas características físicas, químicas e biológicas, assegurando as condições para determinado uso ou conjunto de usos, incluindo-se dentre eles a conservação da natureza (CONAMA, 2005; WHO, 2014, 1996). A alteração desses padrões modifica significativamente o ambiente aquático, dando origem a uma nova dinâmica, que pode ocasionar perda de biodiversidade aquática, alterações no ambiente físico-químico, interferência e mau funcionamento ou interrupção de serviços ecossistêmicos (Kennish, 1991; Schaeffer-Novelli et al., 1990). A água pode ser classificada de acordo com a sua potabilidade, a segurança que apresenta para o ser humano e para o bem estar dos ecossistemas (CONAMA, 2005; WHO, 2014). O monitoramento da qualidade da água permite avaliar o ambiente aquático como um todo, sendo seus resultados essenciais para subsidiar várias atividades de gestão hídrica, incluindo a conservação aquática (Karydis and Kitsiou, 2013; Kennish, 1998; Kitsiou and Karydis, 2011). Monitoramentos de parâmetros físico-químicos das águas naturais também constituem uma ferramenta que permite estudar as áreas estuarinas para esclarecer sobre o seu funcionamento e a detecção das possíveis perturbações e alterações ambientais naturais e/ou de origem antrópica resultantes aos diversos usos dessas águas e do solo circundante (Karydis and Kitsiou, 2013; Kennish, 1998; WHO, 2014, 1996).

3 OBJETIVO GERAL

O objetivo deste trabalho de Dissertação de Mestrado foi avaliar a qualidade da água do sistema estuarino do Rio Goiana, expressa através das variações dos parâmetros físicos e químicos da água do canal principal, em diferentes escalas temporais (anual e sazonal) e espaciais (alto, médio e baixo estuário), possivelmente resultantes de flutuações naturais e/ou intervenções antrópicas.

4 INTERANNUAL WATER QUALITY CHANGES AT THE HEAD OF A TROPICAL ESTUARY

4.1 INTRODUCTION

Water is a critical factor for human development since its quantities and quality can both be limiting of societal performance at many parts of the world. Water quality declines due to population increase associated to a poor context of natural resources management and social welfare (FAO, 2010; WHO, 2014). Some consequences of inadequate water quality are loss of aquatic biodiversity, changes in the physico-chemical environment, interference and malfunctioning or interruption of ecosystems services (Garrison, 2012; Kennish, 1998, 1991; WHO, 2014). Physical, chemical and biological variables together define water quality. Monitoring the changes in variables in a water body is an important management strategy because they vary according to both natural and man-driven phenomena (e.g. draughts, floods and soil erosion), and may support better informed decisions (Marques et al., 2004).

Quality of surface waters depends on the state of economic and societal development in the region, which include type and extension of agricultural practices, industrial demand, forms of occupation and use of the river basin (WHO, 2014). Therefore, dependents on levels measured, it is possible to determine different uses of the water by society and conservation priorities, highlighting the importance of spaito-temporal water quality monitoring (ANA, 2013; Lázaro et al., 2001). To amplify the effects of this investment, data should ideally be made available for public use, including basic and applied research (ANA, 2013). In Brazil, for example, public agencies publish water monitoring data, a directive of the National Water Agency, that aims at stimulate exchange of information and standardization of monitoring programs, and control water quality throughout the basin, including estuarine portion, an important source of resources and environmental services (ANA, 2013, 2007; COGERH, 2002; CPRH, 2005). Estuaries are coastal ecosystems that harbor transitional characteristics between river basins and coastal waters (Attrill and Rundle, 2002; Barletta and Dantas, 2016). Their main function is to transfer matter and energy between these compartments, being themselves extremely rich and productive (Kennish, 1991). Estuarine conditions are the result of riverine and marine influences that awap importance as water flows seaward along the ecocline and for the life cycle of a number of specialized animal and plant groups (Attrill and Rundle, 2002; Barletta and Dantas, 2016; Ribeiro and Kjerfve, 2002).

The head of the Goiana River estuary offers a variety of ecological services as water supply for the city and industries, effluent dilution, fisheries and conservation (Barletta et al., 2008, 2005; Barletta and Costa, 2009; Dantas et al., 2010; Guebert-Bartholo et al., 2011; Possatto et al., 2011; Ramos et al., 2011). In this way, its importance surpasses the obvious socioeconomic limits and lies at the scope of the environmental interests, which aim at conciliate and harmonize the use of natural resources in a sustainable way. The time-frame of the present study (2006 - 2009) was attractive since numerous ecological works have been conducted in the estuary in the same time frame (Dantas et al., 2012, 2010; Guebert-Bartholo et al., 2011; Possatto et al., 2011; Ramos et al., 2012, 2011). The work offers a wide water quality assessment that can be coupled with the findings downstream.

The objective of the present study was to describe and discuss the interannual changes of water quality based on indicators monitored just before Goiana River enters its estuary, as well as identifying the main drivers of such changes.

4.2 METHODS

4.2.1 Study area

Goiana is a coastal municipality of Pernambuco State (Brazilian Northeast) which territory is entirely comprised in the region formerly dominated by the Atlantic Rain Forest (CPRM, 2005) but that was almost entirely occupied by sugar cane plantations in the recent past. It is crossed by the main tributaries of Goiana River, and harbours their confluence from where it becomes a single channel and estuary (7° 30’S – 34° 47’W). The city centre has grown around the head of the estuary, and historically had numerous sugar-cane milling states. At present, other sectors of the economy (e.g. cars, glass and pharmacy) have come forward to diversify the local industry. All the new socioeconomic assets gained are highly dependent on good water, air and soil quality since, in addition to using the natural resources available, they also attract a new contingent of habitants that will work and live there (CPRH, 2005; CPRM, 2005).

Water from Goiana River is used mainly for public supply and irrigation. On the other hand, the main route for domestic and urban effluents dilution in the region is the Goiana River and its estuary. Sugar-cane mills still use the river for dilution of part of its effluents (CPRH, 2005; Garlipp et al., 2010) either directly for irrigation purposes.

The estuarine main channel (25 km of extension) marks the border between Pernambuco and Paraiba states, which confers its waters a transboundary status (Marques et al., 2004; Silva et al., 2013). However, Pernambuco governs most of the basin, and since decades has monitored water quality along its course (CPRH, 2005). Sampling points have been determined based on proximity to potential pollution sources (Barbosa et al., 2011; Barletta and Costa, 2009; CPRH, 2015; Dantas et al., 2010). The climate in the region has two main seasons defined by rainfall patterns (dry season – september thorough february and rainy season – march through august) (Figure 1), rather than by air temperature (Barletta and Costa, 2009; Dantas et al., 2010) or solar incidence.

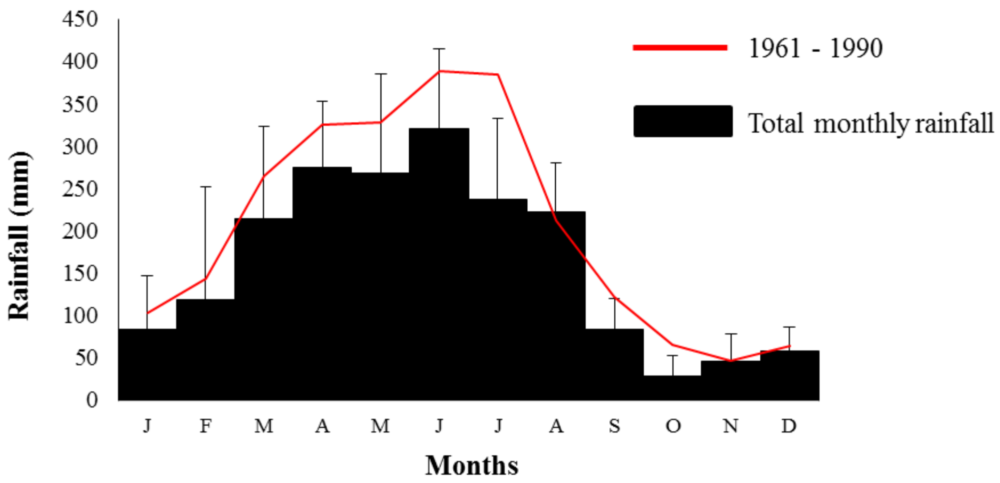

Figure 1: Climatological rainfall average 1961 - 1990 (red line) and total monthly rainfall average for 2006-2009 (black bars) in Goiana River estuary.

The estuary flows through a geologic fault, and before debouching in the Atlantic Ocean spreads across a network of channels and islands covered by a mangrove flooded forest that maintains an interesting faunal diversity and fisheries activities, although it is also affected by various types of pollution (mainly plastic and oxygen consuming effluents) (Barletta and Costa, 2009; Dantas et al., 2010; Lima et al., 2014).

4.2.2 Data acquisition

Data used in the present work were extracted from a larger data set generated by the Pernambuco State Environmental Agency (available in www.cprh.pe.gov.br), and correspond to four years (2006 - 2009) of water quality monitoring immediately upstream from Goiana River estuary, next to the city centre. The Environmental Agency monitors water quality at all river basins within the territory for management purposes, and make them readily available through the internet. Sampling took place bimonthly, so data were averaged (± standard error) per season (Barletta and Costa, 2009). The monitoring points were used as replicates $2 \leq N \leq 9$, to represent the river water that enters the estuarine system (CPRH, 2010, 2009a, 2009b, 2007).Sampling and analysis followed international guidelines (APHA, 2005). Raw data from three points (Figure 2) were chosen for the present study, and ten variables were considered: total monthly rainfall (mm), water temperature (ºC), salinity, dissolved oxygen (mg L^{-1}), oxygen saturation (%), Biochemical Oxygen Demand (BOD) (mg L^{-1}), total phosphorous (mg L^{-1}), pH, turbidity (UNIT) and colour (Pt/Co).

Figure 2: Sampling points (GO-67, GO-80 and GO-85) in the head of Goiana River estuary. Source: Google maps (adapted).

4.2.3 Local classification of natural waters

In water bodies destined for public supply, 6 mg L^{-1} is the minimum desirable level. Also, for aquatic conservation, the minimum recommended levels are 4 - 5 mg L-1 (Osode and Okoh, 2009; Pearce and Schumann, 2001; Shah and Pant, 2012). According to the local legislation, the estuarine portion considered in this study can be classified as brackish water class 1 (OD must not be lower than 5 mg L^{-1} for any sample, pH: 6,5 a

8,5), which has intended uses as public supply, fishing and recreation (Table 1 and Table 2) (CONAMA, 2005). A similar classification is adopted by the USEPA – United States Environmental Protection Agency, based on their WQS - Water Quality Standards Handbook - in which this water body would be framed in class SA, among saline waters (USEPA, 2014).

Table 1: Nacional definitions of water classes according to salinity (CONAMA, 2005). The shaded lines highlight the possible classification of water bodies in the studied area.

Waters classification		
	Salinity	**Classes**
Fresh waters	≤ 0.5	Special, 1, 2, 3 and 4
Brackish waters	0.5 ≤ S ≤ 30	Special, 1, 2 and 3
Saline waters	≥ 30	Special, 1, 2 and 3

Table 2: Brazilian classification of water bodies according to their possible uses (CONAMA, 2005). The shaded lines highlight the classification of water bodies in the studied area.

Brackish waters (0.5 ≤ S ≤ 30)	
Special class	Conservation of aquatic environments in Protected Areas (Marine); Preservation of the natural balance of aquatic communities.
Class 1 (similar to Class SA – US EPA, 2014)	Primary contact recreation; Protection of aquatic communities; Aquaculture and fisheries; Human supply after conventional or advanced treatment; Irrigation of vegetables that are consumed raw and fruits that grow close to the ground and which are ingested raw without removing rind; Irrigation of parks, gardens, sports fields and recreation al grounds.
Class 2	Recreational fishing; Secondary contact recreation.
Class 3	Navigation; Landscape harmony.

4.2.4 Statistical analysis

Data were treated through a descriptive statistic approach after plotting seasonal averages for each year. Student's Test was performed to differentiate the means of the dry and rainy seasons separately for each variable. Cluster analysis and principal components analysis (all ten variables listed above were considered) (PAleontological STatistics – PAST 2.16) was performed using a 95% confidence interval. For the cluster analysis was used the method single linkage Euclidean distance. Clarke and Warwick (2001) suggested that a PCA that explains 70% or more of the initial variations in a data set is a reasonable interpretation of the phenomenon, or global structure of interactions.

4.3 RESULTS

Rainfall ($p < 0.05$) in the study region during the period of interest varied from 52.4 ± 14.3 mm, during the dry period of 2006, and 296.6 ± 35.3 mm, the average calculated for the rainy period of 2009. If only the dry season is considered, the averages ranged from 52.4 ± 14.3 mm in 2006, and the highest was 96.3 ± 44.0 mm, in 2009. Concerning only rainy seasons, total monthly rainfall ranged from 214.9 ± 47.4 mm in 2006 and 296.6 ± 35.3 mm in 2009. The year that registered the highest values of rainfall, on average, was 2009, with 196.4 mm rainfall. On the other hand, the lowest yearly average rainfall, in monthly totals, was 2006, with 133.7 mm. The greatest variability in total monthly rainfall occurred in 2009 (Figure 3a, Appendix 1).

During the study period, water temperature ($p > 0.05$) varied between 25°C and 29°C, on average. During the dry season, averages were 27 ± 0.5°C to 28 ± 0.5°C. During the rainy season, this range was between 25 ± 1.5°C and 29 ± 0.3°C. On average, 2007 was the year with highest water temperatures, and 2009 the year with lowest mean water temperatures for the sampling stations used. The highest variability in water temperature occurred during the rainy season of 2009 (Figure 3b, Appendix 1).

Salinity ($p > 0.05$) varied from 0.20 ± 0.0, during the rainy season of 2009 and 1.17 ± 0.9, for the rainy season of 2008. During the dry season, values were between 0.26 ± 0.0, in 2007, and 0.60 ± 0.3, in 2008, while in the rainy season values remained between 0.20 ± 0.0, in 2009, and 1.17 ± 0.9, in 2008. The year with highest salinity, on average, was 2008, and the year with the lowest salinity values was 2009. During the dry season of 2008, occurred the highest variation in this variable (Figure 3c, Appendix 1).

The values of dissolved oxygen ($p > 0.05$), on average, were between 3.1 ± 0.6 mg L^{-1}, during the dry season of 2007, and 6.7 ± 0.1 mg L^{-1}, during the rainy season of 2009. As for the dry season, values ranged from 3.1 ± 0.6 mg L^{-1}, in 2007, and 4.8 ± 0.6 mg L^{-1}, in 2008. During the rainy season values were between 3.5 ± 0.7 mg L^{-1} (in 2007) and 6.7 ± 0.1 mg L^{-1} (in 2009). The year with highest average concentrations was in 2009, while the lowest oxygen concentrations occurred in 2007. The average with greatest variability was that of the rainy season of 2008 (Figure 3d, Appendix 1).

The percent oxygen saturation ($p > 0.05$) showed average values from 40.2 ± 9.4%, during the rainy season of 2007, and 80.5 ± 3.5%, during the rainy season of 2009. Considering only the dry periods, the lowest value of oxygen saturation was 40.7 ± 7.5% in 2007, and 2008 showed the highest average, 62.0 ± 8.0%. Among rainy periods, 2007 had the lowest value of oxygen saturation, 40.2 ± 9.4%, and 2009 the highest, 80.5 ± 3.5%. The year with highest average saturation levels was 2009, while 2007 was the year with lowest average. The widest variation in this parameter occurred during the dry season of 2009 (Figure 3e, Appendix 1).

BOD ($p > 0.05$) showed average values of 0.8 ± 0.1 mg L^{-1} (rainy season of 2007) to 3.2 ± 1.1 mg L^{-1} (rainy season of 2008). During the dry periods, averages ranged from 1.2 ± 0.2 mg L^{-1} (2008) to 2.2 ± 1.0 mg L^{-1} (2006). The year of 2009 had the lowest values of BOD, on average and 2008 the highest. The greatest variation of this parameter was calculated for the rainy season of 2008 (Figure 3f, Appendix 1).

The average pH ($p > 0.05$) ranged between 7.0 e 7.6. In the dry periods averages were 7.0 ± 0.2 (2006) to 7.6 ± 0.2 (2009). In the rainy season, the average pH values were between 7.0 ± 0.1 (2008) and 7.4 ± 0.2 (2009). The year with highest pH values was 2009, while 2006 showed the lowest yearly average. The widest variation occurred in the dry season of 2006 (Figure 3g, Appendix 1).

For the variable total P ($p > 0.05$), the seasonal average values were comprised between 0.1 ± 0.0 mg L^{-1} and 0.8 ± 0.3 mg L^{-1}. During the dry season, minimum values were 0.1 ± 0.0 mg L^{-1} and maximums reached 0.4 ± 0.1 mg L^{-1}. During the rainy season, values between 0.2 ± 0.2 mg L^{-1} and 0.8 ± 0.3 mg L^{-1} could be observed. The year of 2006 showed the highest concentration of this nutrient, and 2009 the lowest. The highest variability was noted during the rainy season of 2006 (Figure 3h, Appendix 1).

Turbidity ($p <0.05$) varied from 14.6 ± 2.8 UNIT (dry season of 2007) to 63.1 ± 25.6 UNIT (rainy season of 2008). During the dry season, the average values were between 14.6 ± 2.8 UNIT, calculated for 2007, and 25.4 ± 7.2 UNIT, in 2008. In the rainy season, averages were comprised between 46.3 ± 8.5 UNIT, for the year 2007, and 63.1 ± 25.6 UNIT, for the year 2008. On average, the year with greatest water turbidity was 2009, while the lowest values were those registered in 2008. The largest variability was observed during the rainy season of 2008 (Figure 3i, Appendix 1).

The variable colour ($p <0.05$) of the water presented average values between 28.8 ± 4.9 Pt/Co (for the dry season of 2006) and 150.0 ± 50.0 Pt/Co (for the rainy season of 2009). During the rainy season, averages had a minimum of 53.8 ± 13.2 Pt/Co (in 2007) and a maximum of 150.0 ± 50.0 Pt/Co (in 2009). During the dry season, the minimum was 28.8 ± 4.9 Pt/Co in 2006, and the maximum was 68.3 ± 19.7 Pt/Co in 2008. Yearly average values for this parameter were registered in 2009 and the minimum in 2007. Its variation was greatest during the rainy season of 2008 (Figure 3j, Appendix 1).

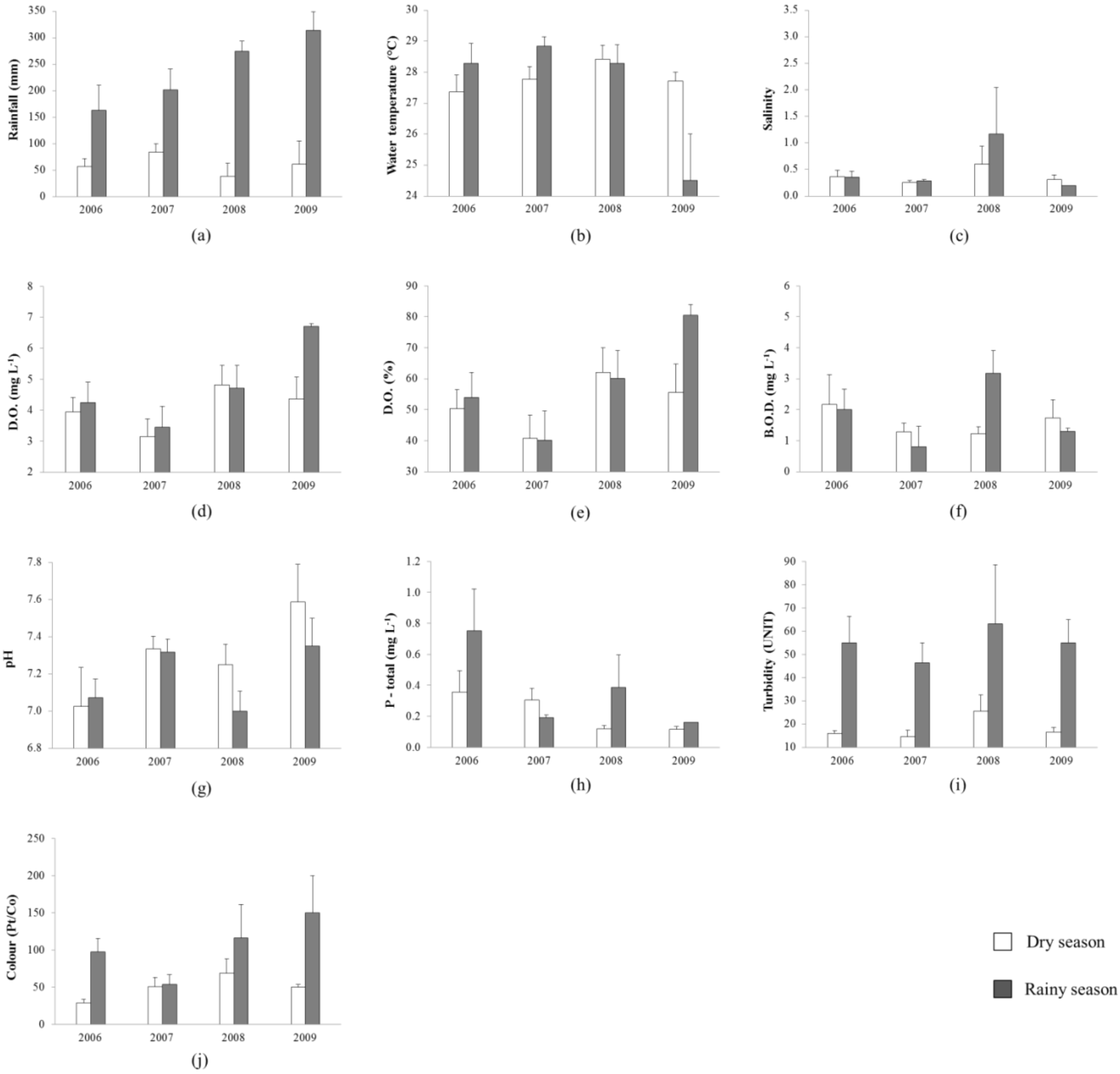

Figure 3: Average (± standard error) of temporal (interannual and seasonal) variations of rainfall (a); water temperature (b); salinity (c); dissolved oxygen (d) and saturation (e); biochemical oxygen demand (f); pH (g); total phosphorus (h); turbidity (i) and colour (j) at the head of Goiana River estuary from 2006 – 2009.

In the cluster analysis, observations were grouped into two main groups, I and II. Group I presented subgroups: IA, contains samples from the rainy seasons of 2006 and 2007, while IB, grouped the rainy seasons of 2008 and 2009. Group II was subdivided in to

IIA formed only by the dry season of 2008 and IIB corresponding to the dry seasons of 2006, 2007 e 2009 (Figure 4).

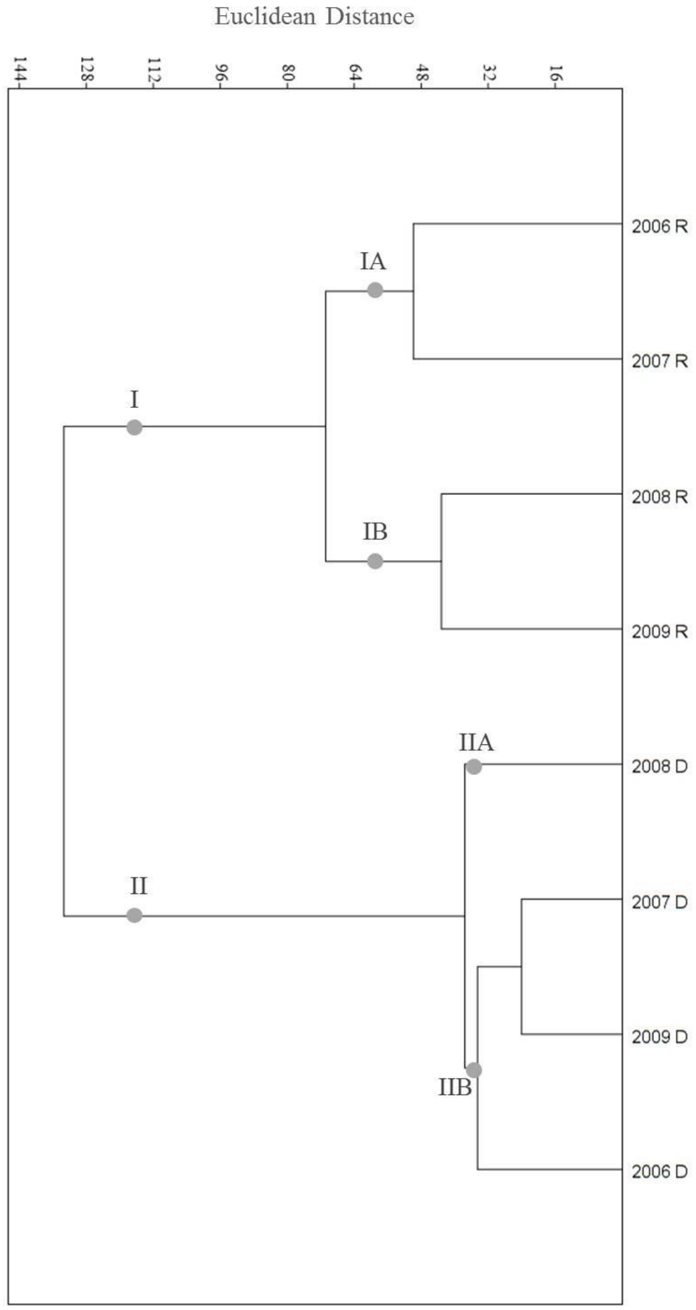

Figure 4: Cluster of interannual seasonal averages of water quality parameters and rainfall at the head of Goiana River estuary through Euclidean distance.

