Universitat Politècnica de Catalunya
BarcelonaTech

Departament d'Enginyeria Civil i Ambiental
Laboratori d'Enginyeria Marítima

Programa de Doctorat en Ciències del Mar

NATURAL AND ANTHROPOGENIC CONTROL OF WATER QUALITY OF AN AMAZON ESTUARY. THE CAETÉ ESTUARY (BRAZIL)

PhD Thesis presented by

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for the degree of Doctor

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Barcelona, February 2017

"For I know the plans I have for you, declares the LORD,

plans for welfare and not for evil, to give you a future and a hope".

Jeremiah 29:11

To Helena and Neuza,

with all my love

Acknowledgements

As a dedicated Christian, I could not begin these acknowledgements without thanking God, above all, for concluding yet another stage in my academic career. I am eternally grateful to Him for guiding and supporting me along this journey.

I am also grateful to Erasmus Mundus and the Brazilian National Council for Scientific and Technological Development (CNPq) for the scholarship that have allowed me to complete my studies in Spain. Both these institutions have been fundamental to the fulfilment of a dream.

I thank my supervisors, Dr. José A. Jiménez and Dra. Luci Cajueiro, for sharing their knowledge with me during the development of my thesis, for helping me to maintain my focus on this research during all these years, and for the final revision, which was so essential to the conclusion of my thesis.

To Professor Dr. Manuel de Jesus Flores-Montes, coordinator of the project that made this research possible.

I would also like to thank the participants of the Laboraroti di Engenharia Maritime (LIM) at Universitat Politècnica de Catalunya, for providing me with such an agreeable working environment. Mercè Casas-Prat, Eva Bosom, Monica Leano, Caridad Ballesteros, Marta Alomar, Manuel Griffol, Tiago Oliveira and Jacqueline Albino, my time together with you all made my journey all the more pleasurable.

To the members of the Coastal and Estuarine Oceanographic Laboratory (LOCE) at the Federal University of Pará – Danielle Guimarães, Ádila Costa, Rosigleyse Félix, Natália Sousa, Nayra Silva, Emarielle Pardal, Suellem Oliveira, Wellington Trindade and Ruben Pessoa. Thank you so much for helping me with the collection of samples in the field and the analyses in the laboratory. Despite the distance that separates us, you have been present in my daily life throughout the development of my thesis.

I am also grateful to the members of the Coastal Geology Laboratory (LAGECO) coordinated by Professor Dr. Nils Edwin Asp, and the Coastal Studies Institute (IECOS), both of the Federal University of Pará, as well as Sergeant Fábio Sadraque of the municipal Fire Department of Santa Maria do Pará, for their assistance during the oceanographic campaigns.

I would also like to acknowledge all the institutions that provided me with the data I used in this thesis – the Bragança office of the Brazilian Institute of Geography and Statistics (IBGE), the Bragança Municipal (PMB) Secretariat for Infrastructure and Planning, and the GPesca Indústria Ltda fish processing plant.

I thank Professor Aninha Moreira M.Sc of the Bragança campus of the Federal Institute of Teaching and Technology of Pará and the environmental administrators Marcelo Mendonça and Marcos Ronielly, who helped me produce the maps used to illustrate this thesis.

Finally, thank my family, especially Helena and Renan for their support. You have been present during each moment of this journey, despite the 4000 miles that separate us. I share with you the merits of this conquest!

Abstract

In the Amazon region, few data are available on the impacts caused by the urban settlements found in the proximity of estuaries. In the estuary of the Caeté River, the focus of the present study, the nutrient input is controlled by both natural features and anthropogenic disturbances generated by local communities. In this context, the principal aim of the study was to analyze the quality of the water of the Caeté estuary, and the relative contribution of natural and anthropogenic forcings. To this end, climatological, hydrodynamic and hydrological features were monitored, and potential sources of pollution were identified in the different sectors of the Caeté estuary. Potential future scenarios for the estuary are also described, based on the analysis of anthropogenic and natural processes, which may contribute to the quality of its waters. The results indicate higher levels of nutrient input in the upper sector of the estuary, where 90% of the local population is concentrated, and most of the region's commercial activities (e.g., public markets, ice factories, and docking facilities) are found. As a consequence, eutrophic waters with high concentrations of faecal coliforms (up to 1100 MPN/100 ml) were observed during spring tides in the dry season when the transport and dilution of the estuary's waters are less effective. Eutrophication also occurred to a lesser extent in the other (middle and lower) estuary sectors, although in this case, the results indicate the influence of natural processes, reflecting the high nutrient concentrations of this Amazonian region. During neap tides, eutrophication was less pronounced, and water quality was improved in both dry and rainy seasons. A comparative analysis showed that, under similar conditions of the flood cycle, the trophic status of the estuary varied little between spring and neap tides. As the population of the region surrounding the Caeté estuary is increasing by 10–20% per decade, resulting in a significant increase in human pressures and impacts on the study area. The current eutrophication status of the estuary may have permanent effects, which may be aggravated during the dry season or drought events, when the estuary is more vulnerable to the retention of nutrients. The water quality of the Caeté Estuary can

be improved by the implementation of the following measures: (i) urban planning to control the discharge of sewage, (ii) the construction of water treatment plants to reduce the input of untreated effluents, and (iii) the introduction of regulations for the use of water based on its current quality.

Resumen

Los impactos más frecuentes en los estuarios se deben a los asentamientos urbanos no planificados. Como consecuencia de dichos asentamientos, los estuarios se han visto expuestos a una serie de perturbaciones ambientales, tales como el incremento en la entrada de nutrientes y cambios en los usos del suelo y en la hidrología local. En el estuario del río Caeté, objeto de este estudio, las perturbaciones antrópicas originadas en las comunidades de alrededor del estuario y el funcionamiento natural del sistema controlan el input de nutrientes en el estuario. El objetivo principal de esta tesis es analizar la calidad del agua del estuario del río Caeté y la influencia de las forzantes naturales y antrópicas que actúan en él. Para tal efecto, los aspectos climáticos, hidrodinámicos e hidrológicos fueron monitorizados y se identificaron las fuentes potenciales de polución en el estuario. Además, se describieron una serie de potenciales futuros escenarios para el estuario basándose en los procesos naturales y antrópicos que pueden afectar la calidad del agua en las próximas décadas. Los resultados muestran que el input de nutrientes disueltos es mayor en el sector superior del estuario, que concentra el 90% de la población local y tiene una alta incidencia de actividades comerciales (mercados públicos, fábricas de hielo, astilleros, entre otros). Como consecuencia, se observaron aguas eutróficas con altas concentraciones de coliformes fecales (até 1100 NMP/100 ml) durante las mareas vivas en la estación seca, cuando el transporte y/o dilución son menos efectivas. La eutrofización, aunque menos pronunciada, también ocurrió en el resto de sectores (medio y bajo estuario). Sin embargo, estos resultados parecen indicar que esto puede deberse a una condición natural de la región amazónica, la cual es naturalmente enriquecida con una elevada cantidad de nutrientes. Durante mareas muertas, la eutrofización fue menos pronunciada y la calidad de agua presentó mejores condiciones en todas las estaciones monitorizadas. El análisis comparativo ha mostrado que bajo condiciones similares (marea llenante) el estado trófico entre mareas vivar y muertas presenta similitudes. Considerando que la población se incrementa entre 10 y 20% por década en la región, esto puede resultar en un incremento significante de

la presión humana y del impacto alrededor del estuario. En este caso, el estado eutrófico observado actualmente podría afectar el estuario de manera permanente. La situación podría agravarse durante la estación seca o eventos de sequía, cuando el estuario es más susceptible a retener los nutrientes. Con el objetivo de mejorar la calidad del agua, se podrían implementar ciertas medidas en el estuario del Caeté basadas en (i) planeamiento urbanístico para controlar la descarga de efluentes en el estuario (ii) construcción de una estación de tratamiento de agua para reducir la entrada de efluentes no tratados y (iii) regular los usos del agua del estuario en función de la calidad de agua.

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Thesis Organization

This thesis is divided into eight chapters. The *first chapter* provides an overview of the importance of estuarine environments and the disturbances that affect them, the objectives of the study, and the hypotheses considered at the beginning of the research. The *second chapter* considers the possible impacts caused by natural and/or human disturbances on the quality of estuarine environments. This chapter also provides information on the different water quality monitoring programs and the indices used to define the trophic status of estuarine environments. The *third chapter* describes the characteristics of the study area. The *fourth chapter* presents the methods adopted for the collection of data during the different phases of the study. The *fifth chapter* describes the anthropogenic pressures and population growth within the area of the Caeté estuary, and provides information on the sources of contamination that affect this area. The *sixth chapter* presents the hydrodynamic, hydrological, and microbiological characteristics of the Caeté, derived from the oceanographic campaigns conducted during the study. The *seventh chapter* predicts the future scenarios for the Caeté estuary considering current trends for the increase in the production of effluents up until the year 2050, together with the occurrence of climatic events. Finally, the *eighth chapter* discusses and compares the findings on the Caeté estuary in the context of regional and global patterns. To conclude this work, the principal findings of the study are compiled and summarised to provide a succinct overview of the results, and management strategies for the Caeté estuary are proposed. In addition, are proposed a number of challenges for the improvement or extension of the database established for the Caeté estuary.

CHAPTER 1

INTRODUCTION

1.1 Background

An estuary can be defined, in the most classical sense, as a semi-closed coastal body of water with a free connection to the open ocean, where seawater is measurably diluted with freshwater derived from the terrestrial drainage system (Pritchard, 1967). These environments are thus characterized by a complex natural dynamic resulting from the mixing of fresh and saline waters (Duarte et al., 2001; Potter et al., 2010) and they constitute an important transition zone between rivers and oceans.

Estuaries are considered to be the most biologically productive systems on Earth (Day et al., 1989; Kennish, 2002). In the tropical region they are often associated with mangroves, which are largely responsible for their productivity (Day et al., 1989; Alongi, 2001). In estuarine environments mean primary production is 1500 g/m²/year (dry matter) in comparison with only 125 g/m²/year for the open ocean, 360 g/m²/year for continental shelf waters, 400 g/m²/year for lakes and streams, and 650 g/m²/year for cultivated land (Whitaker and Likens, 1975). Moreover, they act as important feeding, spawning, and nursery sites for many migratory species of marine fishes and waterbirds (McLusky and Elliott, 2004; Maccarone and Brzorad, 2005; Elliott and Quintino, 2007).

Ecosystem goods and services are provided by estuarine ecosystems on multiple scales, ranging from climate regulation and carbon sequestration (global scale) to flood protection, erosion control, and nutrient cycling, on local and regional scales (DeGroot et al., 2002; Heal et al., 2005; Barbier et al., 2011). Last, but not least, estuaries filter nutrients and chemical compounds from the surrounding watershed before they are discharged into the ocean (Dürr et al., 2011).

Approximately 60% of the largest cities around the globe are located on or near estuaries (Geophysics Study Committee *apud* Miranda et al., 2002), given that they provide both indirect benefits, as mentioned above, and direct uses, such as recreational activities, resource harvesting, and buffers against pollution.

Due to their richness of natural resources, few estuaries have not suffered significant pressures from unplanned population growth (Agardy et al., 2005; Vitousek et al., 1997; Wilson et al., 2005; Lotze et al., 2006). The most common anthropogenic impacts on estuaries are derived from the unplanned growth of urban settlements. This has exposed estuaries to an increasingly complex suite of environmental disturbances, such as nutrient loading, land use changes, and hydrological modifications (Kennish, 2002; Wetz et al., 2011). One of the principal and most common environmental problems found in estuaries is an excess of nutrients induced by human activities, which is known as *cultural eutrophication* (Hasler, 1947). This condition has been detected in estuaries worldwide, in both developing and developed countries, such as China, India, Brazil, Russia, United States, and Australia (Fisher et al., 2006; Martin et al., 2008; Aleksandrov, 2010; Santiago et al., 2010; De et al., 2011; Cheng et al., 2012).

Recently, the increasing frequency and intensity of extreme climatic events, such as droughts, flooding, and cyclones, which are occurring in some parts of the world, have driven research interests in recent years. These events are not only influenced the estuarine water quality and ecological dynamics, but also affect a number of important ecosystem goods and services derived from estuaries (Wetz and Yoskowitz, 2013). A synthesis of the literature shows that climatic events (including El Niño and La Niña) affect estuarine water quality by altering: (1) the input and processing of nutrients and organic matter, (2) physical–chemical properties of the estuary, and (3) ecosystem structure and function (Cloern, 2001; Paerl et al., 2006; Rabalais et al., 2009).

The Amazon coast is a valuable environment rich in natural resources, with considerable potential for economic development, which has provided incentives for urban settlement, where population mainly exploits existing resources. Up until now, few data have been compiled on the impacts caused by these urban settlements located in the proximity of estuaries (Pereira et al., 2010; Monteiro et al., 2011; Monteiro et al., 2016; Monteiro et al., 2016a). It is important to note that, in this region the enormous discharge of freshwater from the Amazon basin and the dozens of other, minor estuaries that flow into the Atlantic Ocean along this coast, together with the high local precipitation rates determines the temporal and spatial fluctuations in the physical and physical-chemical characteristics of the coastal waters.

The Caeté River estuary, the primary of focus this study, is located in the Amazon region and lies within the world’s largest continuous area of mangrove forest. This is also the only

Brazilian region affected by semi-diurnal macrotides, which have a marked influence on coastal hydrodynamics, given that the tide is the primary component of local circulation patterns (Beardsley et al., 1995; Cavalcante et al., 2013). In the same time, this estuary is susceptible to anthropogenic perturbations caused mainly by unregulated urban growth in communities located surrounding this estuary, which is around 20% per decade (IBGE, 2015).

Given this, environmental problems that previously arose on a small scale have become increasingly intense, due to the lack of urban planning or basic infrastructure, such as a public sanitation system, garbage collection, or effluent treatment plants (Pereira et al., 2010; Monteiro et al., 2011). In addition, climatic events, such as El Niño, may also affect the relative volume of freshwater in the estuary, influencing the quality of the water. In this context, the Caeté estuary can be considered to be a useful model for the assessment of the potential effects of anthropogenic stress on natural environments in the Amazon region, especially those susceptible to future climate events. It is essential that the measures adopted to resolve this problem take the natural characteristics of the region into account, including the climatic regime of the region and the high productivity of its aquatic environments.

1.2 Objectives

The main aim of this study is to analyze the environmental quality of the Caeté river estuary and the relative role of existing natural and anthropogenic forcings. Based on this, five specific objectives were defined:

- To create information and knowledge about the site since no significant systematic data do exist. There is a big gap about the knowledge on the functioning of the estuary.
- To identify the potential sources of pollution in the different sectors of the Caeté estuary and define their influence of the quality of the water;
- To analyze how natural forcings (climate and river discharge fluctuations) influence water quality;
- To identify the trophic status of the estuary under different conditions climatological and in areas under different anthropogenic pressures;

– To evaluate possible changes in the water quality under different scenarios, such as population growth and climate change.

1.3 Hypotheses

The main approach of the study is to evaluate the water quality of the Caeté estuary in three distinct zones characterized by different levels of impact from urbanization and alternative forms of land use, and under different local conditions (dry and wet seasons, and spring and neap tides). Based on these considerations, three operational hypotheses have been proposed:

– The different types of land use and occupation observed along the estuary may have different implications for the quality of the water in the different sectors. It is predicted that the more urbanized sector will have more negative impacts on the water quality than the other sectors;

– The natural characteristics of the Amazon region, such as its macrotidal regime, contribute to the turnover of the water in the estuary, and that the spring tides, in particular, favor an improvement in the quality of the water;

- Due to its geographic location on the Amazon coast, the Caeté estuary is affected by the considerable climatic fluctuations that are typical of this region. Periods of high rainfall levels, when the fluvial discharge and the leaching of organic matter from the mangroves increase considerably, result in a marked increase of the input of nutrients into the estuary.

CHAPTER 2

WATER QUALITY IN ESTUARIES

This chapter discusses the possible impacts caused by anthropogenic impacts and/or influenced by natural processes on the quality of estuarine environments. The chapter also provides information on the different water quality monitoring programs and the indices used to define the trophic status of estuarine environments, including those used specifically in the Caeté estuary.

2.1 Human disturbance to estuaries

By virtue of their nature and position, located between marine and terrestrial environments, nearly all estuaries have been influenced in some way by anthropogenic activities, which will become increasingly intense over coming decades, driven by the ongoing population growth in coastal areas (Nedwell and Raffaelli, 1999).

Estuaries have traditionally been the focus of a wide variety of human activities, resulting in the development of ports and major industrial, urban and recreational infrastructure (Ridgway and Shimmield, 2002), as well as a consequent increase in point and nonpoint sources of contamination (Kennish, 1997). Point sources of pollution are single sources of discharge, which can be easily identified. By contrast, nonpoint sources are less easily identified, and may result from a number of different sources or more general land use practices (USEPA, 2007). Table 2.1 shows the most common sources (point and nonpoint) of pollution in the study area, and their respective pollutants (from Kennish, 2002)

One of the principal environmental problems associated with this increase in pollution sources is the loss of water quality, which can be defined in terms of the adequacy of the aquatic environment at a given moment in time for different potential types of use, as defined by the Brazilian Environment Council, CONAMA through resolution nº375/2005. The evaluation of water quality thus varied according to its designated use.

Table 2.1: The most common sources of pollution.

Sources	Common pollutants categories
Point sources	
Municipal sewage tretament plants	BOD, bacteria, nutrients, ammonium, toxic chemicals
Industrial facilities	Toxic chemiclas, BOD
Combined sewer overflows	BOD, bacteria, nutrients, turbidity, total dissolved solids, ammonium, toxic chemicals
Non-point sources	
Agricultural run-off	Nutrients, turbidity, total dissolved solids, toxic chemmicals
Urban run-off	Turbidity, bacteria, nutrients, total dissolved solids, toxic chemicals
Construction run-off	Turbidity, nutrients, toxic chemicals
Mining run-off	Turbidity, acids, toxic chemicals
Septic systems	Bacteria, nutrientes
Landfills/spilss	Toxic chemicals, miscellaneous susbtance
Silvicultural run-off	Nutrients, turbidity, toxic chemicals

Studies conducted by the Joint Group of Experts on the Scientific Aspects of Marine Pollution (GESAMP) and scientific investigators from a number of different countries around the world indicate that there are six primary pathways through which pollutants enter estuarine environments: (1) nonpoint run-off from land; (2) direct pipeline discharge; (3) riverine inflow; (4) atmospheric deposition; (5) maritime transportation; and (6) the dumping of waste at sea (McIntyre, 1992, 1995; Goldberg, 1995; Kennish, 1997). On the other hand, Ridgway and Shimmield (2002) concluded that the most common source of pollution in estuaries is the effluents from sewage treatment plants. In fact, the impact of the discharge of treated or untreated wastewater into estuaries is of great concern in most countries, and has been widely reported (Von Sperling and Chernicharo, 2002).

These pressures result in negative impacts such as (i) the introduction of pathogens (e.g. certain bacteria, viruses, and parasites) and other infectious agents often associated with sewage effluents; (ii) the introduction of heavy metals, and (iii) an increase in nutrient input into the estuary, which will be investigated here. Table 2.2 shows the total amount of nitrogen and phosphate introduced per year by wastewater into some estuarine systems.

The input of nutrients and consequent eutrophication of aquatic environments rank among the most common environmental problems in estuaries. Eutrophic environments are "well-nourished", and this process can be defined as "the enrichment of water by nutrients, especially compounds of nitrogen and/or phosphorus causing an accelerate growth of algae and higher forms of plant life to produce and undesirable disturbance to the balance of organisms present in the water and to the quality of the water concerned'' (OSPAR, 2013).

While eutrophication is considered to be a disturbance rather than a form of pollution, the trophic status of aquatic ecosystems has been considered a good indicator of environmental health, and has been used as a diagnostic tool to characterize the water quality status of many aquatic ecosystems, including polluted estuaries (Kennish et al., 2013).

Table 2.2: Emissions of total nitrogen (N_T) and phosphate (P_T) from wastewater in hydrographic basin and estuarine systems around the world ($t.yr^{-1}$).

	N	P		N	P
United States[1]			*Brazil*[2]*		
Hudson	49,0	9,6	Timonha	50,1	14,0
Missisipi		9,9	Acaraú	238,9	66,9
			Coreaú	233,0	65,2
Baltic[1]			Aracatiaçu	56,6	15,9
Randers Fjord	84,5	0,7	Aracatimirim	52,5	14,7
			Curu	98,3	27,5
United Kingdon[1]			Mundaú	250,0	70,0
Glaslyn-Dwyryd	69,9		Pirangi	76,5	21,4
Mawddach	17,3		Jaguaribe	152,0	42,4
Dyfi	32,8		Icapui	27,5	7,7
			Apodi	400,5	112,5
China[1]			Açu	96,0	27,0
Haihe	20,0	1,6	Guamaré	17,0	4,5
			Ceará Mirim	32,0	9,0
Costa Rica[2]			Guaraíras	96,5	27,0
Tárcoles	2000,0	300,0	Curimataú	57,0	16,0
Reventazón	110,0				
Colombia[2]					
Cauca-Magdalena	130,0				

[1]Treated wastewater [2] Untreated wastewater *Estimated by Lacerda (2006)

Thus, a eutrophication may occur as a natural process over the course of a period of thousands of years, when the waters gradually age and become more productive due to the accumulation of nutrients and organic biomass or through the anthropogenic input of nutrients from point and nonpoint sources, referred to as cultural eutrophication (Mannion, 2014). This process is a global phenomenon, on different scales of intensity and impacts, ranging from the Baltic, Adriatic and Black Seas, to the estuaries and coastal waters of Japan, China, Australia, the

United States and Mexico (Fisher et al., 2006; Martin et al., 2008; Santiago et al., 2010; Aleksandrov, 2010; De et al., 2011; Cheng et al., 2012).

The principal consequences of eutrophication include (i) an increase in particulate organic matter and water turbidity; (ii) the occurrence of phytoplankton and microphyta blooms, which may be responsible for the reduction of the dissolved oxygen concentrations; (iii) a decrease in local biodiversity; (iv) a reduction in the aesthetic quality of the water and the potential for human use, and (v) the loss of economic value (Roberts and Pierce, 1974; Karlson et al., 2002; Kennish, 2002; Anderson et al., 2002; Burford et al., 2012). Overall, then, eutrophication results in a loss of water quality and impacts on the socio-economic and ecological environments (Roberts and Pierce, 1974; Anderson et al., 2002; Karlson et al., 2002; Burford et al., 2012). In order to mitigate these effects, countries are increasingly adopting measures to control anthropogenic sources of pollution and to reduce the input of dissolved nutrients and bacteria into the estuaries. One of the most widespread measures is the construction of sewage treatment plants (Greening and Janicki, 2006).

The input of nutrients and faecal bacteria (including *Escherichia coli*) are considered good indicators of the level of human disturbance, due to their presence in human faeces. Estuaries impacted by untreated effluents from urban areas usually have high concentrations of these bacteria, as observed in Zanzibar in East Africa (Mohammed, 2002), the Minho estuary in Portugal (Anne et al., 2006), and the Ganges estuary in India (Batabyal et al., 2014).

Studies have shown that faecal coliform concentrations correlate with population density in the surrounding hydrographic basin and especially with land occupation within the watershed. However, the most important anthropogenic factor associated with faecal coliform concentrations is the percentage of impervious surface cover, consisting of roofs, paved roads, and other infrastructure. This cover alone may account for 95% of the variability in mean estuarine faecal coliform concentrations (Mallin et al., 1998).

In some cases, wastewater treatment plants have reduced significantly the amount of bacteria present in sewage effluents, exceeding 95% of *E. coli* in Denmark (Bonde, 1967), and reaching 99.9% in Gdańsk-Wschód and Gdynia Dębogórze in Poland (Szumilas et al., 2001). In some regions, however, treatment is insufficient, and the gap between desirable levels of coliform pollution and local practice continues to expand (Von Sperling et al., 2002).

2.2 Natural disturbance to estuaries

On the Atlantic coast of Brazil, estuarine areas are typically associated with mangrove forests (Herz, 1991). These forests are characterised by a complex interaction of physical, chemical and biological process, which sustain high rate of primary productivity (~24 tons/hectare/year), and support an enormous diversity of marine, freshwater and terrestrial species (Macintosh and Asthon, 2002).

In order to understand the interrelationship between estuaries and mangroves, some authors have focused on the relationship between the exportation of nutrients from areas of mangrove and the high productivity of adjacent waters. In 1962, the first studies of the tidal exchange of materials were conducted by Golley et al. and Teal, who studied a mangrove forest and a salt marsh, respectively. Both studies concluded that there is an outwelling of dissolved nutrients to adjacent marine waters.

In 1968, the outwelling hypothesis, which refers to the exportation of nutrients from mangrove forests to the adjacent waters was proposed by Frederic Odun. This author, tried to relate the exportation from mangrove systematically with the high productivity these waters.

From this point onwards, studies focused on the exportation or importation of particulate matter, litter, particulate organic carbon, dissolved nutrients or metabolic nutrient demands from mangroves to others ecosystems until Twilley (1988), through a study of mangrove mass balance, suggested that the exportation of organic matter is a common feature of most mangrove ecosystems, given that their natural characteristics – intense tidal exchange, regular rainstorms, and floating litter – favoured this process.

Simultaneously, other studies found that mangrove forests also import organic carbon and retain large amounts of the litter produced for *in situ* consumption, mainly as a result of the restricted inundation regime (e.g., Twilley et al., 1986; Flores-Verdugo et al., 1987; Lee, 1990). The resulting controversies – exportation *vs.* importation – were resolved by the general conclusion that, while there may be a net importation of inorganic nutrients into mangrove wetlands, there is a net exportation of organic matter from these forests (Twilley, 1988).

Up until now, however, data on mangrove outwelling are available from only approximately 15 countries, corresponding to 10% of the world's mangrove forests, and most of these data refer to carbon, rather than nutrients. Revising these data in detail, Adame and Lovelock (2011) concluded that mangrove forests tend to export carbon in the form of litter and POC (particulate organic carbon) during tidal inundation. Exportation may range from 0.1 g C $m^{-2}year^{-1}$, as recorded in Hong Kong by Lee (1989) to 498.8 g C $m^{-2}year^{-1}$ in Mexico (Flores-Verdugo et al., 1987). In the case of DOC (dissolved organic carbon), exchange rates ranged from the importation of 67.3 g C m^{-2} year $^{-1}$ in Florida (Davis et al., 2003) to the exportation of 138.0 g C m^{-2} year $^{-1}$ in the Caeté estuary, Brazil (Dittmar et al., 2006).

The exchange of dissolved nitrogen is also highly variable, ranging from the exportation of 5.0 gN m^{-2} $year^{-1}$ in the Caeté estuary (Dittmar and Lara, 2001) to the importation of 1.6 gN m^{-2} year $^{-1}$ in Australia (Ayukai et al., 1998). Both these values were recorded in environments dominated by extreme tidal forces, which favour the exchange of dissolved nitrogen. Dissolved phosphate ranged from the exportation of 0.61 gP m^{-2} year $^{-1}$ in Conn Creek, Australia (Boto and Bunt, 1981) to the importation of 1.4 gP m^{-2} year $^{-1}$ in the Taylor River, in the USA (Davis et al., 2001).

Through the high degree of deviation from conservative mixing, Dittmar and Lara (2001) concluded that outwelling from the mangroves of the Caeté estuary in northern Brazil (Amazon region) was higher than the freshwater input into the ocean, and thus that the mangrove rather than the river supports production in the marine environment. This study also showed that the net exports of dissolved nutrients from the Caeté mangrove system exceed those of other mangroves anywhere in the world. Annual exportation was estimated (mol yr^{-1}) to be 30 x 10^9 for POC, 2 x 10^9 for DOC , 0.4 x 10^9 for ammonium, 15 x 10^9 for silicate and 0.04 x $10^9$for phosphate.

Adame and Lovelock (2011) divided the factors affecting material exchange into:

(i) *Global scale*: climate and latitude;

(ii) Regional scale: geomorphological setting and hydrology;

(iii) Local scale: dominant tree species, litter fall, area of forest and nutrient concentrations.

Many studies have reported the influence of these parameters in their observations. For example, Thong et al. (1993) demonstrated that heavy rains which inundate the mangrove, may increase the nutrient export from adjacent bodies of water and Light and Dineen (1994) concluded that the subtropical climate of southern Florida plays a major role in controlling material transportation. Dittmar and Lara (2001) highlighted a number of factors that influenced the high nutrient concentrations recorded in the Caeté estuary, such as the pore water flux, sedimentation-erosion, and litter exportation. Other studies in similar environments to that of the Caeté estuary, dominated by a macrotidal regime, have confirmed that tidal forcing controls the net flux (Kjerfve and McKellar, 1980).

Despite the growing number of studies on nutrient cycling in mangrove systems, phenomena such as primary production, the magnitude of nutrient transport and the dispersal of the material in the adjacent coastal zone has still not been elucidated adequately. Adame and Lovelock (2011) concluded that the main problem for the understanding of the outwelling hypothesis is the diversity of spatial scales and methods, which limits comparisons among studies and sites. Other authors attribute the lack of understanding of this process to the variation in the local factors both among and within mangrove systems, such as geomorphology, tidal amplitude, local climate, the type of vegetation and abiotic factors, which all complicate broader extrapolations (Twilley et al., 1997; Nordhaus et al., 2006).

Adame and Lovelock (2011) nevertheless observed certain tendencies in the data. For example, studies that have investigated the exportation of nutrients in the form of litter and POC have concluded that mangroves export nutrients. On the other hand, studies of the exchange of dissolved nutrients have shown both importation and exportation. Finally, studies that have estimated material exchange by measuring the forest’s metabolic demand for nutrients have shown that mangroves import nutrients.

While the outwelling hypothesis has not yet been fully elucidated, it is clear that the exchange of carbon between tidal wetlands, such as mangrove forests or salt marshes, and coastal waters is a fundamental component of the carbon budget of the oceans (Twilley et al., 1992) and represents an important contribution on a global scale. Similar process also occur with nitrogenous and phosphorous macronutrients.

2.3 Monitoring water quality in estuaries

The monitoring of the quality of the water of estuaries is necessary to guarantee adequate conditions for the current and future use of these environments (Ustin et al., 2014), and to determine whether the water is adequate for specific uses. Many water authorities around the world have created water quality monitoring programmes, such as the National Estuary Program created by the United States Environmental Protection Agency (USEPA), the Water Framework Directive in Spain, and the Nanaimo Estuary Management Plan in Canada.

Water quality monitoring in estuaries has a number of common objectives, including (i) the evaluation of estuary conditions and their potential effects on human activities, (ii) the establishment of guidelines for the regulation of these activities in order to prevent or minimise the negative impacts of these activities on the quality of the water, (iii) the definition of a programme of monitoring for the evaluation of ongoing impacts, (iv) the restauration of degraded habitats, and (v) the establishment of a management plan for the estuaries.

In Brazil, the monitoring of estuarine water is the responsibility of state environmental protection agencies, and should follow the guidelines proposed by the Brazilian Environment Council (CONAMA, resolution nº375/2005). This resolution was introduced in 1986 and revised in 2005 to establish standards and limits for physical-chemical, microbiological, and other pollutant indicators for surface waters in Brazil (including estuaries), as well as sewage discharge levels. The water quality levels are determined according to the specific uses, which are divided into:

- human supply,
- protection and preservation of aquatic communities,
- irrigation,
- aquaculture and fisheries,
- animal watering,
- navigation and
- landscape harmonisation.

Some developed nations have already achieved basic levels of water pollution management (Von Sperling and Chernicharo, 2002), and are currently fine-tuning the control of micro-pollutants and the impact of pollutants in sensitive areas or pollution caused by storm water drainage. Developing nations, by contrast, are under constant pressure, because, while they attempt to adopt increasingly strict international limits and standards, they are generally unable to reverse ongoing trends of environmental degradation.

Unfortunately, few Brazilian environmental protection agencies prioritize the monitoring of estuaries, and government initiatives for estuarine water quality monitoring are scarce or non-existent in some regions, especially northern Brazil. This situation is derived from a lack of resources for most state agencies, reinforced by the complexity of the region’s estuarine environments, which hampers effective monitoring.

2.3.1 Water quality index

The trophic status of an estuary can be characterised by a number of different indices or indicators. A water quality index provides a numerical value that expresses the quality of the water for multiple purposes. This value is obtained from the systematic integration of chemical, physical, and bacteriological data (Tyagi et al., 2013). Water quality indicators are measurements, usually quantitative, that can be used to illustrate complex phenomena simply, including tendencies over time, that can provide important insights into the state of an environment (EEA, 2005).

The first water quality index was proposed by Horton (1965), a German investigator who developed the index to evaluate the reduction of pollution in environments monitored by government programs. This initiated interest in the development of different approaches to the assessment of water quality, with the primary intention of simplifying procedures (Liou et al., 2004).

Water quality indices have been developed to facilitate the study of coastal zones, including estuaries, by permitting the evaluation of anthropogenic pressures on local conditions, and the assessment of ecosystem integrity. These indices summarize a large amount of data into a single, simple and consistent concept accessible to policymakers and the general public (Saeedi et al., 2010). These indices are considered to be one of the most effective ways to describe the quality of aquatic environments.