According to the PCA, the two main components (PC1 and PC2) described 74.06% of the original variations in the data set, satisfactory to explain the inter-relations among variables (Clarke and Warwick, 2001). The PC1 explained 43.04% of the total variance, while PC2 represented 31.02% (Figure 5).

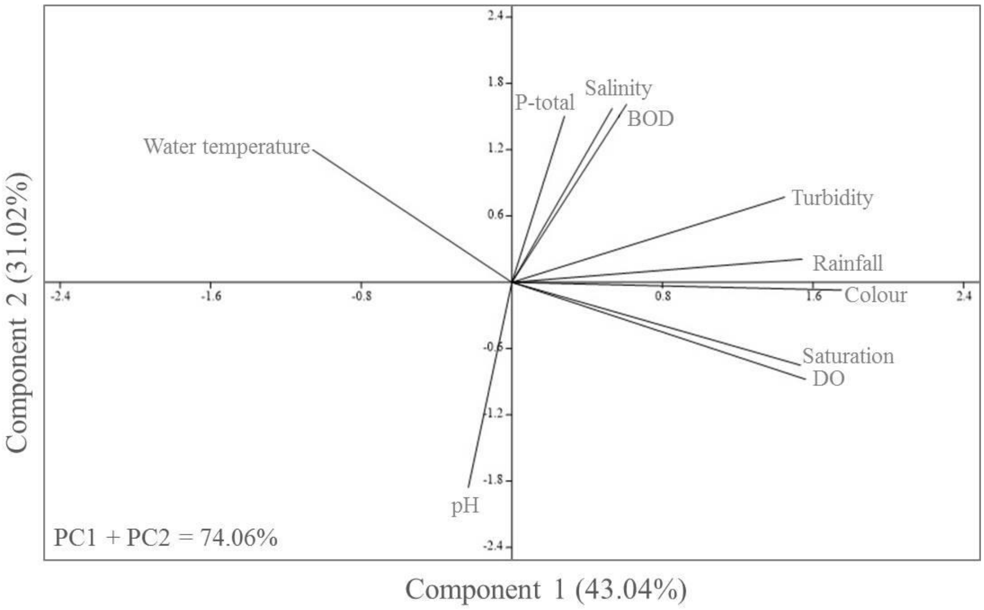

Figure 5: PCA showing the contribution of environmental variables to the water quality patterns at the head of Goiana River estuary from 2006 - 2009.

4.4 DISCUSSION

A number of measurable parameters (physical, biological and/or chemical) describe environmental patterns in aquatic ecosystems. Changes in these patterns might be considered impacts, including pollution, resulting from the addition/suppression of substances or energies that will consequently impair ecosystem functioning and sustainable use (ANA, 2013).

Water temperature and salinity play important roles in the distribution of aquatic biota (Harrison and Whitfield, 2006; Nejrup and Pedersen, 2008), and may be considered as key variables in the determination of ecoclines in estuaries (Barletta and Dantas, 2016; Attrill and Rundle, 2002). At the headwaters of Goiana River estuary, salinity values are small (< 5), and vary very little. Recent studies also show the influence of these parameters in the distribution of microplastics (Lima et al., 2014), accumulation being possible in areas of lower salinity and strong influenced by river flow. Such areas are considered of high ecological importance, directly influencing the abundance of larvae (Barletta et al., 2005). In this study, although there is large freshwater influence in the sampled points, it was possible to identify those areas considered nursery. Water temperature also showed a small variation, and the small differences probably to were related weather. Although water temperatures remained relatively high and stable, as expected for tropical latitudes, sudden and/or large alterations of this parameter might compromise environmental health at different time scales (Harrison, 2004; Harrison and Whitfield, 2006).

Dissolved oxygen is essential for aquatic environments metabolism, especially aerobic processes. Its saturation in the water column is, however, dependant on water temperature, turbulence, atmospheric pressure and salinity. The higher the available amounts of dissolved oxygen, the higher the chance of organic matter being mineralized in the environment at seasonable rates. The dissolved oxygen levels registered during the present study were surprisingly high, in spite of high water temperature and organic matter loads in the system. The concentration of dissolved oxygen expected in natural waters are from 8 - 10 mg L^{-1} at 25°C, the physically possible maximum (Pearce and Schumann, 2001; Shah and Pant, 2012).

Dissolved oxygen levels below saturation maxima suggest excess organic matter in the system, and possibly abnormal growth of primary biomass (Shah and Pant, 2012). During the present study, the dissolved oxygen levels were between 3.0 mg L^{-1} and 7.0 mg L^{-1}, with most saturation levels (except for 2007) above 50 %, which characterizes waters with reasonable quality for aquatic life conservation. Working in other systems, Alves and co-authors (2012) reported that, at Arari river, dissolved oxygen concentrations were higher due to turbulence. The study area is at the headwaters of the Goiana, where three tributaries meet and favour turbulent mixture and diffusion of dissolved oxygen from the atmosphere. The biological oxygen demand is important in assessing the efficiency of aquatic metabolic processes as organic matter remineralization. High BOD values suggest little dissolved oxygen available in the water column. The dilution of organic-rich effluents (domestic sewage and/or sugar cane molasses) increase dramatically this demand (Kennish, 1991). During the present work, BOD values were lower then previous works in the same area, or others conduced at similar environments (Alves et al., 2012; Aprile and Farias, 2001). The increase in river flow during the rainy season, together with better turbulent oxygen diffusion, favours lower BOD levels that might compensate for effluents discharges (Aprile and Farias, 2001).

Phosphorous is a strong indicator of aquatic environments eutrophication. Although essential for primary producers, excess P might cause blooms of opportunistic species of different ecological significance (Esteves, 2011; Eyre, 1997). Sugar cane plantations monoculture are very present in the region around Goiana, replacing originally mangrove and Atlantic Rain forest areas (Barletta and Costa, 2009). The higher P concentrations during the rainy season are probably due to soil surface runoff across the basin, carrying fertilizers and organic matter, phosphorus sources to the river.

Both chemical and biological process in aquatic environments can be related to pH. It is recommended that, for the conservation of aquatic species, pH remain between 6 and 9 (Esteves, 2011). During this study, pH remained slightly basic with small seasonal or interannual variation. The small variations of pH suggest that the aquatic ecosystem is consistently buffered, or with acceleration of aquatic metabolism, as observed during the present study.

Turbidity relates to sunlight scattering in the water column. It is directly influenced by suspended solids and strongly influences the ecology of many biological species from primary producers to vertebrates. Species of fish and other large predators that depend upon sight for preying are disfavoured at turbid coastal waters, which in turn function as protection to larvae and juveniles of other species (Barletta-Bergan et al., 2002; Blaber, 2002; Laroche et al., 1997). The colour of water is also relate to suspended solids, especially colloids (Bennett and Drikas, 1993). Although this characteristic is not necessarily related to water quality, but rather with aesthetics, it is an important variable when water is used for public supply (WHO, 1996). Turbidity and colour were dependent on rainfall that cause the flow of particulate suspended solids to the main channel of the river, and therefore enter the estuary in suspension. Rainfall increased solids runoff, water flow and erosion of the margins, all processes that increased turbidity and change colour of the water.

4.4.1 Variables interdependance

The year 2008 showed atypical rainfall (54.9 ± 24.6 mm) it is the dryer season among the years studied, forming subgroup IIA. The years 2006, 2007 and 2009 show similar rainfall, forming the subgroup IIB. The seasonal approach is representative of environment behaviour, and significantly changed by rainfall. Rainfall influences the runoff natural organic matter and promotes the resuspension of bottom sediments originating from the whole basin, increasing turbidity and colour (Alves et al., 2012; Bennett and Drikas, 1993), as well as the oxygen and its saturation (Garrison, 2012; Kennish, 1991). Total Phosphorous, as BOD, are closely related to sewage discharges (Eyre, 1997) and the sugar cane cycle (including deforestation), as notable along the river basin studied here (Barletta and Costa, 2009). The strong correlation with PC2, probably represents the dilution and assimilation of pollutants loads towards the river mouth. Water temperature was negatively correlated to D.O. and saturation because it influences gas dissolution (Harrison and Whitfield, 2006; Xu et al., 2012). Also, pH was negatively related to total P and BOD since its variation alters the nutrients availability and consequently organic matter production and consumption (Eyre, 1997; Kennish, 1998, 1991).

4.4.2 Management and conservation implications

The eastern most region of South America has no large river basins, but numerous small rivers with limited size and volume are the main source of water for the population in its surroundings (IBAMA, 2006). Rainfall is often the only source of freshwater that recharges river basins and reservoirs, being responsible for their seasonal flush and maintenance (Barletta and Costa, 2009; Lázaro et al., 2001; Sala and Lauenroth, 1982; Schlacher and Wooldridge, 1996), as well as being very important for agricultural water management (Brockmeyer and Spitzy, 2011; Humbert, 2013; Razafimbelo, T.Barthès et al., 2006). These environmental conditions that occur at the Goiana basin also occur at Georges river (Australia) (Ferguson et al., 1996) and another 109 estuaries studied by Harrison (2004) in South Africa. All are highly dependent on local rainfall for the renewal of their water resources and therefore supplying ecological services, including conservation up and downstream. In 2006 and 2007 the studied variables presented a direct relation with rainfall, and their changes can be attributed to seasonality, as also observed by Aprile and Farias (2001) at Goiana River and by Barletta-Bergan and colaborators (2002) at Caeté river at the Eastern Amazon. In 2008, although rainfall presented expected patterns, BOD, total phosphorous, turbidity and colour increased in the rainy season. This might have resulted from the dredging of sand for road building at the upper estuary, which remobilized suspended solids to the water column. In relation to the three previous years, the year of 2009 increased average levels of precipitation during both seasons, enough to cause decrease in water temperature and total phosphorous, as well as an increase in dissolved oxygen and saturation (turbulence). There was a significant increase in turbidity and colour, resulting from augmented water flow, runoff and erosion of the margins. Climatic events, as above-average rainfall years, promote a flushing of tropical aquatic systems and can contribute to improve environmental conditions afterwards (Bouvy et al., 1999; Jackson et al., 2001; Nijssen et al., 2001). At present, climatic variations, including alteration of rainfall patterns and increasing temperatures, are at the centre of attentions. Together with other human interferences in soil use (sugar cane plantations) and gas emissions and other pollutants, these changes might interfere with patterns of the global and local hydrological cycles. In addition, human pressures on these water resources is bound only to increase, and the conservation of water quality will become an undisputable priority (Arnell, 1999; Hughes, 2000; IPCC, 2007; Jackson et al., 2001; Nijssen et al., 2001; Vörösmarty et al., 2000).

4.5 FINAL REMARKS

Our work assessed the environmental conditions at the headwaters of Goiana River estuary from 2006 to 2009, a period when a number of ecological studies were also conducted downstream, along the main channel of the estuary.

Although the data suggest that environmental status, from the point of view of water quality, is reasonable for the uses it has, some attention is to be payed to human interventions (e.g. dredging, daws). Also, in order to increase environmental resilience, some measures as margins restoration can take the whole system from the brink of collapse under aggradation and eutrophication. Therefore, reforestation of the riparian vegetation along the basin and universal basic sanitation are urgently needed. In regions with limitations in river basins, rainfall is important in promoting seasonal flushes that maintain hydrological patterns and ecosystem functions, where care should be increased in the dry season in which the renewal of the water is lower. Water temperature depends upon many physical factors (e.g. depth, water flow, dilution of effluents), and is important since it controls other variables as dissolved oxygen and its saturation.

General recommendations for improving monitoring programs would be the inclusion of other parameters as chlorophyll a and total solids. This would align the local monitoring to other large programs in the contry and abroad. Also, efforts are advised for guaranteeing regular sampling in order to strengthen the databank, parameters to facilitate science communication and comparisons with of other basins, national and internationally, seeking to ensure the quantity and quality of information available.

As suggested by our results, regions already suffering from climatic vulnerability (draughts) and excess demand on water resources (population) should receive special attention regarding future changes in local hydrology.

5 SEASONALITY-DRIVEN CHANGES IN WATER QUALITY IN A TROPICAL ESTUARY

5.1 INTRODUCTION

Estuaries are transitional coastal water body, semi-closed connected to the sea permanently or periodically, which presents a gradient of environmental parameters, influenced by the adjacent sea and the contribution fresh water and includes a peculiar biota (Elliott et al., 2007; Elliott and Quintino, 2007). Estuaries around the world provide essential support to coastal and marine biodiversity and for human populations. Provide ecosystem services that are often irreplaceable, including food security, flood mitigation, cycle of nutrients, energy generation, amenity and cultural significance (Karydis and Kitsiou, 2013; Kitsiou and Karydis, 2011; WHO, 1996).

The largest cities in the world are located around estuaries. The close link between these ecosystems and the main population centres makes estuaries extremely vulnerable to anthropogenic pressures and consequent degradation (Kennish, 1998; Kitsiou and Karydis, 2011).

In a global assessment of coastal and marine ecosystems by Jackson (2008), estuaries were listed among the critically endangered. Among the impacts are pollution (including nutrients and enrichment of organic carbon and chemical contamination), overfishing, diversion of fresh water or other hydrological modifications and introduced species (Eyre, 1997; Gurgel et al., 2016; Harrison and Whitfield, 2006; Lucena-Moya and Duggan, 2017; Mérigot et al., 2016; Statham, 2012; Telesh and Khlebovich, 2010).

Estuarine environmental information is important for the management and restoration of degraded coastal waters (Karydis and Kitsiou, 2013). Spatial and temporal estuarine data are necessary and important for study and management. The spatial dimensions of environmental data facilitate intercomparison between estuaries as well as understanding the internal structure and zoning of an estuary (Hallett et al., 2016a, 2016b, 2016c; Lavery et al., 1993).

The objective of the present study was to describe and discuss seasonal changes of water quality based on physico-chemical variables (water temperature, salinity, dissolved oxygen, saturation and Secchi depth), monitored in the main channel of Goiana River estuary during one year.

5.2 METHODS

5.2.1 Study area

The estuary of the Goiana River (7 30'S - 34 47'W) (Figure 6) is located on the South American east coast, on the coastal border between the states of Paraíba and Pernambuco, presenting a transboundary character of its waters (Barletta and Costa, 2009; CPRH, 2015; Dantas et al., 2010; Marques et al., 2004; Silva et al., 2013). The area has a total length of main channel, from its head in the city of Goiana, until its mouth, of about 25 km (Barletta and Costa, 2009; Marques et al., 2004; Silva et al., 2013). The basin of the Goiana River is very important for the region where it is inserted, composing the main one its source of water for the most diverse uses. Among the activities developed along the basin, one can observe the intense performance of the sugar cane industry; public supply and irrigation; use of water to dilute industrial and domestic effluents in addition to the development of fisheries and shellfish activity, conflicting activities in relation to water quality. (Barletta and Costa, 2009; CPRH, 2015; Garlipp et al., 2010).

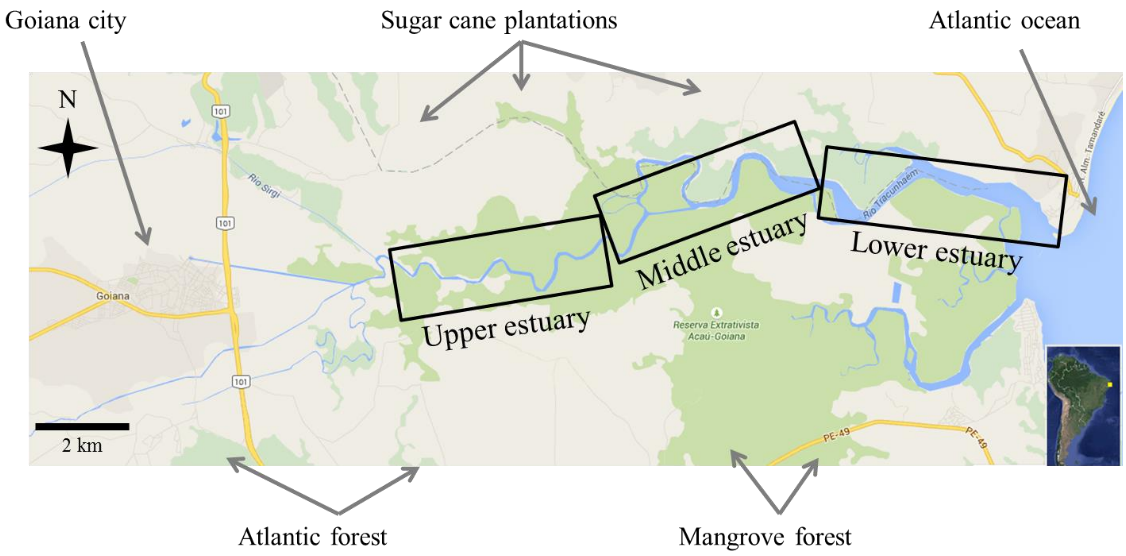

Figure 6: Goiana River Estuary, showing the upper estuary, middle estuary and lower estuary and its main uses. Source: Google maps, adapted.

The estuary was sectioned into three compartments (upper, middle and lower), according to Barletta and co-authors (2005) sampling design. Each section of the channel is an ecosystem habitat, due to the different characteristics, that provide different behaviours and variety of associated organisms, resulting from the ecological gradient (Attrill and Rundle, 2002; Barletta and Dantas, 2016). The estuary is a complex formed by a diversity of environments (rivers, streams, ponds, tidal channels, islands, wetlands and condensed vegetation of mangrove) allowing the use by numerous groups of resident species and visitors (Barletta and Costa, 2009; Dantas et al., 2010; Lima et al., 2014).

5.2.2 Data acquisition

The sampling strategy of this study was based on numerous studies already performed by several authors (Barletta et al., 2008, 2005; Dantas et al., 2010; Lima et al., 2014) by the robustness and efficiency of the sample design, ensuring greater security in the analysis and interpretation of the results.

The strategy was implemented for twelve months (December 2005 to November 2006) in this estuary. Were considered three estuarine areas (upper estuary, middle estuary and lower estuary) and four seasons (late dry, early rainy, late rainy and early dry). Data were collected for water surface and bottom (6 points in each area) including water temperature (°C), salinity, dissolved oxygen (mg L^{-1}) and saturation (%) (measured with WTW LF 197, Wissenschaftlich Technische Werkstätten) and Secchi depth (cm). The total monthly precipitation (mm) was obtained from the public database (www.apac.gov.pe.br), collected from a weather station located 10 km south of the city of Goiana.

5.2.3 Statistical analysis

The data collected was processed using Statistica 7.0. Were realized analyses of one-way and multifactorial variance (ANOVA one-way and MANOVA). Was used to determine whether significant differences in variables (water temperature, salinity, dissolved oxygen, oxygen saturation and Secchi depth) occurred in areas (upper, middle and lower estuary) and seasons (late dry, early rainy, late rainy, early dry). Where ANOVA showed a significant difference, an *a posteriori* Bonferroni test was used to determine which means were significantly different at the 0.05 level of significance. Cluster analysis, was performed using method unweighted pair-group average with Euclidean distance, and principal components analysis was made using a 95% confidence interval, for all variables.

5.3 RESULTS

The variables were studied and analysed separately, in order to know their behaviour (Appendix 2 to 5), where some show differences between surface and bottom. From the analysis results MANOVA, it was observed that the effect of the water column on the parameters studied not remained as important as when looked at separately ($p > 0.05$, no significant difference). Based on this result, this effect was eliminated, and the samples for surface and bottom were treated as replicas, bringing the number from six to twelve.

Rainfall in the studied period ranged from 6.2 mm to 374.0 mm. In late dry season the average was 33.9 ± 10.1 mm. In early rainy season the average was 196.3 ± 133.8 mm and late rainy season the average was 233.4 ± 121.8. Already in early dry season the average was 58.9 ± 45.6 mm (Figure 7).

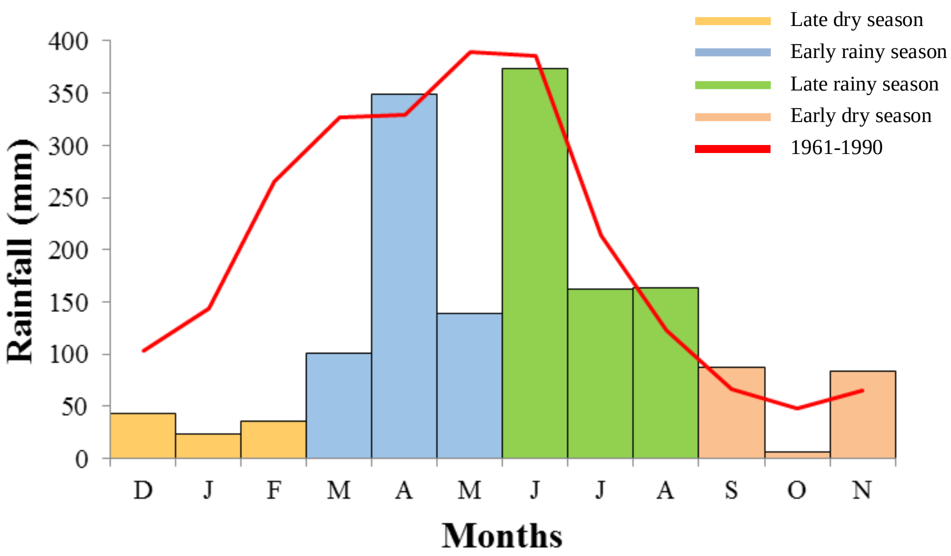

Figure 7: Seasonal variations of rainfall at the Goiana River estuary based on the total monthly rainfall (INMET station nº. 28) for 2006, compared to the climatic average. Seasons divide according to Barletta and Costa, 2009.

Water temperature ($p < 0.01$) varied from 25.8 to 32.0°C (Figure 8). The hightest differences were observed between late dry season and early rainy season. The upper and middle areas, as well as stations early dry and early rainy, were similar (Table 3).

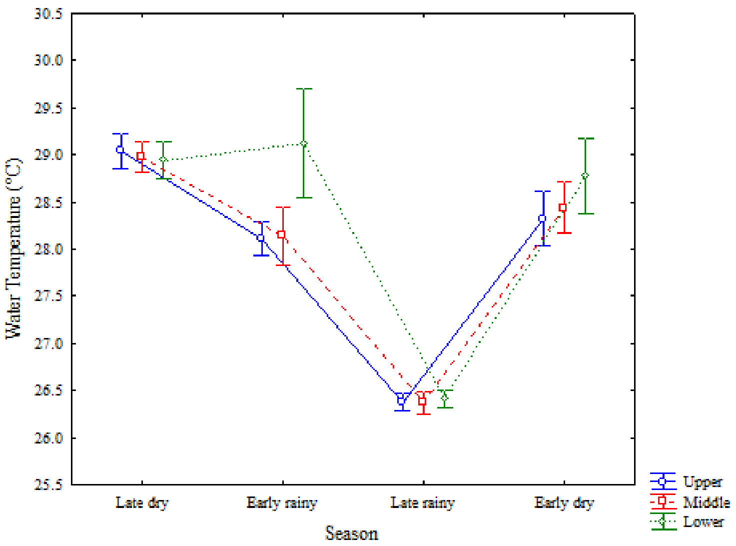

Figure 8: Seasonal average (±standard deviation) of seasonal variations of water temperature (°C) at the main channel of Goiana River estuary during 2006.

Table 3: Summary of the ANOVA results for water temperature, salinity, dissolved oxygen, oxygen saturation and Secchi depth for estuarine area - upper (U), middle (M), lower (L) - for season - late dry (LD), early rainy (ER), late rainy (LR), early dry (ED).

	Source of variance		
Parameters	Area (1)	Season (2)	Interaction
Water temperature	**	**	**
	U M L	LR ED ER LD	1x2
Salinity	**	**	**
	U M L	LR ED ER LD	1x2
Dissolved oxygen	**	**	**
	U M L	LR ED ER LD	1x2
Oxygen saturation	**	**	**
	U M L	LR ED ER LD	1x2
Secchi depth	**	**	**
	U M L	LR ED ER LD	1x2

NS, non-significant differences (p>0.05); *, p<0.05; **, p<0.01; differences among area and season were determined by Bonferroni test (p<0.05) *post hoc* comparisons.

Salinity ($p < 0.01$) varied from 0 to 37.0, with 72 of the 432 sampled values being equal to zero. In middle estuary, presented an intermediate character between the other areas , highlighted in this parameter, influenced by the seasons (Figure 9). The areas and seasons presented independent behaviour for this variable (Table 3).

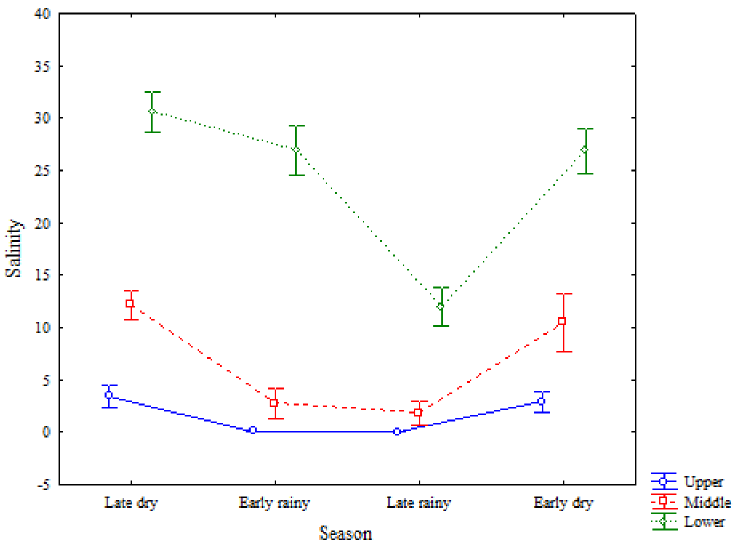

Figure 9: Seasonal average (±standard deviation) of seasonal variations of salinity at the main channel of Goiana River estuary during 2006.

Dissolved oxygen ($p < 0.01$) varied from 0.7 to 11.4 mg L^{-1} in the period, with the highest averages concentrated in the lower estuarine portion (Figure 10). In early dry and early rainy presented similar behaviour (Table 3).

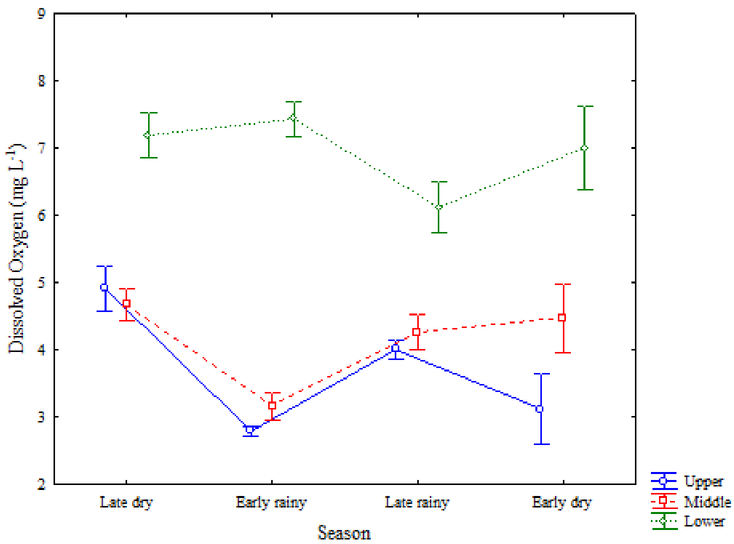

Figure 10: Seasonal average (±standard deviation) of seasonal variations of dissolved oxygen (mg L^{-1}) at the main channel of Goiana River estuary during 2006.

Oxygen saturation ($p < 0.01$) showed values between 6 to 141.0% and followed the trend of averages presented by oxygen (Figure 11). There were no differences between seasons early dry, early rainy and late rainy (Table 3).

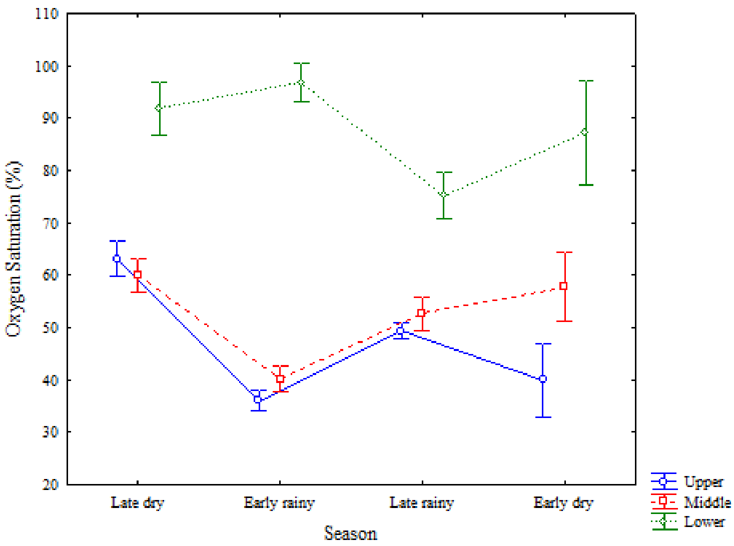

Figure 11: Seasonal average (±standard deviation) of seasonal variations of oxygen saturation (%) at the main channel of Goiana River estuary during 2006.

Secchi depth ($p < 0.01$) varied from 7 to 186 cm, showing large variations between the areas in the dry seasons while in the rainy seasons the measurements were more homogeneous (Figure 12). It showed significant differences between all areas and all seasons (Table 3).

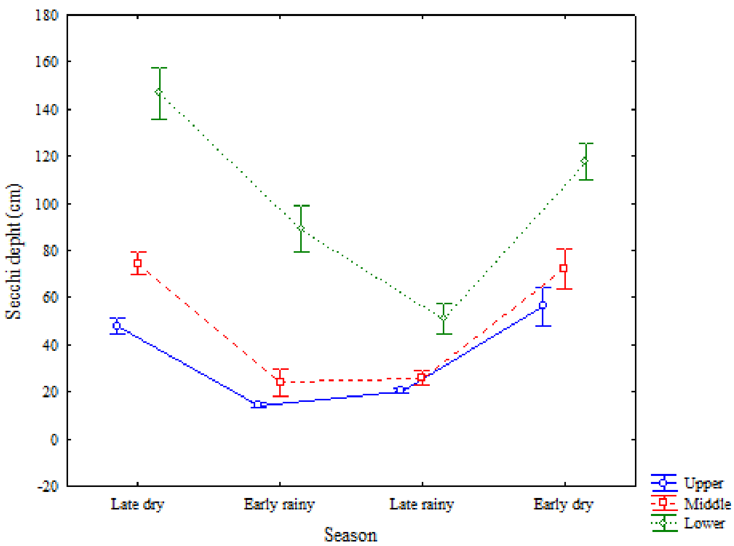

Figure 12: Seasonal average (±standard deviation) of seasonal variations of Secchi depth (cm) at the main channel of Goiana River estuary during 2006.

Multivariate analyses were performed to clarify the interdependence between the parameters studied. For these analyses, the observations were homogenized in averages (n=12), due to the large number of samples (n=432), allowing better observation and interpretation of the results. The averages were made between samples of the same spatiotemporal condition (area and season).

In cluster analysis (Figure 13), the observations were grouped into 2 groups, I e II. Group I gathered the observations of the rainy seasons and was subdivided into 2 subgroups. Subgroup IA, which comprised the sampling in lower area, in the early rainy season and subgroup IB, which comprised the sampling carried out in areas upper, middle and lower, in the early rainy season and late rainy season. Group II gathered the observations of the dry seasons and presented two subgroups: IIA, which comprised the sampling carried out in lower area , in the early dry season and late dry season and in subgroup IIB, which comprised the samplings carried out in areas upper and middle, during early dry season and late dry season.

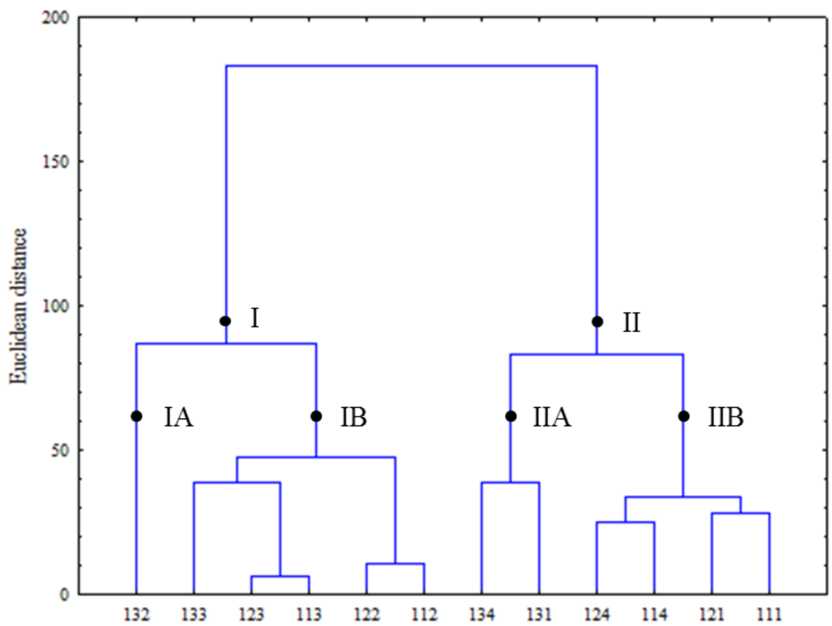

Figure 13: Cluster of seasonal averages of water quality parameters and rainfall at the Goiana River estuary through Euclidean distance. Legend for samples: first numeral represents the year (1 - 2006, 2 - 2007, 3 - 2008, 4 - 2009); second numeral represents estuarine area (1 – upper, 2 – middle, 3 – lower) and thrid numeral represents season (1 – late dry, 2 – early rainy, 3 – late rainy, 4 – early dry). Ex. 134 are samples from 2006, lower estuary, early dry season.

Observing the principal components (PC1 and PC2), 93.47% of the variation of the data are explained, satisfactory to explain inter-relations among variables (Clarke and

Warwick, 2001). The PC1 explained 70.12% of the total variance, while PC2 represented 23.35% (Figure 14).

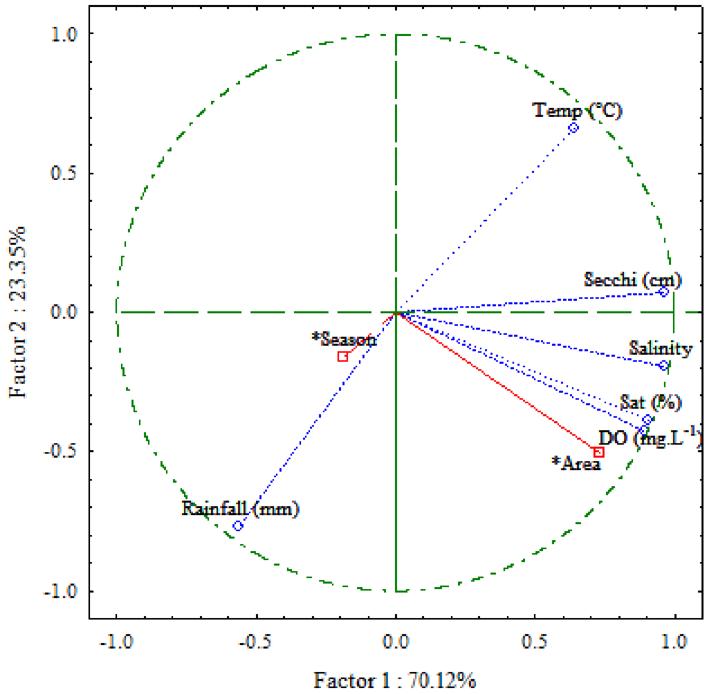

Figure 14: Weight graph (PCA) showing the contribution of environmental variables to the water quality patterns at the of Goiana River estuary.

In scores graph, 3 groups were identified: X, Y and Z. Group X collected the samplings carried out obtained in the lower estuary in four seasons. Group Y collected the samples obtained in the upper and middle areas in the dry seasons. Group Z collected samples from the upper and middle areas in rainy seasons (Figure 15).

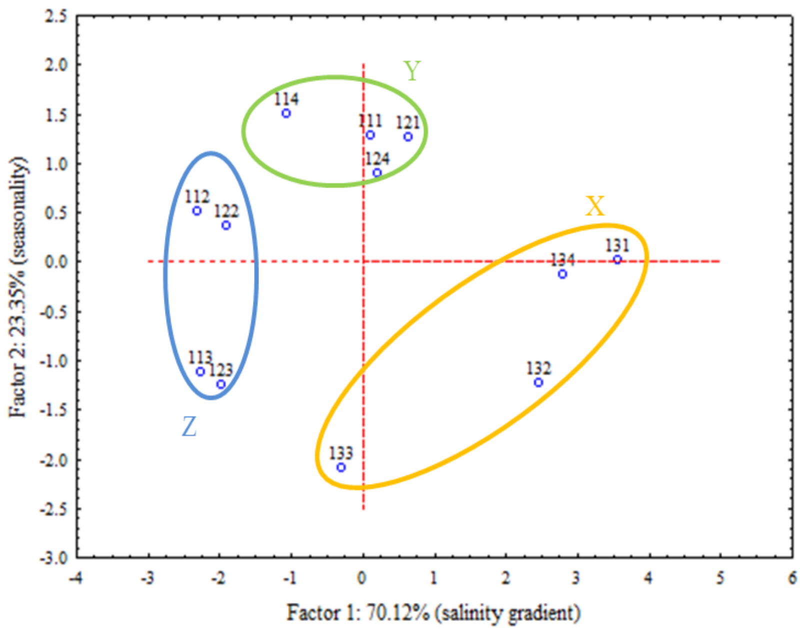

Figure 15: Score graph (PCA) showing the contribution of environmental variables and seasonality to the water quality patterns at the of Goiana River estuary. Legend for samples: first numeral represents the year (1 - 2006, 2 - 2007, 3 - 2008, 4 - 2009); second numeral represents estuarine area (1 – upper, 2 – middle, 3 – lower) and thrid numeral represents season (1 – late dry, 2 – early rainy, 3 – late rainy, 4 – early dry). Ex. 134 are samples from 2006, lower estuary, early dry season.

5.4 DISCUSSION

Abiotic parameters of coastal and estuarine waters are determinant in the establishment of ecoclines (Attrill and Rundle, 2002; Barletta and Dantas, 2016; Harrison and Whitfield, 2006; Nejrup and Pedersen, 2008). Changes in the patterns of these parameters can compromise the quality of the environment by altering the distribution of biota (Lucena-Moya and Duggan, 2017; Paul and Calliari, 2017), the resilience of the environment and the absorption and accumulation of pollutants (Govindasmy and Chandrasekaran, 1992; Ivar do Sul et al., 2014; Ivar do Sul and Costa, 2013; Lima et al., 2014; Telesh and Khlebovich, 2010; Uriarte and Villate, 2004; Whitehead et al., 2009).
The estuary is located in a tropical area (Barletta and Costa, 2009), which favoured high temperatures throughout the year. Water temperature can affect the dissolution of gases like oxygen in the water, decreasing the availability (Harrison and Whitfield, 2006; Kong and Ye, 2014). Early rainy and early dry seasons indicated the beginning of changes in water temperature, resulting from the variation of rainfall in the

environment. Early rainy showed a tendency to fall while early dry showed tendency to increase water temperature.

Salinity followed the estuarine gradient (Attrill and Rundle, 2002; Barletta and Dantas, 2016). In the upper and middle areas, the behaviour dry seasons and rainy seasons were very similar. In the lower area, the late rainy season caused a larger decrease in salinity, coinciding with the higher rainfall.

The dissolved oxygen and oxygen saturation showed similar behaviour, although the water temperature also influenced the oxygen saturation indexes. The variation of the water temperature was not enough to influence the oxygen saturation values, being predominant the interdependence between the dissolved oxygen and its saturation (Nezlin et al., 2009; Shah and Pant, 2012). The oxygen contents were higher in the lower area of the estuary, where there is a greater influence of marine waters, more oxygenated (Zhang et al., 2010).

Secchi depth presented higher values in the dry seasons, where the water column is more stable, lower resuspension of particles, as well as lower flow sediment and particulate leached by rain. In the rainy seasons, especially in late rainy, the lower values are observed, due to the greater volume of the rains, increasing the turbidity (Kronvang et al., 2005; Schlacher and Wooldridge, 1996).

5.4.1 Variables interdependence

Rainfall was the factor with the greatest impact on the formation of the groups in the cluster analysis. The subgroup IA was the main source of data variance. The sampling performed in the early rainy season, in the lower area, resulted in changes in the salinity patterns found in the period examined. Group I grouped the observations of the dry seasons (early and late) while group II gathered the observations of the rainy seasons (early and late). Early dry and early rainy seasons were intermediate in character. However, late dry and late rainy seasons showed extreme conditions which were expressed by variations in environmental variables.

Rainfall is a determinant of water quality, inclusive in estuaries (Corbari et al., 2016; Eyre, 1997; Karydis and Kitsiou, 2013). Freshwater inflow promoted renewal, increased oxygen levels and the dilution of effluents and pollutants (Brooks et al., 2006; Cloern et al., 2014; Kronvang et al., 2005; Osode and Okoh, 2009; Qasim et al., 1968) improving water quality.

Two principal components of the PCA analysis explain 93.47% of the variance of the data. PC1 corresponds to estuarine salinity gradient, with upper area of the estuary (low salinity) represented to the left and the marine area (high salinity) to the right. PC2 represents the effect of seasonality, with the rainfall variable being the, followed by temperature. The distribution of the observations along the graph (Figure 14 and 15) confirms the influence of these two factors. In the weights graph, PC1 (70.12%) represented the estuarine gradient, with the salinity and Secchi depth being the main contributor. Dissolved oxygen and its saturation followed the salinity gradient, increasing towards the mouth of the estuary. With the greater marine influence, characteristic of the lower area of the estuary, these parameters tend to increase (Dantas et al., 2010; Jutagate et al., 2010; Karydis and Kitsiou, 2013). PC2 (23.35%) represented the seasonality, with rainfall being the main forming variable. The water temperature also appeared as a major contributor to the formation of the axis, where the seasonal difference was well marked, mainly due to the location of the estuary (Barletta and Costa, 2009; Blaber, 2002; Harrison, 2004; Harrison and Whitfield, 2006).

Upper and middle areas were grouped according to seasons. In the dry seasons were grouped in group Y and rainy seasons in group Z. However, the lower area presented a predominantly marine character. In all seasons the influence is almost exclusively marine (group X). The fluctuation of salinity gradient in the estuary define the biological assemblages at different estuarine portions, according to their needs and ecological interactions. Fish species that prefer areas with lower salinities for nursery and protection may chose moving among estuarine habitats during the rainy season; in contrast, marine species can enter the estuary and make use of its resources (Barletta et al., 2005; Blaber, 2002, 2013, 2007; Dantas et al., 2010; Lima et al., 2014).

5.4.2 Management and conservation implications

In regions where there are no large river basins, small estuaries along the coast are the main source of water (IBAMA, 2006; WHO, 1996). The most important factor in the renewal and maintenance of these waters is precipitation, improving its quality (Corbari et al., 2016; Eyre, 1997; Karydis and Kitsiou, 2013; Schlacher and Wooldridge, 1996). The important relationship of the dependence of the Goiana River estuary of the rainfall to the renewal of its water resources was also observed in other estuaries. Mérigot and co-authors (2016) observed in four estuarine complexes in Brazil and Harrison (2004), in South Africa, in another 109 studied estuaries. The maintenance of these waters is crucial for the continuity of the provision of ecological services (Corbari et al., 2016; Karydis and Kitsiou, 2013; Marques et al., 2004). Seasonality is a major influence on water quality. In very dry periods (late dry) the quality of the water is affected, changing the conditions for the ecosystem, periods that need more attention from users water management agencies (Barletta and Costa, 2009; Ceesay et al., 2016; Kress et al., 2002). The beginning of the seasons, bring a transitional character, where the environment is being adapted to the new configuration, taking time to express these changes (Ceesay et al., 2016; Dixon et al., 2014; Kress et al., 2002). Previous studies have also found this character mainly with respect to environmental variables (Barletta et al., 2008, 2005; Dantas et al., 2010; Lima et al., 2014).

Surface water quality will need to gain more attention with increasing demand for water resources. Environments such as tropical estuaries will be of great importance and a considerable understanding of the functioning of these ecosystems is needed (IPCC, 2007; WHO, 2014).

5.5 FINAL REMARKS

This work evaluated the environmental conditions of the water in the Goiana River estuary during the period of one year, subdivided into four seasons: late dry, early rainy, late rainy and early dry. The sensitivity and vulnerability of this environment are observed, resulting from human activities (discharge of effluents, sugarcane plantations). The maintenance of environmental quality should be a priority, not only of water, but of all compartments that form the estuarine complex (soil, margins). Approaches such as these are essential for the maintenance of the services offered by the estuary. Rainfall is the most important factor in promoting seasonal discharges and maintaining ecosystem health in regions with resources-limited watersheds. Late dry season is a critical point, where due to tropical temperatures and low water renewal, water quality is reduced. As suggested by this study, early dry and early rainy open conditions intermediate to late rainy and late dry, which present environmental responses to stressors. The assessment of future impacts on estuaries requires a multidisciplinary approach that addresses the interaction between environmental responses, combined with several other sciences.

6 INTERANNUAL AND SEASONAL VARIATIONS IN WATER QUALITY OF A TROPICAL ESTUARY

6.1 INTRODUCTION

Water is an indispensable natural resource for human survival, and essential for the development of most our activities (WHO, 1996). Its abundance on earth's surface gave rise to the thought that it would be an inexhaustible resource, not being initially considered as deserving of conscious use, or reason to significantly shift the demand/availability ratio to an unfavourable condition. Among the multiple uses of water, the highlights are the public and industrial supplies, agricultural irrigation and electricity production. More recently leisure and recreational activities, carried out in various water bodies (WHO, 2014) also became primordial users. However, nature conservation is probably the main present concern, since to guarantee the provision of ecological services and access to resources became a matter of water and food security.

Many communities emerged close to where water could be easily obtained in order to ensure food and maintenance of the population. Estuaries are examples of environments that provide the means necessary for the development of human communities (WHO, 2014, 1996), and support large numbers of individuals. These ecosystems are in coastal areas, in the transitional range between the fluvial and marine environments, influenced by the maritime amplitude, which causes a marked variation of its environmental parameters, such as nutrients and salinity (Kennish, 1998, 1991). On the other hand, fluvial discharge also modulate pulses of flushing driven by rainfall patters. These patterns are especially contrasting (dry and rainy seasons) in tropical latitudes.

The contribution of organic matter from the drainage basin provides the estuarine regions with an important biological productivity potential. Therefore, estuaries have the capacity to shelter numerous species, from the juvenile forms to the adult phases, which use the environment for feeding, breeding or protection from predators; in addition to resident species, that spend their entire life cycle in estuaries, many of these resources reach high economic values (Barletta and Dantas, 2016; Kennish, 1991).

So, estuaries are occupied by much of the world's population (WHO, 2014, 1996), being exposed to different anthropogenic pressures from the entire drainage basin such as effluents releases, as well as local impacts such as port activities (Kennish, 1991;

Marques et al., 2004). These direct and indirect influences cause imbalances on the natural dynamics of these environments, rendering them vulnerable and fragile (Lacerda et al., 2006; Marques et al., 2004; Ribeiro and Kjerfve, 2002).

Water quality loss in estuaries is one of the worst forms of water pollution (Karydis and Kitsiou, 2013; Trott and Alongi, 2000). The main causes of decline quality of the estuarine aquatic bodies are related to damming, water subtraction, releases of agricultural, domestic and industrial effluents, altering the physical, chemical and biological properties of water (Karydis and Kitsiou, 2013; Mohebbi et al., 2013). These changes are promptly transmitted to coastal waters and beyond to the open seas.

Several efforts are currently being made to provide current and future generations with mechanisms and tools to improve the quality of surface water resources (WHO, 2014) on land. Continuous monitoring of water quality parameters is essential for maintaining the best possible water conditions across entire basins, including the estuaries and adjacent coastal waters. Consistent information on water quality and its patterns of change is the key to better manage and use these resources rationally (Karydis and Kitsiou, 2013; WHO, 1996). Being capable of accommodate changes (episodic or permanent) to managerial plans require a solid knowledge about the drives of water quality and natural resources availability at different timescales.