However, water quality status cannot be considered to be a static parameter, given that the coastal zone is a very dynamic environment affected by terrestrial inputs (natural and anthropogenic), and the interaction of inshore and offshore waters, winds and weather conditions. Water quality indices must therefore evaluate both temporal and spatial dimensions in order to characterise the mean or typical conditions found in the target area (Giovanardi and Vollenweider, 2004).

The trophic state of an aquatic environment is currently considered to be an effective measure of the water quality of an aquatic environment, and a large number of trophic indices have been created. Karydis (2009) proposed that a good indicator of trophic state should:

- be able to detect trends that cannot be easily observed from the raw data;
- be used as an early warning system in decision-making when management practices are applied;
- assess the performance of decision-making when management practices are applied; and finally
- assess the degree of severity or remediation in areas with established problems of eutrophication.

Early trophic indices (*e.g.* Trophic State Index and TRIX) were based on a set common indicators, such as chlorophyll *a* and/or nutrient concentrations in the aquatic environment, in particular N and P, which are transported by the runoff of rainfall from agricultural zones or released from urban sewer systems to estuaries. In addition to these parameters, the monitoring of variables such as the transparency of the water, dissolved oxygen and primary productivity have become increasingly widely used to classify aquatic environments, given their vulnerability to pollution.

More recent indices consider other biotic indicators, such as phytoplankton species parameters, primary production, seagrass and harmful algal bloom, which may reflect the severity of pollution levels (Karydis, 2009). Ideally, biotic and abiotic variables should be considered together with the direct and indirect effects of pollution on water quality (Borja et al., 2012).

These indices usually classify the trophic state in scales (*e.g.*, high, good, moderate, poor and bad) or in one three general trophic states – (i) oligotrophic (low nutrient levels, high clarity),

(ii) mesotrophic (moderate nutrient levels, reduced clarity, fewer desirable biological habitats), and (iii) eutrophic (most enriched state, which can result in significant loss of environmental quality).

Each index should be developed for a specific type of environment based on an empirical understanding of local conditions, reducing its applicability in other environments or regions. An index developed for European ecosystems, for example, is unlikely to be appropriate for the Amazon region, given the major differences in local conditions. Indices can nevertheless be adapted to local conditions. For example, Carlson's index was developed for temperate climates, although it has been modified several time for used in different environments and regions (see the Modified Carlson Trophic Index in Toledo Jr. et al., 1983).

Table 2.3 shows a number of different indices used to assess water quality. Many of these indices were created for use in open coastal areas, although they may be used to classify more confined environments, such as lakes, lagoons or estuaries, although without adequate adaptations, their use may present certain limitations (Blanchet et al., 2008) or generate inconsistent results, given that concentration in closed or semi-enclosed systems tend to be higher than in open coastal areas.

Table 2.3: Indices commonly used to evaluate the trophic state of estuaries.

Index	Region using method	Indicators	Authors
TSI	USA	Chl *a*, transparency, TP	Carlson, 1977
TI	Greece, Mexico	N or P	Karydis et al., 1983
TRIX	EU	Chl *a*, DO, DIN, TP	Vollenweider et al., 1998
IFREMER	France	Chl *a*, DO, SRP, TP, TN, NO2, NO3, NH4, OM, phytoplancton, macrophytes, macrobentos, Chl/phaeo, turbidity	Souchu et al., 2000
OSPAR	EU	Nutrient inputs, salinity gradients	OSPAR, 2013
EPA NCA	USA	Chl *a*, water clarity, DO, DIP, DIN	USEPA, 2008
TWQI/LWQI	EU	Chl *a*, DO, DIN, DIP, seagrasses, macroalgae,	Giordani et al., 2009
ASSETS	EU, USA, Asia, Australia.	Chl *a*, DO, macroalgae, seagrasses, nuisance/toxic bloom	Bricker et al., 1999

In the specific case of estuarine environments, which are naturally enriched with nutrients and usually receive a large input from urban areas, high nutrient concentrations are expected. Given this, the choice of index is a very important step towards the reliable understanding of the trophic state of an estuary. Estuaries also present specific problems for the classification of conditions, derived from features such as the tidal regime, flushing time or vertical stratification, which imply the distribution of distinct conditions in the water column and sediments (Ferreira, 2000).

In Brazil the most often used water quality index (IQA_{Cetesb}) was developed by the Environmental Agency of São Paulo – CETESB. The weighted products of the normalized values of nine variables (dissolved oxygen, biochemical demand oxygen, faecal coliforms, temperature, pH, total nitrogen, total phosphorus, turbidity and total residues) are used to calculate this index. The TRIX (Vollenweider et al., 1998) index is also widely used in estuarine environments (Flores-Montes et al., 2011; Guenther et al., 2015).

The data available from the Amazon region indicate that the local estuaries are characterized by high nutrient concentrations, high biological productivity and, consequently, high chlorophyll *a* concentrations (Dittmar and Lara, 2001; Lam-Hoai et al., 2006). Given this, a specific index appropriate to these conditions would be the most adequate for the region. It is important to note, however, that the creation or adaptation of an index to a specific region will require a thorough understanding of the ecological characteristics of the region.

Based on the questions discussed above and the data available for the Caeté estuary, the Trophic indices (TI) developed by Vollenveider et al. (1998) and Karydis et al. (1983) were adopted for the present study. Methods to calculate both these index were described in the Chapter 4.

THE STUDY AREA

AND DATA AND METHODS

CHAPTER 3

THE STUDY AREA

This chapter provides a description of the study area, considering its regional (Amazon littoral) and local (hydrographic basin of the Caeté River) contexts. This description covers the natural (geology, climate, and hydrology) and socio-economic (patterns of land use and occupation) features of the region that potentially influence the dynamics of the Caeté estuary (focus this study) and cause changes in the quality of the water.

3.1 Amazon littoral

The Brazilian Amazon Coastal Zone is located in Northern Brazil and encompasses the states of Amapá, Pará, and Maranhão. It is delimited by the Oiapoque River in the state of Amapá (5°N 51°W) and the São Marcos Bay in the state of Maranhão (2°S 44°W) (Figure 3.1A). Within this context is inserted the world's largest wetland system dominated by mangrove forest (Kjerfve and Lacerda, 1993). The continuity of the mangrove is interrupted in the zone influenced by Amazon River discharge, where the 'várzea' vegetation and herbaceous fields dominate (Guimarães et al., 2011a).

The Amazon coastal zone is influenced by the fluvial discharge of the Amazon River and numerous other local estuaries, and eighteen percent of the World's river water is from Amazon River (Oltman, 1968). Its maximum discharge into the Atlantic Ocean is around 191,000 $m^3.s^{-1}$ in April and the minimum around 98,000 $m^3.s^{-1}$ in November (Molleri et al., 2010). Sediments discharge is expressive around of 1.2 x 10^9 $tons.yr^{-1}$ (Meade et al., 1985). Part of these sediments is deposited on the continental shelf, however, some 20% are taken to the west by the current of North Brazilian and the current of Guianas (Geyer and Beardsley, 1995; Lentz, 1995; Nittrouer and DeMaster, 1996).

3.1.1 Divisions of the Amazon coast

The coastal area of Brazilian states that constitute the Amazon coast (Amapá, Pará and Maranhão) were subdivided here, according to their dominant depositional environments and geomorphological characteristics. These subdivisions, and other geological features, are presented below.

The coast of Amapá is 698 km long and is divided into estuarine (236 km) and Atlantic (462 km) sectors (Figure 3.1B). The Atlantic sector encompasses the transition zone between the ocean and the continent. Geomorphologically, it includes the Amapá-Guiana mud fields and the North Cape, a wetland area of approximately 18,000 km², in addition to mangrove forests, lagoons, estuaries, salt marshes, and *terra firme* forest (Souza-Filho et al., 2005). The estuarine sector encompasses fluvial-marine environments, such as dry grasslands, 'várzea' and secondary forests, rivers, streams, lakes, and seasonally-flooded grasslands. Geomorphologically, this sector includes the mouth of the Amazon and the Gulf of Marajó, and is influenced primarily by the fluvial discharge of the Amazon River, which forms an extensive plume, influenced by the trade winds and coastal currents (Souza-Filho et al., 2005). This plume may extend 100-500 km out into the Atlantic Ocean, and more than 1000 km to the northwest, into the North Atlantic Ocean (Gibbs, 1970; Lentz, 1995; Silva et al., 2005; Ffield, 2007).

The coast of Pará is about 600 km long, between the mouth of the Amazon River and that of the Gurupi River (Figure 3.1C). Franzinelli (1992) divides this coastline into two primary features: (i) the flat emergence coast, represented by Marajó Island; and, (ii) the submergence coast between Marajó Bay and Gurupi Bay. In this second sector, the coastal plateau reaches the shore, forming terraces and active cliffs constituted by tertiary sediments of the 'Barreiras' and 'Pirabas' formations. This region is known as the 'Reentrâncias', a highly indented coastline which contains the greatest diversity of depositional environments found anywhere on the Amazon coast, including beaches, dunes, estuaries, cheniers, tidal mudflats, and coastal plains (Souza-Filho et al., 2005). The dominant type of environment are the estuaries, which are typically associated with tidal mudflats (covered with mangrove) and tidal sandbanks that form the region's sandy macrotidal beaches. Both emergence and submergence coasts can be found in this region, with estuaries of between 60 km and 80 km in length.

The coast of Maranhão can be divided morphologically into three provinces, two of which are part of the Amazon coast: (i) the western coast (part of the 'Reentrâncias') extends for 520 km from the mouth of the Gurupi River to the Gulf of Maranhão (Figure 3.1E). This province is composed of about 20 funnel-shaped estuaries, separated by low-lying mangrove-dominated peninsulas bordered by dynamic barrier islands and tide-modified beaches (Pereira et al., 2016) and (ii) the central section with 490 km occupied by the four main channels of the funnel-shaped Gulf of Maranhão. This gulf is 90 km wide at its mouth and extends 130 km inland, and encompasses mangroves, beaches, dune fields and an estuarine complex that includes major local rivers such as the Mearim, Itapecuru, and Munim (Pereira, op. cit.)

The 'Reentrâncias' coast of Pará and Maranhão is also known as the Amazon Macrotidal Mangrove Coast (AMMC) (Figure 3.1D), which extends 650 km and covers an area of 7591 km², representing approximately 57% of Brazilian mangroves (Oliveira and Maneschy, 2014). The Caeté estuary is located in this sector, and is a low-lying, emerging coastline (0–80 m), with an ample coastal plain, up to 70 km wide, and an extensive continental shelf, stretching as much as 330 km into the ocean (Szlafsztein and Lara, 2002; Souza-Filho et al., 2005).

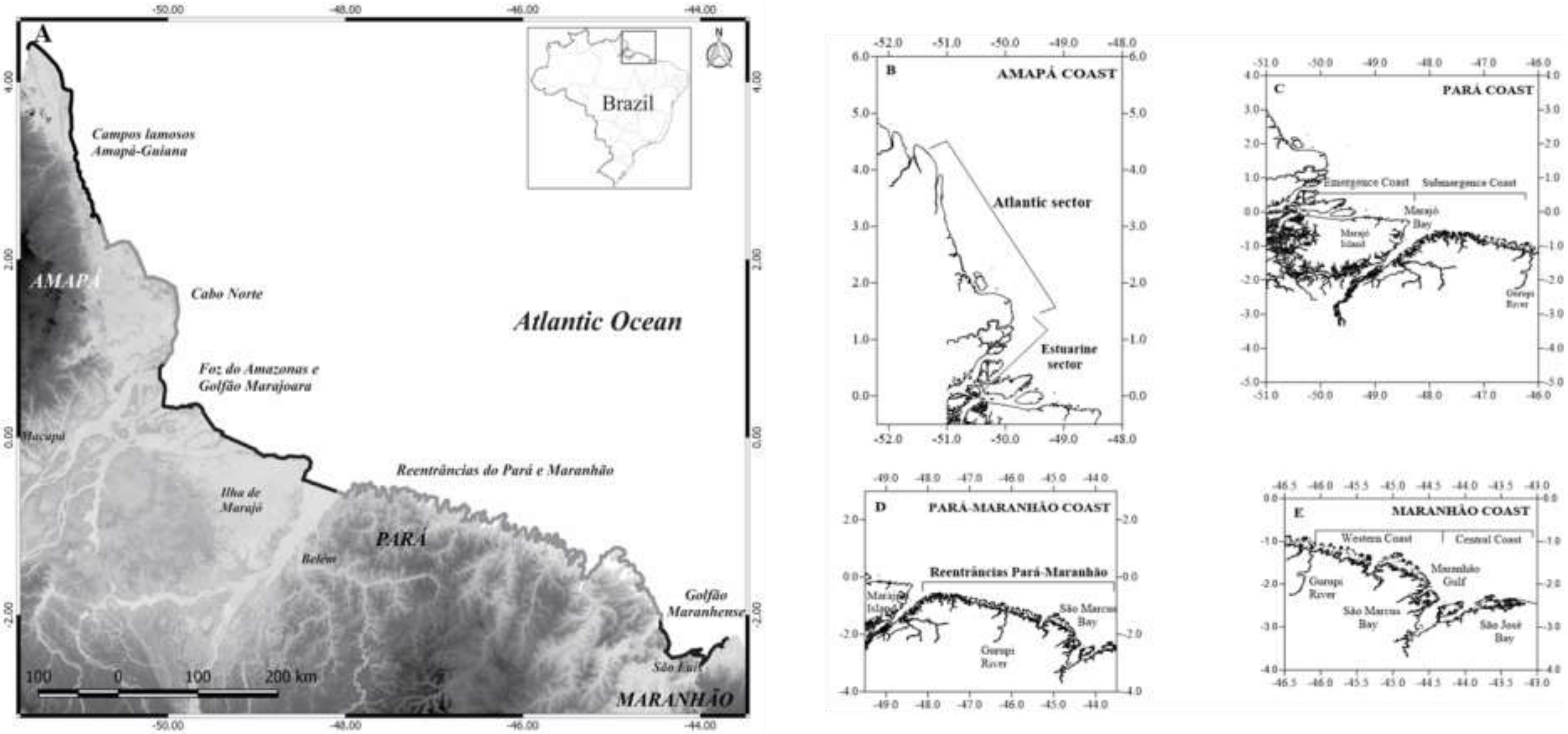

Figure 3.1: Amazon coast (A) and subdivisions of Amazon coastal region including Coast of Amapá (B), Coast of Pará (C), Reentrâncias Pará-Maranhão (D) and Coast of Maranhão (E).

3.1.2 Climatological features

The Amazon region has a hot, humid equatorial climate (CPTEC, 2016). Mean monthly temperatures are between 24 and 28°C, reaching a maximum of more than 30°C, and a minimum of less than 22°C (Martorano et al., 1993). The evapotranspiration rate tends to be high, with little interannual variability and an annual average of approximately 813 mm (Cohen et al., 1998). Annual rainfall may be up to 3,300 mm in some parts of the Amazon Coastal Zone. Figure 3.2 show the long-term mean monthly rainfall data between 1961 and 2015 provided by CPTEC (2016) where highlight the marked seasonal variation in rainfall patterns in the different sectors of the Amazon coast (Macapá-Amapá, Belém-Pará and São Luís-Maranhão), as well as the discreet variation in air temperatures in this region.

The main drivers of annual climate variability in this region are large-scale circulation patterns, including the confluence of the tropical Atlantic trade winds and the displacement of the Inter-Tropical Convergence Zone - ITCZ (Marengo, 1995). The ITCZ consists of a belt of low pressure, which is formed by the hot air of the equatorial region rising up through the atmosphere. The displacement of the ITCZ across the equator is associated with bands of convective clouds and rainfall, which provide a major source of diabatic heat to the troposphere and freshwater to the ocean (Grodsky and Cartyon, 2003). This process depends on the intensity of the northeasterly and southeasterly trade winds, which in turn is associated with the meridional gradient in pressure and sea surface temperatures in the tropical North and South Atlantic (Marengo et al., 2008).

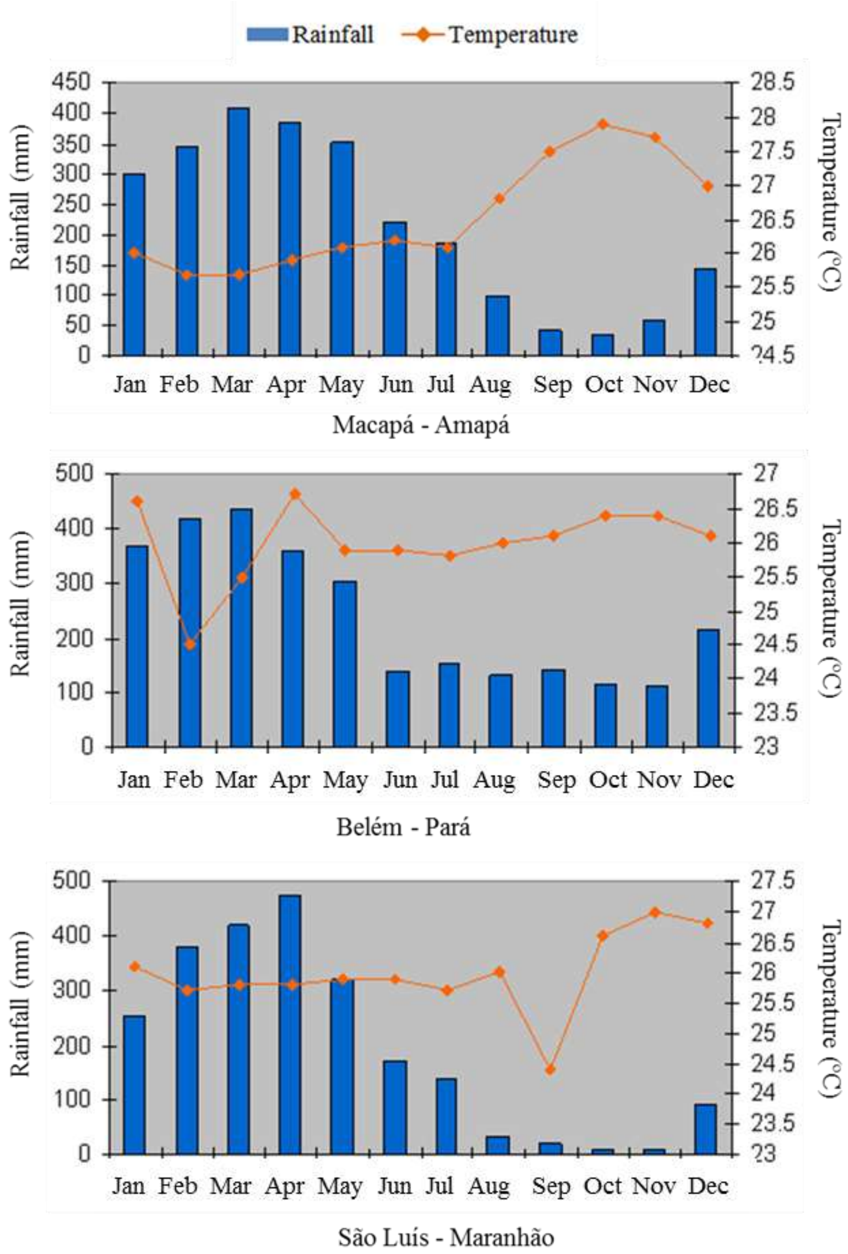

Figure 3.2: Mean annual temperatures and rainfall in three Amazon cities: Macapá (Amapá), Belém (Pará) and São Luís, Maranhão (CPTEC, 2016).

The position of the ITCZ in the Atlantic ranges from 10º North to 10º South (Figure 3.3). In the first half of the year, the ITCZ shifts to the Southern Hemisphere, over the coastal area of Amapá, Pará and Maranhão, triggering the formation of intense convective currents, which cause heavy rainfall (up to 90% of the annual total) and decreasing winds in this coastal region. During the second half of the year, the ITCZ moves to the Northern Hemisphere, to about 10º North (Figure 3.3), causing rainfall to decline in the Brazilian Amazon Coastal Zone (Figueroa and Nobre et al., 1990).

The rainfall patterns observed in the second half of the year are related to large mesoscale convective systems or squall lines. Squall lines are conglomeration bands of cumulonimbus clouds and form on the coast because of the sea breeze. These bands of convective cloud cover extend from latitudes 10º North to 5º South, and from the Guianas to Maranhão, including Amapá and Pará (Cavalcanti, 1982).

When the ITCZ is well established, squall lines are common, although they can also occur independently of the presence of the ITCZ (Cohen et al., 1998). Other systems, such as sea breezes, cyclonic vortexes of air, and easterly waves contribute on a minor scale to the rainfall patterns observed on the Amazon coastal zone during the second half of the year (Figueroa and Nobre, 1990; Marengo, 1995).

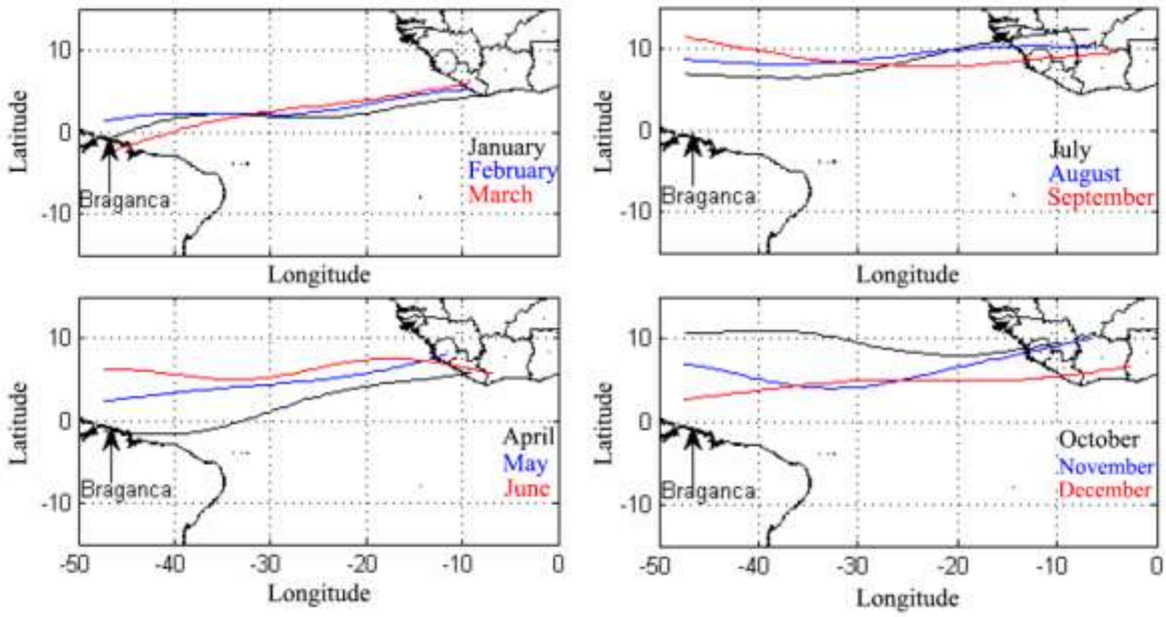

Figure 3.3: Annual displacement of the Intertropical Converge Zone on the northern coast of Brazil (Cavalcante, 2007).

The inter-annual variability of rainfall in the Amazon region, including northeastern Pará, is strongly coupled to low-frequency large-scale oceanic and atmospheric phenomena occurring over the Pacific (El Niño Southern Oscillation - ENSO) and Atlantic (North Atlantic Oscilation - NAO and Multidecadal Atlantic Oscilation - AMO) oceans (Fernandes et al., 2011; García-García and Ummenhofer, 2015).

The ENSO is characterized by events of anomalous warming (El Niño) or cooling (La Niña) of the surface waters in the central and eastern Pacific. El Niño is the primary cause of many drought episodes around the world, including in Amazon region (Zeng et al., 2008; Trenberth et al., 2014). This creates intense air mass sinking over the Amazon region and an anomalously northward displacement of the ITCZ over the tropical Pacific and Atlantic Oceans, inhibiting rainfall in central and western Amazonia. El Niño presents a periodicity ranging from 2 to 7 years (Li et al., 2011) and a typical duration between 8 and 15 months (Mo, 2010). Events with strong intensities were registered in 1982-1983, 1997-1998 and 2002-2003 (NOAA, 2016a). Opposite it, during La Niña events rainfall rates tend to increase (Marengo and Espinoza, 2015). This event present a mean periodicity of 5 years and duration highly variable ranging from 5 months to as many as 30 months (Ray and Giese, 2012).

Previous studies have shown that the northern Atlantic surface sea temperature (SST) plays a secondary role in the variability of the water budget in the Amazon region (Yoon and Zeng, 2010; Coelho et al., 2012; García-García and Unmenhofer, 2015). Abnormally high SST have been associated with reduced rainfall and drought events in the Amazon. By contrast, abnormally low SST are associated with an increase in rainfall (Coelho et al., 2012). The physical mechanism linking the northern tropical Atlantic to reduced precipitation rates in the Amazon is related to the migration of the ITCZ away from the northern coast of South America, which results in net water vapor divergence and anomalous subsidence in the Amazon, leading to reduced precipitation (Yoon and Zeng, 2010).

The drought recorded in 2005, widely considered to be the worst event of the century, was caused by an increase in the SST of the Atlantic Ocean (Marengo et al., 2008). Subsequently, in 2010, SST of the tropical Atlantic reached their highest historical values, resulting in an even more intense drought event than that recorded in 2005 (Coelho et al., 2012).

The periodicity of these events over the Atlantic ocean has been analyzed in a number of studies, which have shown that the AMO follows a 60-year cycle, with a tendency to remain in the same phase during a number of years (Peings and Magnusdottir, 2014). In the case of the NAO, Coelho et al. (2012) concluded that the cycles may be of 2.2, 2.4, 5.8 or 8.0 years, although Olsen et al. (2012) defined cycles of between 3 and 6, 4 and 8 or 8 and 10 years. However, other NAO analysis have identified longer oscillations, of between 50 and 60 years, 55 and 70 years or 65 and 90 years, linked to the AMO.

Figures 3.4 and 3.5 show the ENSO, AMO and NAO indices recorded since 1950. The possible effects of droughts caused by El Niño, NAO or AMO events on the Caeté estuary (the focus of this study) are described in Chapter 7.

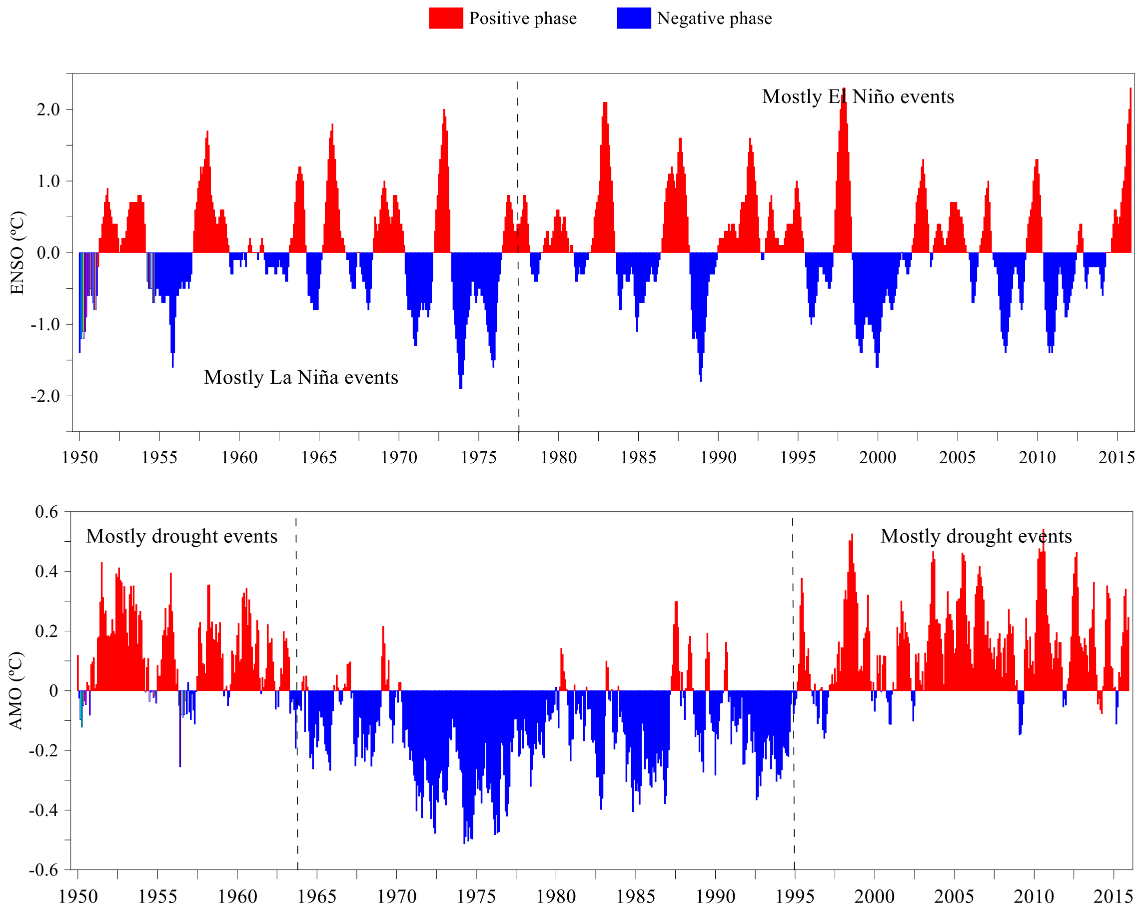

Figure 3.4: Positive and negative phases of the ENSO (A) and AMO events (B) recorded between 1950 and 2015 (NOAA, 2016a, 2016b).

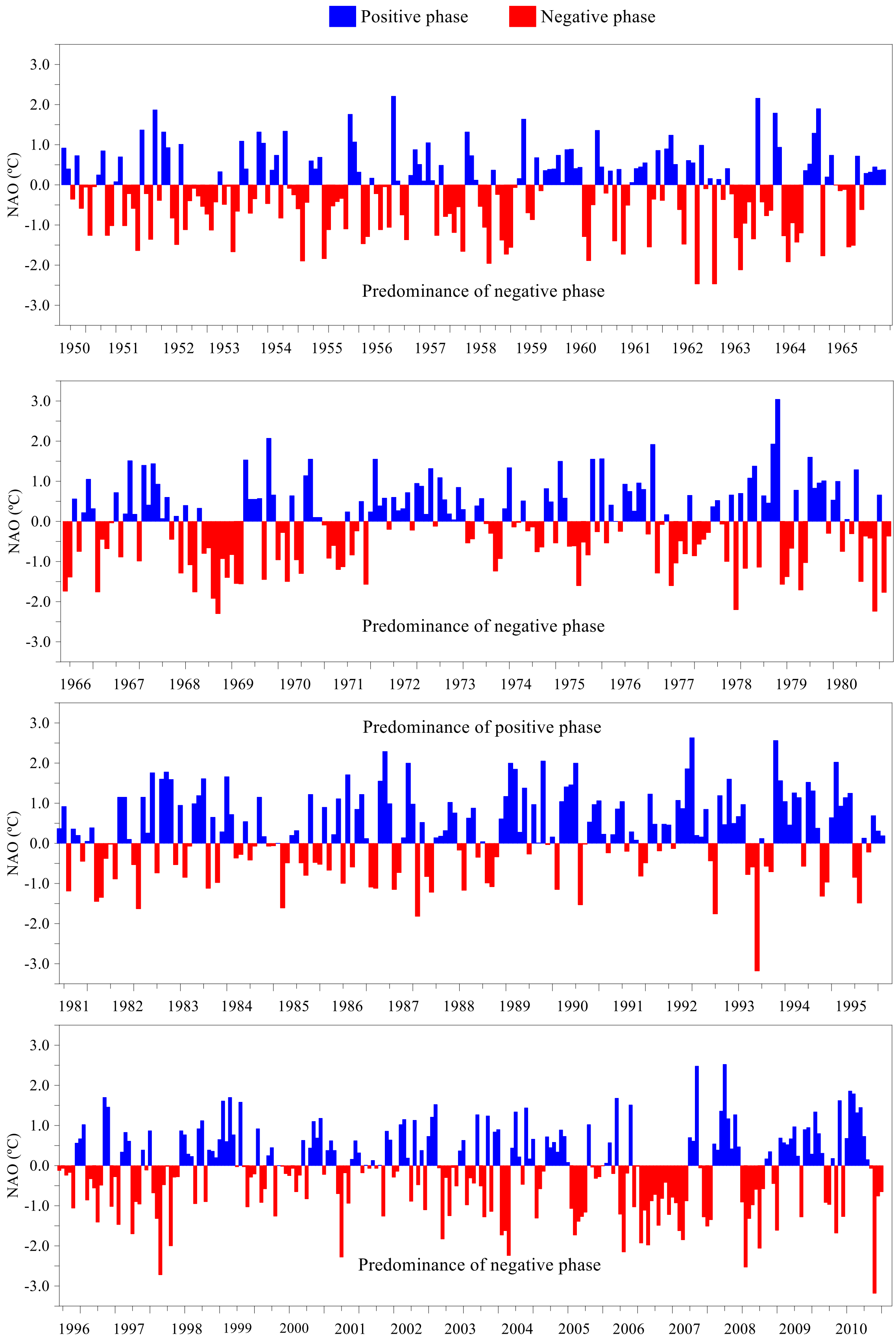

Figure 3.5: Positive and negative phases of the NAO (North Atlantic Oscillation) events recorded between 1950 and 2010 (NOAA, 2016c).