The objective of the present study was to describe and discuss the interannual and seasonal changes of water quality based on indicators monitored in the Goiana River estuary, as well as identifying the main drivers of such changes.

6.2 METHODS

6.2.1 Study area

Situated on the Brazilian east coast, Goiana River estuary (7 30'S - 34 47'W) (Figure 16) is located in the coastal border of Pernambuco and Paraíba states, being their natural territory shared between these two geopolitical units and their transboundary waters (Barletta and Costa, 2009; Dantas et al., 2010; Marques et al., 2004; Silva et al., 2013). The main activities developed along the Goiana River Basin are: sugarcane agro-industry, industrial activities and urban occupation where most of the effluent is discharged directly into the water, causing damages to the fullest extent of the basin, in addition to water use for public supply and irrigation (CPRH, 2015; Garlipp et al., 2010). At the estuary, the impact of greater significance is caused by crops, prawns farming and processing, which are connected directly to the deforestation of the mangrove vegetation (Barletta and Costa, 2009; CPRH, 2015; Garlipp et al., 2010). Despite recent trends in economic diversification, the area remains strongly linked to agricultural activities.

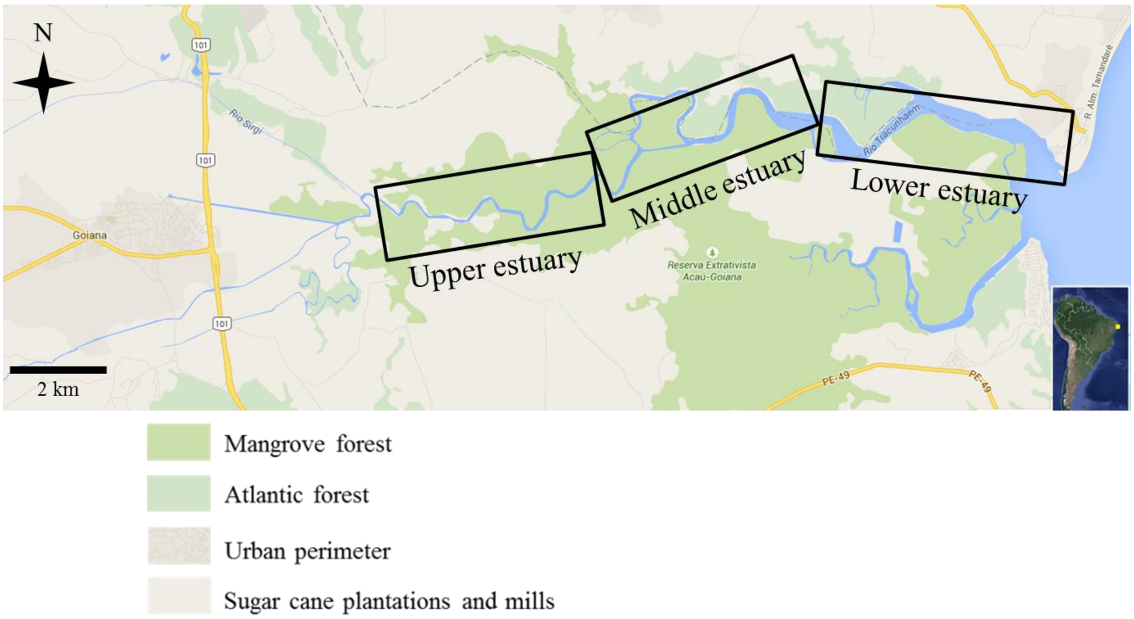

Figure 16: The location of Goiana River estuary, showing the upper estuary , middle estuary and lower estuary along the main channel. Source: Google maps, adapted.

According to Barletta and co-authors (2005), the main axis of an estuary can be sectioned into large compartments or reaches - upper, middle and lower - considering its morphology, as well as water parameters, mainly salinity, since riverine environments down to adjacent coastal areas. Each section of the channel is an ecosystems' habitat, with different biogeochemical behaviour, plant and animal communities, giving rise to an ecological gradient (Attrill and Rundle, 2002; Barletta and Dantas, 2016). Composed of a combination of rivers, streams, ponds, tidal channels, islands, wetlands and flooded mangrove forests, the estuary accommodates a diverse aquatic fauna (fish, mollusks, crustaceans) (Barletta and Costa, 2009; Dantas et al., 2010; Lima et al., 2014) with high conservation, social and economic importance. The main channel has a total length of ~25 km (Barletta and Costa, 2009; Dantas et al., 2010; Marques et al., 2004; Silva et al., 2013). The upper estuary varied in depth from 1.2 to 11.6 m, the midle estuaru ranged from 1.2 to 10.1 m and the lower estuary had a depth variation of 1.0 to 9.1 m.

2.2 Data acquisition

The sampling strategy adopted in this study was successfully used by several authors (Barletta et al., 2008, 2005; Dantas et al., 2010; Lima et al., 2014), attesting for the robustness of sample design. The strategy was implemented from 2006 to 2009 in this estuary. Were considered three estuarine areas (upper, middle and lower estuary) and two seasons (dry and rainy). The months chosen for this study were those at the end of the seasons, where the environment presents clearer responses to the environmental stressors. The information was collected for surface and bottom waters (6 points in each area during three months of each season) and include the water temperature (°C), salinity, dissolved oxygen (mg L^{-1}) and oxygen saturation (%) (measured with a WTW LF 197, Wissenschaftlich Technische Werkstätten doted of a 20 m cable), and Secchi depth (cm). The monthly total rainfall (mm) was compiled from public database (www.apac.gov.pe.br), collected from a weather station located 10 km south of the city of Goiana.

6.2.3 Statistical analysis

The data collected were processed into a perfectly balanced matrix for analysis. First, the analysis of variance (ANOVA and MANOVA) were carried out. Was used to determine whether significant differences in variables (water temperature, salinity, dissolved oxygen, oxygen saturation and Secchi depth) occurred in years (2006, 2007, 2008 and 2009), areas (upper, middle and lower estuary) and seasons (dry and rainy). Where ANOVA showed a significant difference, an *a posteriori* Bonferroni test was used to determine which means were significantly different at the 0.05 level of significance. Cluster analysis was performed using method unweighted pair-group average with Euclidean distance, and principal components analysis was made using a 95% confidence interval, for all variables studied. All procedures used Statistica 7.0.

6.3 RESULTS

The variables (water temperature, salinity, dissolved oxygen, oxygen saturation and Secchi depth) were first studied and analyzed separately, in order to know their individual behaviour (Appendix 6 to 9), and detect possible differences between surface and bottom waters. With the MANOVA results, it was possible to observe that there was no effect of depth on the parameters studied ($p > 0.05$, no significant difference). Therefore, depth was not considered in the further analysis, and the samples from surface and bottom waters were treated as replicates, bringing the sample number from six to twelve.

Monthly total rainfall ($p < 0.01$) in the studied period ranged from 20.2 mm to 364.0 mm. In the dry season the averages were between 33.9 ± 8.5 mm and 184.1 ± 106.0 mm, while in the rainy season the range was 233.4 ± 102.3 mm to 286.6 ± 57.2 mm (Figure 17 and Figure 18). Among the dry seasons, 2006 presented the lowest rainfall (33.9 ± 8.5 mm). Dry seasons of the years 2008 (185.2 ± 144.5) and 2009 (184.1 ± 106.0), presented very similar behavior to rainy seasons of all years (climatic average 1961-1990). Rainy seasons presented a very similar pattern in all the studied years, varying less than dry seasons during the study period in respect to total monthly rainfall.

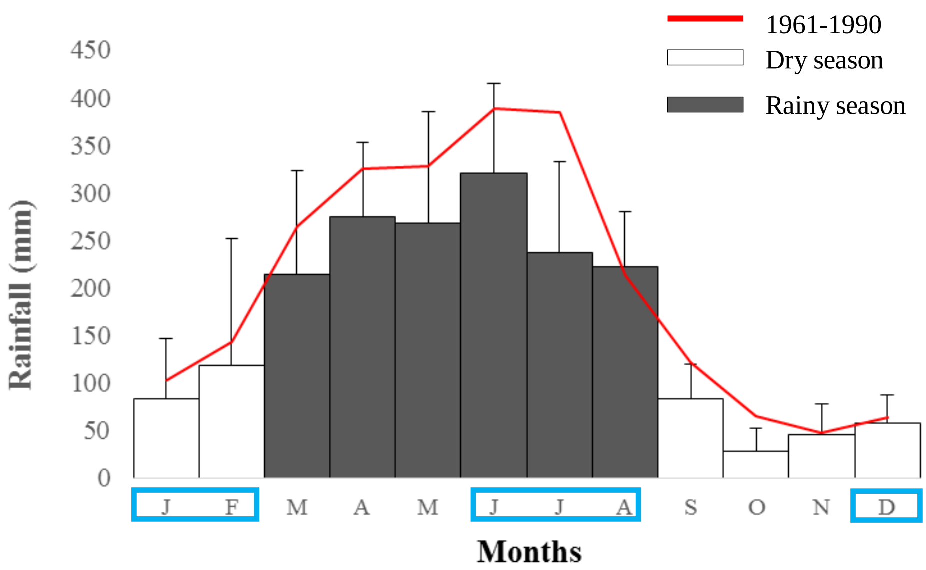

Figure 17: Most recent climatic rainfall average 1961 - 1990 (red line) and at Goiana River estuary in the periods 2006 - 2009 (bars) (highlighted months (blue) were those used in this study).

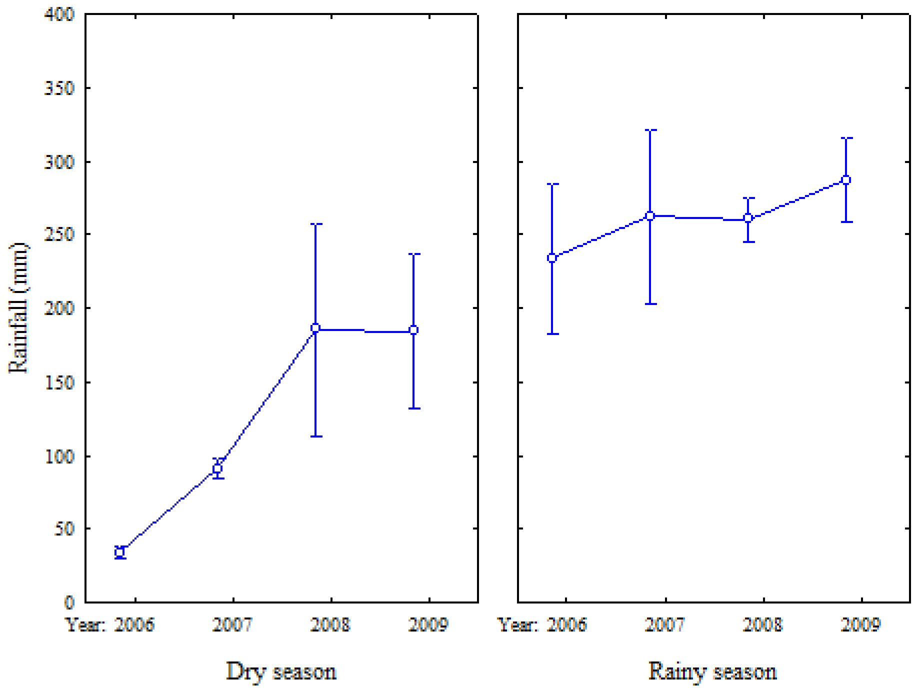

Figure 18: Average seasonal rainfall of the years studied (2006-2009).

Water temperature ($p < 0.01$) varied from 25.3 to 31.4°C, presenting values with small variation between the years and areas, and higher in the dry season (Figure 19). Variations were less prominent in the rainy season. Upper and middle areas showed no differences but were different from the lower area. Year 2009 was different from the others. The seasons were also different (Table 4).

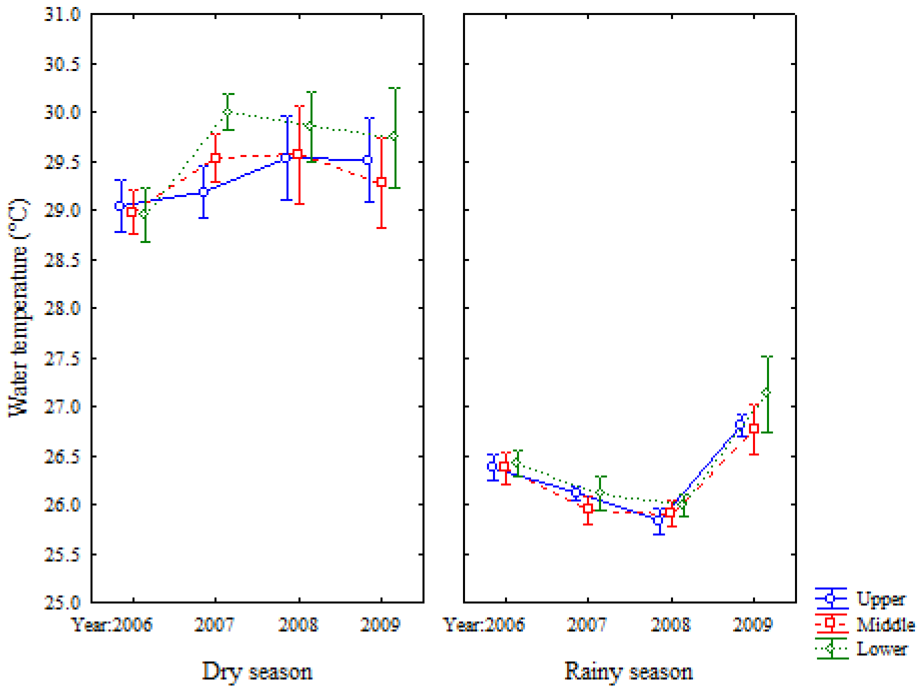

Figure 19: Average (±standard deviation) of temporal (interannual and seasonal) variations of water temperature at the Goiana River estuary from 2006 – 2009.

Table 4: Summary of the ANOVA results for water temperature, salinity, Secchi depth, dissolved oxygen and saturation for year - 2006 (06), 2007 (07), 2008 (08), 2009 (09) for estuarine area - upper (U), middle (M), lower (L) - for season - dry (D), rainy (R)

	Source of variance			
Parameters	Year (1)	Area (2)	Season (3)	Interaction
Water temperature	**	**	**	**
	06 07 08 09	U M L	D R	1x3
Salinity	**	**	**	**
	07 08 06 09	U M L	D R	1x2x3
Dissolved oxygen	**	**	**	**
	06 07 08 09	U M L	D R	1x2x3
Oxygen saturation	**	**	NS	**
	06 07 08 09	U M L		1x2x3
Secchi depth	**	**	**	**
	06 07 08 09	U M L	D R	1x2x3

NS, non-significant differences (p>0.05); *, p<0.05; **, p<0.01; differences among area and season were determined by Bonferroni test (p<0.05) *post hoc* comparisons.

Salinity ($p < 0.01$) varied from 0 to 36.9, with 121 of the 432 sampled values being equal to zero, especially in areas upper and middle during the rainy season. Areas and seasons were different (Table 4) (Figure 20).

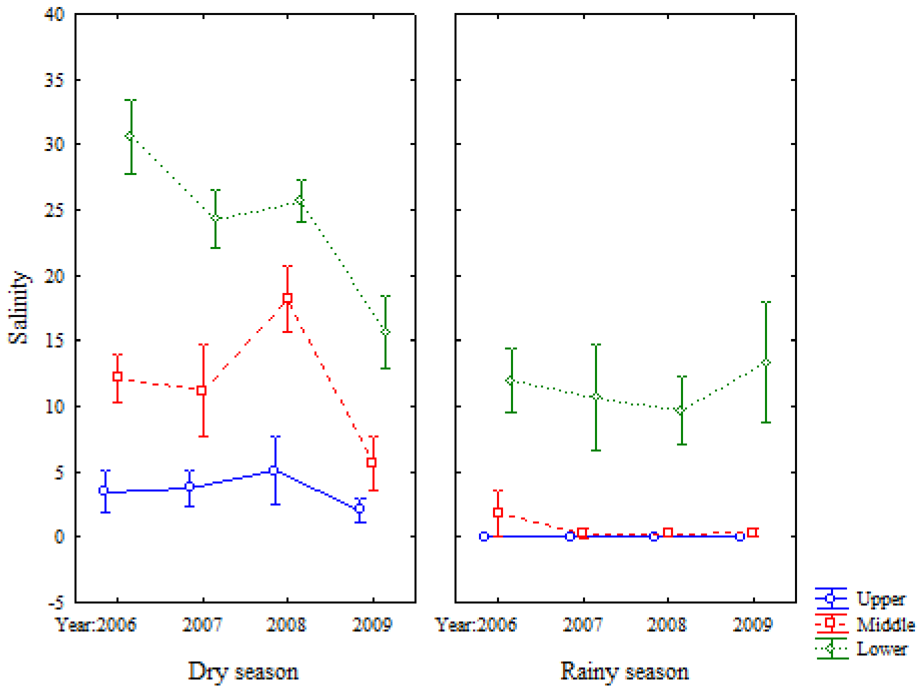

Figure 20: Average (±standard deviation) of temporal (interannual and seasonal) variations of salinity at the Goiana River estuary from 2006 – 2009.

Dissolved oxygen ($p < 0.01$) varied from 1.4 to 10.4 mg L^{-1} in the period, with the highest averages concentrated in the lower estuarine portion (Figure 21). Figure 22 shows the histogram with the normal distribution of the number of observations of dissolved oxygen values obtained (n=432). It is observed that the observations are in a wide range, from 0 to 11 mg L^{-1}, but with a higher number of observations between 4 and 6 mg L^{-1}. For this parameter, 4.2% of the values were between 0 and 2.9 mg L^{-1} (critical); 42.8% between 3 and 4.9 mg L^{-1} (acceptable) and; 53.0% of the values were ≥ 5mg L^{-1} (safe) (Figure 22). The seasons were different, as was the lower area and the year 2009 (Table 4).

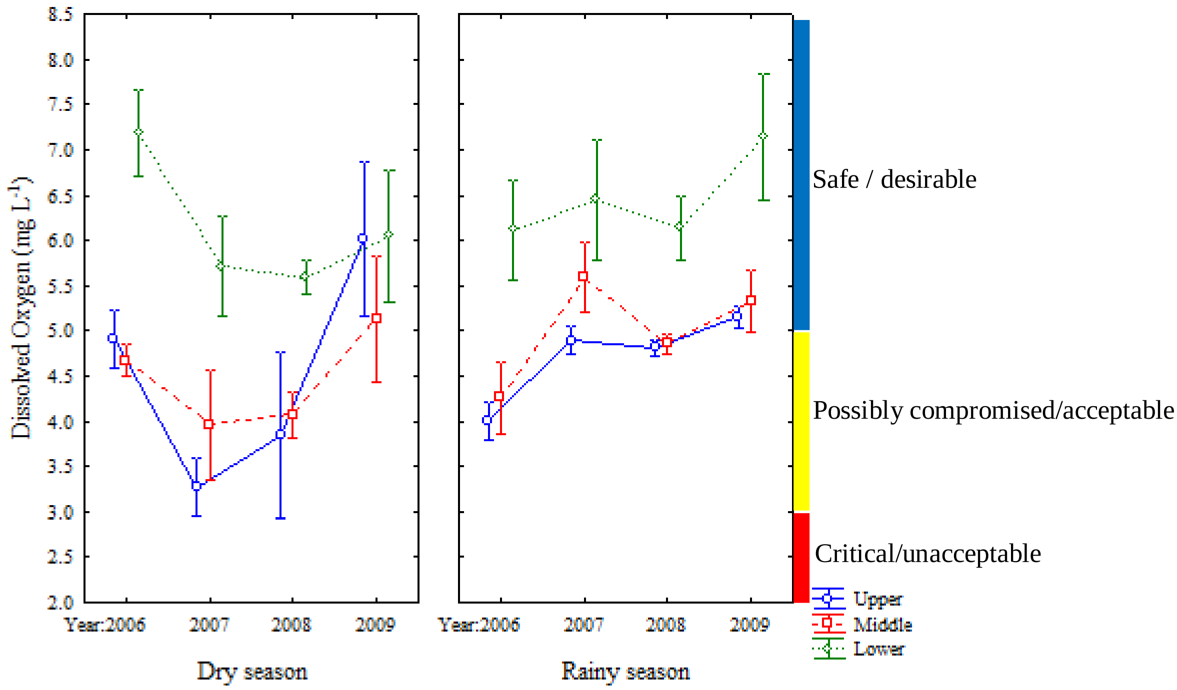

Figure 21: Average (±standard deviation) of temporal (interannual and seasonal) variations of dissolved oxygen at the Goiana River estuary from 2006 – 2009. The colour scale shows the levels of water quality according to this parameter.

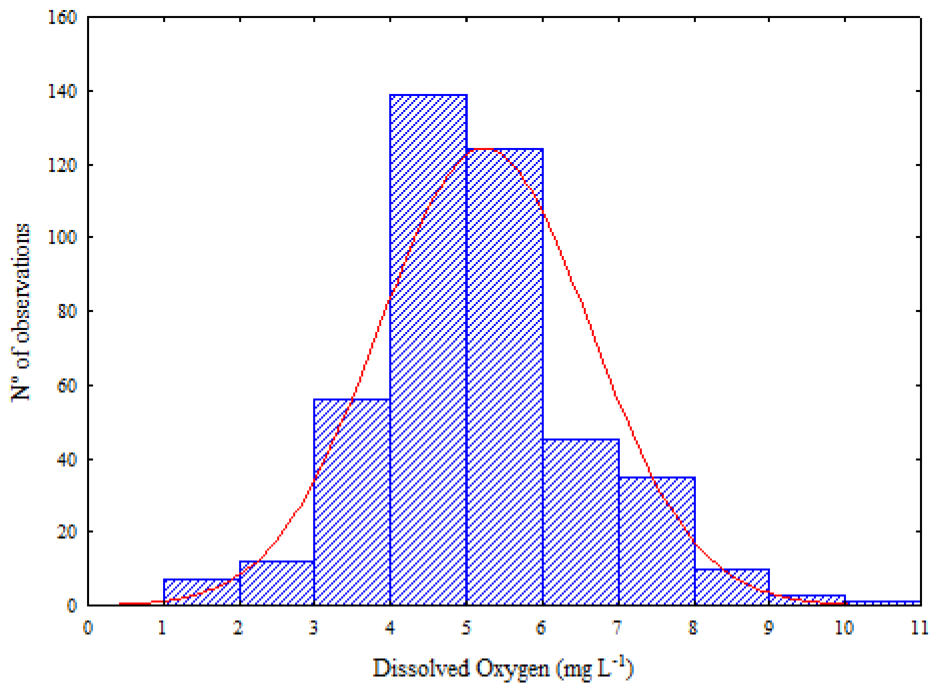

Figure 22: Histogram of observations (n=432) for dissolved oxygen, following the normal distribution.

Oxygen saturation ($p < 0.01$) showed values between 17 to 123.7% and followed the trend of averages presented by dissolved oxygen (Figure 23). There were no significant differences between seasons (Table 4).

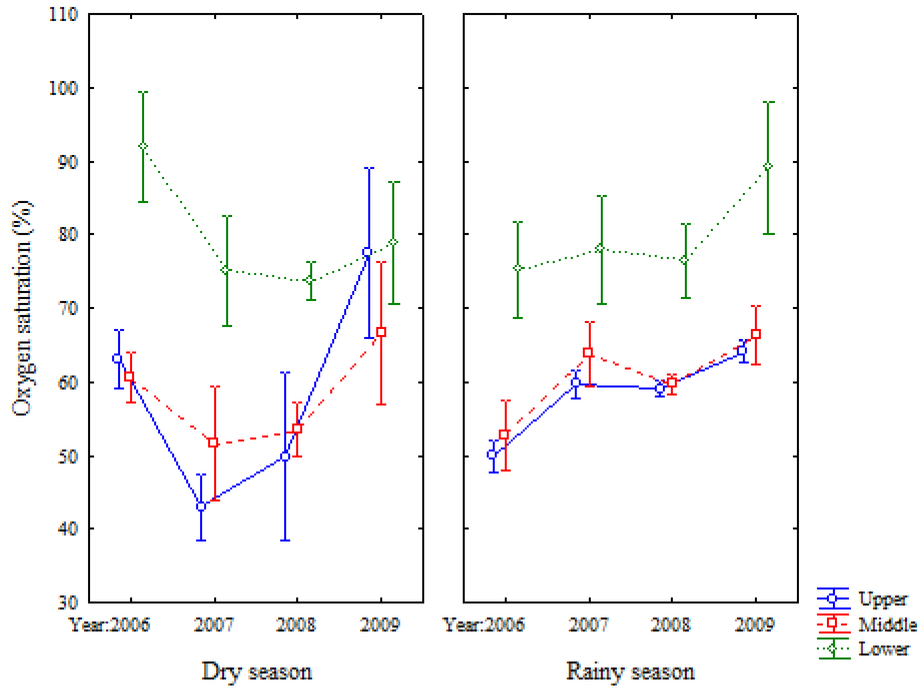

Figure 23: Average (±standard deviation) of temporal (interannual and seasonal) variations of oxygen saturation at the Goiana River estuary from 2006 – 2009.