3.1.3 Hydrodynamic features

Hydrodynamic conditions and circulation patterns in the Amazon coastal zone are affected principally by the (i) macrotidal regime, which generates strong (ii) tidal currents, and (iii) wind and wave forces.

The tides are semidiurnal, generally ranging from 4 to 12 m (Figure 3.6), and the most important local astronomic components are M2 (12.4 h) and S2 (12.0 h). The M2 component is generally propagated towards the mainland, crossing the continental shelf, and entering the local rivers. Tidal incursions of 900 km have been recorded on the Amazon River (Kosuth et al., 2009).

Currents are controlled by two components: (i) the strong semi-diurnal tidal currents that cross the continental shelf, and (ii) a shelf current which causes strong northwesterly surface currents (Geyer et al., 1991; Beardsley et al., 1995). These currents vary considerably between the spring and neap tides, with maximum velocities on the inner continental shelf reaching 2.0 $m.s^{-1}$ on the spring tide and 0.7 $m.s^{-1}$ on the neap tide (Geyer et al., 1991). In the Amazon estuary, currents are controlled by the strong semi-diurnal tidal currents and can reach velocities of over 2.0 $m.s^{-1}$ (Nittrouer and DeMaster, 1986; Lentz, 1995; Asp et al., 2012).

On the Amazon coast, waves are generated by the northeasterly trade winds (Nittrouer et al., 1986). In the offshore zone, the waves come normally from the northeast. In the nearshore zone, the wave energy is modulated by both the tidal elevation and the subtidal sandbanks during low tide (Pereira et al., 2012, 2013; 2014). Typically, the waves are moderate, with a mean height (*Hs*) between 1.0 m and 2.0 m on the continental shelf (Cachione et al., 1995). When they reach the coast and move into the estuaries, in particular toward the upper sector, the wave height is reduced as a result of the shape of the estuaries, although *Hs* values of over 1.0 m can still be recorded in the inner sector of the widest estuaries, such as the Gulf of Maranhão and Guajará Bay in Pará (Pinheiro, 1987; Feitosa, 1989).

The combination of equinoctial spring tides and the high river discharge favors the formation of tidal bores (Kosuth et al., 2009; Freitas et al., 2012). Tidal bores occur when the tide overcomes the resistance of the river flow, and once past the sandbanks that form at the mouth of the river, they run into the estuary, forming a single wave of up to 5.0 m in height, which runs upstream at a speed of 10–20 km per hour (Soares, 1997). Tidal bores are seen in many estuaries in Amapá (rivers Amazon, Gurijuba, Araguari, Amapá Grande, Calçoene, Cunani, Cassiporé), Pará (Capim River), and Maranhão (rivers Arari and Mearim) (Kjerfve and Ferreira, 1993; Costa and Torres, 2000; Freitas et al., 2012).

Figure 3.6: Tidal range on the Brazilian coast, according with DHN data.

3.1.4 Hydrological features

The hydrological features of the Amazon coastal region result from complex interaction of climatic factors, river discharge, strong tidal currents and wind stress (Masson and Delecluse, 2001). For example, salinity is controlled primarily by the freshwater discharge of the Amazon and countless other local rivers (Gibbs, 1970; Vinzon et al., 2008; Rosário et al., 2009). The highest salinity in these coastal areas is typically recorded during the dry season, when rainfall levels and consequently, fluvial discharge are at their lowest levels (Pereira et al., 2012; 2013).

Alkaline waters are typical of Amazon coastal environments, but in addition to its dissolved salt content, the pH of the water also may be influenced by biological, physical and chemical processes, such as photosynthesis (Santos et al., 2008; Magalhães et al., 2013). In estuarine environments, principally at the mouth of the river, the pH is normally alkaline during the dry season. During the wet season, waters acidified further upstream mix with the organic acids produced by the mangroves to lower the pH (Berredo et al., 2008; Duncan and Fernandes, 2010). The waters of the Amazon coastal zone are well oxygenated due to the high local rates of photosynthetic activity, intense water-atmosphere interactions, and high hydrodynamic energy (Santos et al., 2008; Pereira et al., 2012; 2013).

The turbidity of the coastal waters of the Amazon littoral is influenced primarily by the high levels of fluvial discharge and hydrodynamic energy. The particulate material is derived from both lithogenic processes and biological materials. Tidal and currents processes (Beardsley et al., 1995) and wave action (Sternberg et al., 1996) are the predominant mechanisms that resuspend the sediments of the inner shelf. The local mangroves are also very extensive, and the runoff of sediments from the many local rivers also contributes to the high turbidity of the coastal waters (Milliman and Boyle, 1975; Costa et al., 2013).

The Amazon basin is the largest river system in the world, discharging an enormous volume of water into the coastal zone, which represents a major source of both organic and inorganic nutrients. However, a number of studies have also emphasized the importance of the offshore advection of nutrients into coastal areas (Gibbs, 1972; Milliman and Boyle, 1975; Sprintall and Tomczac, 1992; Pailler et al., 1999; Silva et al., 2005; 2007; Ffield, 2007; Subramaniam et al., 2008). The local mangrove forests, which are flooded every fortnight, during the spring tides, also play an important role in the nutrient profile of these coastal waters (Lara and Dittmar, 1999). In many estuarine systems, including the Caeté, the infiltration of the nutrient-rich groundwater by the estuary water may also be an important source of nutrients (Lara and Dittmar, op cit.). As a result, the coastal waters of the Amazon are relatively nutrient-rich, and support a high phytoplankton biomass (DeMaster et al., 1986; Santos et al., 2008; Pamplona et al., 2013; Goes et al., 2014).

3.1.5 Socio-environmental features

The Brazilian Amazon Coastal Zone has major environmental value and, given its natural resources, it also has considerable potential for economic development. This represents an attracting force for urban settlements, whose populations depend primarily on the exploitation of local natural resources.

This coastal zone includes the major metropolitan urban centers of Macapá-Santana, in the Brazilian state of Amapá, Belém in Pará State, and São Luís in Maranhão State, with a total population of around three millions inhabitants (IBGE, 2010). There are also isolated areas with no inhabitants or sparsely-distributed traditional populations (Szlafsztein and Sterr, 2007).

The economy activities found in the urban centers include a range of manufacturing and food processing industries, shipping, fisheries, tourism, commercial trading, real estate, and cattle ranching. In the smaller coastal communities, the local economy is based primarily on agriculture and/or fisheries (Pereira et al., 2009).

Over the past decade, the population of the Brazilian Amazon Coastal Zone has grown about 20% (IBGE, 2010). However, local infrastructure and services have not kept up with population growth, and public sanitation systems and water supplies are grossly inadequate in most cases. This generates additional anthropogenic stresses on natural environments, with negative impacts on local ecosystems (Pereira et al., 2010; Gomes et al., 2011; Trindade et al., 2011).

The inadequate use and unplanned occupation of coastal areas are among the principal anthropogenic problems observed on the Amazon littoral. In Brazil, the occupation on dunes, cliffs, the intertidal zone and mangroves is prohibited by federal law number 7661 of May 16th, 1988 (Brasil, 1988). However, a number of studies (e.g., Guimarães et al., 2009; Szlafztein, 2009; Guimarães et al., 2011; Pinto et al., 2011; Gomes et al., 2014) have shown that the inadequate occupation of these coastal features is widespread in the principal urban centers of the Amazon region, and in many coastal communities.

The discharge of untreated sewage into aquatic environments also is forbidden in Brazil by resolution nº 357/2005 (article 24) of the National Environment Council (CONAMA). However, only 4% of Amazon coastal states (Amapá, Pará and

Maranhão) have sewage treatment system (SNIS, 2013). As a result, untreated sewage are commonly discharged directly into aquatic environments, with negative consequences for water quality (Pereira et al., 2010; Monteiro et al., 2011; Trindade et al., 2011; Silva et al., 2013).

In order to protect and preserve the valuable natural resources of the Amazon, as well as optimizing the use and conservation of coastal environments, while also reducing anthropogenic impacts, a number of conservation initiatives have been implemented for the protection of coastal ecosystems and the traditional populations that inhabit them. One of the main results of this initiative has been the creation of management units of both integral protection and sustainable use types. The principal conservation units already established in the Amazon coastal region include a number of different categories of protected area. In Amapá, these areas include the Aldeia Ekinox Private Natural Heritage Reserve (RPPN Aldeia Ekinox) and the RPPN Revecon, the Cajari Extractive Reserve, the Maracá agro-extractivist settlement, the Rio Curiaú Environmental Protection Area (APA Rio Curiaú) and the APA Fazendinha, and the Parazinho Biological Reserve. In Pará, there are two Environmental Protection Areas, APA Marajó Archipelago and APA Ilha de Canela, and five Marine Extractive Reserves (MER), MER Araí-Peroba, MER Caeté-Taperaçu, MER Gurupi-Piriá, MER Soure, and REM Tracuateua. In Maranhão, there are two Environmental Protection Areas, APA Ilha dos Caraguejos and APA Reentrâncias Maranhenses, as well as the Lagoa da Jansen Ecological Park.

The Brazilian National Coastal Mangement Plan (GERCO) also represents an important practical tool for the conservation of the Amazon coastal zone. Unfortunately, recent research (Pereira et al., 2009; Slazfztein, 2009; Silva et al., 2013) has shown that the performance of the public sectors in the states of Pará and Maranhão responsible for the application of the policies and measures proposed by the plan has been unsatisfactory. However, while GERCO has been reasonably successful in Amapá, a number of considerations, such as the vast size of the region, its unique physical and geomorphological characteristics, and the lack of specialized personnel place serious limitations on the potential for the implementation of the program on the Amazon coast (Gomes et al., 2011).

3.2 Caeté hydrographic basin

The hydrographic basin of the Caeté River has a total area of 2,195 km^2 and the main river is 149 km long from its source (in the municipality of Bonito) to its mouth (in Bragança and Augusto Corrêa) (Figure 3.7A). This is the principal drainage basin in northeastern Pará. Its freshwater catchment basin is estimated to cover 3,000 km^2, of which 6% (190 km^2) is covered by mangrove (Dittmar and Lara, 2001).

This basin drains seven municipalities (Bonito, Tracuateua, Ourém, Capanema, Santa Luzia do Pará, Bragança, and Augusto Corrêa) with a total population of some 300,000 inhabitants (IBGE, 2010). Almost half (40%) of this population is found in 18 riverside communities (known as the Caeteuara communities) located on the margins of the Caeté (Gorayeb, 2008).

The principal economic activities of the Caeteuara communities found in the middle and upper reaches of the Caeté are smallholder farming (subsistence agriculture and orchards), quarrying, cattle ranching, the extraction of plant resources, and artisanal fishing. On the lower Caeté, the principal activities are semi-industrial fisheries and the artisanal harvesting of fish, crustaceans, and mollusks (Krause and Glaser, 2003; Glaser and Diele, 2004; Guimarães et al., 2011) (Figure 3.7B-F).

The degradation of aquatic environments is one of the main anthropogenic impacts observed in the Caeté basin. This is due to the inadequate disposal of solid waste and the discharge of untreated effluents directly into local bodies of water. Public sanitation is absent from the whole of the hydrographic basin, and solid waste can be observed in open spaces almost everywhere (Gorayeb, 2008, Guimarães et al., 2011). An estimated 28.6 t of garbage is produced per day in the town of Bragança, of which, approximately 70% ends up on the municipal dump (CPRM, 1998; Gorayeb, 2008), which is located less than 3 km from the Chumucuí River, which discharges into the Caeté.

A number of studies have shown that the quality of the water in many of the region's aquatic environments, including the Chumucuí River, suffer negative impacts. The Chumucuí has high concentrations of dissolved oxygen, faecal coliforms and chlorophyll *a*, which exceed the public health standards established by CONAMA and Health Ministery (Gorayeb, op. cit.). This has direct implications for the local populations that depend on these bodies of water as sources of water for human and animal consumption, irrigation, leisure activities, and so on (Gomes et al., 2009; Silva et al., 2009; Pereira et al., 2010). Other environmental problems observed in the region include the illegal capture of ornamental fish, quarrying, the over-exploitation of fish and crab stocks, deforestation, and oil spills (Guimarães et al., 2011).

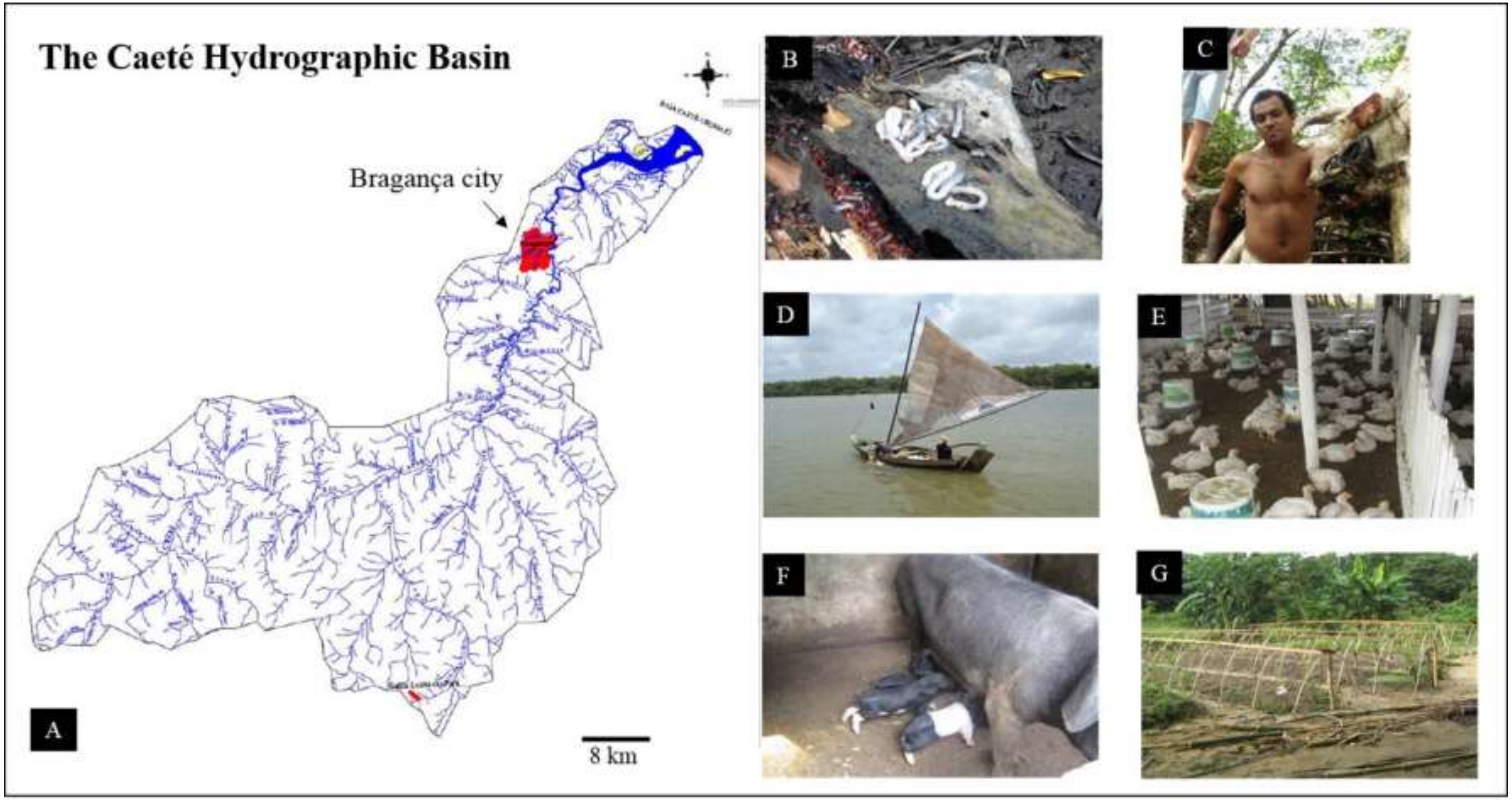

Figure 3.7: The Caeté hydrographic basin (A) and some of the economic activities engaged in the communities: fishing (B, C and D), poultry (E) and pig farming (F), and subsistence agriculture (G) (modified from Gorayeb, 2008).

3.3 Caeté estuary

The Caeté estuary (Figure 3.8), located in northeastern Pará, on the Bragança Peninsula, around 150 km southeast of the mouth of the Amazon River, occupies the lower portion of the Caeté hydrographic basin.

This estuary is funnel-shaped which is the result of the coastal evolution of mangrove deposits. Its channel is classified as permanently open and has a uniform cross section which receives the discharge from two main tributaries, with minor contributions from smaller creeks flowing in through the mangrove forest (Cavalcante et al., 2013).

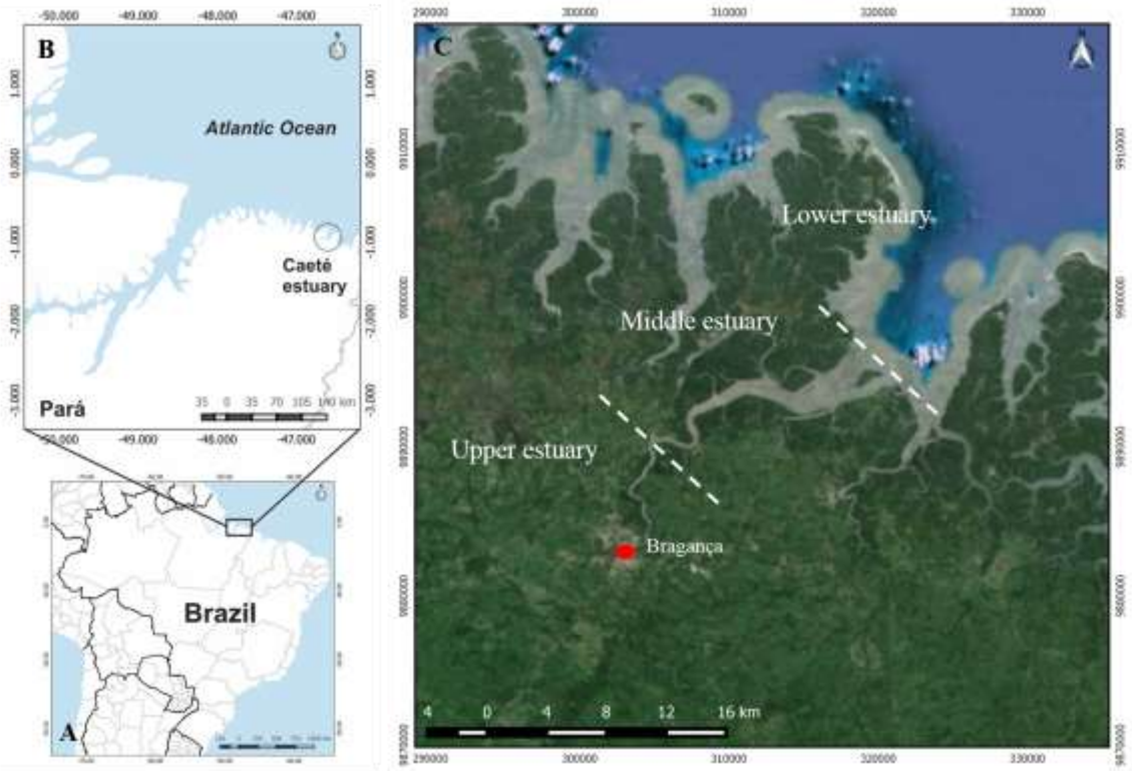

Figure 3.8: Location of study area on the northeast coast of Brazil (A and B) emphasizing the Caeté estuary (C).

According to existing bathymetric data upper sector of the estuary is the narrowest, with a mean width of 160 m (varying from 60 m to 266 m), and a mean depth of 3.4 m (range 1.0–6.3 m) during low tide of neap tides. The estuary widens to a mean of 270 m in its mid-sector (194–809 m), with virtually the same mean depth (3.6 m), although deeper channels of up to 11 m in depth can be found, approximately 15 km from the mouth of the estuary (Unpublished data, Figure 3.9). The total width of the estuary at the river mouth is about 4600 m (Guerra and Cunha, 1998).

3.3.1 Mangroves

The drainage area of the Caeté estuary is composed mainly of mangrove forest, with a total area of approximately 180 km² (Krause et al., 2001). This tide-dominated allochthonous system (according to the Thom, 1984) is formed by various creeks and channels, the dynamics of which are determined mainly by tides and rainfall.

The forest comprises a well-developed environment with trees reaching 10 m to 25 m in height, however, dwarf forms of the same species, which are no taller than 1 m, can be observed in the intertidal zone. The predominant three species found in this mangrove are *Rhizophora mangle* (Rhizophoraceae), *Avicennia germinans* (Avicenniaceae), and *Laguncularia racemosa* (Combretaceae). *Avicennia* dominates the higher ground, while *Rhizophora* and *Avicennia* occur together in the intermediate areas, and *Rhizophora* dominates the lowest ground, including the borders of the tidal creeks and channels (Menezes et al., 2003). *Laguncularia* is widely distributed, but only predominates at disturbed sites, such as the borders of channels (Thullen and Berger, 2000).

Cohen and Lara (2003) showed that the elevated flats in the inner part of the peninsula are flooded much less frequently (<28 days per year) than the lower mangrove. These areas are only flooded during the highest spring tides and constitute a hyper-saline habitat (salinity between 90 and 100), found mainly during the dry season. This area ends in a wide area of mudflats covered by mangroves, extending down to the mid-tide mark for 3–6 km. These mud flats have a gradient of around 1:3000, and are dissected by creeks which are much deeper than those in the elevated flats. The upper mud flats are flooded only during normal spring tides (28–78 days/yr) with pore water salinity of between 50 and 90. Considering the local tidal regime, Cohen et al. (2004) concluded that around 70% of the study area is flooded at high tide during neap tides (~4.9 m tide), and more than 92% during spring tides (~5.7 m tidal range).

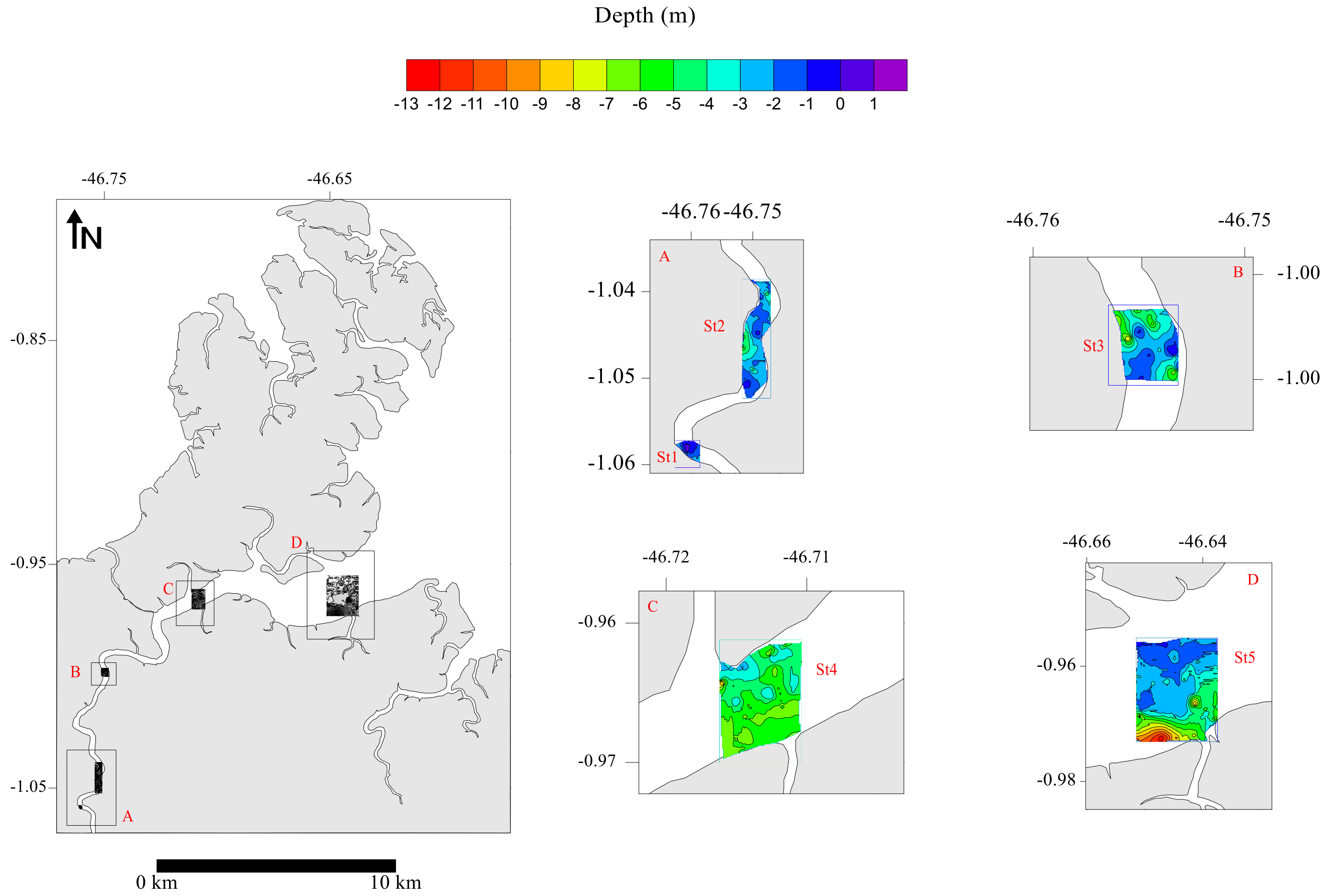

Figure 3.9: Bathymetry at 5 stations along the Caeté estuary*. Upper estuary (A and B) and middle estuary (C and D) (unpublished data).

*Bathymetric survey was collected in the upper and middle sectors of the estuary, at five stations (St1–St5). At each station, 10 transversal profiles were taken perpendicular to the estuary channel, each separated by a distance of approximately 100 m, covering a 1 km stretch of the estuary at each station. To reduce the effects of the tide on the bathymetric readings, tide height was measured in the middle and upper sectors of the estuary.

3.3.2 Meteo-oceanographic characteristics

Based on a 34 year data series (from 1974 to 2011, except 1981, 1983, 1986 and 1989) provided by the National Meteorology Institute (INMET, 2014), total annual rainfall in the study ranged historically between 1,400 mm and 4,100 mm. Figure 3.10 show annual total rainfall emphasizing years which rainfall rate should be affected by ENSO, AMO or NAO events

Overall, more than 80% of the total rainfall occurs during the first half of the year, the wet season, which typically extends from January to July, with February, March, April, and May being the wettest months. The dry season typically lasts between August and December, and normally accounts for less than 20% of total annual rainfall. September, October and November are normally the driest month of the year (Figure 3.11).

The Caeté River and its 22 tributaries are the main source of the freshwater discharge into the Caeté estuary. Based on a 22 year data series (1965 to 1971 and 2000 to 2014) provided by the Brazilian National Water Agency (ANA, 2015), from a gauge station approximately 20 km from study area, the average annual river discharge of the Caeté ranges between 23.9 $m^3.s^{-1}$ and 59.7 $m^3.s^{-1}$ (Figure 3.12).

Typically, around 70% of annual discharge is recorded during the first half of the year (wet season), with the highest monthly levels being observed in March, April and May. Discharge during the dry season rarely exceeds 30% of the annual total, however. Discharge tends to be lowest in October, November and December. The minimum, mean and maximum discharge rates recorded during the wet and dry are shown in the figure 3.13.

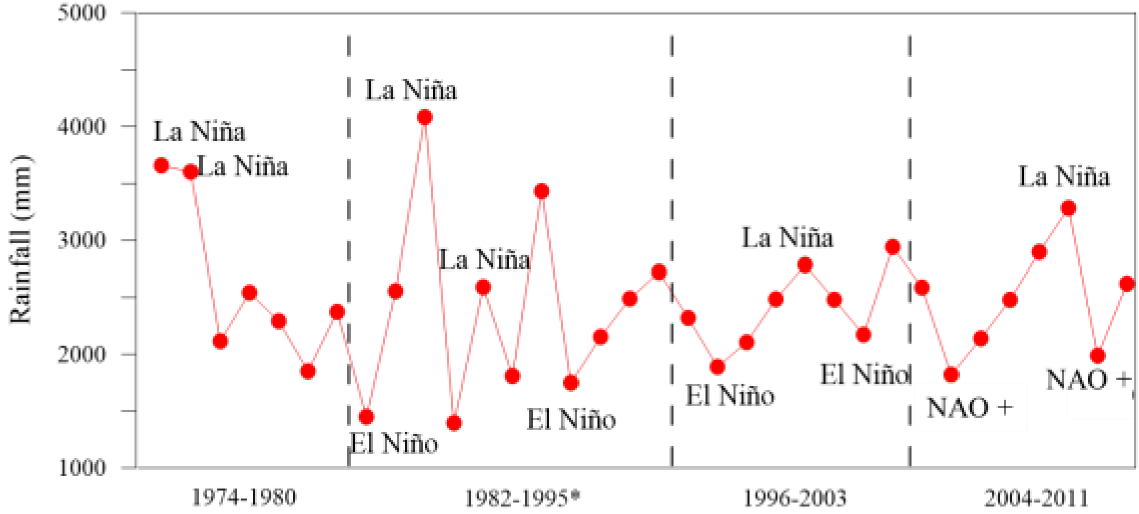

Figure 3.10: Annual rainfall in the Bragança region based on a 34 year data series. *No data were recorded in 1981, 1983, 1986 and 1989.

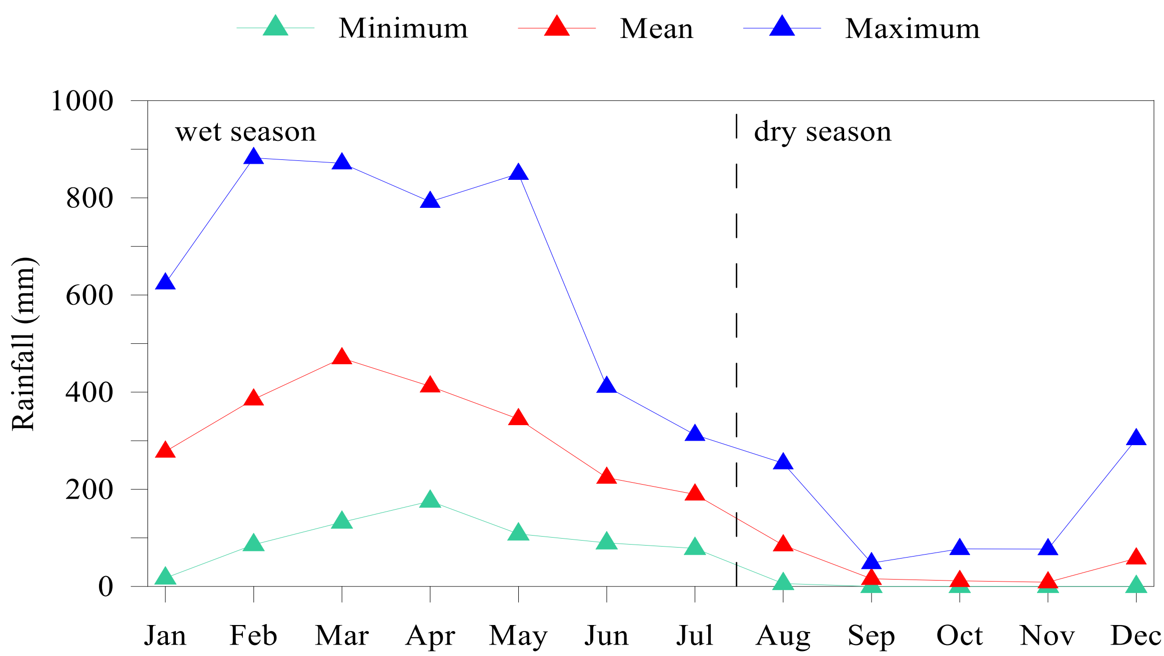

Figure 3.11: Minimum, mean and maximum monthly rainfall in the Bragança region, based on a 34 year data series.

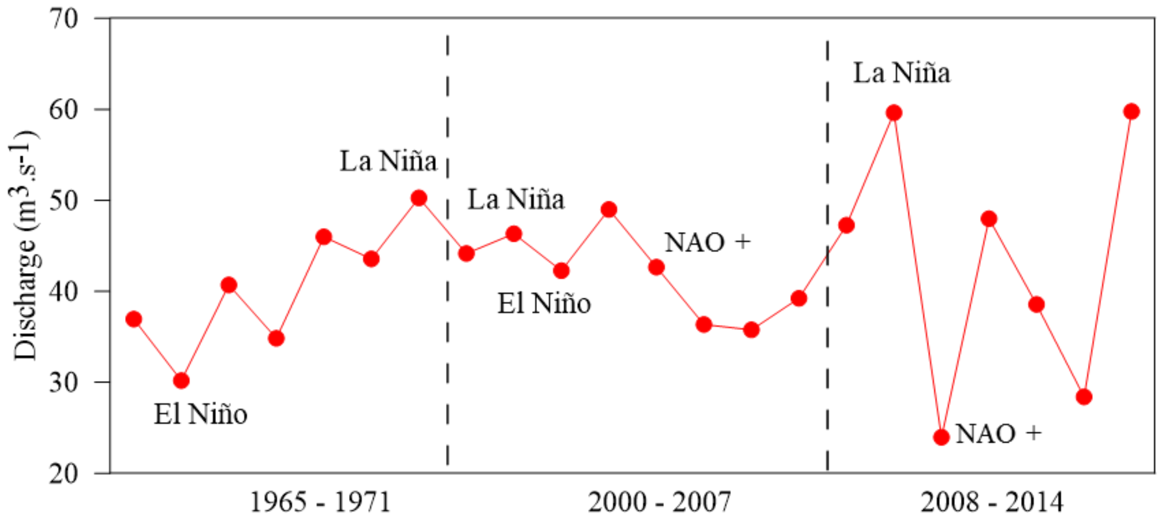

Figure 3.12: Mean annual discharge of the Caeté river based on a 22 year data series.

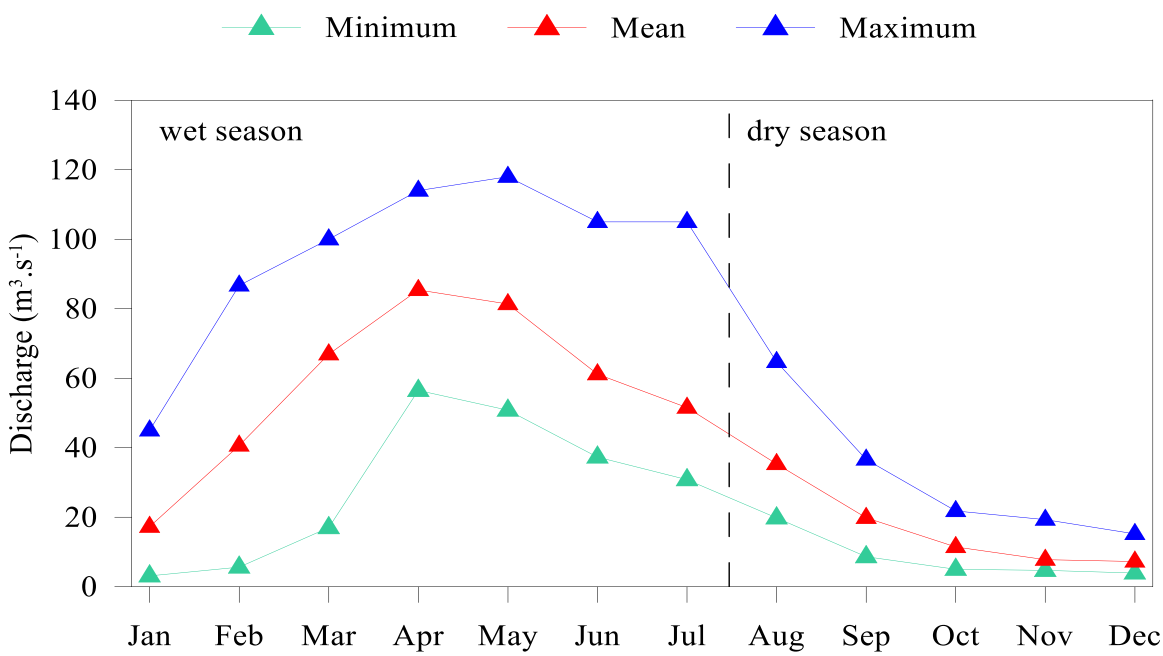

Figure 3.13: Minimum, mean and maximum monthly discharge of the Caeté river, based on a 22 year data series.

The Caeté estuary, like the rest of the northern Brazilian coast, is dominated by the local macrotides (Asp et al., 2012). The tidal range oscillates between 2 and 4 m during the neap tide, and is from 4 to 6 m during spring tides (Figure 3.14), which is consistent with a macrotidal regime in the classification of Davies (1964).

The tidal cycle is semi-diurnal with asymmetric phases. The M2 astronomic component dominates tidal patterns within the Caeté estuary, and is thus the predominant water circulating force within the estuary. Together with the N2 and S2 components, it accounts for 85% of total tidal variation in the region.

Tidal currents dominate this region and can reach up to 1.2 $m.s^{-1}$ in the wet season and 0.7 $m.s^{-1}$ in the dry season (Gomes et al., 2013). Circulation patterns in the Caeté estuary are driven by the interaction between the local river discharge and coastal tide forces, combined with moderate easterly winds and waves (Cavalcante et al., 2010).

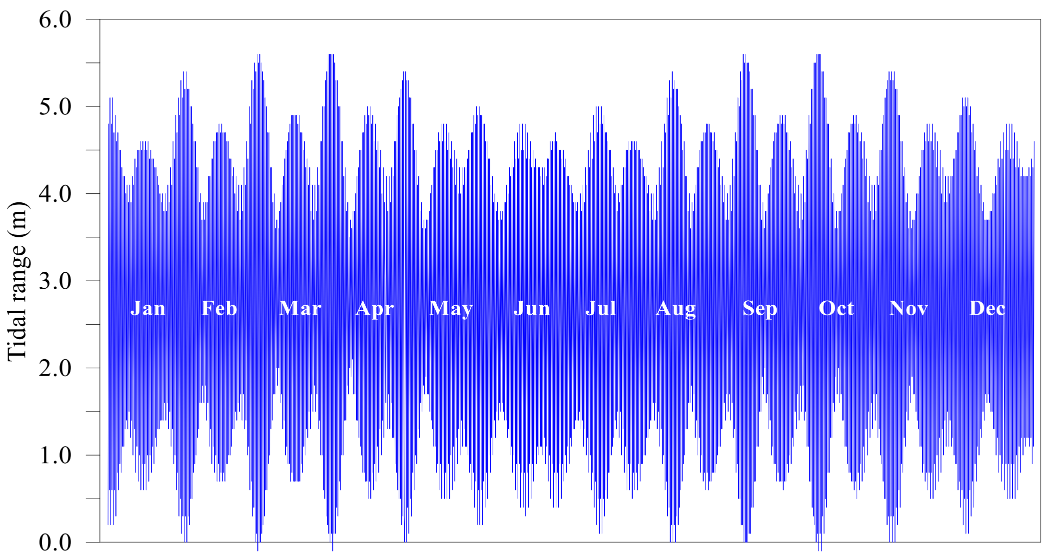

Figure 3.14: Tidal wave during the spring and neap tides in the coastal area adjacent to Caeté estuary, according to DHN data.

3.3.3 Socio-environmental features

Nine communities (Maranhãozinho, Fazendinha, Bragança, Camutá, Vila q Era, Bacurituea, Caratateua, Vila dos Pescadores and Ponta do Urumajó) are found on the margins of the Caeté estuary, with a total of 80,880 inhabitants (Guimarães et al., 2011; IBGE, 2013), of which approximately 90% are found in the upper, more urbanized sector. This sector includes the town of Bragança, considered to be the region's most important urban and commercial center.

Fishing is considered the most important economic activity in the region. At the present time, more than 6000 t of fish are landed annually in the Caeté estuary. This estuary rank as the third most important fishing center in Pará and the largest extractive fishing producer of Brazil (IBAMA, 2005; Isaac et al., 2008). Although industrial development in the region is limited, installations such as ice factories, fish processing plants, fish markets, and dry docks for boat repairs can be found in many parts of the estuary, mainly in the town of Bragança.

The middle and lower sectors of the estuary have a low population density. These sectors have approximately 7,627 and 587 inhabitants, respectively (Guimarães et al., 2011). The resident population is dependent on the public services provided in the upper sector of the estuary. In the middle sector, subsistence agriculture is intensive. Cassava, rice, and beans are the principal local crops. In the lower sector, fishing is the main subsistence activity (Krause and Glaser, 2003; Glaser and Diele, 2004; Gorayeb, 2008).

Table 3.1 shows the number of inhabitants per sector and the expected level (qualitative) of impact caused by unplanned urban growth (e.g., sewage discharge) and by economic activities (e.g., fishing and commerce), based on the studies of Gorayeb (2008), Guimarães et al. (2009, 2011), Pereira et al. (2010), Monteiro et al. (2011) and IBGE (2013).

Table 3.1: Population and activities developed along the estuary and their potential impacts in relative terms. Key: *** high; ** moderate; * low.

	Population in 2013	Potential impact from population related to sewage discharge	Activities developed	Potential impact of activities
Upper sector	72,621	***	Fishing and commercial	***
Middle sector	7,672	**	Fishing	**
Lower sector	587	*	Fishing	*

On May 20th 2005, the Caeté-Taperaçu Extractive Reserve was created to protect and preserve the region's natural resources. This reserve with a total area of 42,068 ha and about 3000 resident families, which exploit its natural resources in a sustainable manner, encompasses the whole of the Caeté estuary and the communities found along its margins.

Krause and Glaser (2003) and Glaser and Diele (2004) showed that approximately 75% of the households in the villages surrounding the Caeté estuary are economically dependent on the rich natural resources of the mangrove, mainly by fishing, crabbing and harvesting mollusks. The most important mangrove resource is the ocypodid crab *Ucides cordatus*. These crabs are captured for sale live in local or regional markets or for the production of processed crab meat, for sale to regional and national consumers (Krause et al., 2001; Magalhães et al., 2007). Other important resources are fish, shrimp, and other invertebrates, which are also are harvested for consumption by the local population.

In spite of the extraordinary environmental value due of these natural resources and their enormous potential for economic development, the unplanned growth of urban settlements along the estuary and the lack of adequate infrastructure have led to increasing anthropogenic stress on the estuary (Pereira et al., 2010; Guimarães et al., 2011; Monteiro et al., 2011). There is no public sewage treatment system in the town of Bragança, for example, or any of the surrounding settlements, leading to the effluents from 26,221 residences (IBGE, 2010) being released directly into the local aquatic environments (including the Caeté estuary) or onto the ground in public areas or private properties.

Silva et al. (2006) and Gorayeb (2008) found that not only domestic effluents, but also waste from fishing boats, fish processing plants, filling stations and hospitals is discharged directly into the estuary or into open public spaces, leading to the degradation of the estuary’s waters, making them inappropriate for most types of use. In addition to these sources of pollution, the Cereja River discharges into the upper Caeté estuary. This tributary has a depth of 1.40 m, width of 6 m, and length of 5 km which crosses the southern margin of Bragança to reach the eastern margin of the Caeté. These environmental impacts are exacerbated by the deforestation of the local mangroves and the over-exploitation of local natural resources (Guimarães et al., 2011).

CHAPTER 4

DATA AND METHODS

To achieve the proposed objectives, it was necessary to characterize the local climatic, hydrological, and oceanographic conditions, as well as how urban growth has developed in the region of the estuary over the past decades, and to identify the principal anthropogenic pressures resulting from this urban growth. This chapter provides a detailed description of the methods used to obtain these data, that is, the compilation of data provided by local and national institutions (INMET, DHN, ANA, IBGE, Bragança town hall and GPesca Indústria Ltda.), the fieldwork, and the laboratory analyses.

4.1 Compilation of data on the study area

A literature search was conducted to compile data on the demographic and urban growth of the town of Bragança, and the settlements located along the margins of the estuary of the Caeté River, as well as information on the patterns of land use. The Brazilian Institute for Geography and Statistics (IBGE) provided data from the demographic censuses conducted between 1940 and 2010. Data about urban growth and settlements were obtained from the Armando Bordallo da Silva Municipal Library. Bragança town hall also provided information on the growth of commercial activities in the town.

4.2 Database: rainfall, river discharge, winds and tidal range

To characterize the effects of rainfall patterns on the oscillations in hydrological variables in the Caeté estuary, rainfall data were obtained from the Brazilian Meteorology Institute - INMET, at its conventional meteorological station located 36 m above the ground at Tracuateua - Pará (-1.06º S, -46.9º W), 17 km from the upper estuary. Daily data on rainfall were used to obtain the monthly total for the study period. Months with total precipitation of less than 200 mm were considered to represent the dry season. These data were analyzed at two temporal scales: (i) during the years in which the oceanographic campaigns were conducted (2006-2007 and 2010-2011), and (ii) over a historical period of four decades (1974-2013*). In Chapter 6, the historical data are compared with those of the study period. In Chapter 7, these data were important for the understanding of the effects of rainfall on the oscillations in hydrological variables in Caeté estuary, in two different scenarios: (i) during years of *typical* rainfall levels, and (ii) during *drought events*, when rainfall is greatly reduced.

As rainfall levels influence the discharge of the Caeté River on the estuary, data on the flow of this river were obtained from the Brazilian Water Agency - ANA (Nova Mocajuba fluvial station -1.16º S, -46.5º W), approximately 20 km upstream from the upper sector of the Caeté estuary. Daily data on river discharge were obtained for the period of the oceanographic campaigns (2006-2007 and 2010-2011) and for previous years (1965-1971; 2000-2013**). In Chapter 6, the historical data were compared with those from the study period and in Chapter 7, alternative conditions were considered, including a reduction in a river discharge.

Data on wind speed and direction were also obtained from INMET station (-1.06º S, -46.9º W) for the period of oceanographic campaigns. These data were obtained at 60-minute intervals by an automatic station at a height of 23 m above the ground at a site approximately 90 km from the study area.

To characterize the tidal regime in the lower estuary during monitored period, tide elevations were obtained from the Hydrographic and Navigation Department - DHN (Salinopólis port station) located 95 km from the mouth of the Caeté estuary in the coastal region of Salinopólis. These data consist of the daily predictions of high and low tides. Tidal data in the middle sector of the estuary were obtained using tide data loggers (TWR 2050) recording data at 10 minute-intervals from time-averaging of 10 seconds.

*The precipitation data for 1981, 1983, 1986 and 1989 are unavailable due to technical problems at the INMET meteorological station.
**The river discharge data for the period between 1972 and 1999 are unavailable due to technical problems at the ANA gauge station.

4.3 Fieldwork

The oceanographic campaigns focused on the different sectors of the estuary, where data were obtained on hydrodynamics, and the hydrological and microbiological features of the estuary. The campaigns were conducted during spring and neap tides. Complementary fieldwork was necessary to charcaterize the circulation of the estuarine waters during the *neap tides* and to identify the principal sources of contamination that affect the quality of the water of the Caeté estuary. The procedures used to collect data in these campaigns are described in detail as follows.

- *Spring tide condition (phase I)*

Oceanographic campaigns were conducted during the spring tide every two months between April 2006 and February 2007. Figure 4.1 shows the tidal oscillation in the lower sector from data provided by DHN for the months of the field campaigns, where the read arrows indicate the sampling day. To estimate the tidal range in the estuary, a tidal gauge was fixed in the upper sector of the estuary. Data were recorded at 10 minute intervals over a 25-hour period.

To acquire physical and physical-chemical data on the water column, a boat was anchored at each fixed pre-established station (St1: upper estuary; St2: middle estuary and St3: lower estuary*, Figure 4.2). At each station, current speed and direction data were collected using a current meter (Sensordata SD 6000) bottom-mounted at a depth of 3.0 m from the waterline over a 25-hour period. The device was programmed to record data every minute and generate a mean value every 10 minutes.

Water samples were taken simultaneously in the three estuary sectors to analyse salinity, pH, dissolved oxygen, dissolved nutrients (nitrate–NO_3^-, nitrite–NO_2^-, ammonium–NH_4^+, phosphate–PO_4^- and silicate–S_iO_2), chlorophyll *a*, and faecal coliforms. These data were collected with a 5 L Niskin bottle (General Oceanics™) at a depth of 3.0 m from the surface at intervals of 6.25 h during a 25-hour period, encompassing two ebb and two flood cycles.

*Limits among different the sectors were established by Barletta-Bergan et al. (2002) according to the salinity gradient of estuary

During this phase, a total of 72 samples were taken for each parameter, except for faecal coliforms (36 samples), which were collected only during the first ebb/flood cycle. Once collected, the water samples were stored in 250 ml polyethylene flasks. For the analysis of dissolved oxygen, the samples were stored in amber-coloured flasks and to faecal coliforms were used glass flasks. All flaks were cleaned according the procedures described by APHA (1992). To fix the dissolved oxygen in the field, 1 ml of a solution of manganese sulphate ($MnSO_4$) and 1 ml of an alkali-iodide-azide solution which contains sodium hydroxide, NaOH, sodium iodide, NaI, and sodium azide, NaN_3. All the water samples were stored at 4ºC prior to processing in the laboratory.

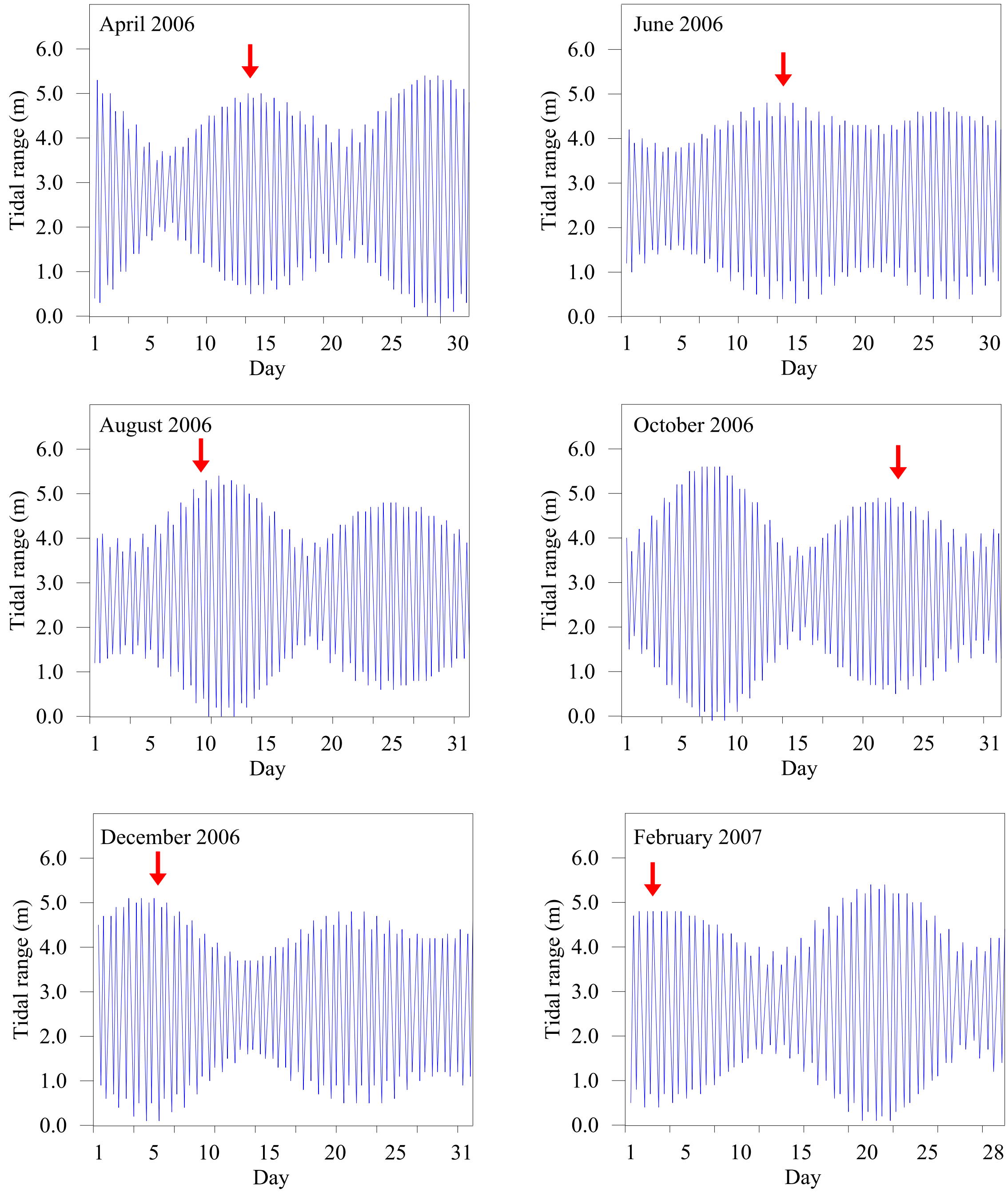

Figure 4.1: Tide chart showing the tidal oscillations in the lower sector of the estuary during the months of the campaigns conducted during phase I. The red arrow indicates the estimated tide height during data.

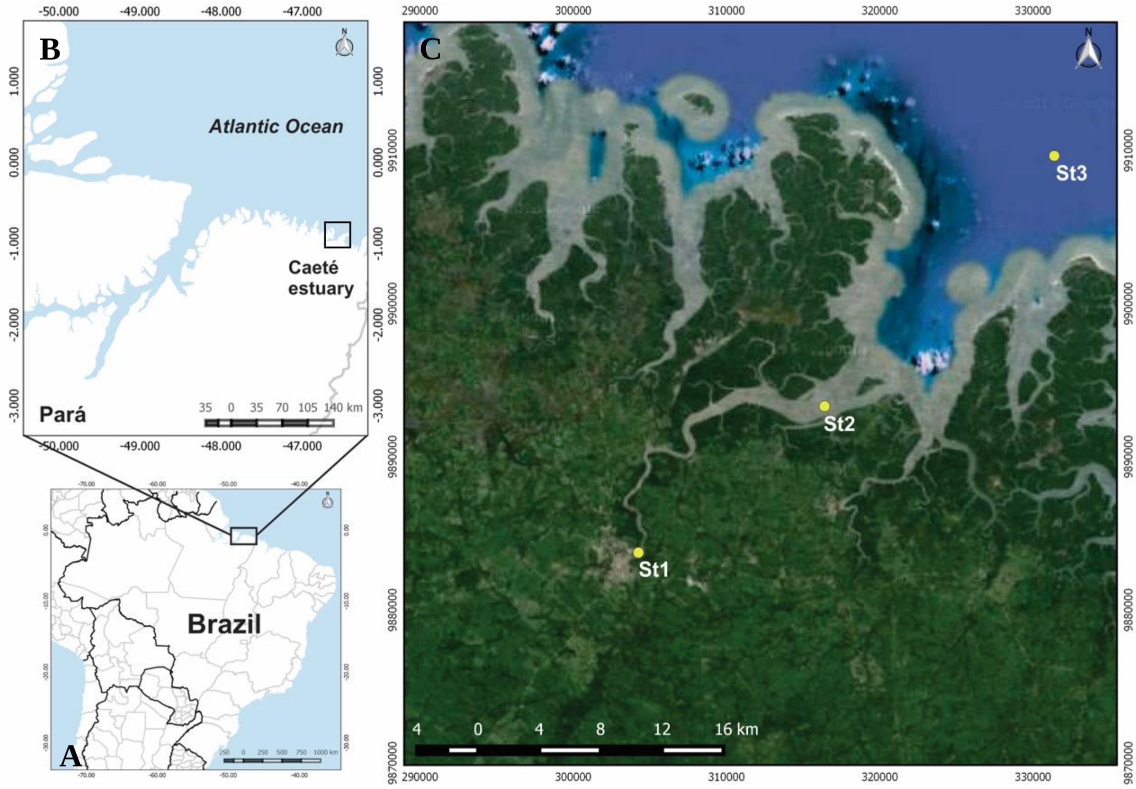

Figure 4.2: Location of northeast coast of Brazil (A and B) and the sampling stations in the Caeté estuary (phase I) St1: Upper estuary; St2: Middle estuary, and St3: Lower estuary (C).

- *Neap tide condition (phase II)*

During phase II, the oceanographic campaigns were conducted during the neap tide, every two months between September 2010 and September 2011, with an additional campaign in October of 2011. The tide charts for the campaign months of phase II are shown in Figure 4.3, and the red arrow indicates the day data were collected during the neap tide period. During this phase, tidal height was measured in the upper and middle estuary, using tide data loggers (TWR 2050), which were moored in each sector. Data were recorded every minute for approximately 13 hours, encompassing a full ebb and flood cycle.

As the analyses run in phase I proved the homogeneity of the variables between the tidal cycles (ebb and flood) and the sampling stations, in phase II, physical-chemical and microbiological data were collected only during flood tides. In order to detect potential spatial differences within the estuary, the distance between stations was reduced in comparison with phase I. The upper estuary was represented by two fixed stations (St1 and St2), and the middle (St3, St4 and St5) and lower (St6, St7 and St8) by three fixed stations each, with a total of eight sampling points (Figure 4.4). To detect possible vertical differences in the data, samples were taken at 1.0 m below the surface of the water and 1.0 m from the bottom of the estuary.

Vertical salinity, turbidity, dissolved oxygen and oxygen saturation were recorded every 5 min by CTDOs equipped with dissolved oxygen and turbidity sensors (RBR XR-420). Niskin oceanographic bottles of 5 L (General Oceanics^{TM}) were used at each station to obtain vertical water samples (surface and bottom). These samples were used to determine pH, dissolved nutrients (nitrate–NO_3^-, nitrite–NO_2^-, ammonium–NH_4^+, phosphate–PO_4^- and silicate–S_iO_2), and chlorophyll *a* and thermotolerant coliform concentrations. A total of 128 water samples were collected during this phase, except for thermotolerant coliforms, which were sampled only in the surface layer, with a total of 76 samples being collected.

Figure 4.5 shows different moments during the collection of the data, and data obtained in the oceanographic campaigns of phases I and II were summarized in Table 4.1.

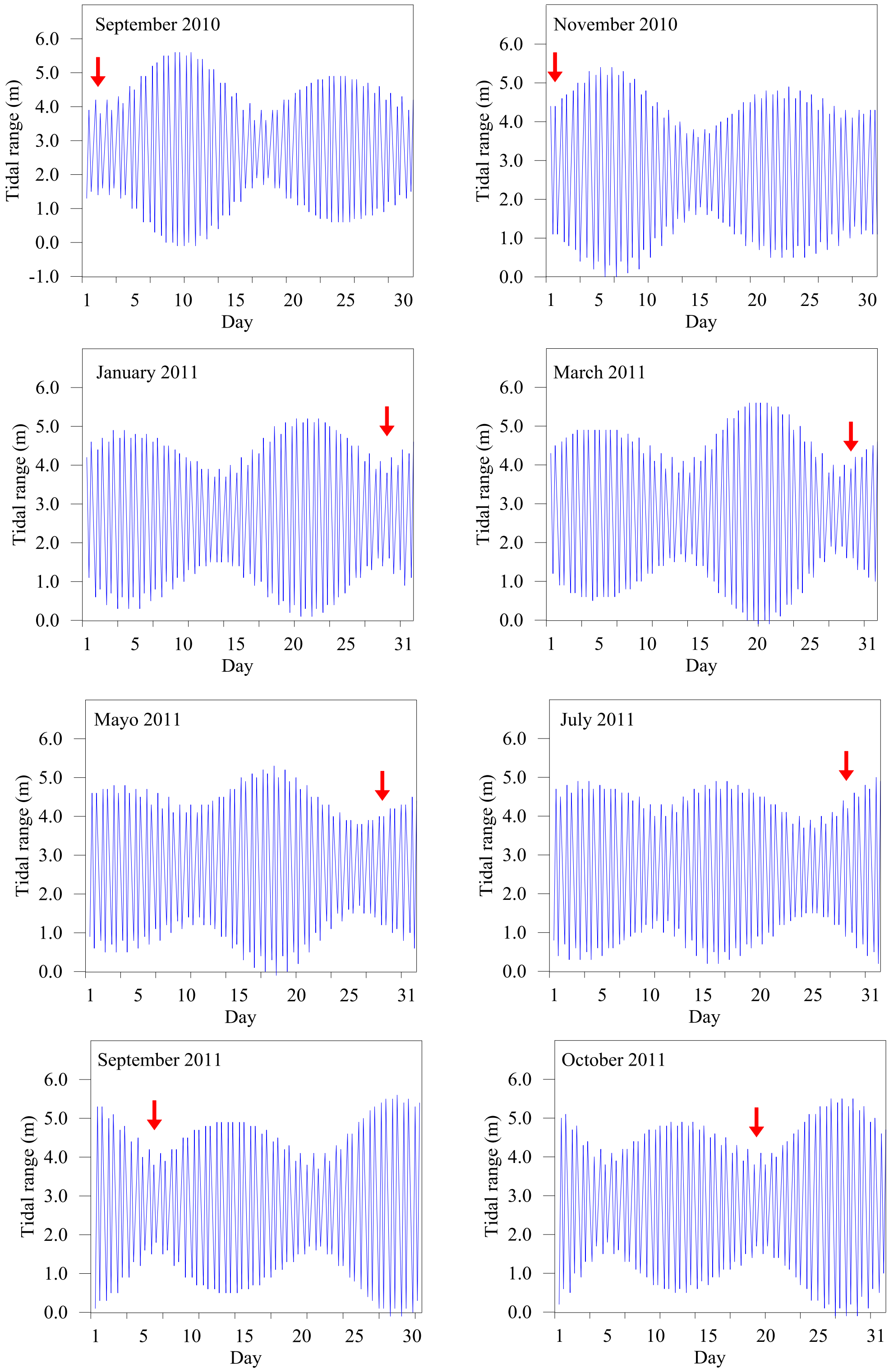

Figure 4.3: Tide chart showing the tidal oscillations in the lower sector of the estuary during the sampling months of phase II. The red arrow indicates the estimate of tide height, during the data collection period.

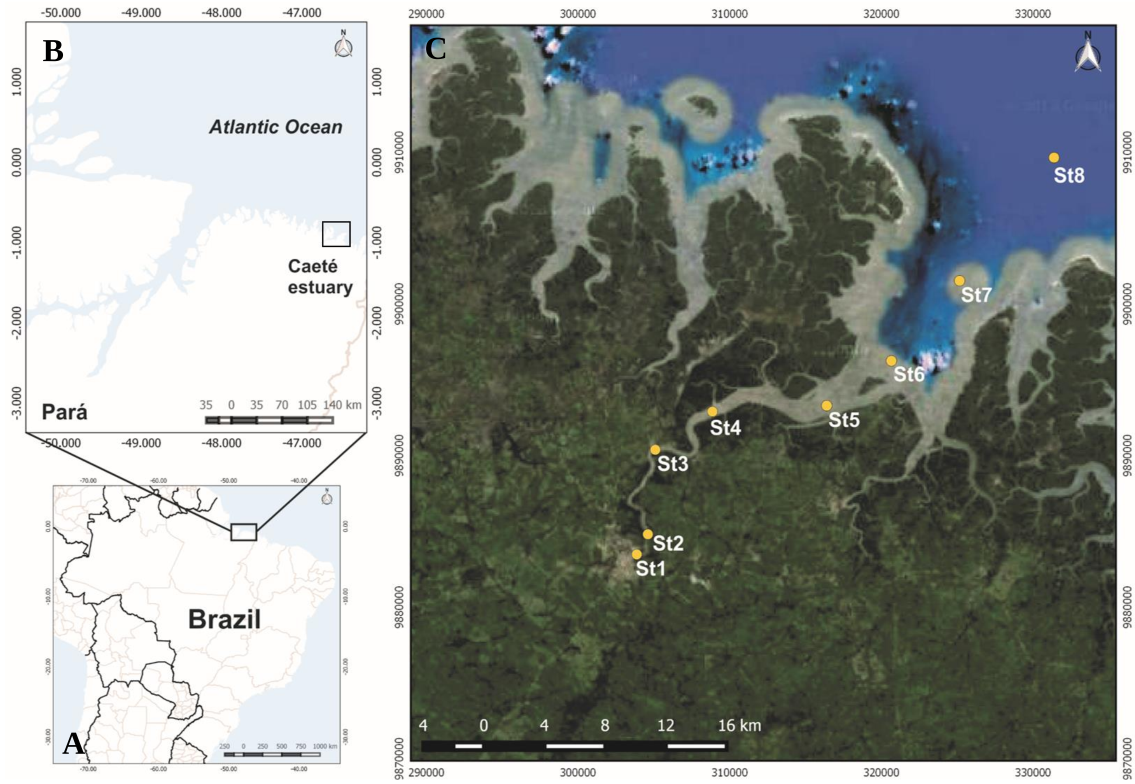

Figure 4.4: Location of northeast coast of Brazil (A and B) and the sampling stations in the Caeté estuary (phase II) St1 and St2: Upper estuary; St3, St4 and St5: Middle estuary, and St6, St7 and St8: Lower estuary (C).

Figure 4.5: Oceanographic campaign. Type of vessel used during data collection (A), CTDO sensor (B) and Niskin oceanographic bottle (C).

Table 4.1: Summary of physical, physical-chemical, and microbiological data collected during phases I and II in the Caeté estuary (U: upper estuary; M: middle estuary, and L: lower estuary).