Secchi depth ($p < 0.01$) varied from 12 to 276 cm, showing large variations between the years in the dry season, while in the rainy season the measures were more homogeneous, once again showing less variability during the rainy season (Figure 24). All factors (year, area and season) were significantly different (Table 4).

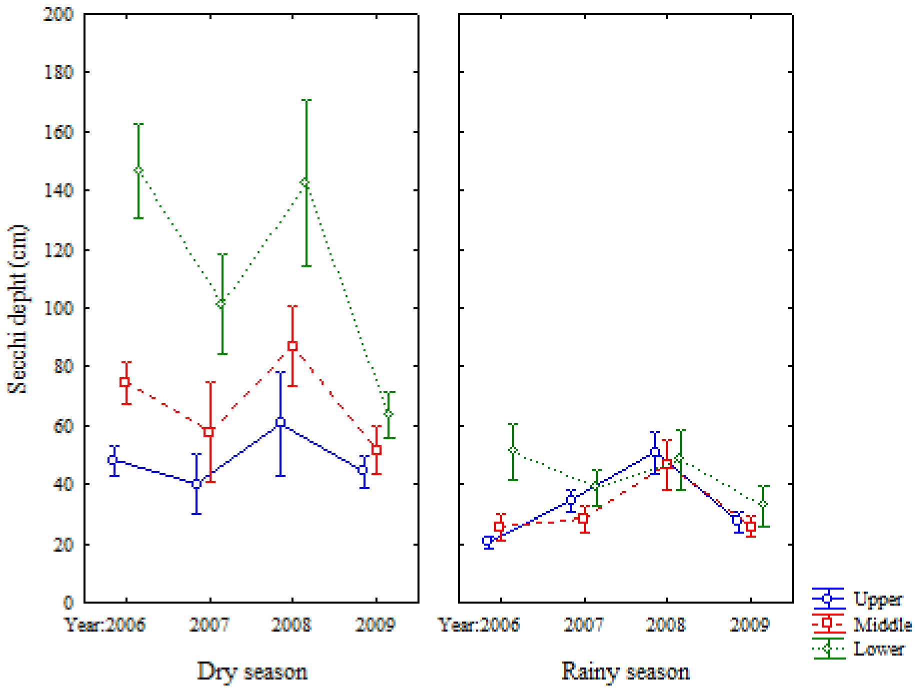

Figure 24: Average (±standard deviation) of temporal (interannual and seasonal) variations of Secchi depth at the Goiana River estuary from 2006 – 2009.

The multivariate analyses highlight the inter dependency among water physico-chemical parameters. For these analyses, observations were homogenized in averages (n=24), due to the large number of samples (n=432), allowing for better observation and interpretation of results. The averages were made between samplings of the same spatiotemporal condition (year, area and season).

In the cluster analysis (Figure 25), the observations were grouped into 2 major groups, I e II. Group I was subdivided into 2 subgroups. Subgroup IA, comprises samples from 2008, in lower area, in the dry season; subgroup IB, was subdivided in IB1, samples taken in years 2008 and 2009, in the three areas, during the dry season, with the exception of one sample from 2006, middle area in the rainy season and; IB2, samples from all 4 years in the three areas during the rainy season. Group II presented two subgroups: IIA, which comprised the samples from year 2006, in lower area, in the dry season. In subgroup IIB were samples from years 2006 and 2007, in upper and middle areas, during the dry season.

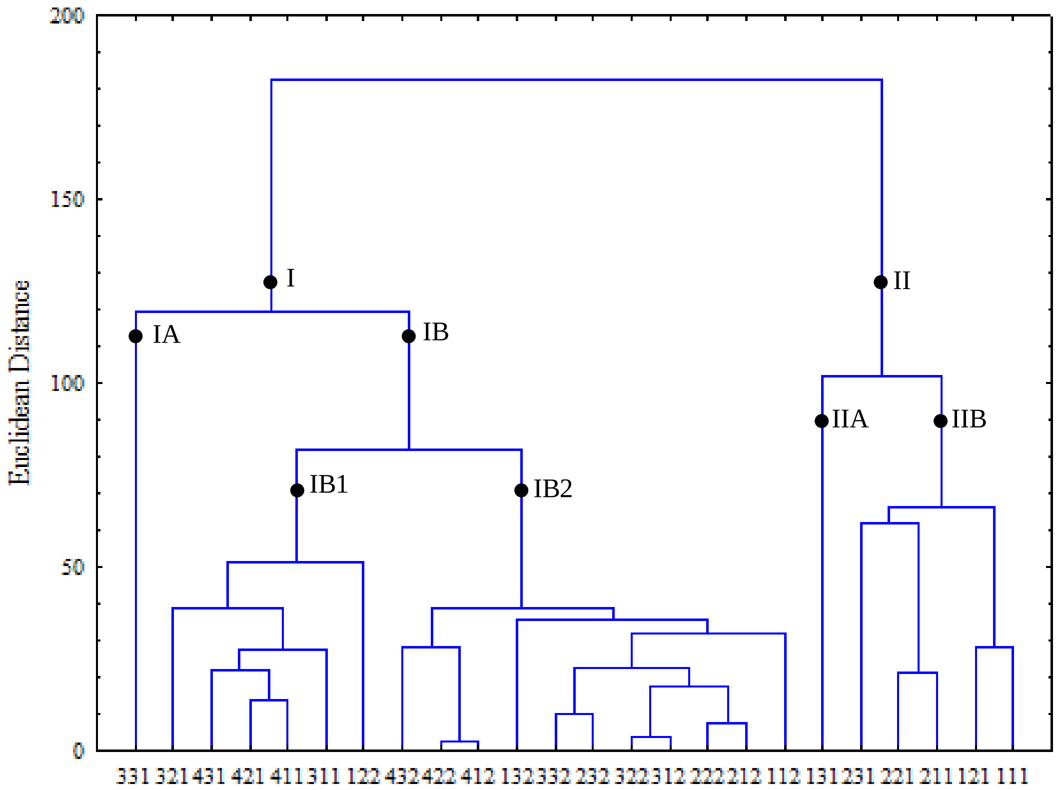

Figure 25: Cluster of interannual seasonal averages of water quality parameters and rainfall at the Goiana River estuary through Euclidean distance. Legend for samples: first numeral represents the year (1 - 2006, 2 - 2007, 3 - 2008, 4 - 2009); second numeral represents estuarine area (1 – upper, 2 – middle, 3 – lower) and thrid numeral represents season (1 – dry, 2 – rainy). Ex. 132 are samples from 2006, lower estuary, rainy season.

Interpreting the principal components analysis, 87.23% (PC1 and PC2) of the variation of the data are satisfactory explained, revealing inter-relations among variables. According to Clarke and Warwick (2001), a PCA must explain 70% or more of the initial variations in a data set. If so, it is a reasonable interpretation of the phenomenon, or global structure of interactions. In this case, PC1 explained 52.60% of the total variance, while PC2 represented 34.63% (Figure 26).

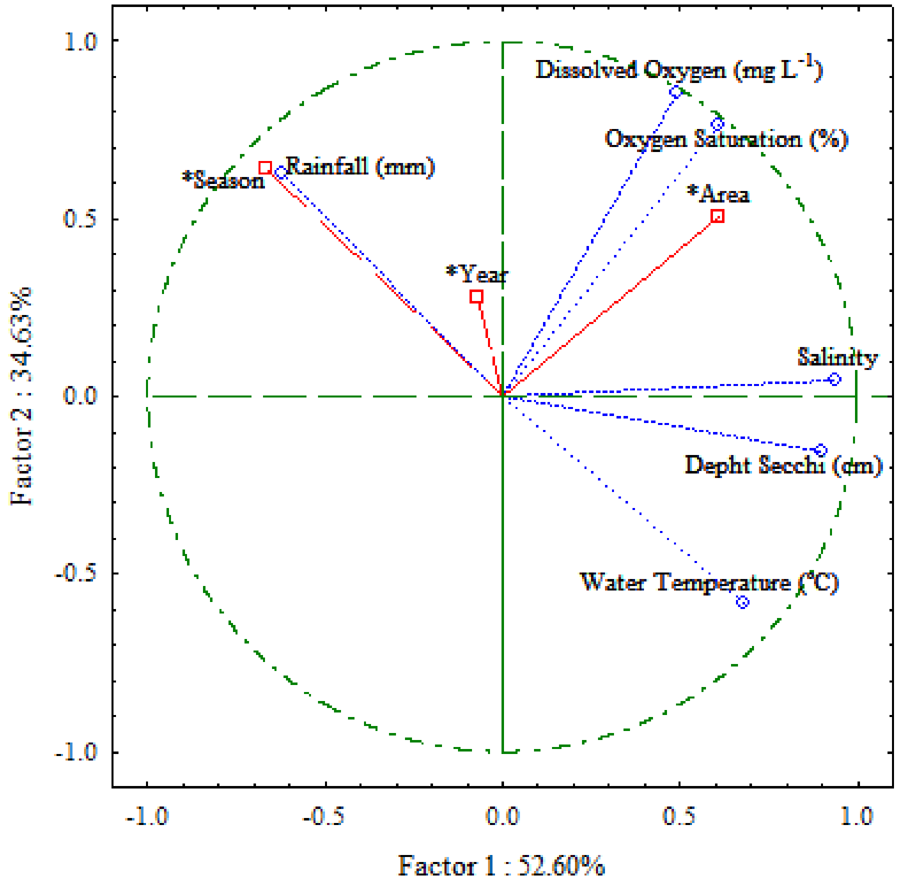

Figure 26: Weight graph (PCA) showing the contribution of environmental variables to the water quality patterns at the Goiana River estuary from 2006 - 2009.

In the scores graph, 4 groups were identified: X, Y, W e Z. Group X collected the samplings carried out in the upper and middle areas in the rainy season. Group Y collected the samples obtained in the lower area in the rainy season. Group W collected the samples from the lower area in the dry season and group Z collected samples from the upper and middle areas in the dry season (Figure 27).

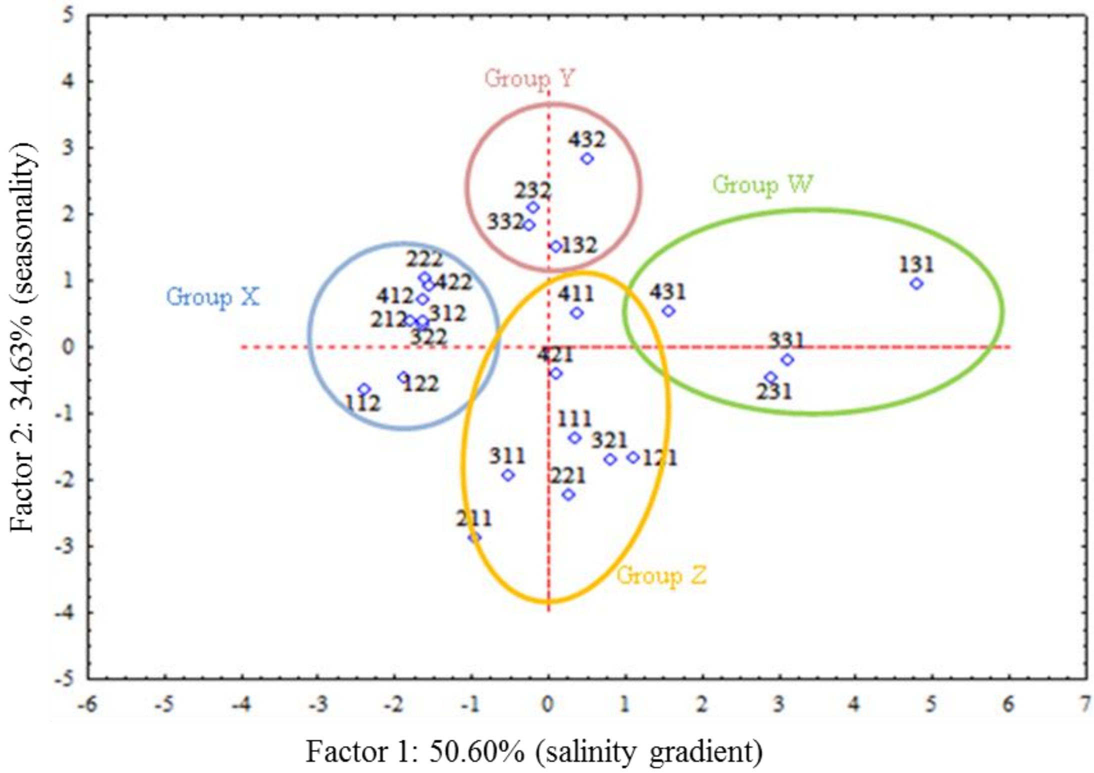

Figure 27: Score graph (PCA) showing the contribution of environmental variables to the water quality patterns at the Goiana River estuary from 2006 - 2009. Legend for samples: first numeral represents the year (1 - 2006, 2 - 2007, 3 - 2008, 4 - 2009); second numeral represents estuarine area (1 – upper, 2 – middle, 3 – lower) and thrid numeral represents season (1 – dry, 2 – rainy). Ex. 132 are samples from 2006, lower estuary, rainy season.

6.4 DISCUSSION

The parameters of interest were analysed individually and integrated in order to give a clearer and complete description of their interactions and processes occurring in the main channel of the estuarine environment.

Water temperature was strongly marked by seasonality. The difference between years was small, but the difference between seasons was highlighted. The estuary is located in a tropical area (Barletta and Costa, 2009), which favoured high water temperatures throughout the year. This factor can affect the dissolution of gases like oxygen in the water, decreasing the availability (Harrison and Whitfield, 2006; Kong and Ye, 2014).

Salinity variations defined the estuarine gradient (Attrill and Rundle, 2002; Barletta and Dantas, 2016). In the year 2006, the dry season was very severe (33.9 ± 8.5 mm), decreasing freshwater intake in the estuary and significantly increasing salinity locally, with the greatest marine influence on the estuary.

Water temperature and salinity are important abiotic variables, which together play an important role in the distribution of aquatic biota, with the determination of ecoclines (Attrill and Rundle, 2002; Barletta and Dantas, 2016; Harrison and Whitfield, 2006; Nejrup and Pedersen, 2008). Sudden and/or large changes in these parameters may compromise environmental quality over time, as may change the composition and distribution of biota (Lucena-Moya and Duggan, 2017; Paul and Calliari, 2017), alteration of areas of high ecological importance considered nursery (Barletta et al., 2005; Blaber, 2013), increase the effect of pollution on estuaries as may distribution of plastics and microplastics (Ivar do Sul et al., 2014; Ivar do Sul and Costa, 2013; Lima et al., 2014; Possatto et al., 2011), dilution of effluents (Govindasmy and Chandrasekaran, 1992; Telesh and Khlebovich, 2010; Uriarte and Villate, 2004; Whitehead et al., 2009), absorption and accumulation of pollutants by biota (Zhou et al., 2017).

The dissolved oxygen and oxygen saturation showed similar behaviour, although the water temperature also influenced oxygen saturation indexes. The temperature variation was small, being predominant the interdependence between the dissolved oxygen and its saturation (Nezlin et al., 2009; Shah and Pant, 2012). The oxygen contents were higher in the lower area of the estuary, where there is a greater influence of marine waters, more oxygenated (Zhang et al., 2010). The year 2009 presented an atypical character related to the oxygen concentrations, due to the dry season of this year to have similar pluviometric indices of the rainy season of that same year. There was homogenization of the oxygen distributed, making the values measured for this parameter similar in all the estuarine areas. The levels of dissolved oxygen recommended for aquatic conservation are above 4 - 5 mg L^{-1} (Osode and Okoh, 2009; Pearce and Schumann, 2001), being in some moments lower values, resulting from anthropic interference.

Secchi depth presented higher values in the dry season, when the water column is more stable, lower resuspension of particles, as well as lower flow sediment and particulate leached by rain. In the rainy season as well as in the dry season of 2009, lower values are observed, due to the greater volume of the rains, increasing the turbidity, being able to shift the primary production (Kronvang et al., 2005; Schlacher and Wooldridge, 1996). The variation of solar radiation is not a determining factor because the estuary is located in a tropical area (Kronvang et al., 2005; Qasim et al., 1968).

6.4.1 Episodic hypoxia

According to Zhang and co-authors (2010), hypoxia in coastal waters can be of natural and/or anthropogenic origin, and is defined by levels of dissolved oxygen < 2 mg L^{-1} and < 30% of oxygen saturation. In this study, there were some episodes of hypoxia (18 in 432 observations), mainly during the dry season, in the upper and middle areas of the estuary (Figures 21 and 22). In these moments, river flow and the renewal of the waters was severely affected by lack of rainfall both along the basin and locally. Concentrations of dissolved oxygen in surface waters are regulated by the balance between production, consumption (respiration and other chemical reactions) and exchange with the atmosphere (Uriarte and Villate, 2004; Wannamaker and Rice, 2000). The decrease in renewal caused the consumption of available oxygen in the water to almost its entirety. Also, less flow results in limited turbulence and consequently less diffusion from the atmosphere. Hypoxia is a typical consequence of continued decline in water quality. It may result in habitat degradation and habitat loss (Gelesh et al., 2016; Wannamaker and Rice, 2000). In the South American continent, a number of hypoxia cases have already been reported in the scientific literature (Costa and Barletta, 2016). Authors call the reader's attention to the inevitable vulnerability of shallow and warmer waters from tropical estuaries.

Hypoxic conditions will, eventually, be responsible for decrease in biota abundance and diversity (Uriarte and Villate, 2004), altered growth and mortality rates of juvenile fish (Wannamaker and Rice, 2000), altered behaviour, feeding and other habits change (Zhang et al., 2010), methane production (Gelesh et al., 2016). The phenomenon is, in addition, aggravated by acidification (Miller et al., 2016) and global warming (Zhang et al., 2010). All these changes concur for permanent environmental changes and, finally, resilience rupture at an ecosystem scale.

The samples analysed in the present work were taken from the main channel of the estuary, where water is expected to have the best possible chances of renewal and oxygen diffusion/production. There is a higher than average chance that hypoxia is already installed at smaller tidal creeks and less turbulent reaches of the drainage system that composes the estuary (Ramos et al., 2011). If, the frequency, range and duration of such hypoxia episodes increase in the Goiana River estuary in the future, there will be cause of concern for the conservation of water resources, and should therefore be closely monitored.

6.4.2 Variables interdependence

In 2006 and 2007, seasons (related to rainfall) were better defined, expected for the region. Already in the years 2008 and 2009 presented the rainfall throughout the year more homogeneous and in greater quantity, condition other than the region default. Due to this fact, even in the dry season, the estuary presented the behavior similar to that presented in the rainy seasons of the studied years. The change in the quality of the water resulting from the change in the amount of rainfall was noticed thanks to the monitoring carried out. Planned monitoring is also an important tool for the detection of cyclic phenomena, which are detected only at larger temporal scales (Karydis and Kitsiou, 2013; Renjith et al., 2011; Silva et al., 2013).

In estuaries, basin-wide to local rainfall is one of the main factors determining the quality of its waters (Corbari et al., 2016; Eyre, 1997; Karydis and Kitsiou, 2013). Although it temporarily reduces the depth of sunlight penetration into the water column, limiting primary production (Cloern et al., 2014; Kronvang et al., 2005; Qasim et al., 1968), the freshwater input promoted the increase of available oxygen, as well as the diffusion, dilution and transportation of effluents and pollutants (Brooks et al., 2006; Osode and Okoh, 2009).

In the weights graph (Figure 26), PC1 (52.60%) represented the estuarine gradient or ecocline, with the salinity being the main determinant. Dissolved oxygen, its saturation and Secchi depth followed the salinity gradient, increasing towards the mouth of the estuary. These parameters tend to increase in waters with greater marine influence, the striking characteristics of the lower estuary area (Dantas et al., 2010; Jutagate et al., 2010; Karydis and Kitsiou, 2013). PC2 (34.63%) represented the seasonality, with rainfall being the main forming variable. The water temperature also appeared as a major contributor to the formation of the axis, where the seasonal difference was well marked, mainly due to the location of the estuary (Barletta and Costa, 2009; Blaber, 2002; Harrison, 2004; Harrison and Whitfield, 2006).

In the scores graph it is possible to observe that the upper area presents a greater stability throughout the year, being an area used as nursery, cited by several authors (Barletta et al., 2008, 2005, Blaber, 2002, 2013; Cabral et al., 2012; Ceesay et al., 2016; Dantas et al., 2010; Franco et al., 2008; Jutagate et al., 2010; Lima et al., 2014; Lucena-Moya and Duggan, 2017; Reis-Filho and Santos, 2014). The intermediate character of middle area is well marked. Influenced by the rainy season, the behavior similar to that of the upper area (group X), while in the dry season presents behavior tending to the marine (group Z), as described by (Barletta et al., 2005; Dantas et al., 2010; Lima et al., 2014). The middle estuary behaves as a buffer between the two other habitats, preventing sudden and/or wide changes in water quality (including pollutants; see Lima et al., 2014) in the upper and lower reaches. Only a strong seasonal flush caused by the river discharge during end of rainy season can briefly break this system and allow river water to reach the sea without previous mixing. However, the lower area presented a predominantly marine character. Due to the occurrence of rainy season (group Y), the characteristics of this estuarine portion approximate slightly the characteristics of the other portions of the estuary, influenced by freshwater input. In dry season the influence is almost exclusively marine (group Z). These fluctuations in the estuary define the use made by biota and humans. Species that use areas with lower salinities as nursery and for protection may enjoy larger spaces during the rainy season; in contrast, marine species enter the estuary and make use of larger areas primarily for food (Barletta et al., 2005; Blaber, 2002, 2013, 2007; Dantas et al., 2010; Lima et al., 2014).

6.4.3 Management and conservation implications

Water scarcity is a critical problem in the world. In the area to the east of South America there are no large river basins, so the numerous small estuaries along the coast are the most important source of water for the most diverse uses (IBAMA, 2006; WHO, 1996). A number of times, rainfall is the most important factor in the renewal and maintenance of these waters (Schlacher and Wooldridge, 1996), causing considerable improvement in their quality (Corbari et al., 2016; Eyre, 1997; Karydis and Kitsiou, 2013), however, of a temporary nature.

The important relationship dependence of the Goiana River estuary of the precipitation to the renewal of its water resources was also observed in other estuaries. Mérigot and co-authors (2016) observed in four estuarine complexes in Brazil and Harrison (2004), in South Africa, in another 109 studied estuaries. The maintenance of these waters is crucial for the continuity of the provision of ecological services (Corbari et al., 2016; Karydis and Kitsiou, 2013; Marques et al., 2004).

Climatic events, such as above-average precipitation years (2008 and 2009), contribute in principle to improving environmental conditions (Bouvy et al., 1999; Jackson et al., 2001; Nijssen et al., 2001). However, changes in rainfall and freshwater discharge patterns from basins can increase freshwater flows, to change the flow rate and to increase the sedimentary loads with potential to alter the morphology of the environments, as well as altering natural biogeochemical cycles, thus impacting habitats (Arnell, 1999; Whitehead et al., 2009). Since such changes are driven by deforestation of the basin soil and estuary margins, consequences are permanent, although partially reversible if the vegetation is minimally restored.

The Goiana River estuary is under human interferences. Like many other estuaries, it is highly impacted by sugarcane plantations (Brockmeyer and Spitzy, 2011; Davis et al., 2013; Gurgel et al., 2016; Thorburn et al., 2011; Valera et al., 2016).

The tropical soils present low levels of organic matter, causing difficulties for their maintenance for the cultivation of sugarcane. The use of large quantities of fertilizers is necessary for the yield of crops which are carried towards the estuarine channel by the rainfall (Brockmeyer and Spitzy, 2011; Govindasmy and Chandrasekaran, 1992; Humbert, 2013).

The projected trend of change influenced by anthropogenic actions in the global climate includes several events: water heating (change in chemical kinetics of reactions in the estuary, stratification of the water column); rising sea levels; reduction of water pH (acidification); loss/replacement of habitats (species migration, invasion of exotic species) and the expansion of the tropics (IPCC, 2007; Madsen et al., 2014; Whitehead et al., 2009; Zhang et al., 2010). The importance of environments such as tropical estuaries will be even more prominent in the near future, demanding a considerable understanding of the functioning of these ecosystems. In addition the demand for water resources tends to increase and the quality of surface water will become a priority (IPCC , 2007; WHO, 2014).

6.5 FINAL REMARKS

Our work assessed the water quality conditions at the main channel Goiana River estuary from 2006 to 2009, a period when a number of other ecological studies were also conducted along the main channel of the estuary. The sample design used allowed for the detection of interannual changes in water quality due mainly from variations in rainfall patterns. It also corroborated previous ecological studies by confirming that the aquatic habitats of the main channel offer conditions to the maintenance of biological resources most of the time.

Water quality in the study area remains overall reasonable, despite hypoxia events. These events should be seen as a warning sign of the sensitivity and vulnerability of this environment to human interferences (e.g. domestic effluents discharge, sugarcane irrigation, fertilization and milling effluents).

As a way to maintain environmental quality, measures to mitigate impacts on the aquatic habitas start with basin-wide mitigation actions, and include the estuarine region. Soil use and occupation, as well as water uses (restoration of riparian vegetation, soil recovery, and effluents treatment before disposal) must be improved. Measures such as these are essential for the maintenance of the ecosystem services offered by the estuary. There is uncertainty about the likely impacts on water quality due to changes in regional rainfall patterns - especially due to deforestation and increasing demands on water resources. Projects for new water supply, urban drainage and water treatment systems will have to account for the effects of local climate change.

Rainfall is an important factor in promoting seasonal discharges and maintaining ecosystem health in regions with resources-limited watersheds, especially those where flow control is in place. The dry season is a critical period, where due to tropical temperatures and low water renewal, the quality of the water can be severely reduced. As suggested by our results, the regions that are most sensitive to environmental and socioeconomic changes and overuse of their water resources should pay more attention to changes in seasonal and climatic rainfall patterns.

7 ANÁLISE INTEGRADA DA QUALIDADE DA ÁGUA NA BACIA E NO COMPLEXO ESTUARINO DO RIO GOIANA

7.1 INTRODUÇÃO

Os estuários são ambientes transicionais que oferecem inúmeras oportunidades de acesso a recursos e serviços essenciais para a sociedade, sendo por isso necessário encontrar um equilíbrio entre o uso humano e a sua conservação e, consequentemente a garantia da continuidade dessa oferta (Elliott et al., 2007; Elliott and Quintino, 2007). São sistemas muito produtivos e dinâmicos, muitas vezes associados a centros urbanos extensos e infraestruturas vitais (Harrison, 2004; Kennish, 1991). Avaliar os processos e recursos ecológicos em termos de bens e serviços que eles fornecem é atraente para diversos ramos da ciência e da sociedade, principalmente para os gestores responsáveis por garantira sustentabilidade ao uso de ecossistemas costeiros (Statham, 2012; Uriarte and Villate, 2004).

O enriquecimento das águas costeiras com excesso de nutrientes antrópicos é motivo de preocupação para os gestores de recursos responsáveis pela manutenção ou melhoria da qualidade da água (Li et al., 2015; Reed et al., 2016; Statham, 2012). Os nutrientes entram nas águas costeiras através de diversos mecanismos, incluindo escoamento da bacia hidrográfica, deposição atmosférica, águas residuais e efluentes (Statham, 2012). Identificar e quantificar estas várias cargas de nutrientes e gerir o seu componente antropogênico é um enorme desafio. Em muitas regiões, programas de monitoramento da qualidade da água fornecem conjuntos de dados para a avaliação quantitativa e os boletins de avaliação, que sintetizam os resultados (Hallett et al., 2016a, 2016b, 2016c).

O monitoramento contínuo de massas de água é uma tarefa complexa, uma vez que exige uma recolha de dados frequente e detalhada, além de esforços de interpretação (Karydis and Kitsiou, 2013). Apenas esforços consistentemente planejados e intensivos de amostragem e análise podem captar plenamente a variabilidade espacial e temporal de uma multiplicidade de indicadores-chave. Isto conduz necessariamente a um compromisso entre o número de estações de amostragem, frequência amostral e a necessidade de se manter os custos dentro de limites razoáveis (Karydis and Kitsiou, 2013; Kitsiou and Karydis, 2011; Lavery et al., 1993; Hallet, 2016), sobretudo se levarmos em consideração que esse tipo de atividade terá caráter permanente com o aumento da população costeira e as mudanças globais (ex. clima, ciclo hidrológico, variação do nível do mar) que se fazem cada vez mais presentes e impactam cada vez mais a qualidade das águas costeiras.

No mundo, há diversos problemas relacionados à falta de padronização de informações sobre coletas, análises laboratoriais e interpretação de dados em diversas escalas espaciais e temporais, o que torna os resultados existentes, muitas vezes, menos úteis e sua interpretação de difícil transposição entre regiões distintas (Karydis and Kitsiou, 2013; Lavery et al., 1993; Hallet, 2016), ou momentos distintos em uma mesma região. No Brasil, a compartimentalização da gestão das bacias agrava esta realidade (CPRH, 2015). Esse fato, somado a divulgação das informações para a população e os tomadores de decisão serem insuficientes na maioria das Unidades da Federação, gera dificuldades para a análise efetiva da evolução da qualidade das águas e elaboração de diagnósticos regionais e nacional (CPRH, 2015; CPRM, 2005). O objetivo deste capítulo foi integrar em uma única análise numérica e interpretação dados provenientes dos dois bancos de dados distintos, estimando assim a potencialidade desse tipo de iniciativa na detecção/interpretação das mudanças interanuais e sazonais da qualidade da água em parte da bacia e no estuário do Rio Goiana, estendendo/ampliando assim o alcance de diferentes estratégias amostrais.

7.2 METODOLOGIA

7.2.1 Área de estudo

O Rio Goiana (7 30'S - 34 47'W) (Figura 28), situado na costa leste brasileira, entre os estados de Paraíba e Pernambuco, tem uma área de drenagem de 2.878,30 km^2 (CPRH, 2015; Dantas et al., 2010). Seus principais tributários são o Rio Capibaribe Mirim e Rio Tracunhaém (CPRH, 2015). As principais atividades desenvolvidas ao longo da Bacia do Rio Goiana são: a indústria da cana-de-açúcar, policulturas, pecuária, as atividades industriais, ocupação urbana, abastecimento, irrigação e recepção de efluentes (domésticos, industriais, agroindustriais e agropecuários) (Barletta and Costa, 2009; CPRH, 2015; Garlipp et al., 2010).

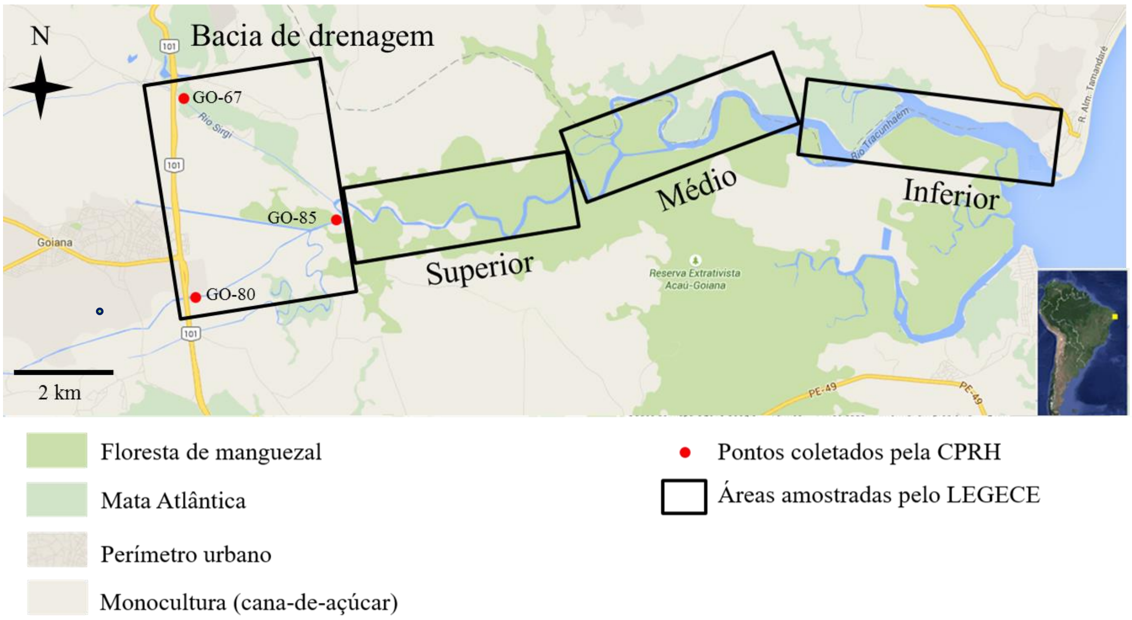

Figura 28: Rio Goiana, mostrando três pontos de coleta da CPRH (Estações GO-67, GO-80 e GO- 85) e a divisão do canal principal do estuário nas porções superior (1), média (2) e inferior (3). Fonte: Google maps, adaptado.

O estuário do Rio Goiana é composto por uma combinação de ambientes, como córregos, canais de marés, ilhas, zonas úmidas e vegetação de manguezal, por este motivo, abrigando uma fauna diversa (peixes, moluscos, crustáceos) (Costa et al., 2009; Dantas et al., 2010; Lima et al., 2014). Segundo a metodologia desenvolvida por Barletta e colaboradores (2005), o estuário foi seccionado em três compartimentos – superior, médio e inferior – considerando características geológicas, morfológicas e ecológicas, bem como a variável salinidade. Cada seção estuarina é um habitat de ecossistema, com comportamentos diferentes e organismos associados (gradiente ecológico) (Attrill and Rundle, 2002; Barletta and Dantas, 2016).

7.2.2 Aquisição de dados

Os dados utilizadosforam recortados de conjuntos contendo informações coletadas durante quatro anos (2006 - 2009) na região imediatamente a montante e no canal principal do estuário do Rio Goiana.

Foram então compilados dados coletados pela Agência Estadual de Meio Ambiente – CPRH (www.cprh.pe.gov.br) (pontos imediatamente a montante do estuário), e pelo Laboratório de Ecologia e Gerenciamento de Ecossistemas Costeiros e Estuarinos – LEGECE (amostragens nos três habitats do canal principal do estuário). Foram considerados então quatro áreas ou habitats estuarinos: bacia de drenagem (CPRH) e três áreas superior, média e inferior (LEGECE) até os limites da região costeira adjacente. Em cada área, duas estações do ano foram adotadas: estação seca, compreendendo amostras tomadas de setembro a fevereiro e estação chuvosa, amostragens de março a agosto. As amostragens e análises realizadas pela agência estadual foram bimensais distribuídas pelos 6 meses de cada estação ($2 \leq N \leq 9$). Já as coletas realizadas pelo LEGECE foram realizadas nos três últimos meses de cada estação (n=36). Os parâmetros avaliados (4) foram aqueles que existiam em comum entre os programas amostrais: temperatura da água (°C), salinidade, oxigênio dissolvido (mg L^{-1}) e saturação de oxigênio (%). A precipitação total mensal (mm) foi compilada a partir da base de dados pública (www.apac.gov.pe.br), coletadaa a partir de uma estação meteorológica situada a 10 km da cidade de Goiana. As observações foram homogeneizadas em médias (n=64), devido à diferença no número de amostras nos bancos de dados utilizados ($2 \leq n \leq 36$), permitindo assim a observação, comparação e interpretação dos resultados. As médias foram feitas entre amostras da mesma condição espaço-temporal (ano, área e estação).

7.2.3 Análises estatísticas

As médias obtidas (n=64) foram processadas usando o software Statistica 7.0. Primeiro realizou-se uma análise de variância (MANOVA). Foi utilizada para determinar se ocorreram diferenças significativas nas variáveis (temperatura da água, salinidade, oxigênio dissolvido e saturação de oxigênio) nos anos (2006, 2007, 2008 e 2009), nas áreas (estuário superior, médio e inferior) e estações (seca e chuvosa). Quando a ANOVA mostrou diferença significativa, foi utilizado um teste *a posteriori* de Bonferroni para determinar quais médias foram significativamente diferentes no nível de significância de 0,05. A análise de cluster foi realizada utilizando-se o método UWPGA (*unweighted pair-group average*) com distância euclidiana, e a análise dos componentes principais (ACP) foi feita utilizando-se um intervalo de confiança de 95%, com todas as variáveis. Clarke e Warwick (2001) sugeriram que uma ACP que explica 70% ou mais das variações iniciais em um conjunto de dados é uma interpretação razoável do fenômeno, ou estrutura global de interações.

7.3 RESULTADOS

A precipitação total mensal ($p < 0,01$) apresentou média global de 184,9 ± 89,3 mm. A menor média registrada foi referente ao ano de 2006 na estação seca, com 33,9 mm. Já a maior média registrada foi de 296,6 no ano de 2009 na estação chuvosa (Figura 29).

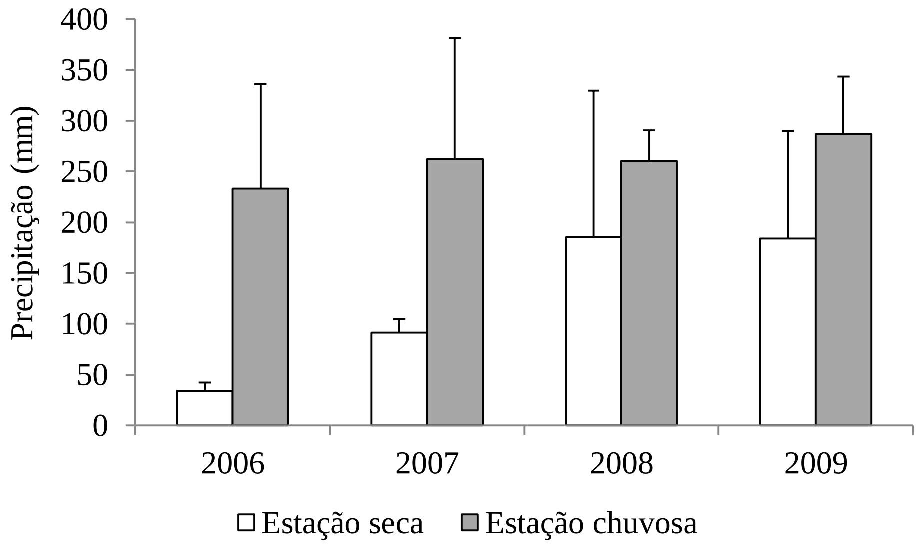

Figura 29: Variação das médias (± desvpad) de precipitação total mensal (mm) entre os anos de 2006 a 2009 provenientes da Estação 28: Goiana (Itapirema - IPA).

A média da temperatura da água ($p < 0,01$) variou de 25,3°C a 31,4°C, apresentando valores com pequena variação entre os anos e áreas na estação seca, e maior variação na estação chuvosa quando consideradas todas as áreas. A cabeceira do estuário apresentou características semelhantes de temperatura durante todo o ano, com exceção da média obtida na estação chuvosa do ano de 2009 (Figura 30). Os fatores ano e área não foram significativamente diferentes, apenas o fator estação. A interação mais importante ocorrida envolve os três fatores (ano, área e estação) (Table 5).

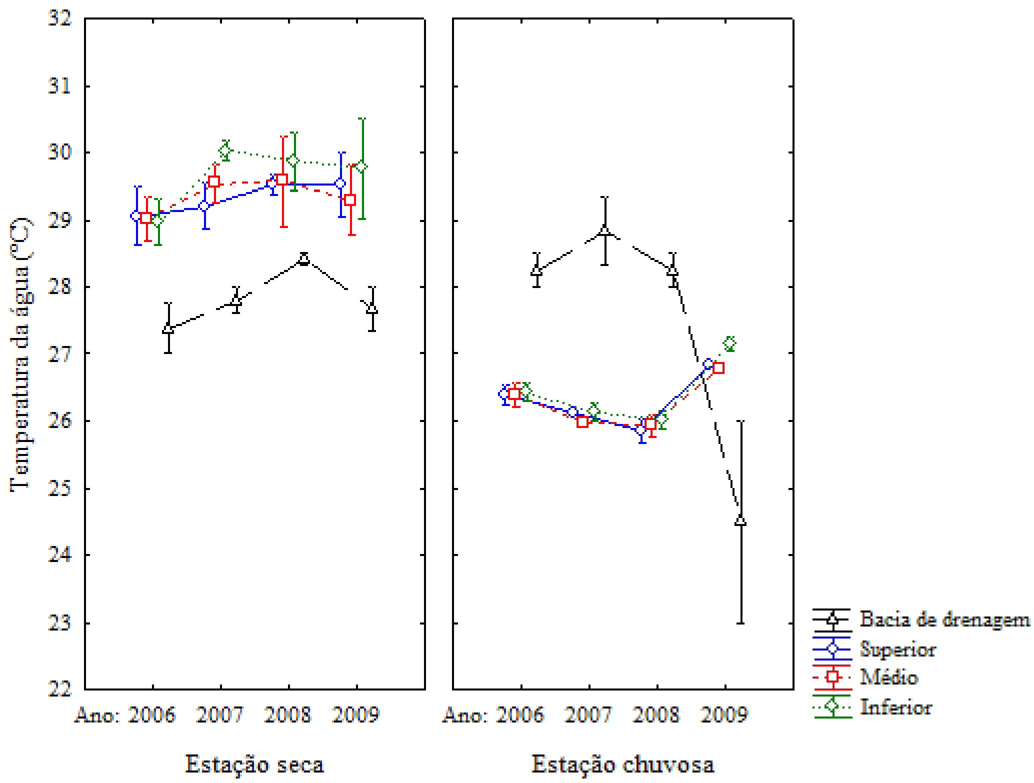

Figura 30: Variação da média da temperatura da água (°C) no estuário do Rio Goiana no período de 2006 a 2009.

Table 5: Sumário da ANOVA para temperatura da água, salinidade, oxigênio dissolvido e sua saturação por ano - 2006 (06), 2007 (07), 2008 (08), 2009 (09) - área - bacia de drenagem (BD), superior (S), médio (M), inferior (I) - por estação - seca (S), chuvosa (C).

	Fonte de variância			
Parâmetros	Ano (1)	Área (2)	Estação (3)	Interação
Temperatura da água	NS	NS	** S C	** 1x2x3
Salinidade	** 08 06 07 09	** BD M S I	** S C	** 2x3
Oxigênio dissolvido	** 06 07 08 09	** BD S M I	** S C	** 1x3
Saturação de oxigênio	** 06 07 08 09	** BD S M I	** S C	NS

NS, non-significant differences (p>0.05); *, p<0.05; **, p<0.01; differences among area and season were determined by Bonferroni test (p<0.05) *post hoc* comparisons.

As médias de salinidade (p < 0,01) variaram entre 0 e 30,6. Na estação seca, cada área apresentou características próprias em relação à salinidade, realçando o gradiente ambiental do estuário. Abacia de drenagem e as áreas superior e média apresentaram um caráter muito similar entre si no período chuvoso, enquanto a salinidade da área inferior, mesmo reduzida, ainda se mostrou maior que as demais (Figura 31 e Tabela 5). A interação mais importante foi entre área e estação (Tabela 5).

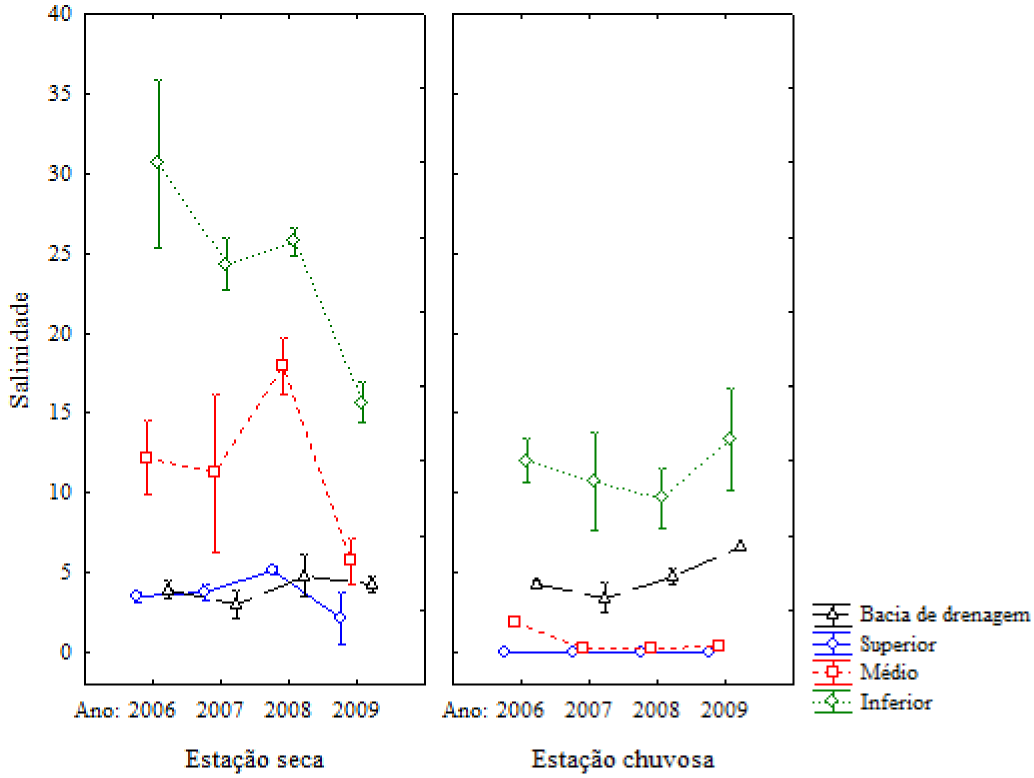

Figura 31: Variação da salinidade no estuário do Rio Goiana no período de 2006 a 2009.

O teor de oxigênio dissolvido ($p < 0,01$) teve suas médias variando entre 3,1 mg L^{-1} e 7,2 mg L^{-1} no período estudado, com as áreas mais a montante mais semelhantes e médias mais altas concentradas na porção inferior do estuário (Figura 32). As áreas mais a montante do estuário se mostraram semelhantes, enquanto a área inferior apresentou um comportamento distinto. As estações não apresentaram diferenças (Tabela 5).

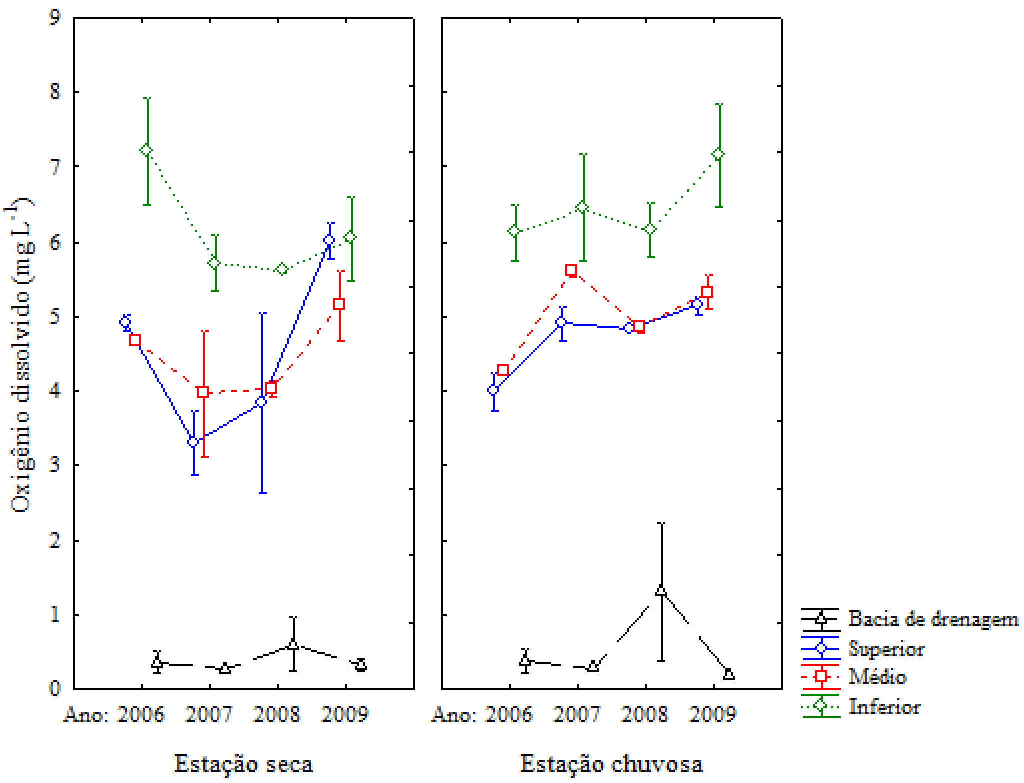

Figura 32: Variação do oxigênio dissolvido (mg L^{-1}) no estuário do Rio Goiana no período de 2006 a 2009.

A saturação do oxigênio ($p < 0,01$) apresentou médias entre 40,2% e 91,9% e seguiu a mesma tendência das médias apresentadas pelo teor de oxigênio dissolvido (Figura 33). Para esta variável, o ano de 2009 e a área inferior do estuário, tiveram comportamento distinto, enquanto não houve diferenças entre as estações (Tabela 5).