<table>
<tr><th></th><th colspan="2">Station</th><th colspan="2">Methods</th><th colspan="2">Tidal cycle</th><th colspan="2">Depth</th><th colspan="2">Periods</th><th colspan="2">Total samples</th></tr>
<tr><th></th><th>phase I</th><th>phase II</th><th>phase I</th><th>phase II</th><th>phase I</th><th>phase II</th><th>phase I</th><th>phase II</th><th>phase I</th><th>phase II</th><th>phase I</th><th>phase II</th></tr>
<tr><td>Current data</td><td>U, M and L</td><td>U and M</td><td>Current meter</td><td>ADCP</td><td rowspan="9">2 flood and 2 ebb</td><td>1 flood and 1 ebb</td><td>3.0 m from surface</td><td>from the surface to the bottom, each 0.5 m</td><td rowspan="10">April, June, August, October and December of 2006 and February 2007</td><td>November of 2010 and April of 2013</td><td>425 hrs</td><td>26 hrs</td></tr>
<tr><td>Tidal range</td><td>U and L</td><td>U, M and L</td><td>Tidal gauge and DHN</td><td>Tide logger and DHN</td><td>-</td><td>-</td><td>-</td><td rowspan="9">September and November of 2010; January, March, May, July, September and October 2011</td><td>450 hrs</td><td>312 hrs</td></tr>
<tr><td>Salinity</td><td rowspan="2">U, M and L</td><td rowspan="8"></td><td>Niskin bottle</td><td>CTDO</td><td rowspan="8">1 flood</td><td rowspan="8">3.0 m from surface</td><td rowspan="7">1.0 m from the surface and 1.0 from the bottom</td><td rowspan="7">72 samples</td><td rowspan="7">128 samples</td></tr>
<tr><td>pH</td><td colspan="2">Niskin bottle</td></tr>
<tr><td>Dissolved oxygen</td><td>U and L</td><td>Niskin bottle</td><td>CTDO</td></tr>
<tr><td>Saturated oxygen</td><td>-</td><td>-</td><td>CTDO</td></tr>
<tr><td>Turbidity</td><td>-</td><td>-</td><td>CTDO</td></tr>
<tr><td>Dissolved nutrients</td><td rowspan="3">U, M and L</td><td colspan="2" rowspan="3">Niskin bottle</td></tr>
<tr><td>Chlorophyll a</td></tr>
<tr><td>Faecal coliforms</td><td>1 flood and 1 ebb</td><td>1.0 m from the surface</td><td>36 samples</td><td>76 samples</td></tr>
</table>

Additional campaigns

(i) Currents

Due to logistic problems, data on current speed and direction were not collected during phase II. To overcome this problem, two specific campaigns were conducted to obtain these data under similar climatic and oceanographic conditions, that is, during neap tides in the dry (October 2010) and wet (April 2013) seasons.

In each campaign, 30 transversal currents profiles (15 during the ebb cycle and 15 during the flood cycle), separated by a distance of about 1 km were conducted from a boat along the Caeté estuary from the upper (St1) to the middle (St6) sectors. Current profiles were not compiled in the lower sector due to the wind-wave action combined with the small size of the vessel used to collect data. In each profile, data on current speed and direction were obtained in the water column with a vertical beam of 0.5 m. This data were recorded with an Acoustic Doppler Current Profile (ADCP) Workhorse 1200 kHz model by Teledyne® RDI™.

(ii) Survey of sources of contamination

Sources of contamination, including the outfalls of domestic waste water, waste dumps, septic tanks, etc., were identified in situ in the study area in March 2013. In December 2014, the GPesca Indústria Ltda. fish processing plant, located in the middle estuary, was visited for the measurement of the types and quantities of effluents produced by this industrial installation. All sources of pollution were photographed with a Sony 21 MP digital camera and georeferenced (GPS Garmin 72) for the production of a map of the zones most affected by these pollution sources This map was drawn up using aerial photographs and satellite images (Landsat 8 TM and Spot 5 HGR).

The magnitude of sewage effluents produced by the local population was estimated by assuming that each inhabitant produced a minimum of 150 l per day of sewage effluents containing 54.0 g of DBO, 8.0 g of Nitrogenous and 2.5 g Phosphorous compounds (ABNT, 1993; Von Sperling, 1996). The total of inhabitants in each sector was estimated based on previous studies carried by Guimarães et al. (2009) and IBGE (2015).

4.4 Laboratory procedures

4.4.1 Rainfall classification

Rainfall classification was established according to the monthly rate recorded as shown in Table 4.2. This classification was based on month rate recorded by long-term data series in the study area.

Table 4.2: Rainfall classification

Rainfall (mm)	**Classification**	**Period**
>400	Extreme rainfall	wet
200-400	Heavy rainfall	
100-200	Moderate rainfall	dry
<100	Light or no rainfall	

4.4.2 Tidal and current analysis

In order to evaluate the water volume flows in and out in the estuary and to understand the residual flow were calculate the tidal prism and asymmetry index, respectively. In this study, the tidal prism is defined as the volumetric flux passing a cross-section during a flooding cycle. The tidal prism can be estimated by relationship:

$$P = H * A$$

Where *H* is the average tidal range and *A* is the average surface area of the basin (220 km^2 according Wolff et al., 2000).

Residual flow of the estuary was obtained through Asymmetry Index (AI_{DV}) proposed by Mantovanelli et al. (2004). This dimensionless index was based on parameters proposed by Lincoln and Fitzgerald (1988) and is represented by the sum of duration asymmetries (A_D) and velocity (A_V) between the ebb and flood periods.

$$AI_{DV} = AD + AV;$$

$$AD = (t_e - t_f)/(t_e + t_f);$$

$$AV= (\bar{U}_e - |\bar{U}_f|)/(\bar{U}_e + |\bar{U}_f|)$$

Where: t_e is the duration of ebb period; tf is the duration of flood period; $\bar{U}_e$ is the average ebbing time; $\bar{U}_f$ is the average flooding time. In accordance with the results obtained, the tides can be characterized as:

$AI_{DV} = 0$, the tidal wave is symmetrical for time and velocity;

$AI_{DV} > 0$, the residual circulation and water transport are directed to ebb;

$AI_{DV} < 0$, the residual circulation and water transport are directed to flood.

4.4.3 Water sample analysis

The water samples taken during the ocenanographic campaigns (phase I and phase II) were analysed at the Coastal and Estuarine Oceanography Laboratory (LOCE) at the Federal University of Pará (UFPA) in Brazil. In phase I, salinity was measured with a salinity meter and dissolved oxygen concentrations were estimated using Winkler's iodometric method, as modified by Strickland and Parsons (1968). In phases I and II, pH values were determined using an electronic pH meter (Labmeter, modeloPH2/PHS–3B).

Water samples were vacuum-filtered through glass-fibre filters (Milipore GF/F 0.7 µm, 47 mm), and the samples and filters were then freeze-dried for the analysis of the dissolved nutrients and chlorophyll *a* content, respectively. Dissolved inorganic nutrient concentrations (nitrate–NO_3^-, nitrite–NO_2^-, ammonium–NH_4^+, phosphate–PO_4 and silicate–SiO_2) were determined by spectrophotometric methods, following the procedures described by Strickland and Parsons (1972) and Grasshoff et al. (1983). Chlorophyll *a* was extracted from the acetate filters with 90% acetone v.v. and determined spectrophotometrically, according to Parsons and Strickland (1963) and UNESCO (1966). Equations were applied to obtain the saturated oxygen and chlorophyll *a* concentrations of each sample.

The analysis of thermotolerant coliforms was based on the multiple tube technique described in the *Standard Methods for the Examination of Water and Wastewater* manual (APHA, 1992). This method is based on the inoculation of the sample in sodium lauryl sulphate broth (presumptive test) and brilliant green (confirmatory test), followed by incubation for 48 hours at 35±2ºC. Positive samples were inoculated in *Escherichia coli* (EC) selective broths for 48 hours at 44.5ºC. In both stages, the presence of bacteria is detected by the clouding of the water and the formation of gas in the Duhran tubes.

4.4.4 Water quality framework

Oxygen saturation was measured using the correlation between the data on temperature, salinity, and dissolved oxygen, using the International Oceanography Tables (UNESCO, 1973). Saturation levels were classified according to the scheme proposed by Macedo and Costa (1978) for tropical environments, as shown in Table 4.3.

Table 4.3: Classification of oxygen saturation levels.

Classification	Oxygen Saturation Level
Unsaturated	25%
Subsaturated	>25 - 50%
Moderately Saturated	>50 - 80%
Saturated	>80 - 100%
Supersaturated	>100%

A conservative mixing diagram was used to verify the possible relationship between salinity and dissolved nutrients, based on a linear regression. The trophic status of the estuary was determined using the indices proposed by Karydis et al. (1983) and Vollenweider et al. (1998). The Karydis index considers nitrogen and phosphorous concentrations, and the loading of the study area by each nutrient. This index is dimensionless and can be applied to various types of water, and is sensitive to the stressful effects of eutrophication by the follow equation:

$$TI = \frac{C}{C - \log x} + \log A$$

where *TI* is the nutrient eutrophication index, *C* is the log of the total loading of nitrate in an area and *x* is the total concentration of nitrate at certain station and *A* number of stations. The scores generated provide a continuous assessment of water quality, with eutrophic waters scoring values higher than 5, mesotrophic waters values of 3 to 5, and oligotrophic waters, scores of less than 3.

The Vollenweider index was given by:

$$TRIX = (\log_{10}[\text{ Chl } a \text{ x } |DO_2\%| \text{ x DIN x DIP}] + k)/m$$

where Chl *a* is the chlorophyll *a* concentration, $DO_2\%$ is the oxygen saturation rate, DIN is the dissolved inorganic nitrogen (NO_2^- + NO_3^- + NH_4^+), and DIP is the concentration of dissolved inorganic phosphorus (PO_4), while k and m are constants with values of 1.5 and 1.2, respectively. Water is classified on the following scale: (i) 0–4: low eutrophication and high water quality; (ii) > 4–5: moderate eutrophication and good water quality; (iii) > 5–6: high eutrophication and bad water quality and, (iv) > 6–10: elevated eutrophication and poor water quality. This index was not applied to the data collected in the middle sector during the spring tide (phase I) due to the lack of data on dissolved oxygen levels in this sector.

Dissolved inorganic nitrogen (DIN) concentrations were determined from the sum of the inorganic nitrogen compounds: nitrate (NO_3^-), nitrite (NO_2^-) and ammonium (NH_4^+). To determine the molar N:P and Si:P ratios, the dissolved nutrient concentrations (NID, phosphate and silicate) were divided by their respective atomic masses (14, 31, 28). In order to better define potential nutrient controls on biological productivity, nutrient ratios were compared to those proposed by Redfield in 1958 (N:Si:P = 16:15:1)

The microbiological conditions of the estuary were assessed based on the criteria of the Brazilian National Environment Council’s (CONAMA) law number 357/2005, which provides guidelines on water quality, according to its primary use. The principal uses considered here were navigation (upper sector), the preservation of aquatic environments in conservation units (middle sector) and navigation and landscape harmony (lower sector). In all these cases, thermotolerant coliforms should not exceed a concentration of 1000 per 100 millilitres in 80% or more of six samples collected every two months over an annual period.

4.4.5 Statistical analysis

Statistical procedures were applied to evaluate the significance of the spatial and seasonal variation found in the physical-chemical and microbiological parameters of the Caeté estuary. The normality of the data was assessed using the Lilliefors test (Conover, 1971), and when normality was not confirmed, the data were log-transformed (x+1) in PRIMER v6 (Clarke and Warwick, 2001) and tested again. The homogeneity of the variances was evaluated using Bartlett's Chi-square, χ^2 (Sokal and Rohlf, 1969).

When the variances were homogeneous, a one-way Analysis of Variance (ANOVA, $\alpha < 0.05$) was used to determine the significance of differences between seasons (dry/rainy), months, and tidal cycle (flood/ebb), and when necessary, Fisher's *post-hoc* LSD test was applied. However, when the variances were heterogeneous, the nonparametric Mann-Whitney's U and Kruskal-Wallis H test (Zar, 1999) were used to evaluate the differences. Correlations between environmental variables were evaluated using Spearman rank correlation analysis with 95% confidence intervals and P value ≤ 0.00001. These analysis were run in STATISTICA® v6 (StatSoft, 2001).

RESULTS

CHAPTER 5

ANTHROPOGENIC DRIVING FORCES ON THE WATER QUALITY OF THE CAETÉ ESTUARY

This chapter describes the urban growth of the town of Bragança and the occupation of the territory of the Caeté estuary between the colonial period and the present day. The results of a survey of the sources of contamination found in the estuary are also presented. These sources were considered to be the principal anthropogenic factors influencing the quality of the water within the estuary.

5.1 Anthropogenic pressures

The first reports of the occupation of the margins of the Caeté estuary date back to the beginning of the 17th century (1613), when French explorers visited the region and landed in the Caeté, which was then inhabited by the native Tupinambás. The French did not establish a permanent settlement, using the area only as an operational base for the exploration of other areas in the Amazon region. The first Europeans to settle in the region were the Portuguese, who established an urban nucleus on the right margin of the Caeté, founding Vila Souza do Caeté in around 1640. Shortly afterwards, in 1644, the settlers migrated to the left margin, founding Vila Bragança on the site of the present. In the 18th century (1750), the local authorities established the first formal policies for the Portuguese occupation and colonisation of Vila Bragança. To support the settlement, Africans were brought in from the Azores to occupy the region and live alongside the local natives, distributed among the 74 houses established on the margin of the estuary.

The occupation process intensified during the 19th century (1850), with the advent of the steamship lines established between Europe and the Amazon. During this period, Vila Bragança became the town of Bragança. In 1900, the local population had reached 2,900, of which approximately 70% (1945) were Brazilian, and 30% (956) Spanish, mostly concentrated in the town of Bragança. Just one year later, the number of settlers had risen to 4,585.

During this period, the land surrounding the estuary was occupied by farms. The produce supplied Bragança and the state capital, Belém, approximately 220 km to the west, as well as other towns in the Brazilian Amazon basin, which had expanded rapidly during the Rubber Boom, when locally-produced latex was exported to markets in Europe and the United States.

At the beginning of the 20th century, significant transformations occurred in the urban environment of the town of Bragança, with the construction of a railway that linked the town to Belém. This railway, inaugurated in 1908, greatly facilitated the development of Bragança and the expansion of its commerce, although its principal objective was the transportation of agricultural produce. This period led to the founding of the first industries in Bragança, and by 1955, ten factories had been established (mainly for the processing of agricultural produce, such as rice and other cereals) and a total of 200 shops.

In the 1970s, the Brazilian Amazon region, including the town of Bragança, was, once again, a focus of colonisation, this time stimulated by official government incentives. As a result, the local population, which had been growing by 3% per decade, increased by 35% between 1970 and 1980. The population of the Bragança region doubled between 1940 and 2010 (Figure 5.1).

In around 1970, Bragança underwent a process of transition, during which farming became less significant, while artisanal and semi-industrial fisheries became the region’s principal economic activity. In 1983, the construction of the 36 km long PA-458 highway, parallel to the estuary, provided a new, terrestrial route of access to the small communities located in the middle and lower estuary. During this period, immigrants arrived from other Brazilian states, principally Ceará and Maranhão, arrived in Bragança, attracted by the local fisheries. New land use patterns began to emerge, and Bragança expanded due to the increase in the population in the outskirts of the town, and in neighbouring communities.

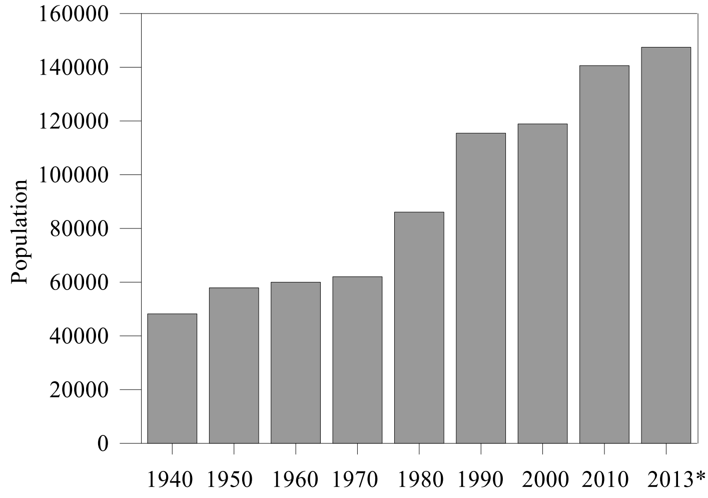

Figure 5.1: Population growth in the Bragança region (urban and rural area) between 1940 - 2013. Source: IBGE (2015). (*) estimated value.

At the present time, the nine communities (Maranhãozinho, Fazendinha, Bragança – urban area, Camutá, Vila q Era, Bacuriteua, Caratateua, Vila dos Pescadores and Ponta do Urumajó) established along the margins of the Caeté estuary have a total of 80,800 residents (Guimarães et al., 2009; IBGE, 2010), of which, 90% live in Bragança, in the upper sector of the estuary (72,621 inhabitants). Some 26,222 residential properties are found in this sector, of which, approximately 15% are located on the margin of the estuary, in the neighbourhoods of Riozinho, Centro and Aldeia (IBGE, 2010; Figure 5.2). According to the data available from IBGE (2010), 620 of the residences have no sewage disposal system whatsoever, and only 331 of the 26,222 residences are connected to the town's public sanitation system, which consists only of the sewers that carry the effluents to their final destination, on bare ground or in bodies of water, including the Caeté estuary. A further 3,538 residences have septic tanks, for the retention of solid waste, whereas the other 21,733 or so households depend on alternative systems, typically the piping of effluents directly into local bodies of water, including the Caeté estuary, vacant lots or the open street.

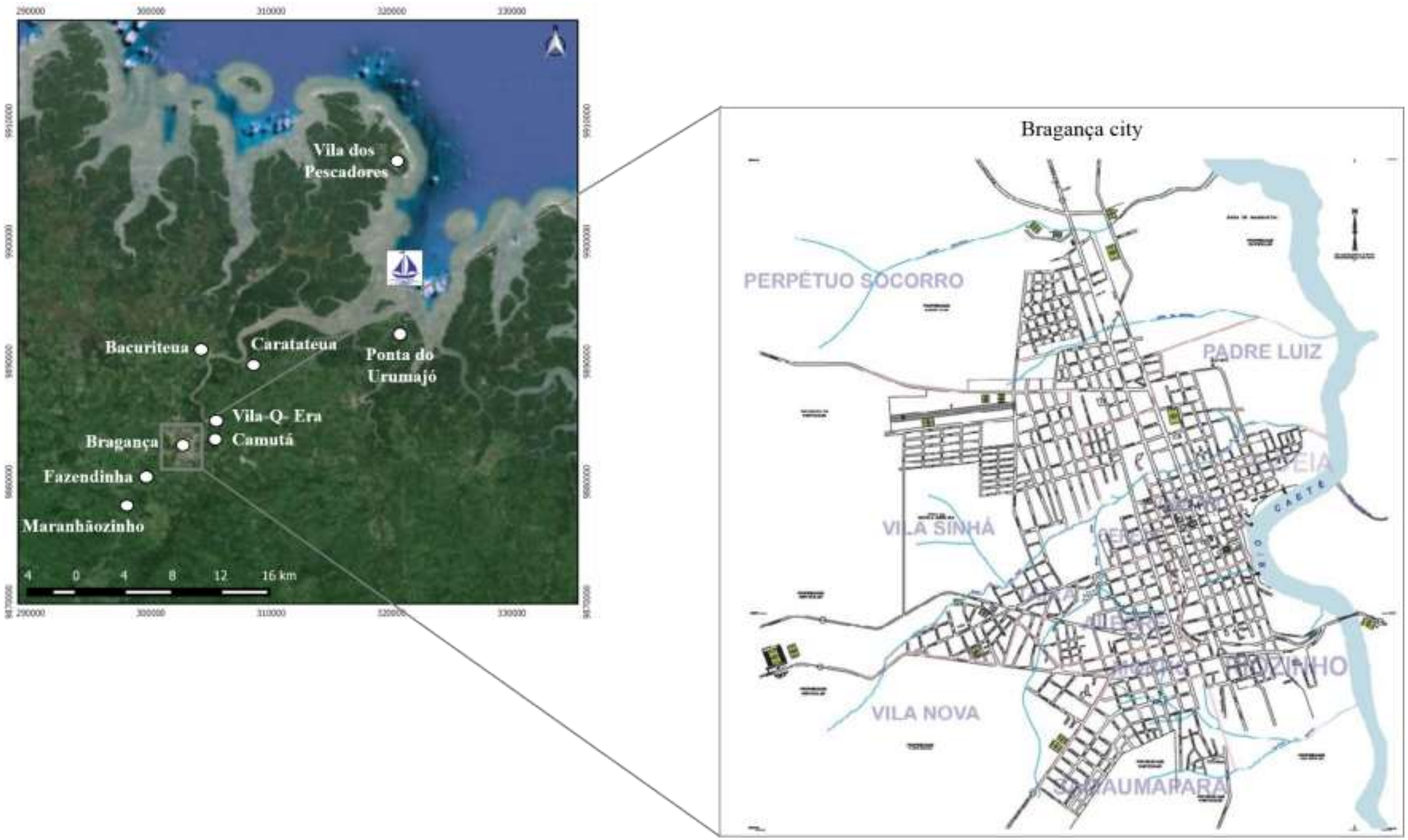

Figure 5.2: Communities located along the Caeté estuary.

In addition to the residential properties, 1,613 retail businesses are found in the upper sector. Most of these businesses trade in supplies for the local fishery industry, including ice factories, fuelling stations, dry docks, and landing piers. At the present time, 140 new commercial establishments are installed each year (data provided by the Bragança Town Council). The other estuary sectors are characterised by much smaller settlements, with a total population of 7,672 inhabitants in the middle sector, and 587 in the lower estuary (Guimarães et al., 2009; IBGE, 2015). The principal processes that contributed to the colonisation of the estuarine sector are shown in Figure 5.3.

Despite the current political incentives for the occupation of the region, as mentioned above, and the recent growth of its population, there has been no investment in the consolidation and expansion of the urban infrastructure to meet the basic needs of the growing population. As a result, the town still lacks an efficient public water supply, sewage system or storm drains, and refuse collection services are irregular and inadequate. Clearly, then, the unplanned urban growth of the region has been accompanied by a widespread increase in anthropogenic impacts, and environmental problems that occurred previously on a small or local scale, such as the pollution of the estuary's waters, have taken on major proportions. Given this, the present study considered population growth in the estuary to be the principal factor influencing the quality of its water.

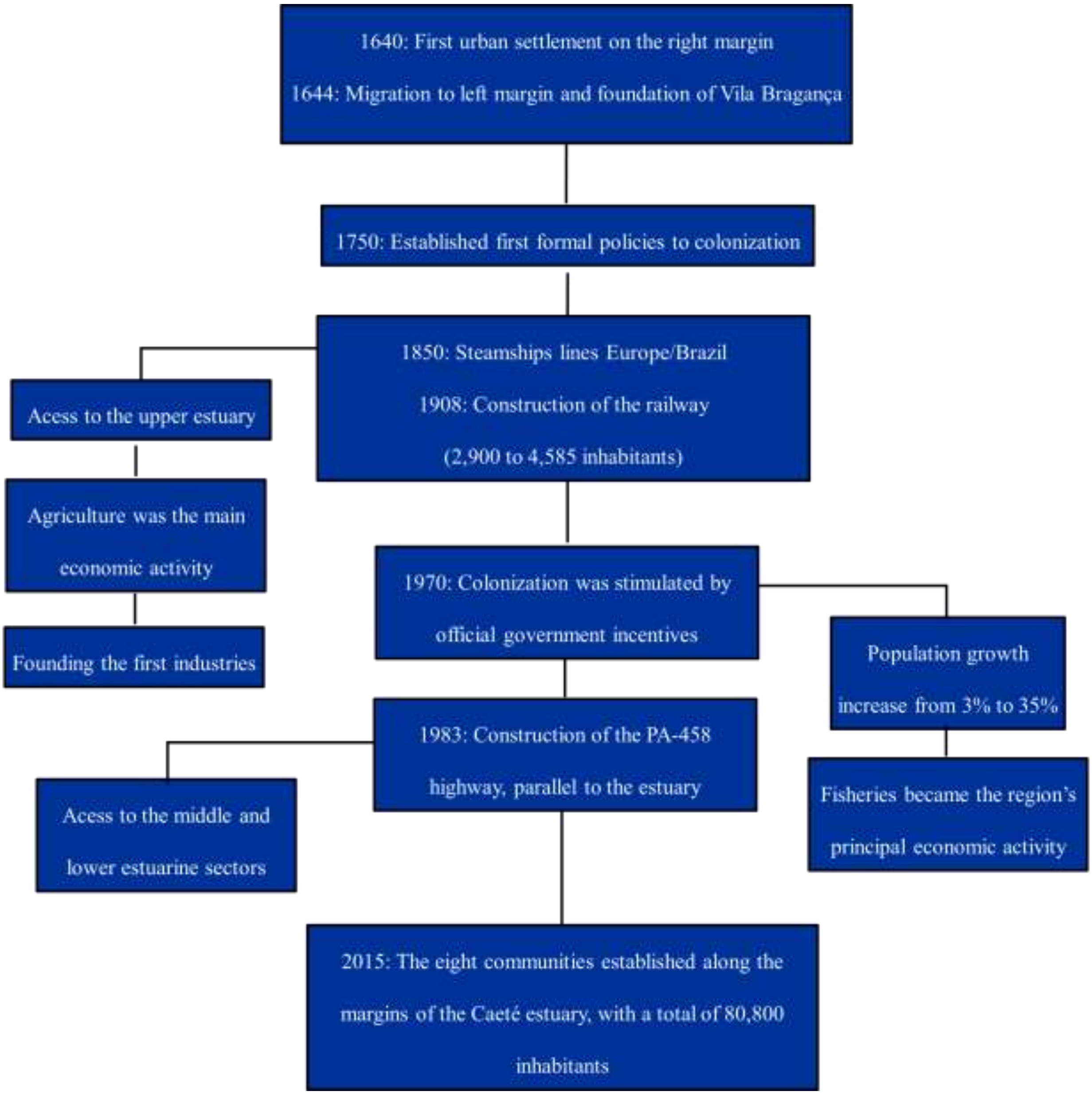

Figure 5.3: Diagram showing the history of the occupation of the Caeté between the first European colonisation and the present day.

5.2 Inventory of pollution sources in the Caeté estuary

A number of different sources of pollution, including sewage outfalls, ice factories, fish processing plants, refuse disposal areas, fishing boats and the Cereja River, were identified in the area surrounding the Caeté estuary, primarily in the upper estuary, on the Bragança waterfront.

No quantitative data are available on the amounts of dissolved nutrients and faecal coliforms discharged into the estuary by these sources. Despite this, we surveyed all existing sources to estimate their respective contributions to the decline in the quality of the water of the Caeté estuay. The contribution of each source is described below.

Sewage outfalls

A total of 12 sewage outfalls were identified on the Bragança waterfront (upper estuary). These outlets are fed through underground pipelines from residences, markets, hospitals, and industries, and the effluents are discharged directly into the Caeté estuary.

An IBGE survey (2010) showed that only around 13% of the 26,222 residences in Bragança are connected to septic tanks. These tanks retain part of the solid residues and eliminate the excess water by percolation into the soil. All other households are either connected to the public sewer system (which discharges untreated effluent directly into the estuary) or discharge their effluents directly onto the ground or into other bodies of water. In all cases, part of the effluents produced reach the estuary in the water that does not percolate into the ground, through the bodies of water that traverse the town and discharge into the estuary, or through the channelling of effluents through open-air drains (Figure 5.4).

Figure 5.4: Effluent input into the Caeté estuary: sewer being channelled into the estuary (A), sewage outlets seen during low tide (B and C), and effluents channelled through open-air drains that flow into the estuary (D).

According to NBR 7229 (ABNT, 1993) and Von Sperling (1996), the residents of Brazilian urban centres produce at least 150 l per day of sewage per day, containing 54 g of DBO, and 8 g of Nitrogenous and 1 g Phosphorous compounds. Assuming that this estimate is valid for the Bragança region, the population in the area surrounding the Caeté estuary (80,880 inhabitants) would produce approximately 12,000 m^3 of sewage per day. This corresponds to the production of 4.3 tons of DBO, 0.6 ton of nitrogenous and 0.08 ton of phosphorous compounds per day. Each inhabitant also produces 100–400 billion faecal coliforms per day, with a total production of 81×10^{12} to 323×10^{12} MPN/100 ml.

As mentioned above, most of these effluents reach the upper sector of the Caeté estuary. The analyses of the water from this sector sampled during the spring (April 2012) and neap (May 2012) tides indicate water rich in dissolved nutrients. The high concentrations of faecal coliforms (≥ 1100 MPN/100 ml) recorded at the sampling stations reflects the influence of anthropogenic impacts in the vicinity of these settlements (Figure 5.5).

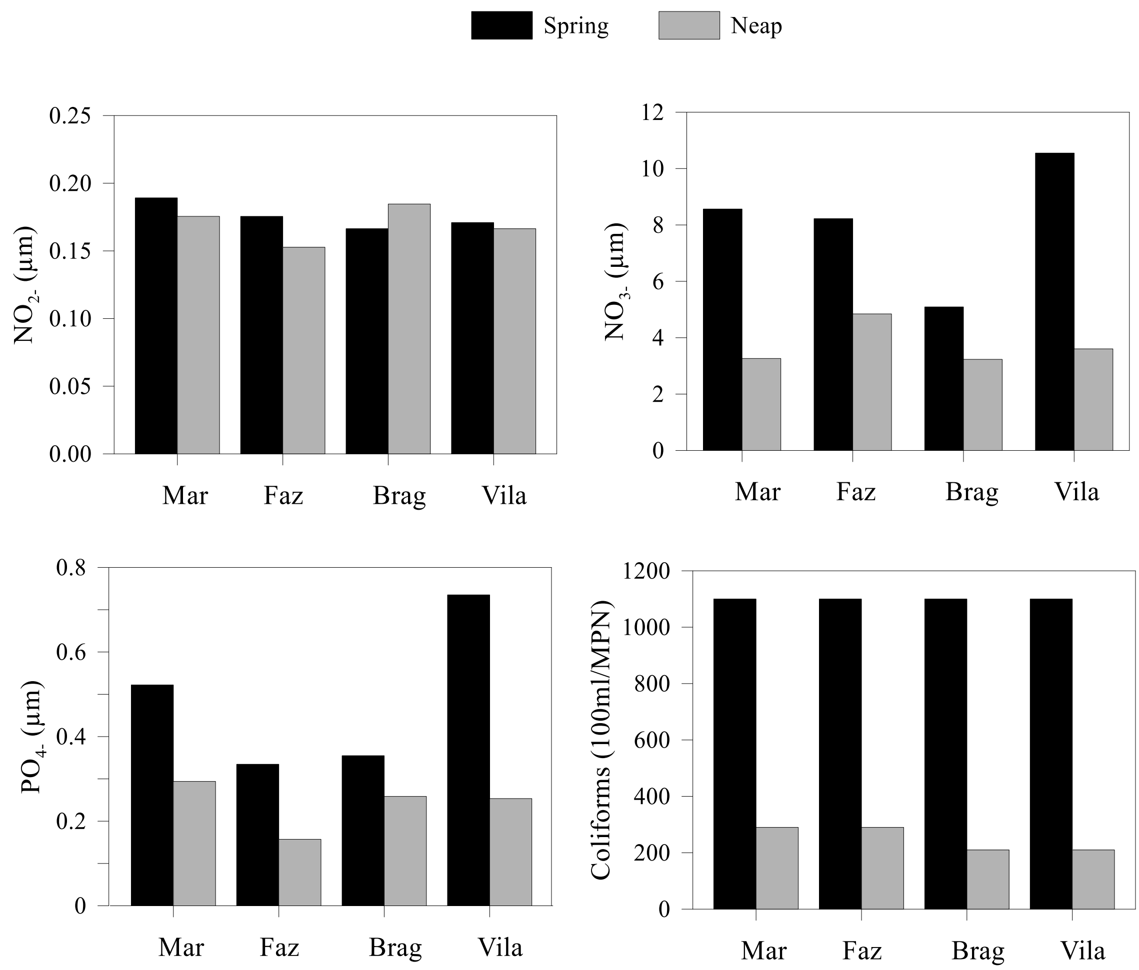

Figure 5.5: Concentrations of dissolved nutrients and faecal coliforms recorded in the settlements located in the upper estuary (Mar: Maranhãozinho, Faz: Fazendinha, Brag: Bragança, and Vila: Vila q Era).

Ice factories

Four of the five ice factories located on the Caeté estuary are found in the upper sector and one in the middle sector. These facilities support the fishing industry, and produce large quantities of ice to conserve incoming catches, and the fishery exported to other regions.