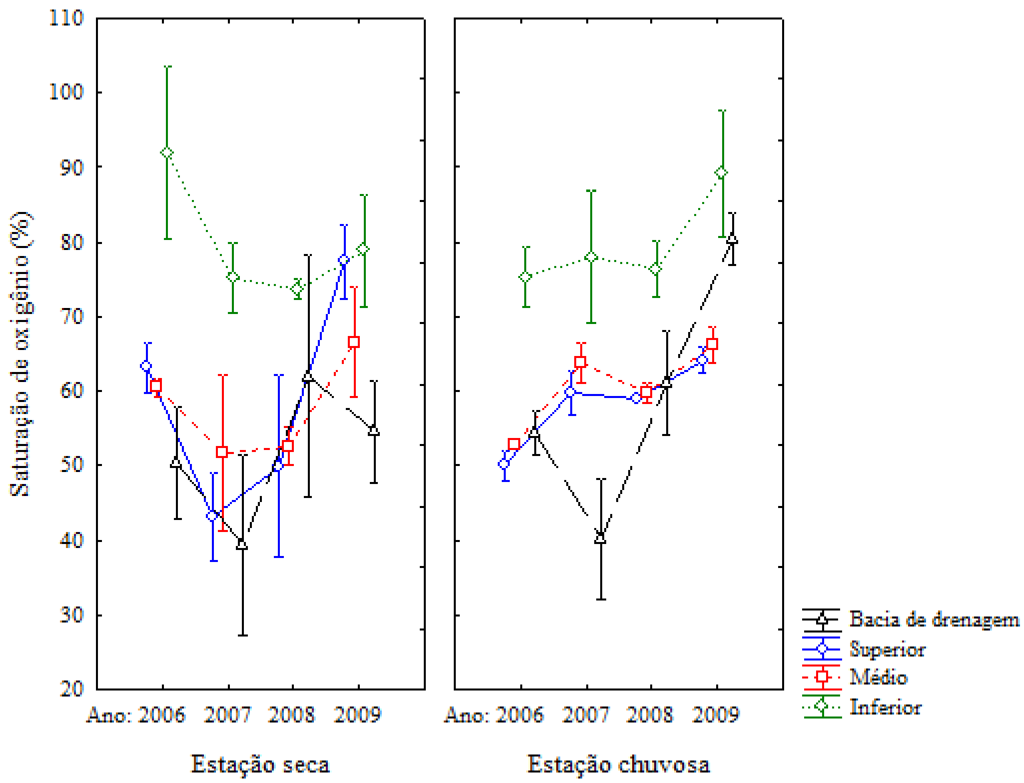

Figura 33: Variação da saturação de oxigênio (%) no estuário do Rio Goiana no período de 2006 a 2009.

Na análise de agrupamento (Figura 34), as observações agruparam-se em 2 grupos, I e II. O Grupo I foi subdividido em dois subgrupos. O subgrupo IA reuniu as médias dos anos de 2008 e 2009, durante a estação seca, nas áreas superior e média do estuário. O subgrupo IB reuniu as observações da estação chuvosa, de todos os anos e áreas. Já o grupo II reuniu as médias das estações secas dos anos de 2006 e 2007 e as estações secas de todos os anos na bacia de drenagem.

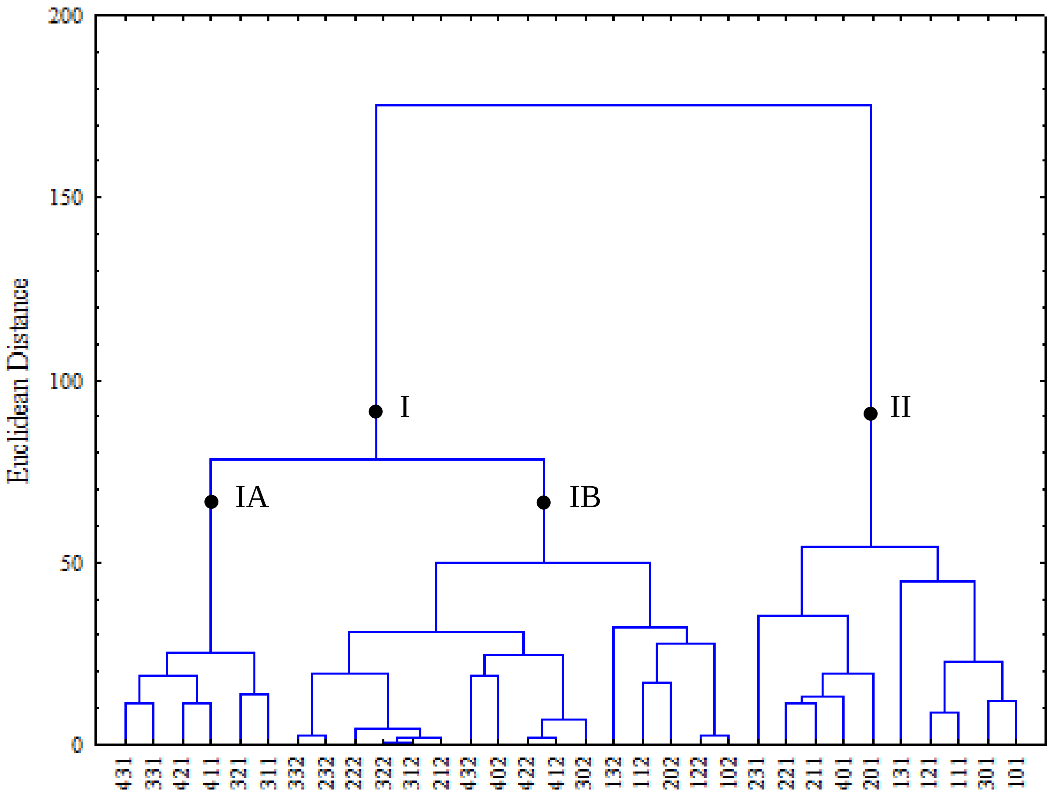

Figura 34: Agrupamento de médias dos parâmetros de qualidade da água no estuário do Rio Goiana utilizando a distância euclidiana. Legenda para amostras: o primeiro numeral representa o ano (1 - 2006, 2 - 2007, 3 - 2008, 4 - 2009); o segundo numeral representa a porção estuarina (0 – bacia de drenagem, 1 – superior, 2 – média, 3 – inferior) e o terceiro numeral representa a estação (1 – seca, 2 – chuvosa). Ex. 132 são as amostras coletadas no ano de 2006, no baixo estuário, na estação chuvosa.

Analisando-se os componentes principais (CP1 e CP2), são explicados 86,80% da variação dos dados, satisfatório para explicar as inter-relações entre as variáveis CP1 explicou 47,87% da variância e CP2 explicou 38,93% (Figura 35).

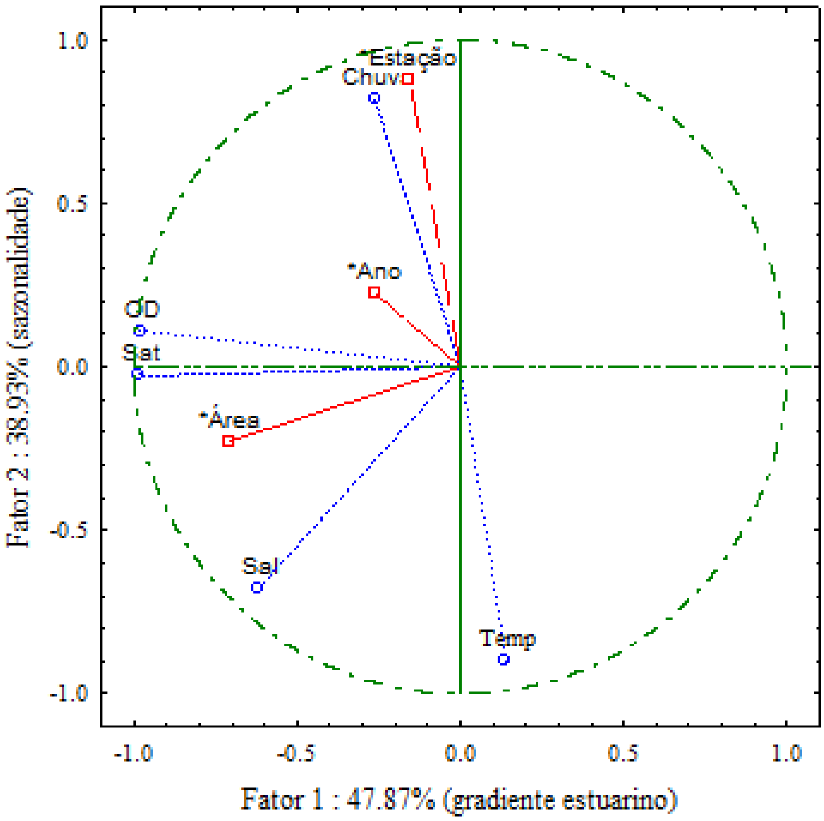

Figura 35: Gráfico de pesos (ACP) mostrando a contribuição das variáveis ambientais para os padrões de qualidade da água no estuário do Rio Goiana de 2006 a 2009.

No gráfico de scores foram identificados dois grupos: o grupo X que reuniu as médias na área inferior nas duas estações, enquanto o grupo Z reuniu as médias da bacia de drenagem eáreas superior e média também nas duas estações. Na parte superior do gráfico encontram-se todas as médias da estação chuvosa e na parte inferior, todas as médias obtidas na estação seca (Figura 36).

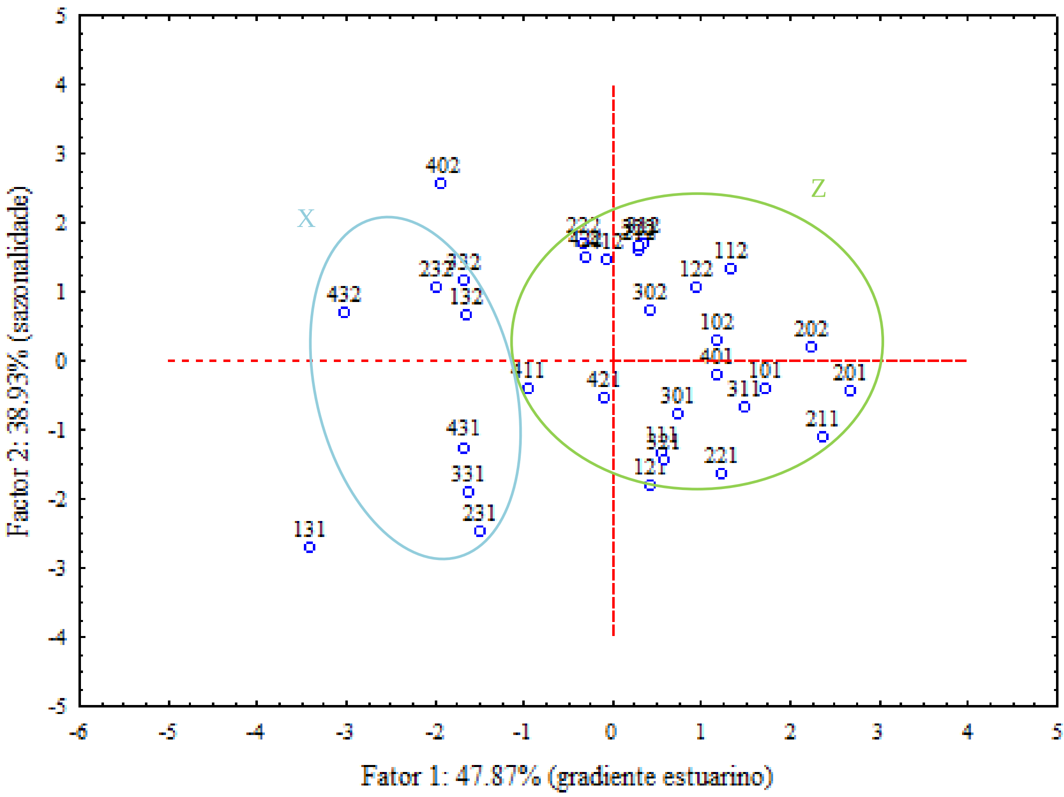

Figura 36: Gráfico de scores (ACP) mostrando a contribuição das variáveis ambientais para os padrões de qualidade da água no estuário do Rio Goiana de 2006 a 2009. Legenda para amostras: o primeiro numeral representa o ano (1 - 2006, 2 - 2007, 3 - 2008, 4 - 2009); o segundo numeral representa a porção estuarina (0 – bacia de drenagem, 1 – superior, 2 – médio, 3 – inferior) e o terceiro numeral representa a estação (1 – seca, 2 – chuvosa). Ex. 132 são as amostras coletadas no ano de 2006, no baixo estuário, na estação chuvosa.

7.4 DISCUSSÃO

A temperatura da água foi fortemente marcada pela sazonalidade, característico de ambientes tropicais (Barletta and Costa, 2009), com exceção da bacia de drenagem, onde a temperatura apresentou pequenas variações, mesmo com a mudança de estação do ano. A salinidade definiu claramente o gradiente estuarino (Attrill and Rundle, 2002; Barletta and Dantas, 2016), sobretudo na estação seca. A temperatura da água e a salinidade são importantes variáveis abióticas, que desempenham um papel fundamental no estabelecimento de gradientes ambientais, ou ecoclinas, em ambientes aquáticos (Attrill and Rundle, 2002; Barletta and Dantas, 2016; Harrison and Whitfield, 2006; Nejrup and Pedersen, 2008).

Mudanças nestes parâmetros podem comprometer a qualidade ambiental e os limites entre diferentes habitats ao longo do tempo, podendo alterar áreas de alta importância ecológica, consideradas berçários ou de alimentação, crescimento e reprodução. Áreas que apresentam relativa estabilidade destes parâmetros, como a bacia de drenagem e área superior do estuário, são propícias para estes usos por diversas espécies de animais (Barletta et al., 2005; Blaber, 2013), apesar de seu reduzido volume de água e vulnerabilidade a interferências antrópicas.

O oxigênio dissolvido e o percentual de saturação de oxigênio apresentaram comportamentos semelhantes, porém sem um padrão definido. As maiores concentrações de oxigênio foram encontradas na região inferior do estuário, que sofrem maior influência direta de águas marinhas, mais turbulentas e oxigenadas (Zhang et al., 2010). Os níveis de oxigênio dissolvido recomendados para a conservação aquática estão entre 4 e 5 mg L^{-1} (Osode and Okoh, 2009; Pearce and Schumann, 2001), mostrando que mesmo sob forte influência antrópica (efluentes domésticos, industriais e agrícolas), o estuário ainda mantem a sua capacidade de autodepuração, desde que haja chuvas sazonais de boa intensidade. A falta de chuvas na época e quantidades esperadas pode comprometer o pulso de vazão e autodepuração do estuário, dificultando a manutenção da qualidade da água e o ciclo de vida de alguns recursos vivos importantes.

Na análise de cluster, o fator com maior impacto na formação dos grupos foi a precipitação total mensal. O grupo II contém a principal fonte de variação de dados (observações 131). O grupo II agrupou as observações do período mais seco estudado (estações secas dos anos 2006 e 2007). O grupo I reuniu as observações de uma estação seca pouco severa e todas as observações das estações chuvosas. Isso demonstra que a qualidade da água do estuário está diretamente relacionada ao volume de chuvas, mas também vale a pena ressaltar que barramentos e subtração de água para abastecimento humano podem ter efeitos semelhantes a uma seca severa, e permanente.

Em 2006 e 2007 as estações foram bem definidas, conforme esperadas para a região. Já os anos de 2008 e 2009 apresentaram as chuvas ao longo de todo ano mais homogênea mente distribuídas e em maior quantidade. Devido a isso, mesmo na estação seca, o estuário apresentou comportamento semelhante ao apresentado nas épocas de chuvas dos anos estudados. A mudança na qualidade da água resultante da mudança na quantidade de chuvas foi notada graças ao monitoramento realizado pela agência estadual e laboratório envolvidos. O monitoramento contínuo é uma importante ferramenta para a detecção de fenômenos cíclicos, que são observados apenas em grandes escalas temporais (Karydis and Kitsiou, 2013; Renjith et al., 2011; Silva et al., 2013). Nos estuários, a precipitação é um dos principais fatores que determinam a qualidade de suas águas (Corbari et al., 2016; Eyre, 1997; Karydis and Kitsiou, 2013). A entrada de água doce promoveu o aumento do oxigênio disponível, bem como a diluição e transporte de efluentes e poluentes (Brooks et al., 2006; Osode and Okoh, 2009), aumentando a qualidade e quantidade da agua disponível neste ambiente.

Os dois componentes principais da análise de ACP conseguiram explicar 86,80% da variância dos dados. CP1 corresponde ao gradiente do estuário, com a cabeça do estuário (baixa salinidade) representada à direita e a área marinha (alta salinidade) à esquerda. CP2 representa o efeito da sazonalidade, sendo a variável precipitação a mais importante, seguida pela temperatura. A distribuição das observações ao longo do gráfico de scores também confirma a influência preponderante destes dois fatores sobre a qualidade da água.

No gráfico de pesos (Figura 35), CP1 (47,87%) representou o gradiente estuarino do alto ao baixo estuário, sendo o oxigênio e a saturação seus principais formadores. A salinidade também contribuiu no estabelecimento desse gradiente estuarino. Estes parâmetros tendem a aumentar de valor em águas com maior influência marinha, característica marcante da área do baixo estuário (Dantas et al., 2010; Jutagate et al., 2010; Karydis and Kitsiou, 2013). CP2 (38,93%) representou a sazonalidade, sendo a precipitação sua principal variável de formação. A temperatura da água também apareceu como um grande contribuinte para a formação desse eixo, inversamente proporcional a quantidade de chuvas, onde a diferença sazonal foi bem marcada, principalmente devido à localização do estuário (Blaber, 2002; Costa et al., 2009; Harrison, 2004; Harrison and Whitfield, 2006).

No gráfico de scores é possível observar que a bacia de drenagem e a área superior apresentam maior estabilidade ao longo do ano, sendo áreas propícias para utilização como berçário e para outras funções biológicas que requerem proteção e condições osmóticas especificas (alimentação, crescimento, reprodução, fuga do predador), conforme citado por vários autores (Barletta et al., 2008, 2005, Blaber, 2002, 2013; Cabral et al., 2012; Ceesay et al., 2016; Dantas et al., 2010; Franco et al., 2008; Jutagate et al., 2010; Lima et al., 2014; Lucena-Moya and Duggan, 2017; Reis-Filho and Santos, 2014).

A área inferior do estuário, independente da época do ano, é altamente influenciada pelas águas marinhas (grupo X). A estação chuvosa é um fator de homogeneização de grande parte do estuário (grupo Z), e pode fazer com que algumas variáveis (ex. salinidade) variem profundamente mesmo em habitats como o baixo estuário. Esse habitat não deixa de existir, mas se desloca para a área costeira adjacente, outra região que precisa ser acompanhada para ser integrada a analises come estas. Estas flutuações no estuário definem o uso do ambiente feito pela biota e consequentemente o acesso humano aos recursos naturais e serviços ecossistêmicos. Espécies que utilizam áreas com menores salinidades como berçário e para proteção podem desfrutar de espaços maiores durante a estação chuvosa; em contrapartida, as espécies marinhas entram no estuário e utilizam áreas maiores principalmente para alimentação durante a estação seca (Barletta et al., 2005; Blaber, 2002, 2013, 2007; Dantas et al., 2010; Lima et al., 2014).

7.5 CONSIDERAÇÕES FINAIS

O objetivo deste capítulo foi integrar os dados provenientes de bancos de dados distintos, estimando assim as mudanças interanuais e sazonais da qualidade da água em toda a extensão do estuário do Rio Goiana.

A integração dos dados mostrou que um desenho amostral balanceado e seguido corretamente é muito importante para a análise e interpretação dos dados. Através dessa integração, foi possível conhecer a reação das variáveis ambientais a situações diferentes de seca e chuvas ao longo dos anos e a qualidade da água/ambiente resultante. A homogeneização dos dados espaciais e temporais em médias pode ser feita de diversas formas (recortes), o que possibilita se amostrar dentro de bancos de dados diferentes e se fazer comparações inicialmente não compatíveis. Analisar localmente e no menor espaço de tempo possível, mantendo o significado ecológico, mostra uma realidade muito mais consistente.

Segundo estes resultados, do ponto de vista da qualidade da água, o estuário do Rio Goiana ainda apresenta condições compatíveis com os seus principais usos pretendidos, apesar de já demonstrar sinais de alerta devido à intensificação dos usos e limitações no fluxo do rio.

8 CONCLUSÕES

Este trabalho cumpriu o seu principal objetivo de avaliar a qualidade da água no estuário do Rio Goiana, entre os anos de 2006 a 2009, ao longo do seu canal principal, dessa forma gerando uma significativa *contribuição para a ciência*. A qualidade do desenho amostral que permitiu o estudo de diversas variáveis (bióticas e abióticas) com possibilidade de realização de análises estatísticas correlatas. Neste período, foram desenvolvidos vários outros estudos ecológicos na mesma área cujas interpretações podem agora ser corroboradas e ampliadas.

Ações como a inclusão de outros parâmetros (como clorofila a e sólidos totais), a garantia da amostragem regular para fortalecer o banco de dados, o desenvolvimento de um desenho amostral mais equilibrado permitirão uma melhora na confiabilidade, ampliando a aplicabilidade destes dados. A coleta de parâmetros para facilitar a comunicação científica e comparações com de outras bacias, nacionais e internacionais, buscando e garantir a quantidade e a qualidade da informação disponível é também fortemente recomendado, oferecendo melhora significativa nos programas de monitoramento disponíveis. Esta comunicação é essencial para o cálculo de índices consagrados na literatura, como o IQA – Índice de Qualidade da Águas.

As análises dos dados demonstram que, do ponto de vista da qualidade da água, o ambiente ainda apresenta condições compatíveis com os seus principais usos pretendidos, apesar de chuvas fortes para a renovação de suas águas serem indispensáveis. Dessa forma, anos sucessivos de chuvas próximas ou abaixo da média poderiam levar a situações delicadas para a sua qualidade da água.

Dentre os principais sinais de alerta no estuário se encontram os eventos de hipóxia episódica, característicos da estação seca. A resiliência ambiental foi afetada nestas épocas, períodos de menor renovação das águas e de maiores temperaturas, provocando queda das taxas de oxigenação da água. A temperatura da água é influenciada também por outros fatores físicos (por exemplo, profundidade, fluxo de água, diluição de efluentes) e é importante controladora de outras variáveis como oxigênio dissolvido e sua saturação. Esses eventos devem ser tratados como um alerta do ambiente aos lançamentos de efluentes (domésticos e agroindustriais) e subtração de água (abastecimento e irrigação). Essa descoberta foi uma importante *contribuição para o* *meio ambiente* tendo em vista que a sua conservação dependerá de medidas que evitem a recorrência desses eventos de hipóxia no canal principal.

Em consequência da variedade de impactos sofridos pelo estuário, há uma gama de medidas mitigadoras para os impactos já sofridos (restauração de margens, tratamento de efluentes, recuperação do solo, saneamento básico) que devem ser aliadas a diminuição dos impactos causados. Estas medidas são essenciais para a manutenção dos serviços oferecidos pelo estuário, e estão previstas em lei. O esclarecimento desta questão pode servir de gatilho para o avanço social. Fica demonstrado que a ação de conservação ambiental resgatará possibilidades, não apenas de convivência com um ambiente saudável, mas também o acesso a recursos e serviços ambientais, *contribuindo para uma melhor qualidade de vida da sociedade local.*

Diante destas conclusões, é possível conjecturar que, embora haja consenso quanto ao aumento da temperatura global, há menos certeza quanto aos prováveis impactos na qualidade da água resultantes das mudanças nos padrões de chuvas regionais. A avaliação dos impactos futuros das alterações climáticas nos estuários requer uma abordagem multidisciplinar que aborda a interação entre as respostas ambientais, combinada com várias outras ciências.

O estuário do Rio Goiana é um modelo não apenas ecológico, mas também gerencial. Nele pode-se notar a importância da conservação da qualidade e quantidade da água que vem de sua bacia hidrográfica para a biota e para as populações do entorno, tradicionais ou não. As escolhas feitas em relação à sua conservação enquanto ecossistema e de toda sua bacia hidrográfica, demonstram a fragilidade do sistema às mudanças dos interesses políticos e econômicos. Devido a sua resiliência, o longo prazo dos efeitos das intervenções antrópicas foi negligenciado. Mas atualmente já é possível detectar-se sua dependência de uma estação de chuvas forte, sinal de que as mudanças climáticas globais e locais podem, em poucos anos, causar mudanças permanentes na qualidade da água – não necessariamente em prol de sua conservação.

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APÊNDICES

Appendix 1: Descriptive table of the results obtained in 2006 a 2009.

Year: 2006

	Dry Season					Rainy Season				
Environmental variables	**N**	**Mean**	**Min**	**Max**	**Standard error**	**N**	**Mean**	**Min**	**Max**	**Standard error**
Rainfall (mm)	6	52.4	6.2	83.6	14.3	6	214.9	100.7	374.0	47.4
Water temperature (°C)	8	27.4	25.0	30.0	0.5	7	28.3	26.0	30.0	0.6
Salinity	8	0.4	0.2	1.2	0.1	7	0.4	0.2	1.0	0.1
D.O. (mg L^{-1})	8	4.0	2.0	5.8	0.5	7	4.2	2.0	6.4	0.7
D.O. (%)	8	50.4	25.0	71.0	6.1	7	54.0	30.0	79.0	8.1
B.O.D (mg L^{-1})	8	2.2	0.5	8.6	1.0	7	2.0	2.0	2.0	0.0
P-total (mg L^{-1})	8	0.4	0.1	1.0	0.1	7	0.8	0.2	1.7	0.3
pH	8	7.0	6.8	7.9	0.2	7	7.1	6.8	7.6	0.1
Turbidity (UNIT)	8	16.0	10.0	20.0	1.2	7	55.0	35.0	120.0	11.3
Colour (Pt/Co)	8	28.8	17.5	50.0	4.9	7	97.1	50.0	200.0	18.4

Year: 2007

	Dry Season					Rainy Season				
Environmental variables	**N**	**Mean**	**Min**	**Max**	**Standard error**	**N**	**Mean**	**Min**	**Max**	**Standard error**
Rainfall (mm)	6	77.6	43.7	133.8	15.6	6	233.5	168.0	425.2	39.6
Water temperature (°C)	9	27.8	26.0	30.0	0.4	6	28.8	28.0	30.0	0.3
Salinity	9	0.3	0.2	0.5	0.0	6	0.3	0.2	0.4	0.0
D.O. (mg L^{-1})	9	3.1	0.8	5.3	0.6	6	3.5	1.0	5.4	0.7
D.O. (%)	9	40.7	10.0	68.0	7.5	6	40.2	13.0	66.0	9.4
B.O.D (mg L^{-1})	9	1.3	0.5	3.3	0.3	6	0.8	0.5	1.2	0.1
P-total (mg L^{-1})	9	0.3	0.1	0.6	0.1	6	0.2	0.2	0.3	0.0
pH	9	7.3	7.0	7.6	0.1	6	7.3	7.0	7.5	0.1
Turbidity (UNIT)	9	14.6	6.0	35.0	2.8	6	46.3	17.0	70.0	8.5
Colour (Pt/Co)	9	50.3	17.5	100.0	12.6	6	53.8	17.5	100.0	13.2

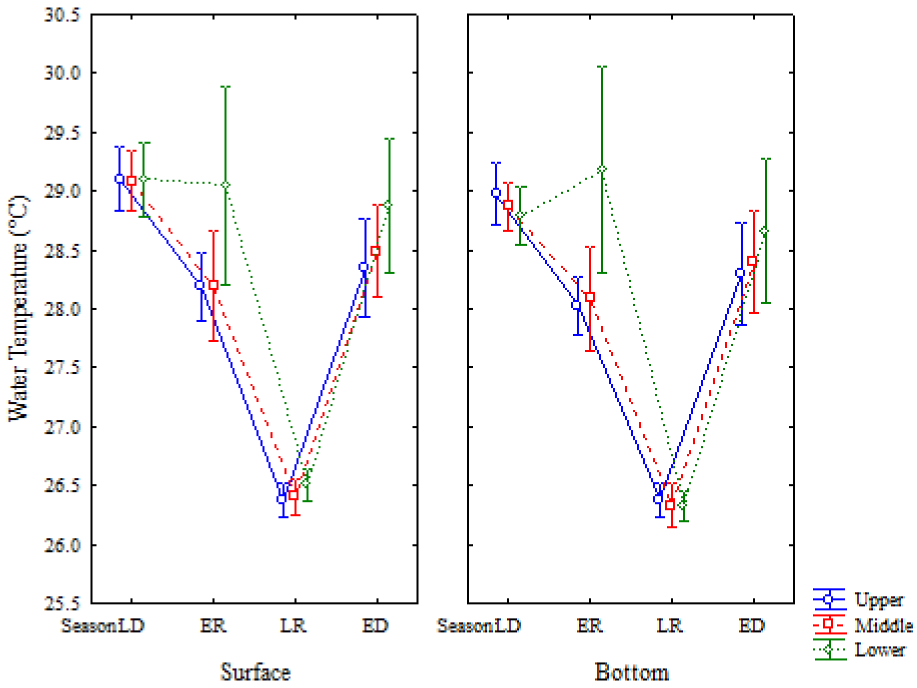
Year: 2008

	Dry Season					Rainy Season				
Environmental variables	**N**	**Mean**	**Min**	**Max**	**Standard error**	**N**	**Mean**	**Min**	**Max**	**Standard error**
Rainfall (mm)	6	54.9	4.8	172.1	24.6	6	282.4	224.7	363.4	19.1
Water temperature (°C)	6	28.4	27.0	30.0	0.5	7	28.3	27.0	30.0	0.6
Salinity	6	0.6	0.2	2.3	0.3	7	1.2	0.1	6.4	0.9
D.O. (mg L^{-1})	6	4.8	2.7	6.3	0.6	7	4.7	1.6	6.5	0.7
D.O. (%)	6	62.0	35.0	79.0	8.0	7	60.1	44.0	82.0	8.9
B.O.D (mg L^{-1})	6	1.2	0.6	1.8	0.2	7	3.2	0.8	8.2	1.1
P-total (mg L^{-1})	6	0.1	0.1	0.2	0.0	7	0.4	0.1	1.6	0.2
pH	6	7.3	6.8	7.5	0.1	7	7.0	6.5	7.3	0.1
Turbidity (UNIT)	6	25.4	7.5	50.0	7.2	7	63.1	6.5	200.0	25.6
Colour (Pt/Co)	6	68.3	20.0	150.0	19.7	5	116.0	40.0	200.0	45.2

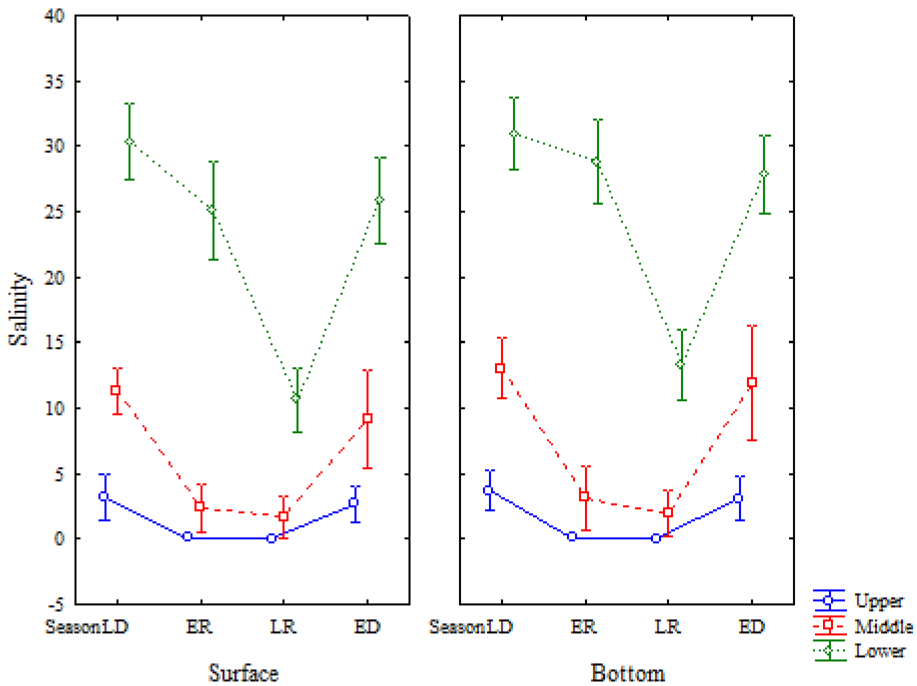
Year: 2009

	Dry Season					Rainy Season				
Environmental variables	**N**	**Mean**	**Min**	**Max**	**Standard error**	**N**	**Mean**	**Min**	**Max**	**Standard error**
Rainfall (mm)	6	96.3	13.0	310.4	44.0	6	296.6	184.0	418.2	35.3
Water temperature (°C)	7	27.7	27.0	29.0	0.3	2	24.5	23.0	26.0	1.5
Salinity	7	0.3	0.2	0.8	0.1	2	0.2	0.2	0.2	0.0
D.O. (mg L^{-1})	7	4.4	1.8	6.7	0.7	2	6.7	6.6	6.8	0.1
D.O. (%)	7	55.6	23.0	87.0	9.2	2	80.5	77.0	84.0	3.5
B.O.D (mg L^{-1})	7	1.7	0.5	5.2	0.6	2	1.3	0.7	1.9	0.6
P-total (mg L^{-1})	7	0.1	0.1	0.2	0.0	2	0.2	0.2	0.2	0.0
pH	7	7.6	6.7	8.0	0.2	2	7.4	7.2	7.5	0.2
Turbidity (UNIT)	7	16.4	10.0	25.0	2.1	2	55.0	45.0	65.0	10.0
Colour (Pt/Co)	7	50.0	40.0	60.0	3.8	2	150.0	100.0	200.0	50.0

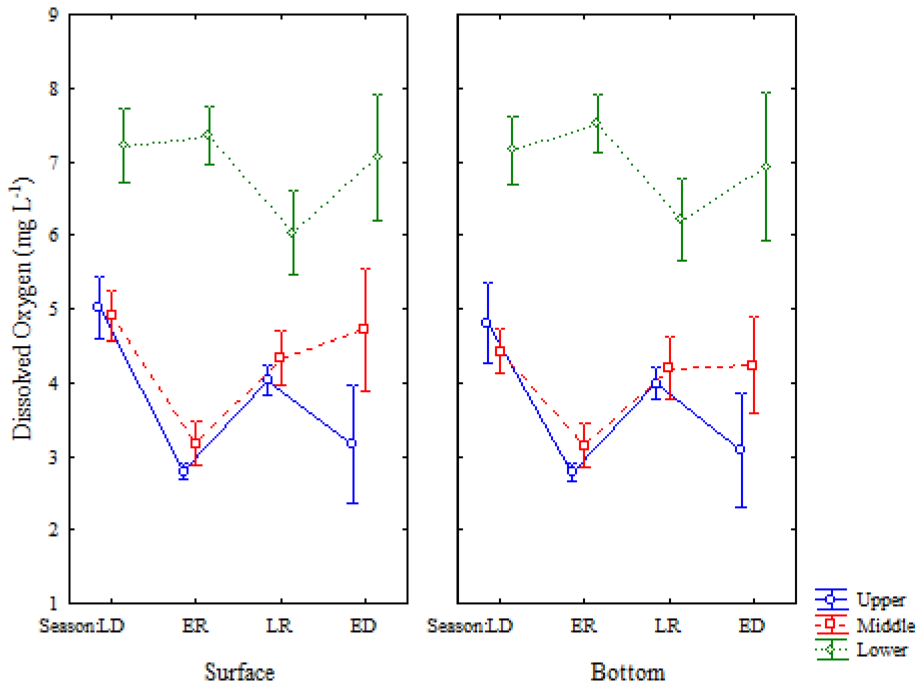
Appendix 2: Analysis of the differences between surface and bottom for water temperature (°C).



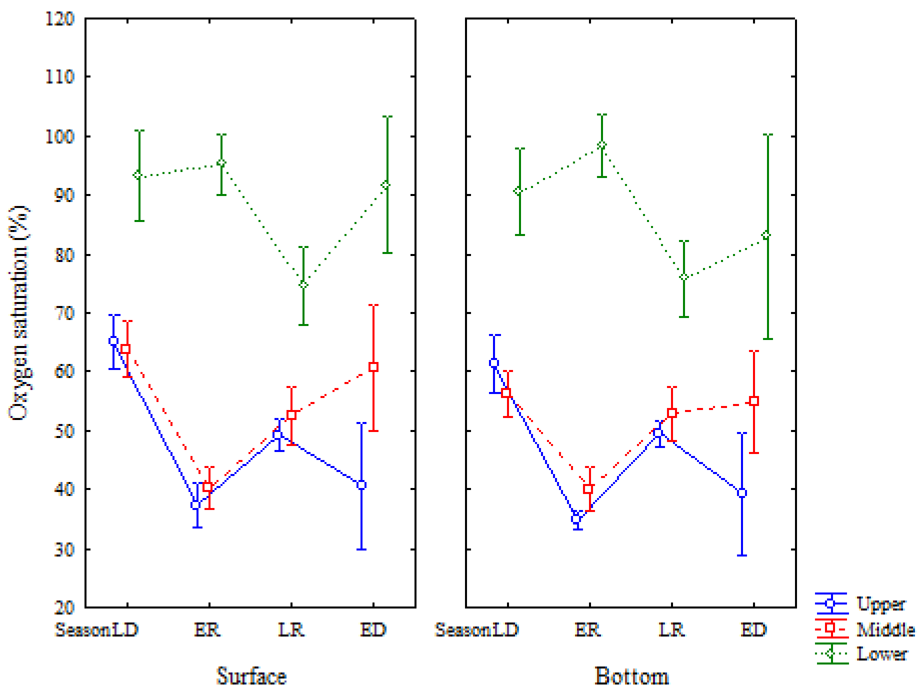
Appendix 3: Analysis of the differences between surface and bottom for salinity.



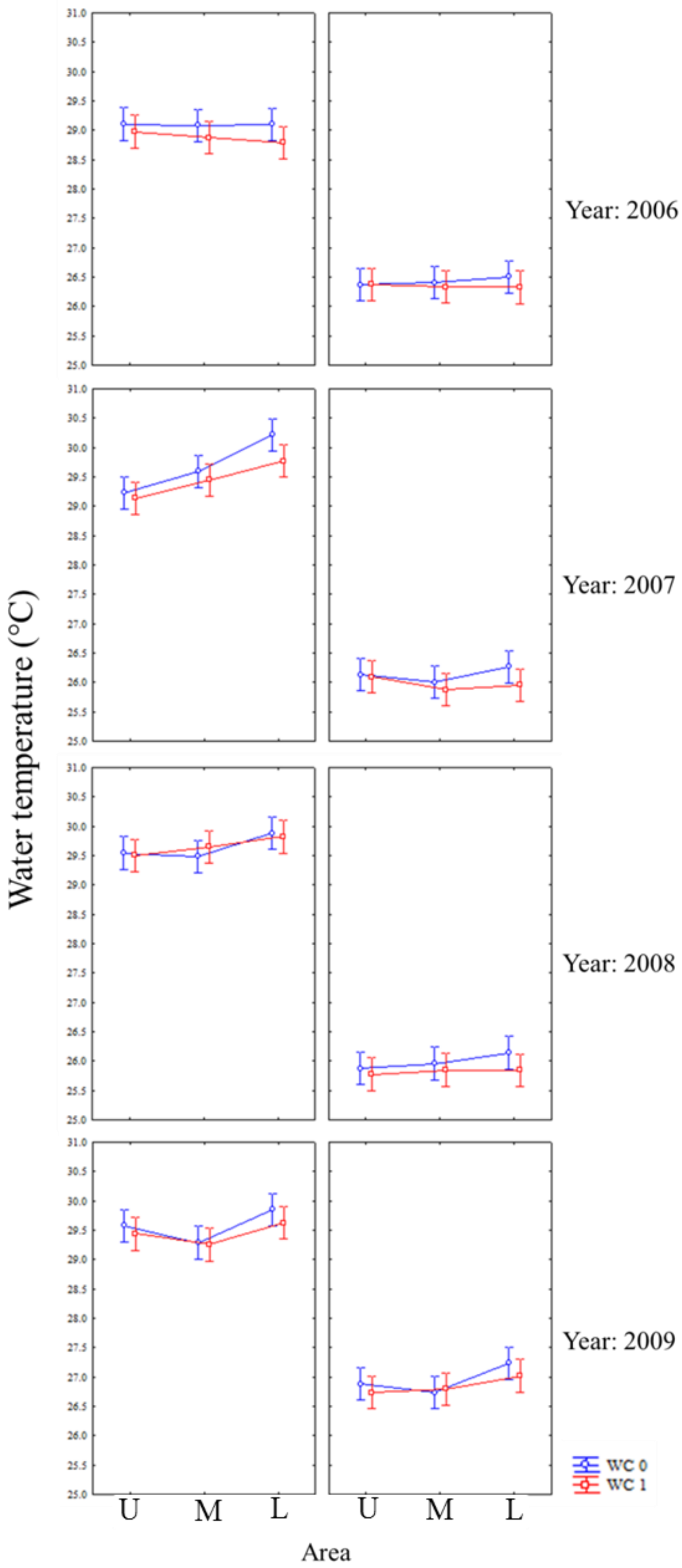
Appendix 4: Analysis of the differences between surface and bottom for dissolved oxygen (mg L^{-1}).



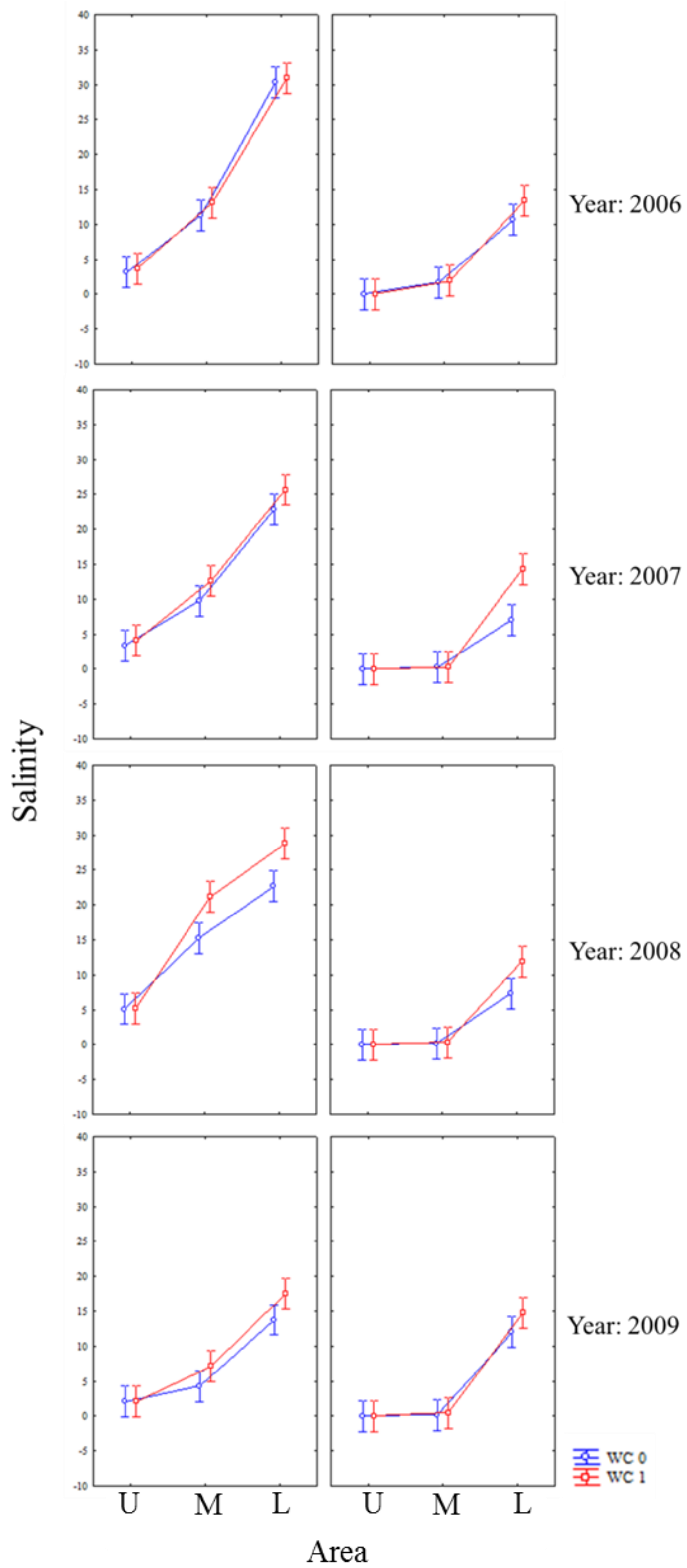
Appendix 5: Analysis of the differences between surface and bottom for oxygen saturation (%).



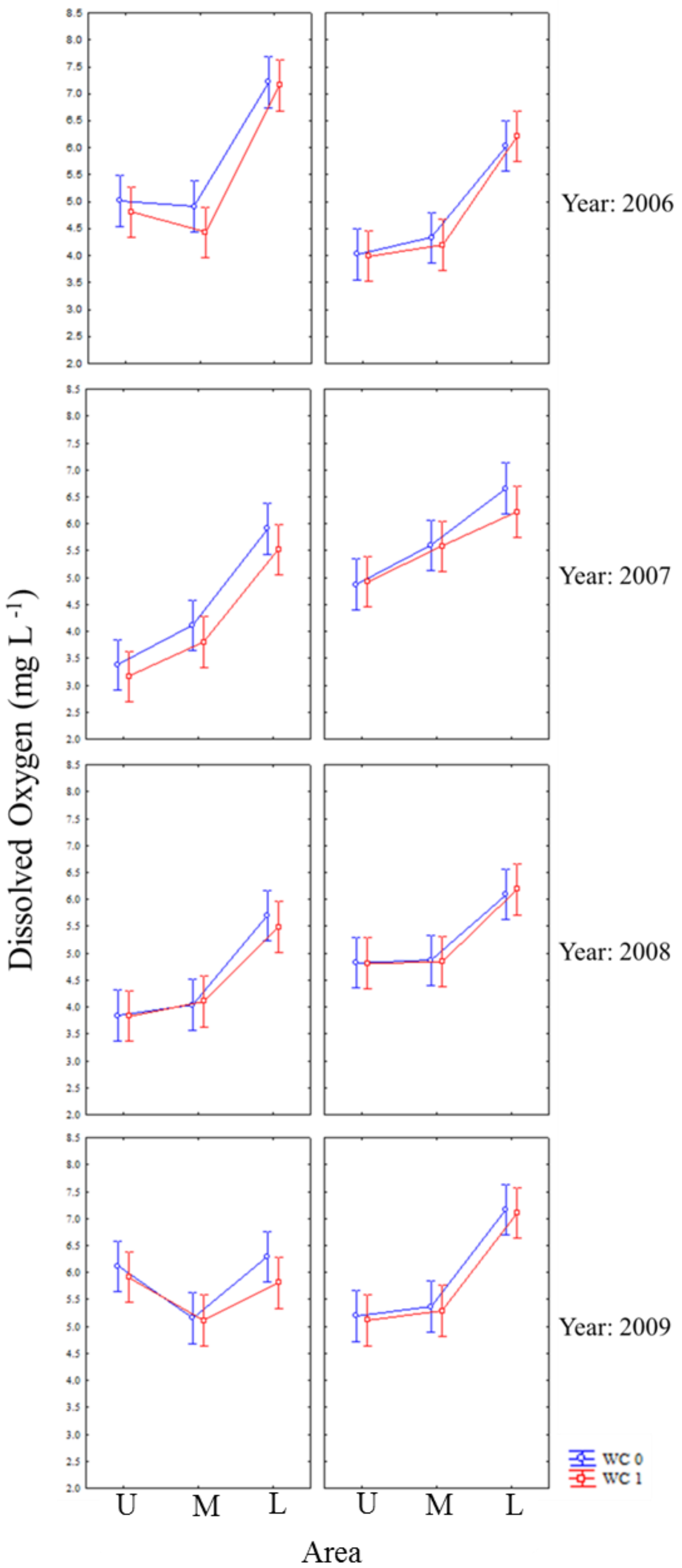
Appendix 6: Analysis of the differences between surface (WC: 0) and bottom (WC: 1) for water temperature for years (2006, 2007, 2008 and 2009) for areas (U – upper, M – middle and L – lower).



Appendix 7: Analysis of the differences between surface (WC: 0) and bottom (WC: 1) for salinity for years (2006, 2007, 2008 and 2009) for areas (U – upper, M – middle and L – lower).



Appendix 8: Analysis of the differences between surface (WC: 0) and bottom (WC: 1) for dissolved oxygen for years (2006, 2007, 2008 and 2009) for areas (U – upper, M – middle and L – lower).



Appendix 9: Analysis of the differences between surface (WC: 0) and bottom (WC: 1) for oxygen saturation for years (2006, 2007, 2008 and 2009) for areas (U – upper, M – middle and L – lower).