All the ice factories located on the Caeté estuary consume large amounts of gas and liquid ammonium during the refrigeration process (Figure 5.6). As there are no septic tanks in which to treat these compounds adequately, the fraction of liquid that comes into contact with the sewage pipeline flows into the Caeté estuary, which is the final destination of most of the effluents produced in the town of Bragança. In its gaseous form, ammoniacal nitrogen (NH_3^-) is readily biodegradable and water soluble. When dissolved in water, it reacts by ionization to form ammonium (NH_4^+), which is assimilated by bacteria such as the species of the genus *Nitrosomona*, which then converts it into nitrites (NO_2^-) through the ammonification process (Schmidt et al., 2004; Cébron et al., 2005; Ward et al., 2008). Although ammonia is a nutrient required by these bacteria, the NH_3^- and NH_4^+ forms are both toxic to aquatic life in excessive amounts, and can lead to eutrophication and to metabolic changes and death by inhibiting and/or accelerating algae growth (Widiastuti et al., 2011), as well as the eutrophication of estuaries.

Figure 5.6: Ammonia cylinder employment during the refrigeration process.

Fish processing plants

A fish processing plant (GPesca Comercial Ltda.), located in the middle sector of the Caeté estuary, has been in operation since 2002. This plant, one of the most important in the state of Pará, produces an average of 130 m^3 of liquid effluents per day.

All the effluents produced by the GPesca plant are treated before being discharged into the Caeté estuary. This treatment has four stages, the first three of which involve the retention of solid residues using filters. The first stage has three filters tanks, the second stage, two tanks, and the third stage, one filter tank. Once all the solid residues have been removed from the effluent, it passes to the fourth stage, which consists of the metabolisation of the organic matter through aerobic filters. By the end of this process, the pollutants have been removed and the organic content of the liquid has been reduced considerably. The effluent is then piped through the mangrove to a tidal creek in the Caeté estuary (Figure 5.7).

The solids residues, such as fish heads, entrails, fins, and scales (Figure 5.7), which are by-products of the production process are stored and donated for the production of animal feed. While no systematic record is kept of the amount of solid waste produced each day, an estimate based on the weight and number of containers discarded indicates that the total may be as much as 1 ton.

Figure 5.7: Different stages in the treatment of the residual water produced by GPesca Ltda. Removal of the solid residues (A), filtering of the solid residues (B), tank for the metabolisation of the organic matter (C), the pipeline that discharges the residual water into the Caeté estuary (D and E), effluent piped through the mangrove to a tidal creek in the Caeté estuary (F).

Based on the quantity of effluents produced and the concentrations of dissolved nutrients found per litre of water released in the estuary, it is possible to estimate the volume of BOD, nutrients, and faecal coliforms discharged into the Caeté estuary per day (Table 5.1). Unfortunately, it was not possible to obtain data from other local fish processing plants, which operate illegally during the peak harvesting periods of commercially-valuable species such as the Southern red snapper, *Lutjanus purpureus* (Figure 5.8). However, it can safely be assumed that these plants produce large quantities of effluents rich in BOD and dissolved nutrients (Islam et al., 2004), similar to the output recorded at the GPesca Ltda. plant.

Table 5.1: Estimate (tons) of the BOD and dissolved nutrients discharged daily by GPesca Comercial Ltda. into the Caeté estuary.

	Discharge point	
	Min	Max
BDO (mg)	1,50	21,20
Total phosphorus (µm)	0,00	0,57
Nitrate (µm)	0,21	0,54
Nitrite (µm)	0,00	0,11
Ammonium (µm)	0,07	6,80
Faecal colifms (MPN)	34,50	0,26

Figure 5.8: Illegally fish processing plants in the upper sector of Caeté estuary

Refuse disposal area

On the Bragança waterfront in the upper Caeté estuary, there are two refuse containers and a number of sites at which solid waste is discarded directly onto the ground, at the edge of the river (Figure 5.9). The refuse deposited here is derived from households, public markets, hospitals, and public toilets located nearby. The leachates produced by the decomposition of this refuse end up in the estuary, creating a source of contamination.

Leachates contain large amounts of organic and inorganic nitrogen (Kulikowska et al., 2012) which can be transported to the estuary during heavy rainfall. These substances are usually acidic and rich in organic matter, which should affect the pH and turbidity of the waters they come into contact with. Increasing turbidity tends to impede the production of oxygen and increase the biochemical demand for oxygen, with deleterious effects for many aquatic organisms (Srivastava and Kumar, 2013; Jones et al., 2015). It also seems reasonable to assume that the flow of leachates is also a source of contamination by bacteria, considering that waste from domestic and public toilets are disposed along the margins of the estuary.

Figure 5.9: Areas in which waste accumulates along the margins of the estuary. Residues discarded directly onto the ground (A) and container for the collection of waste (B).

Fishing boats

A total of 794 fishing boats are registered at the Bragança Fisher Colony, of which 540 are motorized fishing boats that spend 10–70 days at sea before returning to port to land their catches (IBAMA, 2005). These boats dock in Bragança (Figure 5.10) and discharge their stored sewage directly into the Caeté estuary. Human faeces contain a large quantity of pathogens (including *Escherichia coli*) which cause substantial alterations to the quality of the water and restrict its suitability for human activities, especially those that involve direct contact or consumption.

Figure 5.10: Fishing boats on the Bragança waterfront, where the crews normally discharge the faeces accumulated during trips.

Effluent discharge into the Cereja River

The Cereja River is 4 km long, and traverses Bragança before flowing into the Caeté estuary. The river crosses six neighbourhoods with approximately 380 households and 1500 residents (Santos et al., 2014). Costa (2012) affirm that 43% of the residences located along the margins of the Cereja River have no septic tank and release their domestic effluents directly into the river. The other 57% have septic tanks, which retain the solid residues, with the liquid fraction being piped into the river (Figure 5.11). In both cases the effluents (solid or liquid) reach the Cereja River and eventually flow into the Caeté estuary.

Guimarães et al. (2009) recorded high concentrations of dissolved nutrients in the Cereja River with values between 7.0 and 55.5 µM of nitrate-NO_3, 0.7 and 2.2 µM of nitrite-NO_2, and from 0.6 to 1.85 µM of phosphate-PO_4. Faecal coliforms reach concentrations of over 1100 MPN/100 ml in the Cereja River, which acts as an important source of contamination for the Caeté estuary during the wet season when the river floods and absorbs sewage directly from concealed, as well as other substances from the lixiviation of the surrounding areas.

Figure 5.11: Pollution in the Cereja River. Solid waste in the river bed (A) and typical wastewater piping found in the local households, which directs effluents directly into the river (B).

All the sources of contamination identified and mapped during the survey are shown in Figure 5.12.

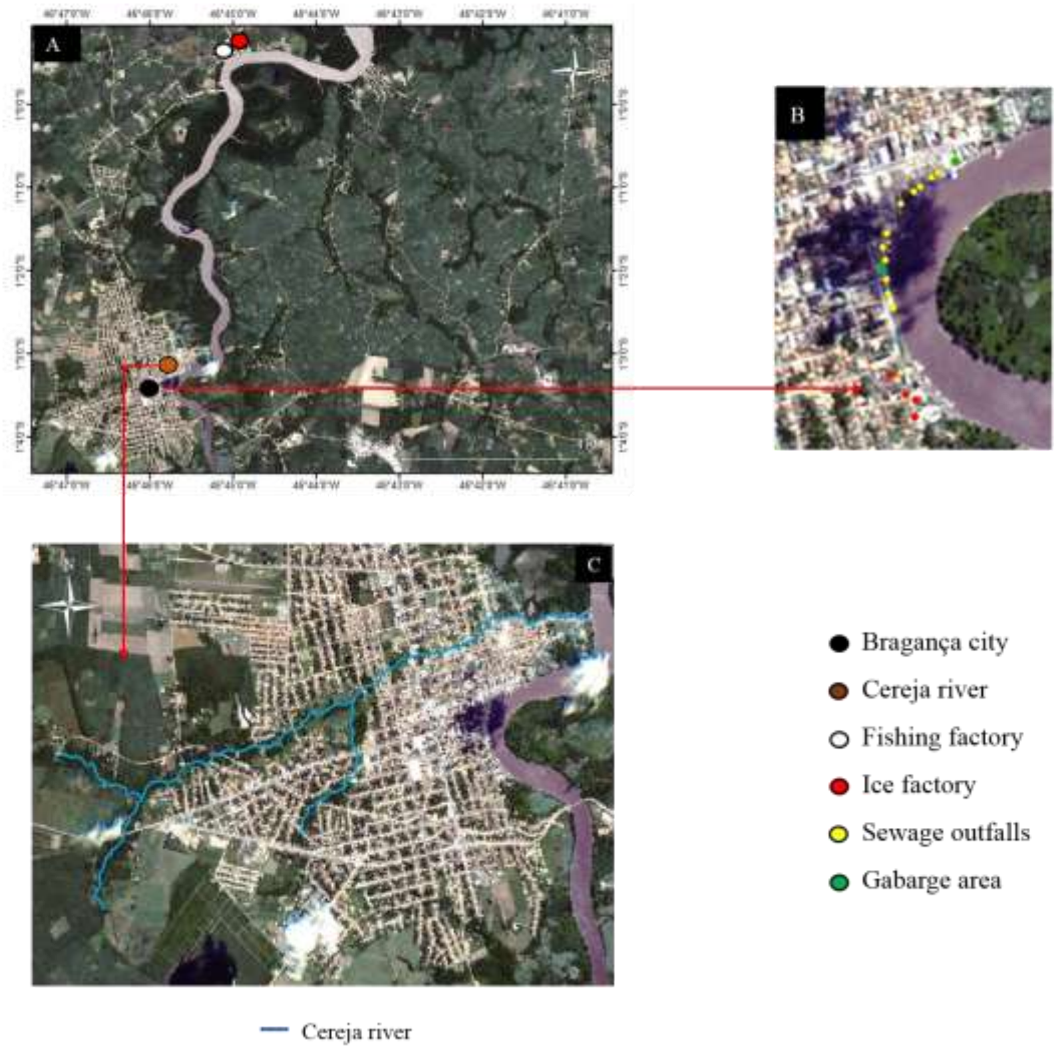

Figure 5.12: Sources of contamination identified in the upper Caeté estuary: upper and middle estuary (A), concentration of pollution sources in the town of Bragança (B) and Cereja River (C).

Information available in this chapter indicate that while Bragança has only 72,621 inhabitants, the unplanned settlement of the area and the economic activities developed in the region have placed increasing pressure on the Caeté estuary. These pressures are concentrated in the upper estuary (Figure 5.7), which is the most urbanized sector and contains the highest concentration of pollution sources identified during the survey. The input of dissolved nutrients and faecal coliforms from these sources was considered to be the principal anthropogenic influence on the quality of the water of the Caeté estuary, with little annual variation (not considered directly in the survey). The principal driving force of this pressure was the unplanned urban development (including the lack of a public sewage treatment system or the adequate disposal of refuse) and the lack of any effective controls or regulation of the economic activities developed in the region.

CHAPTER 6

ENVIRONMENTAL ASPECTS

This chapter provides a detailed analysis of the hydrodynamic, hydrological, and microbiological variables of the Caeté estuary. The oceanographic data were analysed in terms of their temporal and spatial variation, and in order to better understand the oscillations in hydrodynamic, hydrological, and microbiological variables, the mid-and long-term series of rainfall, fluvial discharge and wind data were analysed into three perspectives – (i) spring tide condition (Phase I), (ii) neap tide condition (Phase II) and (iii) the relationship between these phases.

6.1 Spring tide condition (Phase I)

6.1.1 Rainfall, freshwater discharge and winds

A 39-year series of rainfall data were analysed to understand the rainfall patterns observed during the study period. The results indicate mean annual precipitation of approximately 2500 mm in the Bragança region, with two well-defined seasons, the wet and the dry seasons. The rainfall recorded during the present study period was typical in 2006 (87% of the historical mean values), although the period monitored in 2007 (January and February) were a typically low, corresponding to only 8% of the historical mean (Figure 6.1).

During this phase, approximately 90% (2000 mm) of the total rainfall occurred during the wet season (January–July 2006), with the highest monthly total being recorded in March 2006. During the dry season (August 2006 to February 2007) total rainfall level was only 208 mm, corresponding to 10% of the total rainfall recorded during phase I (Figure 6.1). It is important to note that the dry season in the Bragança region normally ends in December, although this season lasted until February 2007 in the present study. As a consequence, the variables analyzed in this month were considered to be representative of the dry period.

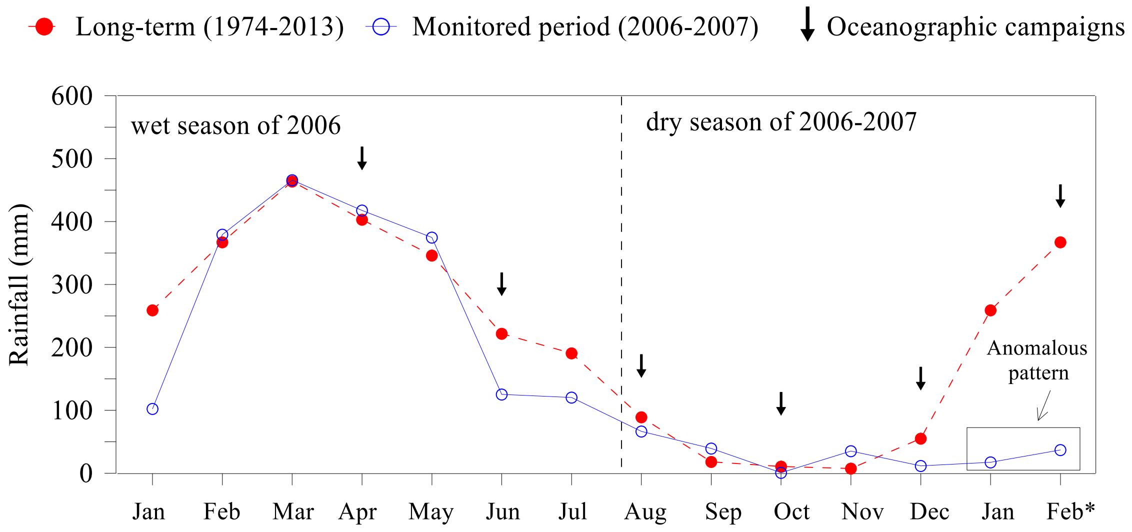

Figure 6.1: Long-term data and monthly rainfall level in Bragança. (*) Total rainfall until the field campaign in 07 February 2007.

A general characterization of the rainfall data allows to group the monitored months into different categories, as shown in the table 6.1.

Table 6.1: Rainfall classification according to the monthly rate. (*) Periods influenced by equinoctial spring tides

Rainfall (mm)	Months	Classification	
>400	March and April* of 2006	Extreme rainfall	wet
200-400	February and May* of 2006	Heavy rainfall	
100-200	January, June and July of 2006	Moderate rainfall	
<100	August, September*, October* and November of 2006 and January and February of 2007	Light or no rainfall	dry

As rainfall levels have a direct effect on fluvial discharge, the long-term data available on the discharge of the Caeté River were also considered in this study. The mean discharge of the Caeté in 2006 (36 $m^3.s^{-1}$) was similar to the historical mean of 40 $m^3.s^{-1}$ (Figure 6.2). Approximately 81% of the total discharge recorded in 2006 was registered during the wet season, when the monthly mean was 82.5 $m^3.s^{-1}$. The highest monthly discharge was recorded in April 2006, as a consequence of the peak in the rainfall recorded in March 2006. The remaining 19% of the total discharge was recorded during the dry season, when the mean monthly discharge was 19.3 $m^3.s^{-1}$. Reflecting the trend in rainfall, the discharge of the Caeté in January 2007 was only 18% of the historical mean.

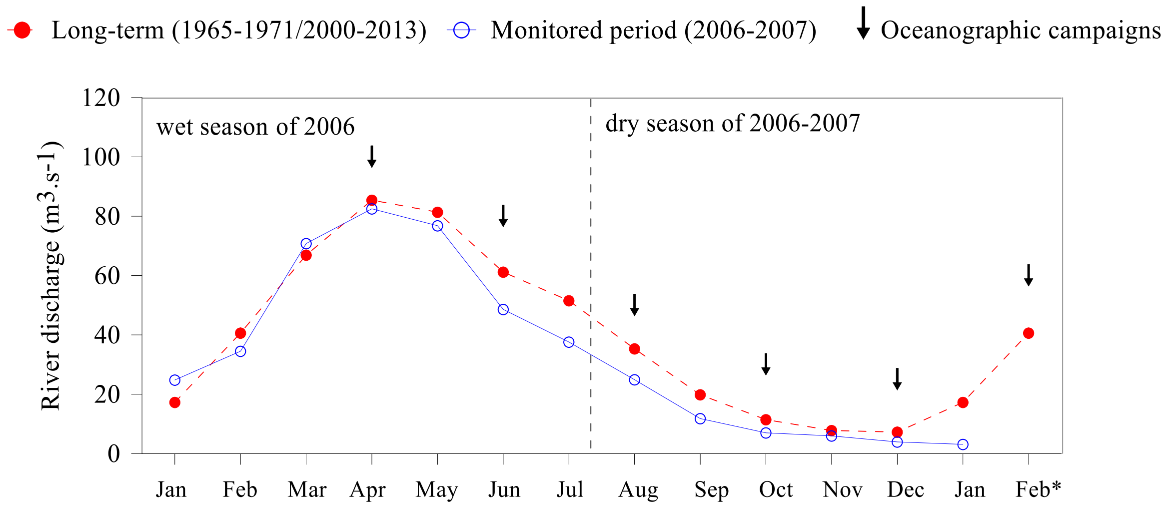

Figure 6.2: Long-term data and monthly river discharge data measured in the upper Caeté estuary during the study period. (*) Data not available for 2007.

Winds also presented a seasonal pattern. The highest wind speeds were recorded during the dry season, when maximum average velocities of 4.0 to 8.0 $m.s^{-1}$ were recorded frequently. Exceptionally, brief gusts with velocities above 12.0 $m.s^{-1}$ were recorded. By contrast, wind speeds were low during the wet season, with a predominance of maximum average velocities of 1.0 $m.s^{-1}$ or less (Figure 6.3).

North-westerly winds ($270^o < \theta < 315^o$) predominated during the wet season, principally between April and June 2006. North-easterly winds were recorded during only 20% of the time during this season (Figure 6.3). During the dry season, by contrast, north-easterly winds ($0^o < \theta < 45^o$) predominated, accounting for approximately 75% of the records between October 2006 and February 2007.

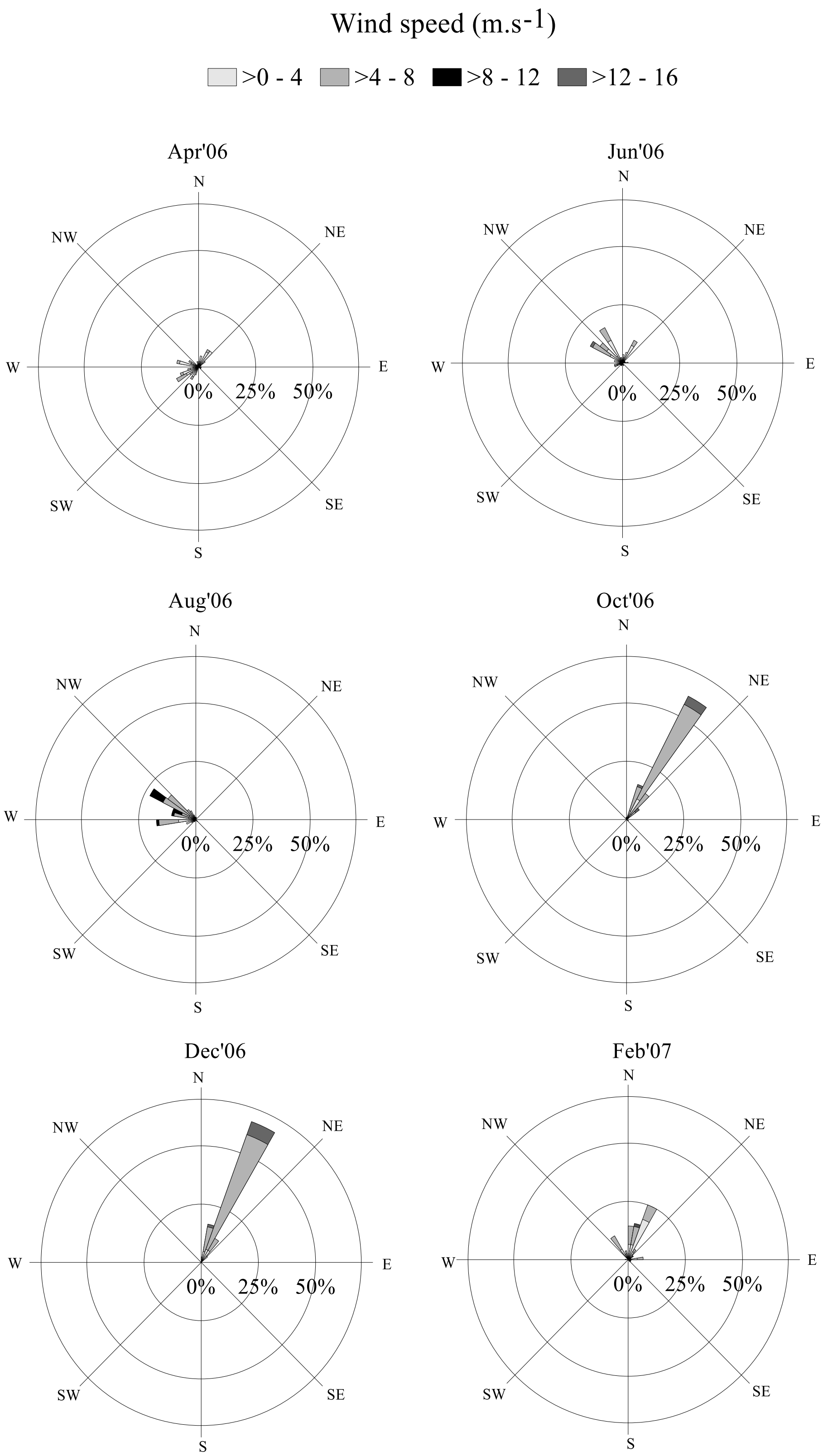

Figure 6.3: Wind speeds and directions measured at the Salinópolis station during the study period.

6.1.2 Hydrodynamic aspects

Tidal heights in the upper and lower Caeté estuary are shown in table 6.2. An amplification between 0.10 and 0.40 m being recorded going upstream. This amplification was more pronounced during the dry season when river discharge was reduced.

Table 6.2: Tidal heights recorded in the upper and lower sectors of the Caeté estuary.

		Tidal range (m)	
		upper	lower
wet	Apr'06	4.3	4.3
	Jun'06	4.2	4.1
dry	Aug'06	4.6	4.6
	Oct'06	4.4	4.2
	Dec'06	4.6	4.2
	Feb'07	4.3	4.1

The tides were asymmetric. High water reaches the upper sector with a delay of 1.1–2.6 hours, whereas there is a delay of 2.0–3.0 hours at low water. The asymmetry was less pronounced in the lower sector, with minimal differences between the flood (5.3-6.0 hours) and ebb (6.3-7.2 hours) phases (Table 6.3). As expected, tidal asymmetry was less pronounced during the dry season when river discharge was reduced.

Based on the asymmetry index (AI_{DV}), the ebb phase dominated in the upper sector during both the wet and the dry seasons. However, this dominance pattern was observed only during the wet season in the lower sector, whereas the flood tide predominated during the dry season (Table 6.3). The estimated mean tidal prism during the study period was 93 x 10^6 m^3 (Figure 6.4), with peak of 103 x 10^6 m^3 in August 2006.

Table 6.3: Tidal asymmetry in the Caeté estuary and the classification based on the asymmetry index (AI_{DV}).

		Asymmetry (hours)				Asymmetry index	
		upper		lower		upper	lower
		ebb	flood	ebb	flood		
wet	Apr'06	8.3	3.8	7.2	5.3	ebb dominance (AI_{DV} 0.6)	ebb dominance (AI_{DV} 0.3)
	Jun'06	8.0	4.2	6.3	5.5	ebb dominance (AI_{DV} 0.5)	ebb dominance (AI_{DV} 1.8)
dry	Aug'06	7.3	5.0	7.0	5.3	ebb dominance (AI_{DV} 0.4)	ebb dominance (AI_{DV} 0.2)
	Oct'06	7.5	4.3	6.7	5.3	ebb dominance (AI_{DV} 0.3)	flood dominance (AI_{DV} -0.1)
	Dec'06	7.5	4.7	6.8	5.7	ebb dominance (AI_{DV} 0.5)	flood dominance (AI_{DV} -0.2)
	Feb'07	7.5	4.6	6.3	6.0	ebb dominance (AI_{DV} 0.5)	symmetrical wave (AI_{DV} 0.0)

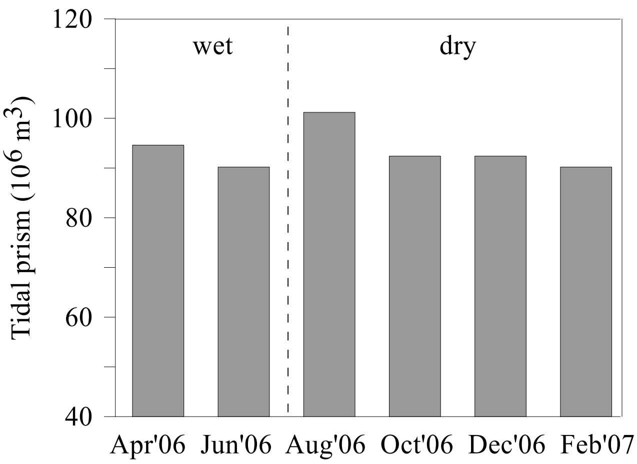

Figure 6.4: Tidal prism estimated for the Caeté estuary from the DHN tidal data under spring tide conditions.

High current velocities were recorded in all three estuary sectors, reaching a maximum of 1.2 $m.s^{-1}$ in the upper sector, 2.0 $m.s^{-1}$ in the middle, and 1.7 $m.s^{-1}$ in the lower sector (Figure 6.5). The increased river discharge during the wet season resulted in the highest ebb current velocities recorded in the upper sector (around 1.2 $m.s^{-1}$). During the dry season, the increased influence of marine forces and the reduced fluvial discharge contributed to stronger flood tide currents in both the middle (from August to October

2006) and lower sectors (October of 2006) (Figure 6.5). The data indicate the occurrence of a strict slack tide in the Caeté estuary (up to 0.5 hours), while peak velocities tend to occur in the middle of the tidal phase.

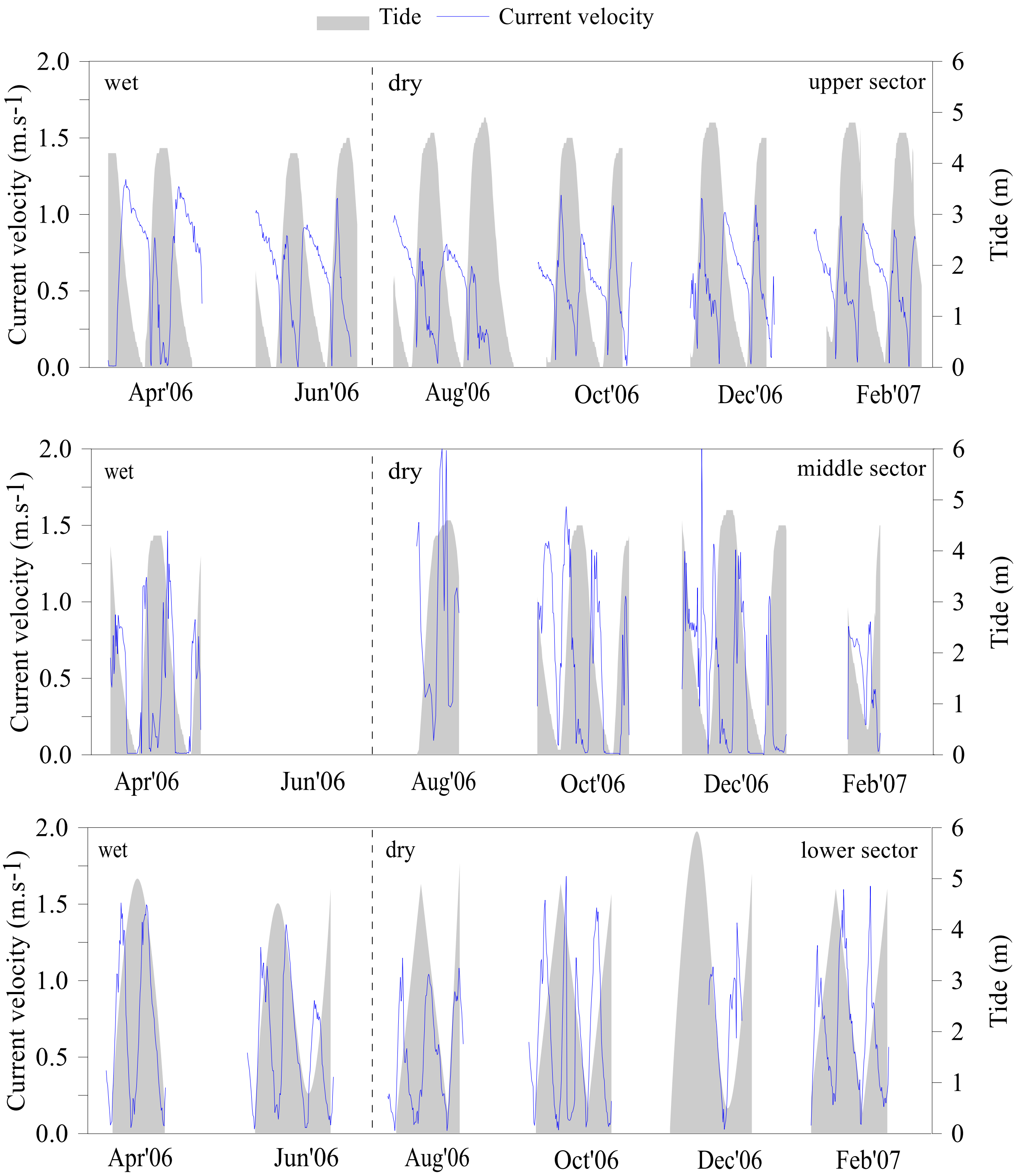

Figure 6.5: Current velocities in the Caeté estuary during the spring tide.

In general terms, the highest current velocities (> 1.6 $m.s^{-1}$) were recorded in the middle estuary (Table 6.4), which is probably due to the presence in this sector of sand banks that narrow the main channel of the estuary, as observed in Figure 3.9 (Chapter 3).

Table 6.4: Frequency of current velocities values recorded in the upper, middle and lower sectors.

	Frequency (%)				
sector	0-0.4 $m.s^{-1}$	>0.4-0.8 $m.s^{-1}$	>0.8-1.2 $m.s^{-1}$	>1.2-1.6 $m.s^{-1}$	>1.6-2.0 $m.s^{-1}$
upper	37.5	48.2	27.4	0.2	0.0
middle	37.5	27.4	22.5	10.8	2.9
lower	36.7	27.1	24.5	11.2	0.5

The progressive current vector indicated the maximum displacement was 41 km during period of extreme rainfall which coincided with peak of fluvial discharge (April) in the upper estuary. In the middle estuary, the maximum was 36 km during the driest month and equinoctial spring tides (October), and in the lower estuary the maximum displacement was 17 km in periods influenced by equinoctial sprig tides (April and October, Figures 6.6, 6.7 and 6.8).

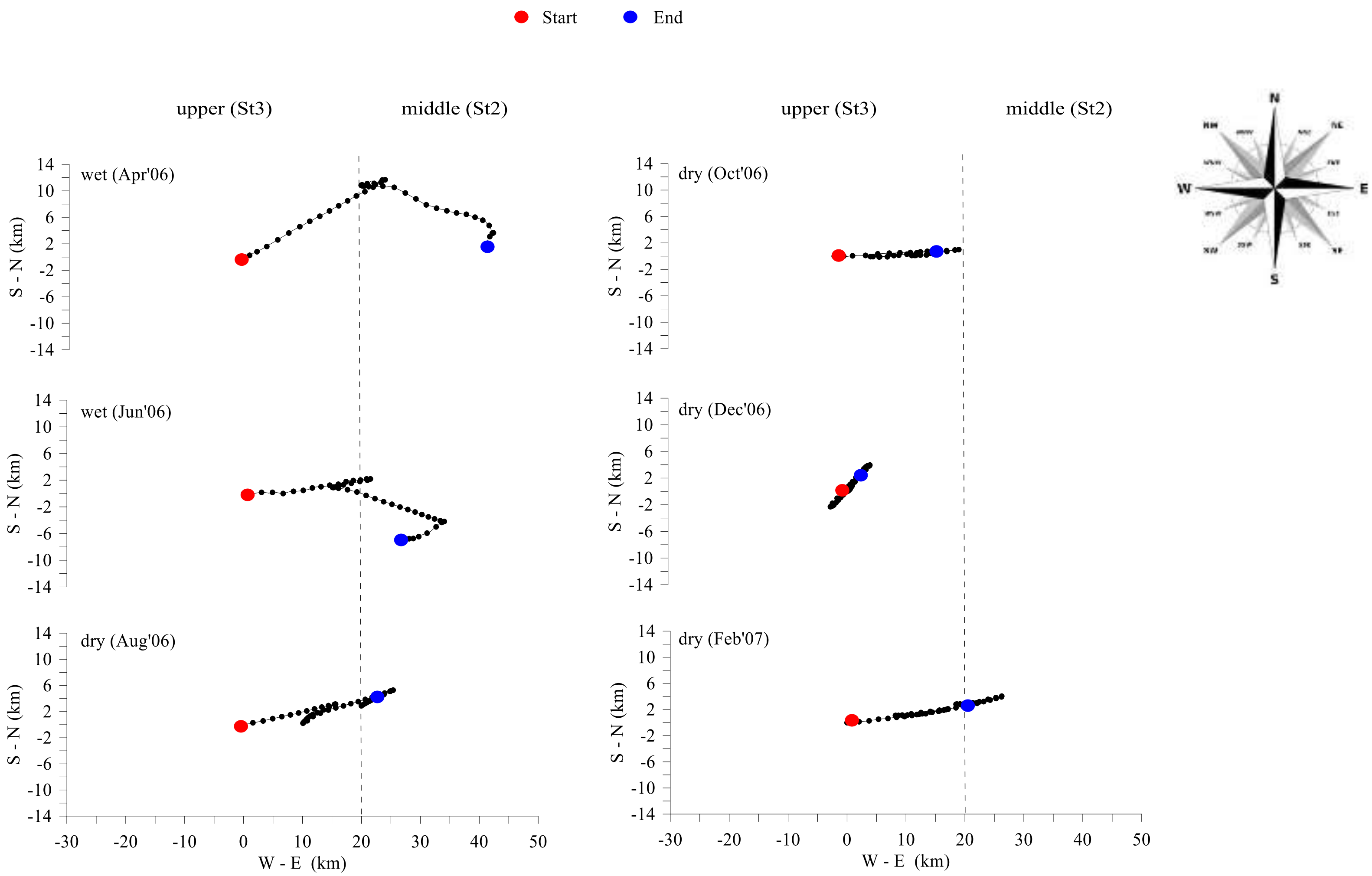

Figure 6.6: Current displacement in the upper sector of the estuary over a 25-hour period.

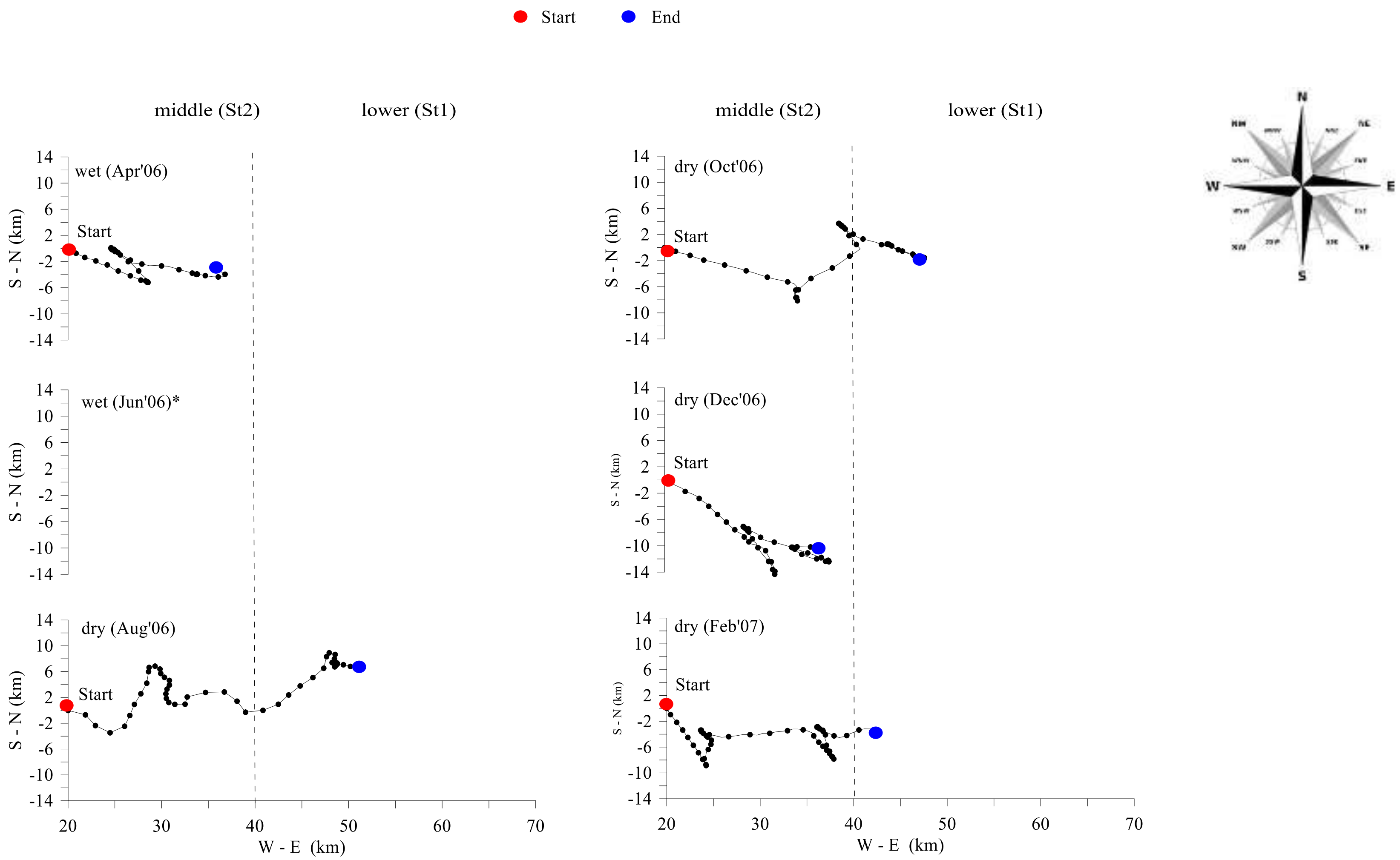

Figure 6.7: Current displacement in the middle sector of the estuary over a 25-hour period. (*) No current data.

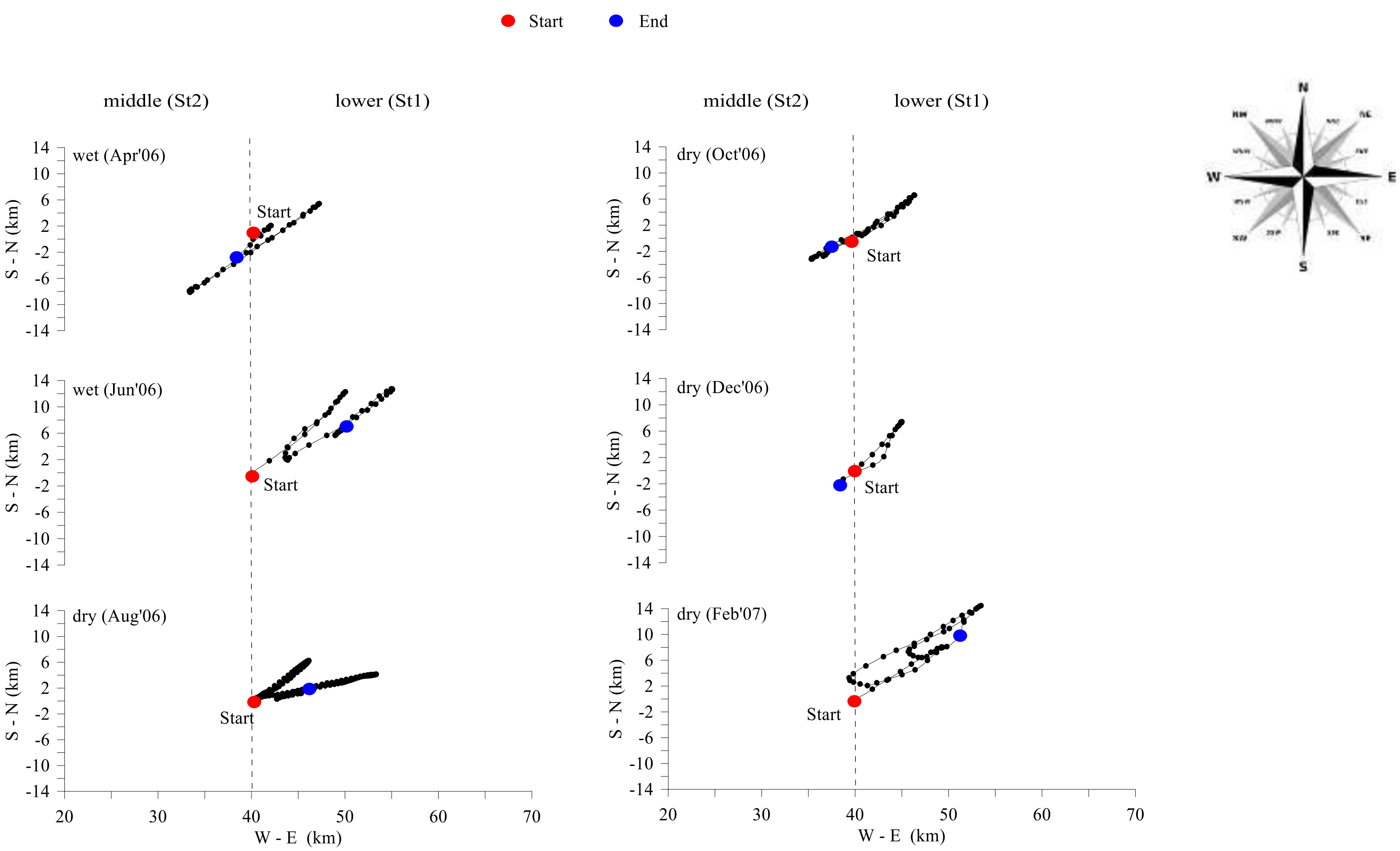

Figure 6.8: Current displacement in the lower sector of the estuary over a 25-hour period.

6.1.3 Hydrology and microbiological aspects

Figure 6.9 shows main variables in the different sectors during wet and dry season. Under spring tide conditions, only salinity and pH varied significantly between seasons, with the highest values being recorded during the dry season (salinity: U = 198, p = 0.00; pH: F = 6.9, p = 0.00) when the discharge of the Caeté declines (salinity reached 40.0 and the pH was 7.9 in December 2006). As the fluvial discharge increases during the wet season, salinity fell to between 0.0 and 25.0, while pH was between 6.2 and 8.0.

In addition to this seasonal pattern, salinity also presented a spatial gradient within the estuary, with lowest values being recorded in the upper sector (0.0 to 8.7), which is most influenced by fluvial process, and highest in the lower sector (6.6 to 40.0), which is affected by marine process. The pH followed a similar longitudinal pattern, ranging from slightly acid to alkaline in the upper estuary (6.2 to 7.8) to alkaline, in the lower sector (7.3 to 8.0, Figure 6.9).

The highest dissolved oxygen (DO) concentrations were recorded during the period of moderate rainfall and highest fluvial discharge (June 2006) in the upper estuary, *i.e.* when ebb currents are their strongest. Values below 5.0 $mg.L^{-1}$ predominated in this sector during the dry season, with a saturation rate of 70-90%, reflecting saturated conditions (Figure 6.9). In the lower sector, the water was more oxygenated, mainly during the periods influenced by equinoctial spring tides, which favour strong tidal currents (April and October 2006), and when the winds blew more strongly, in October 2006 (mean of 5.2 $m.s^{-1}$) and December 2006 (mean of 5.1 $m.s^{-1}$), as a consequence of the intense interactions between the water and the atmosphere. During these periods, DO concentrations were normally above 5.0 $mg.L^{-1}$ with saturation rates of up to 140%, that corresponding to supersaturated water (Figure 6.9). A similar relationship between DO and chlorophyll *a* concentrations in the upper sector indicated the possible contribution of photosynthesis to the oxygenation of the water, despite the reduced level of correlation ($R^2 \leq 0.07$) between these variables (Figure 6.9).

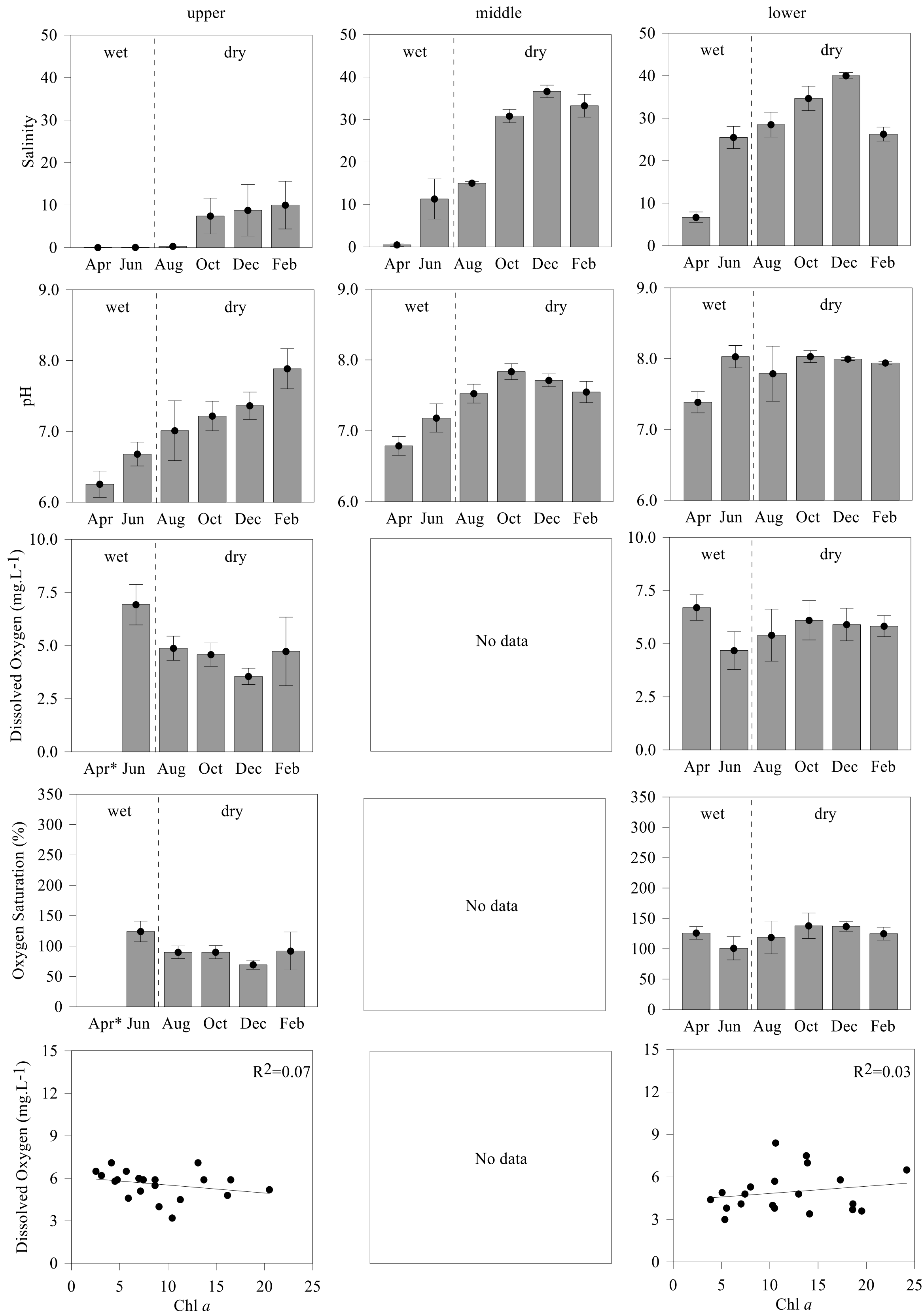

Figure 6.9: Physical and physical-chemical variables in the Caeté estuary between April 2006 and February 2007. (*) Not sampled.

During the wet season, reduced dissolved nutrient concentrations were recorded in the upper sector (Nitrite-NO_2^-: 0.3 µm; Nitrate-NO_3^-: 4.5 µm; Ammonium-NH_4^+: 0.1 µm; Phosphate-PO_4: 0.3 µm, and Silicate-SiO_2: 30.1 µm), indicating that the discharge of the Caeté was not the estuary's principal source of nutrients during this period. In this season, effluents released in the estuary at the town of Bragança, which represent a constant input of nutrients without seasonal variation (see Chapter 5), tend to be diluted by the high rainfall levels. In addition, the stronger (> 1.0 $m.s^{-1}$) and longer (up to 8.0 h) ebb currents as well as the displacement from the upper sector of around 40 km as described previously (Figure 6.5, Table 6.3 and Figure 6.6), resulting from the increase in river discharge contributed to the more effective transportation of nutrients from the upper estuary to its mouth. This appears to have contributed to a decrease in dissolved nutrients in the upper sector and an increase in the middle and lower sectors. During the dry season, by contrast, when the ebb currents have a reduced influence, the highest concentrations were recorded in the middle and upper sectors (Figure 6.10).

The conservative mixing diagram (dissolved nutrients *vs*. salinity) presented a seasonal variation, despite the weak correlation (R^2 $0.00 \leq 0.77$) observed in both the wet and dry seasons (Figure 6.11). During the wet season, nutrient concentrations (except ammonium) were more constant along the salinity gradient (from the upper estuary to the mouth) indicating an equilibrium between the sink (removal) and source (release) of dissolved nutrients in the Caeté estuary. During the dry season, nitrogenous nutrients increased slightly within the estuary (areas with lower salinity), where the sources of contamination are concentrated, and were removed at the mouth (areas with higher salinity). The phosphate and silicate concentrations followed the opposite pattern, increasing near the mouth of the estuary during this period, due to the marine contribution.

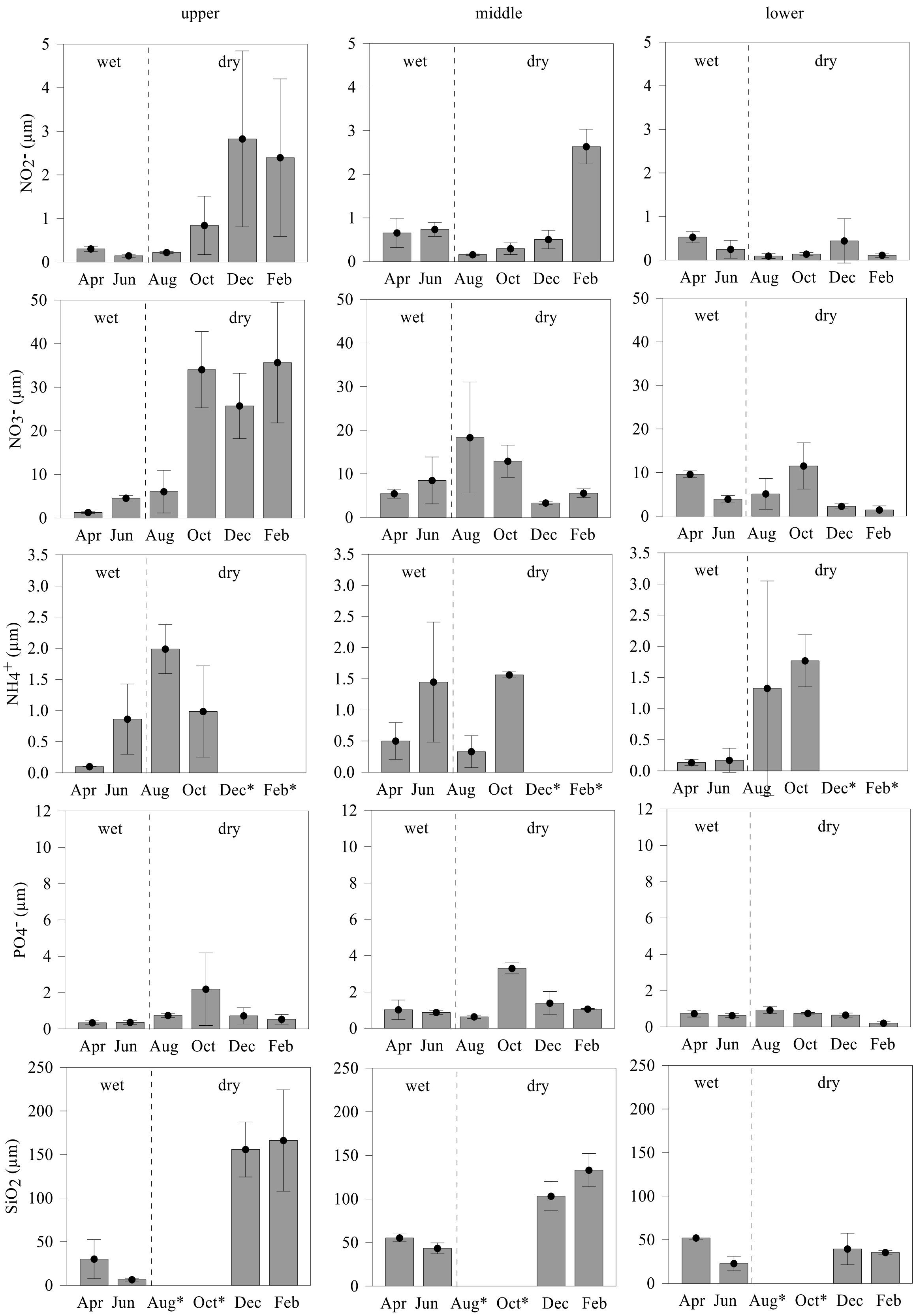

Figure 6.10: Dissolved nutrients in the Caeté estuary between April 2006 and February 2007. (*) Not sampled.

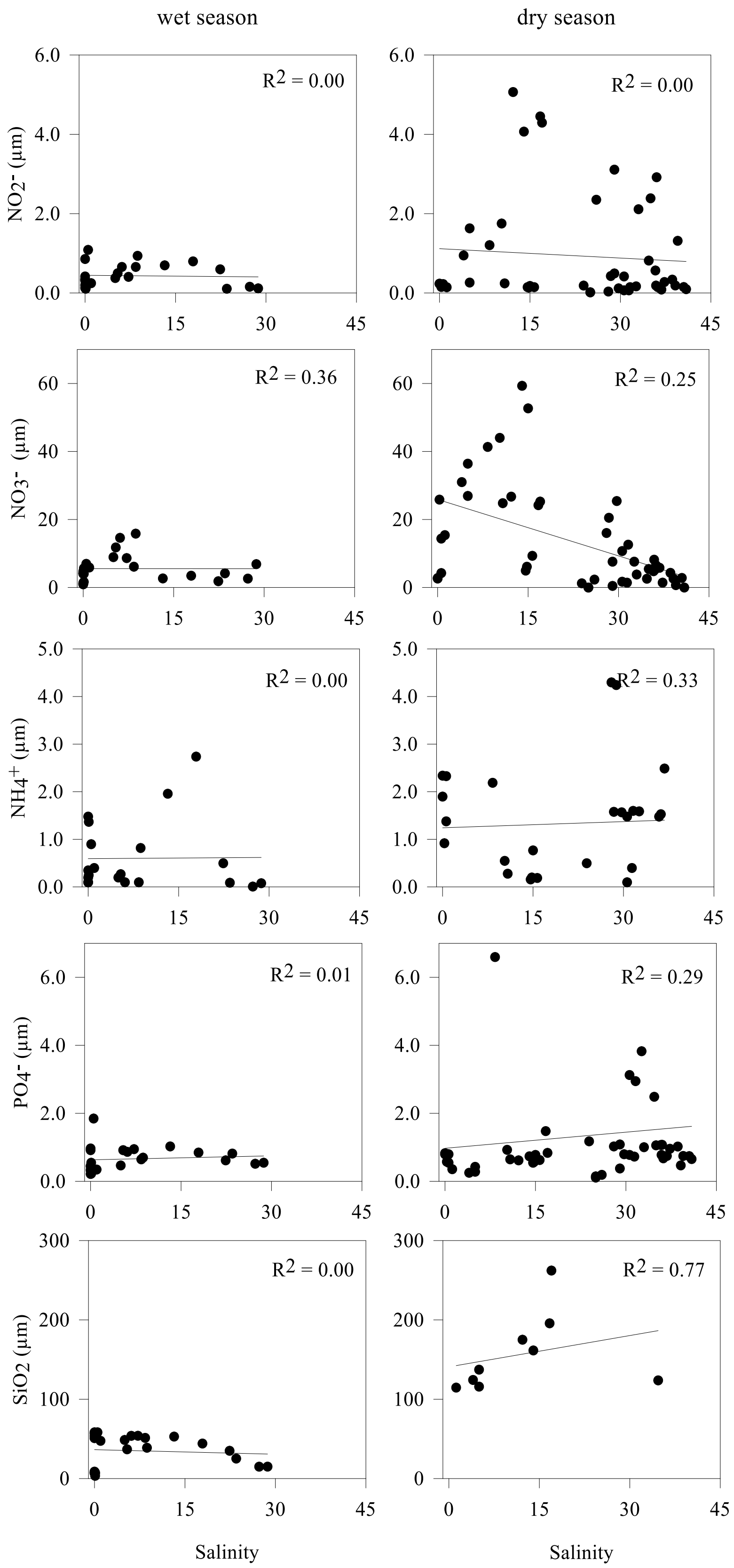

Figure 6.11: Mixing diagrams along the salinity gradient in the Caeté estuary.

Two indices of water quality were integrated into a trophic index for the estuary. The Karydis index, based on nutrients concentrations, indicated that the waters of the estuary were mesotrophic further upstream during the wet season (from eutrophic to mesotrophic), and eutrophic further downstream (from mesotrophic to eutrophic) during the dry season (Figure 6.12). This pattern reflects that of the dissolved nutrient concentrations, observed previously. The worsening eutrophication observed during the dry season in the upper sector indicate that the natural conditions (the capacity to dilute and transport nutrients) found in the region during this period were inadequate for the reduction or elimination of the excess of nutrients found in the water column. The results obtained from TRIX, based on nutrients, chlorophyll *a* and oxygen dissolved, indicated a lack of any major variation among seasons or periods, although in the upper sector of the estuary, where the sources of contamination are concentrated, a slight increase in eutrophication was observed, principally during the dry season. The TRIX recorded poor water quality and high levels of eutrophication in all the sectors of the estuary (Figure 6.12). It is important to highlight that in the Caeté estuary, the water assumes this characteristic due to the natural input of dissolved nutrients from mangrove area (see Chapter 3). Thus, poor quality designation, cannot be adequate for the Caeté estuary, as explained in Chapter 8.

In all the sectors of the estuary, during both the wet and the dry seasons, nitrate were the main form of DIN (dissolved inorganic nitrogen), representing up to 70% of the DIN at all the stations monitored (Figure 6.13). This indicates high levels of bacterial oxidation and equilibrium conditions within the estuary. However, the increase in the contribution of ammonium in the upper sector during the dry season (Figure 6.13), when discharged effluents were diluted and transported less efficiently by the reduced fluvial discharge, indicate a reduction in the quality of the water in this sector during this period. This was corroborated by the high levels of eutrophication observed in this sector during dry season.

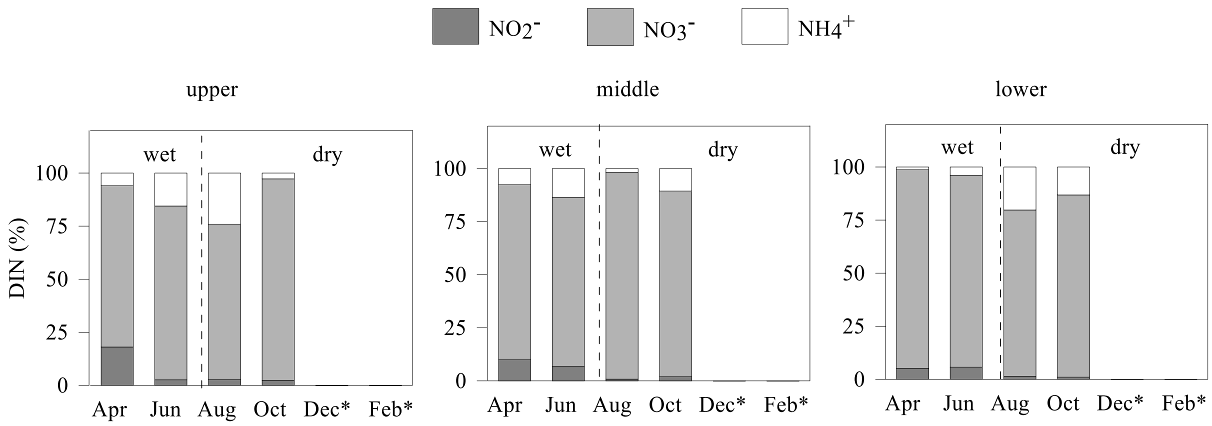

Figure 6.12: Trophic status of the Caeté estuary during the wet and dry seasons. (*) This classification has been discussed in the Chapter 8.

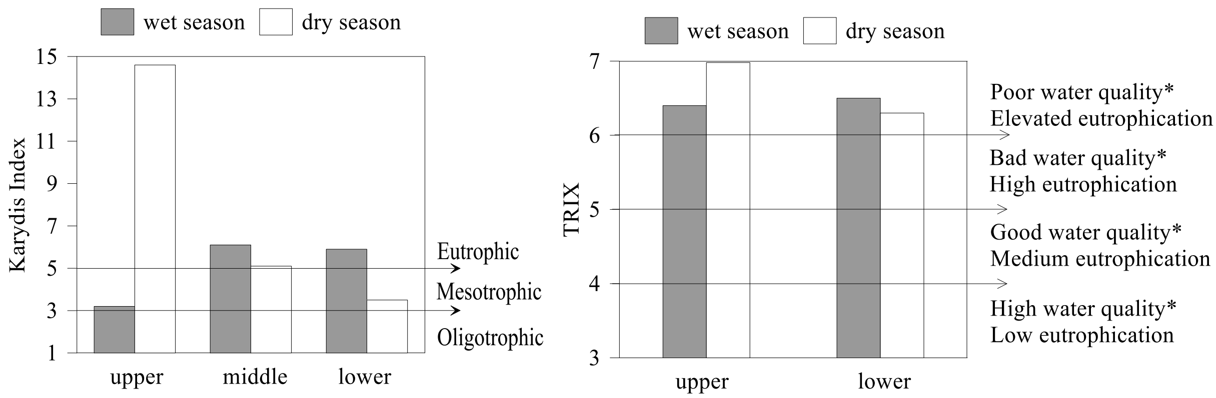

Figure 6.13: Dissolved inorganic nitrogen in the Caeté estuary during the wet and dry seasons. (*) Not ammonium data.

The molar DIN:DIP ratios recorded in the three sectors during the study period is shown in Figure 6.14. Low values, below the threshold proposed by Redfield (16:1), predominated in all months, indicating a deficit of nitrogen, except in the period marked by the absence of rainfall (October 2006) in the upper sector, when an excess of nitrogen was recorded. By contrast, the DSi:DIP ratios were higher than the Redfield threshold, indicating an excess of silicate in the Caeté estuary, primarily during the dry season, when a maximum of 322:1 was observed in the upper sector (Figure 6.14).

Chlorophyll *a* did not present a seasonal pattern, with peaks being observed in both the wet and dry season, with concentrations ranging from 4.4 to 16.5 $mg.m^{-3}$ in the wet season and from 3.92 to 17.6 $mg.m^{-3}$ in the dry season. The highest chlorophyll *a* values (above 15.0 $mg.m^{-3}$) were recorded in the upper sector, which presents the highest dissolved nutrient concentrations. Concentrations were lower in the others sectors, but still reflected the high productivity of the estuary (Figure 6.14).

Faecal coliforms are an important indicator of water quality in environments affected by anthropogenic impacts, like the Caeté estuary. The low faecal coliforms concentrations recorded during the wet season (maximum of 110 MPN/100 ml) confirmed the capacity of the fluvial discharge of dilute contaminants during this period. The increase in faecal coliform concentrations observed during the dry season indicate higher levels of contamination and a poor water quality, as indicated by the trophic indices (Figure 6.14).

As expected, faecal coliform concentrations presented a marked spatial gradient from the upper to the lower estuary, with increasing closer to the pollution sources. Concentrations of over 500 MPN/100ml were recorded only in the upper sector, where they corresponded to 40% of the samples, whereas in the other sectors, values were invariably lower than 500 NMP/100 ml (Figure 6.14). This supports the highest level of anthropogenic impacts found in this sector, as shown in Chapter 5.

The correlation matrix for the variables analysed in the present study (included only those with a full dataset) is shown in Table 6.5. As observed above, salinity correlated positively with pH and phosphate concentrations. This reflects the increase in pH observed during the dry season due to the increased influence of marine waters, and also indicates that they may represent an important source of phosphate for the estuary, contributing to the increased concentrations recorded during this period in the middle and upper sectors of the estuary as shown in the Figure 6.9 and 6.10.

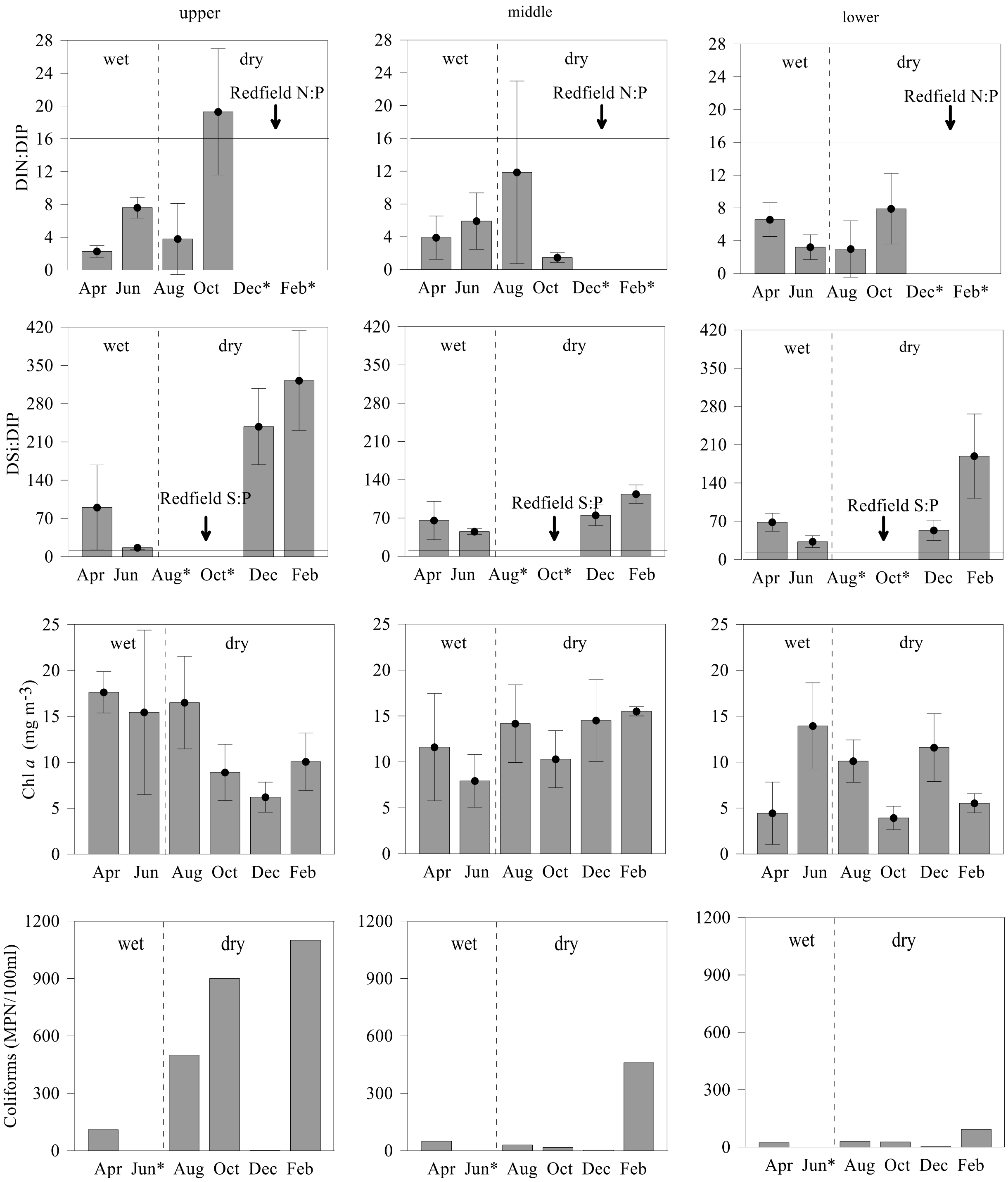

Figure 6.14: Redfield ratios, chlorophyll *a* and faecal coliform concentrations recorded in the Caeté estuary between April 2006 and February 2007. (*) Not data.

Table 6.5: Spearman correlation matrix for the variables monitored during the spring tide period.

	Salinity	pH	Nitrate	Nitrite	Phosphate
pH	**0.76***				
Nitrate	-0.11	0.02			
Nitrite	-0.06	-0.22	0.22		
Phosphate	**0.43***	0.12	0.15	0.38	
Chl *a*	-0.03	-0.06	-0.05	0.06	-0.07

Significant correlations in bold *Significance level ($p < 0,00001$)

6.2 Neap tide condition (Phase II)

6.2.1 Rainfall, freshwater discharge and winds

The rainfall recorded during the oceanographic campaigns of 2010 (August–December, 363 mm) was 100% higher than that of the 39-year historical average for the same period (180 mm). The increase was due to the high rate of rainfall recorded in December of 2010, approximately 2 times higher than registered by long-term data series (Figure 6.15) due do the La Niña recorded in this period. The total rainfall recorded between August and December corresponds to 18% of the annual total recorded in 2010 (1987 mm). September, October, and November 2010 was considered the driest quarter, with month rates lower than 28 mm (Figure 6.15).

In 2011, the total rainfall recorded during the oceanographic campaigns (January–October, 2617 mm) was similar enough to the historical mean for the region (2369 mm for the same period) for the year to be considered typical (Figure 6.15). Approximately 95% of this total was recorded during the wet season (January–July, 2483 mm). April was the rainiest month, with a total of 503 mm. During the dry season, however (August–October) a total of only 135 mm was recorded, corresponding to only 5% of the annual total.

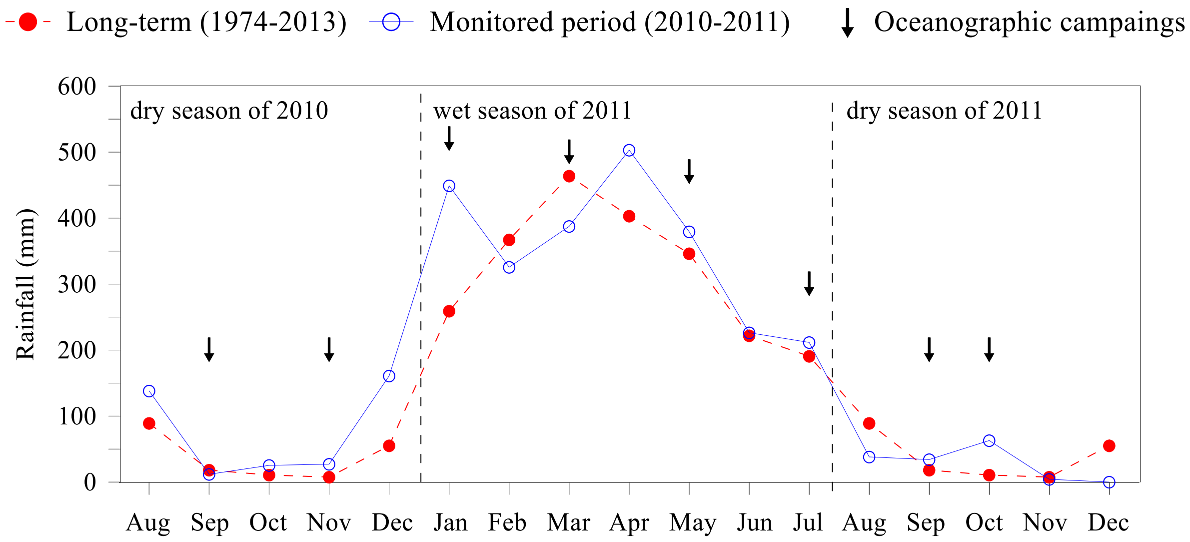

Figure 6.15: Long-term data and monthly rainfall level in Bragança.

A general characterization of the rainfall data allows to group the monitored months into different categories, as shown in the table 6.6.

Table 6.6: Rainfall classification according to the monthly rate. (*) Periods influenced by equinoctial spring tides.

Rainfall (mm)	Months	Classification	
>400	January and April* of 2011	Extreme rainfall	wet
200-400	February, March, May*, June and July of 2011	Heavy rainfall	
100-200	August and December of 2010	Moderate rainfall	dry
<100	September*, October* and November of 2010 and August, September*, October*, November and December of 2011	Light or no rainfall	

The average fluvial discharge during the dry season of 2010 (August–December, 9.1 $m^3.s^{-1}$) was 45% lower than the historical mean (16.3 $m^3.s^{-1}$) recorded over a 19-year period (Figure 6.16). The mean discharge recorded during the 2011 oceanographic campaigns (January–October) was 73.6 $m^3.s^{-1}$ during the wet season (January–July), which corresponds to a rate 30% higher than the long-term series recorded to this same period, and 17.1 $m^3.s^{-1}$ during the dry season (August–October), which is similar to the long-term series recorded. Monthly rates varied from 4.6 $m^3.s^{-1}$ to 103.0 $m^3.s^{-1}$ (Figure 6.16).

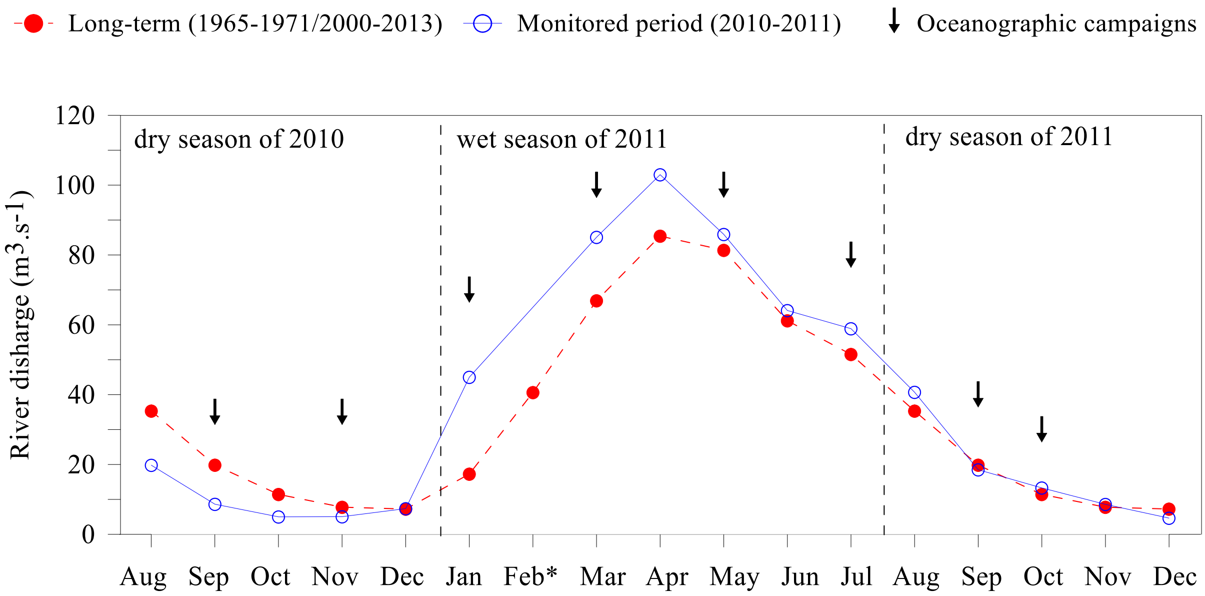

Figure 6.16: Long-term data and monthly river discharge data measured in the upper Caeté estuary during the study period. (*) Data not available for 2011.

Little seasonal variation was observed in wind speed or direction (Figure 6.17). Wind speeds typically ranged from 3.0 to 6.0 $m.s^{-1}$ in both seasons. The highest speeds, between 9.0 and 12.0 $m.s^{-1}$, were recorded mainly during the dry seasons of 2010 and 2011, although they corresponded to little more than 10% of the records during this period. Only 2% of the records collected during the wet were these high. North-easterly winds ($0^o < \theta < 45^o$) predominated during both seasons, with a frequency of approximately 95% during the dry season and 80% during the wet season.

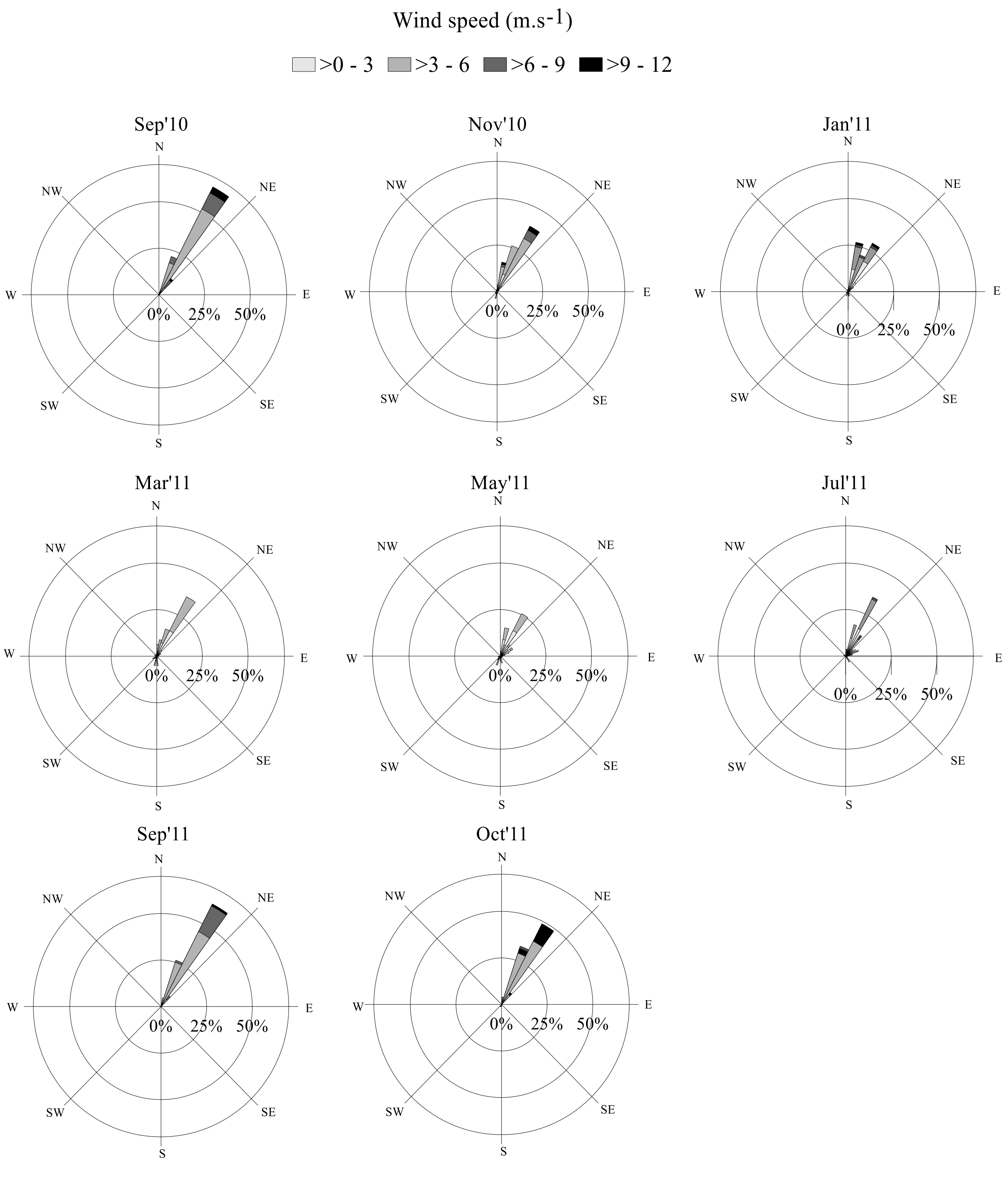

Figure 6.17: Wind speeds and directions recorded at the Salinópolis station during the study period.

6.2.2 Hydrodynamic aspects

Tidal heights recorded in the Caeté estuary are shown in table 6.7. Tidal amplification of 0.1 to 0.7 m is observed in the middle sector due to the reduction of the width of the channel, as observed through bathymetric data described in Chapter 3 (St4, Figure 3.9). This is followed by damping of up to 0.9 m as the tide is propagated to the upper sector.

As expected, the tidal prism was lower during the neap tide than the spring tide, ranging between 50 and 72 x 10^6 m^3, with the highest values being recorded in November 2010 and July 2011, when the oceanographic campaign was conducted during the transition between neap and spring tides (Figure 6.18). The reduction of the tidal prism observed during this phase may have also contributed to the reduction in the tidal current velocities observed during this period, which ranged between 0.2 and 0.7 $m.s^{-1}$ in both wet and dry seasons (Figure 6.19).

Table 6.7: Tidal heights recorded in the upper, middle and lower sectors of the Caeté estuary during the wet and dry seasons.

		Tidal range (m)		
		upper	middle	lower
dry	Sep'10	2.7	2.7	2.6
	Nov'10	3.4	3.6	3.3
wet	Jan'11	3.1	3.2	2.6
	Mar'11	2.2	3.1	2.6
	May'11	3.0	3.3	2.8
	Jul'11	3.8	3.8	3.3
dry	Sep'11	2.9	3.0	2.3
	Oct'11	2.3	2.6	2.4

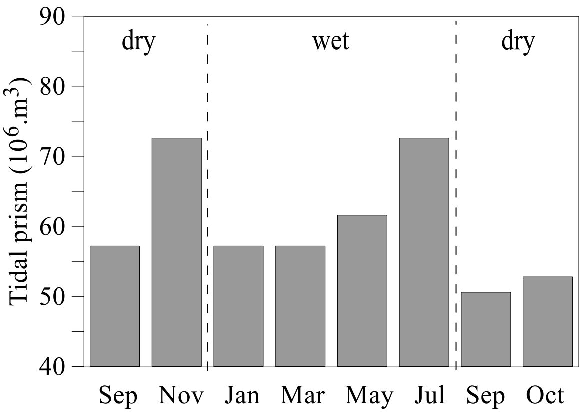

Figure 6.18: Tidal prism estimated for the Caeté estuary from the DHN data under neap tide conditions.

A seasonal pattern similar to that recorded during the spring tides was also observed here, with current velocities being influenced strongly by local climatological variables. During the wet season, the highest values (between 0.6 to 0.7 $m.s^{-1}$) were observed during the ebb phase, whereas during the dry season, they were recorded in the flood phase (Figure 6.19).

The vertical current profile of the Caeté estuary was homogeneous, with differences of typically little more than 0.1 $m.s^{-1}$ between the surface and the bottom (Figure 6.20). This indicates a lack of gravitational circulation and a predominance of mixing between the freshwater and marine waters (as confirmed by the vertical salinity data in the next section, see section 6.2.3). The greatest differences between surface and bottom velocities were recorded during the wet season (0.5 $m.s^{-1}$), indicating weaker mixing and a certain degree of stratification, which was also confirmed by the vertical salinity. This pattern was observed primarily during heavy rainfall periods (May 2011), when the higher fluvial discharge was recorded (mean of 85.9 $m^3.s^{-1}$).

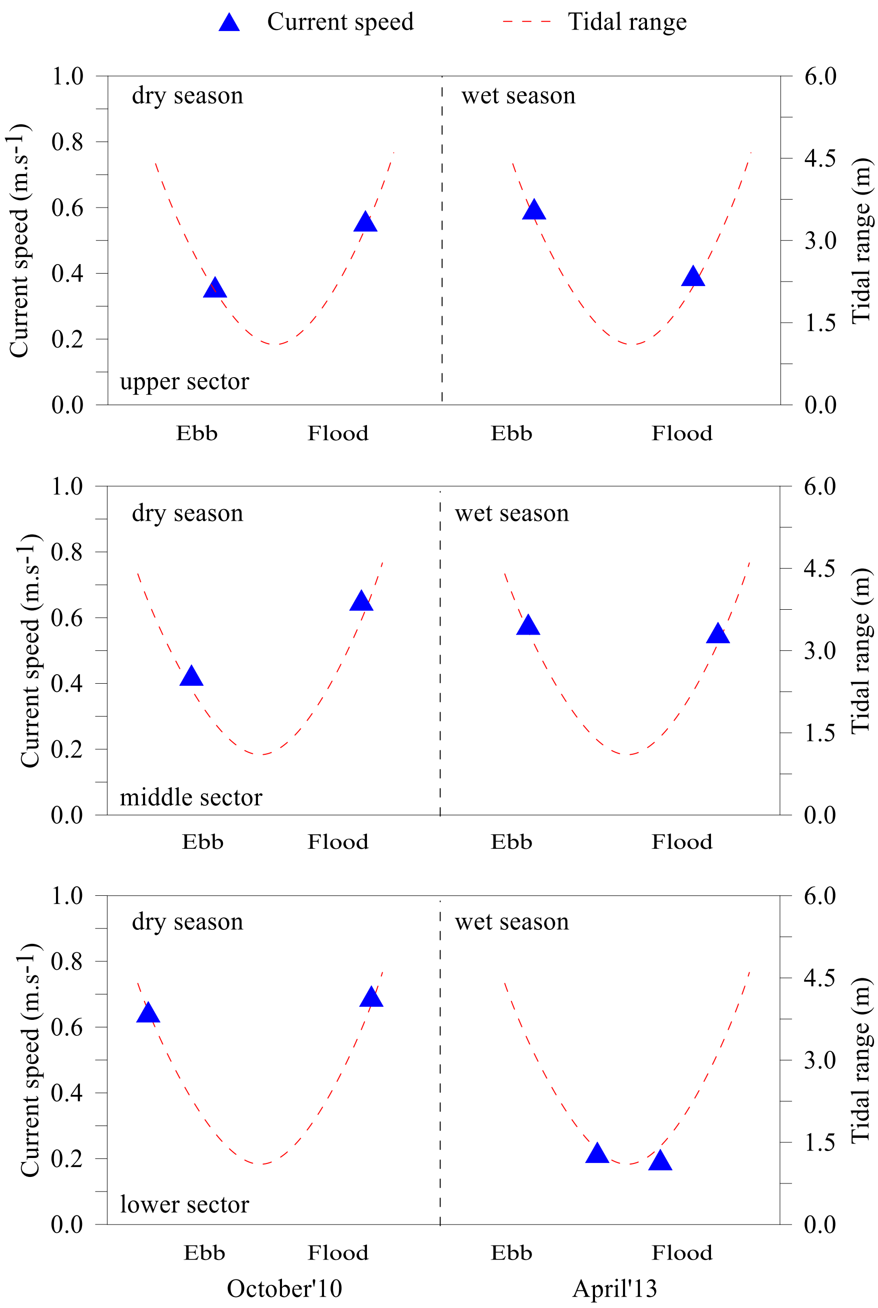

Figure 6.19: Current velocities in the Caeté estuary during the wet and dry seasons. The tidal range was obtained from the DHN.

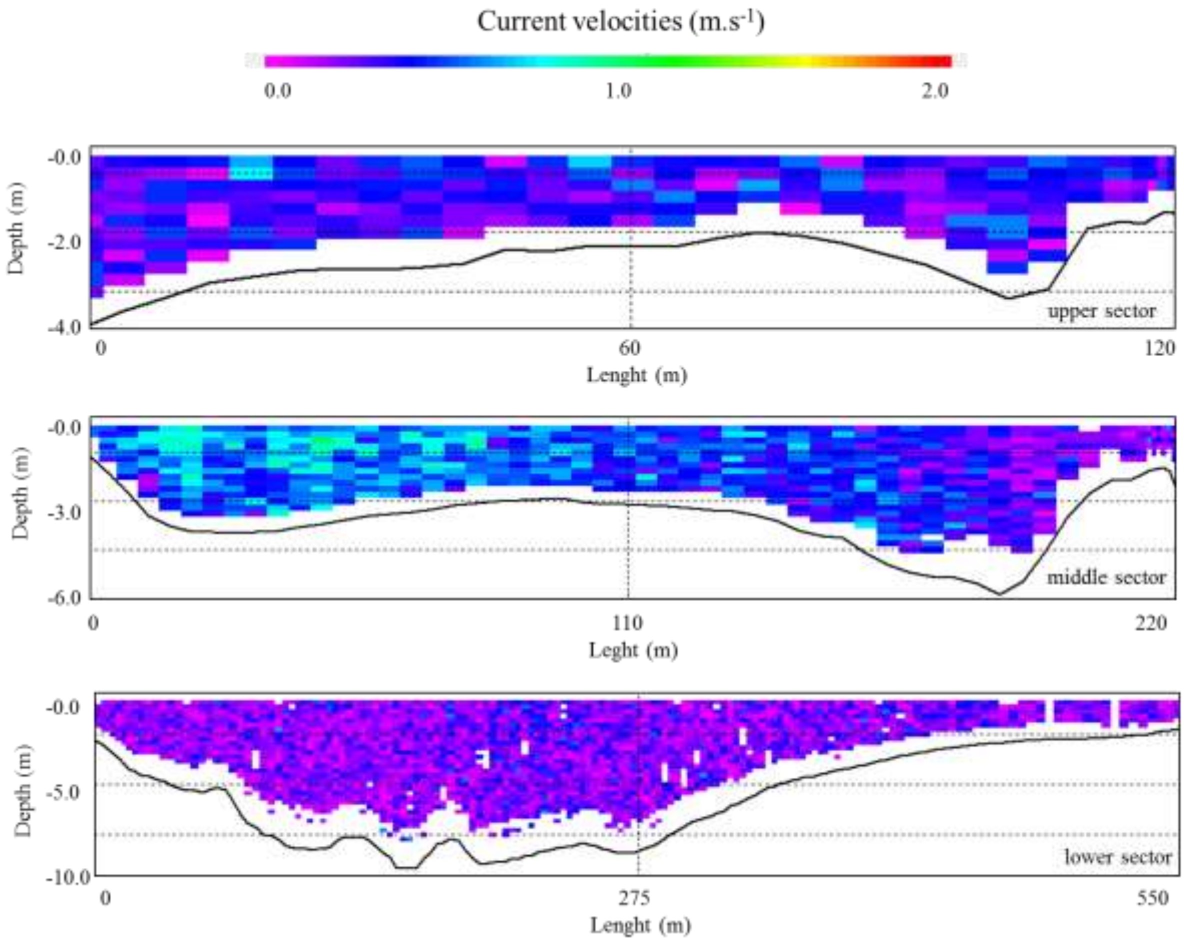

Figure 6.20: Vertical profile of the current velocities in the Caeté estuary.

6.2.3 Hydrology and microbiological aspects

Hydrological data obtained during the neap tide (flood cycle) indicated that there was no significant variation between the surface and the bottom. Given this, the mean of the values recorded from these different strata was used to represent the water column.

Significant seasonal differences were recorded in salinity and pH, with higher values being observed during periods of light or absence of rainfall (salinity: $U = 1479$, $p = 0.00$; pH: $U = 1476$, $p= 0.00$). These variables followed the opposite pattern of rainfall and fluvial discharge with the highest values been recorded during the dry season (salinity of 34.9 and pH of 8.2), in comparison with the wet season (salinity of 22.7 and pH 7.2, Figure 6.21).

While no significant spatial (vertical or longitudinal) variation was found in any of the variable monitored, during period of heavy rainfall (May 2011), when fluvial discharge was higher (mean of 85.9 m^3.s-1), the greatest difference was recorded between the salinity of the surface and bottom, reaching 5.0 in the middle sector and 3.0 in the upper sector, indicating weak mixing and a slight stratification on the water column. In all other months the maximum difference was less than 1.0.

As expected, the lowest salinity (less than 3.0) was recorded in the upper sector, when the lowest tidal prism values were recorded (September 2010, and September and October 2011) and higher fluvial discharge (May 2011). The highest values (> 30.0) were recorded near the mouth of the estuary. A similar pattern was observed in the pH, which was more acid (4.7-6.0) in the upper estuary and alkaline (6.6-8.2) in the middle and lower sectors (Figure 6.21).

Turbidity did not present any systematic seasonal pattern, with peaks being observed in both wet and dry seasons. In the upper sector, a peak was observed during the dry season (September 2010, 277 NTU), a period marked by equinoctial spring tide and high wind speeds (Figure 6.17), which supports the resuspension of sediments. In the middle sector a peak was recorded during period of extreme rainfall (January 2011, 428 NTU) when rainfall level was 66% higher than the historical average (Figure 6.21).

In the upper and middle sectors, turbidity of up to 155 NTU was frequently observed (Figure 6.21). The influence of fluvial process in the upper estuary (where salinity was low) and the strong currents in the middle sector favour the resuspension of the sediments, contributing for the high turbidity recorded in these sectors. The adjacent mangroves and the local macrotides also contribute to the quantity of suspended particles and humic acids in the water, and thus to its turbidity. In addition, effluent discharge in the upper estuary and the algal growth (high chlorophyll *a* concentrations) observed in the middle and upper sectors also constitute an important source of suspended materials within the estuary, further contributing to the high turbidity. In the lower sector, on the other hand, where marine influence predominate, turbidity decreases abruptly, and most recorded values were lower than 65 NTU (Figure 6.21). In this sector, turbidity increased during the periods of equinoctial spring tide (September 2010) and greatest river discharge (January–May 2011).

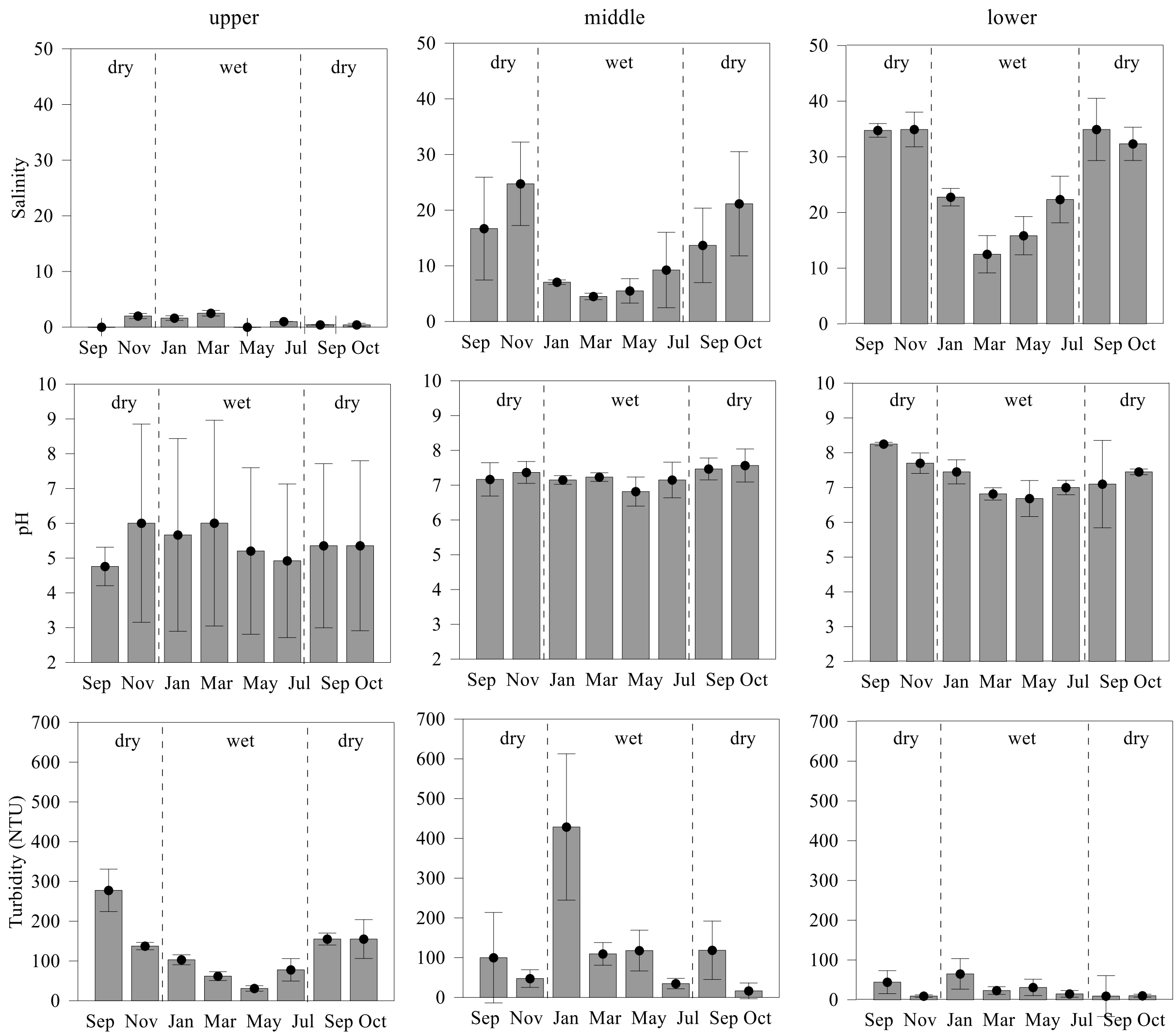

Figure 6.21: Physical and physical-chemical variables in the Caeté estuary between September 2010 and October 2011.

Dissolved oxygen concentrations peaked during the dry season of 2011 (September and October influenced by the equinoctial spring tides), when the values in the upper (6.7 $mg.L^{-1}$) and middle (5.9 $mg.L^{-1}$) sectors were similar to those recorded at the mouth of the estuary. The slight stratification observed in May 2011 contributed to the reduced mixing and oxygenation of the water in all the estuarine sectors (Figure 6.22). In general, the waters of the lower sector were supersaturated (saturation rate > 100%) with concentrations between 4.1 $mg.L^{-1}$ and 7.0 $mg.L^{-1}$ (Figure 6.22). In the other sectors, recorded values were lower than 6.7 $mg.L^{-1}$ (saturation rate ≤ 100%). The weak correlation between chlorophyll *a* and dissolved oxygen concentrations ($R2 \leq 0.01$) indicates that the production of oxygen in the estuary is influenced by additional factors, such as ocean-atmosphere exchange.

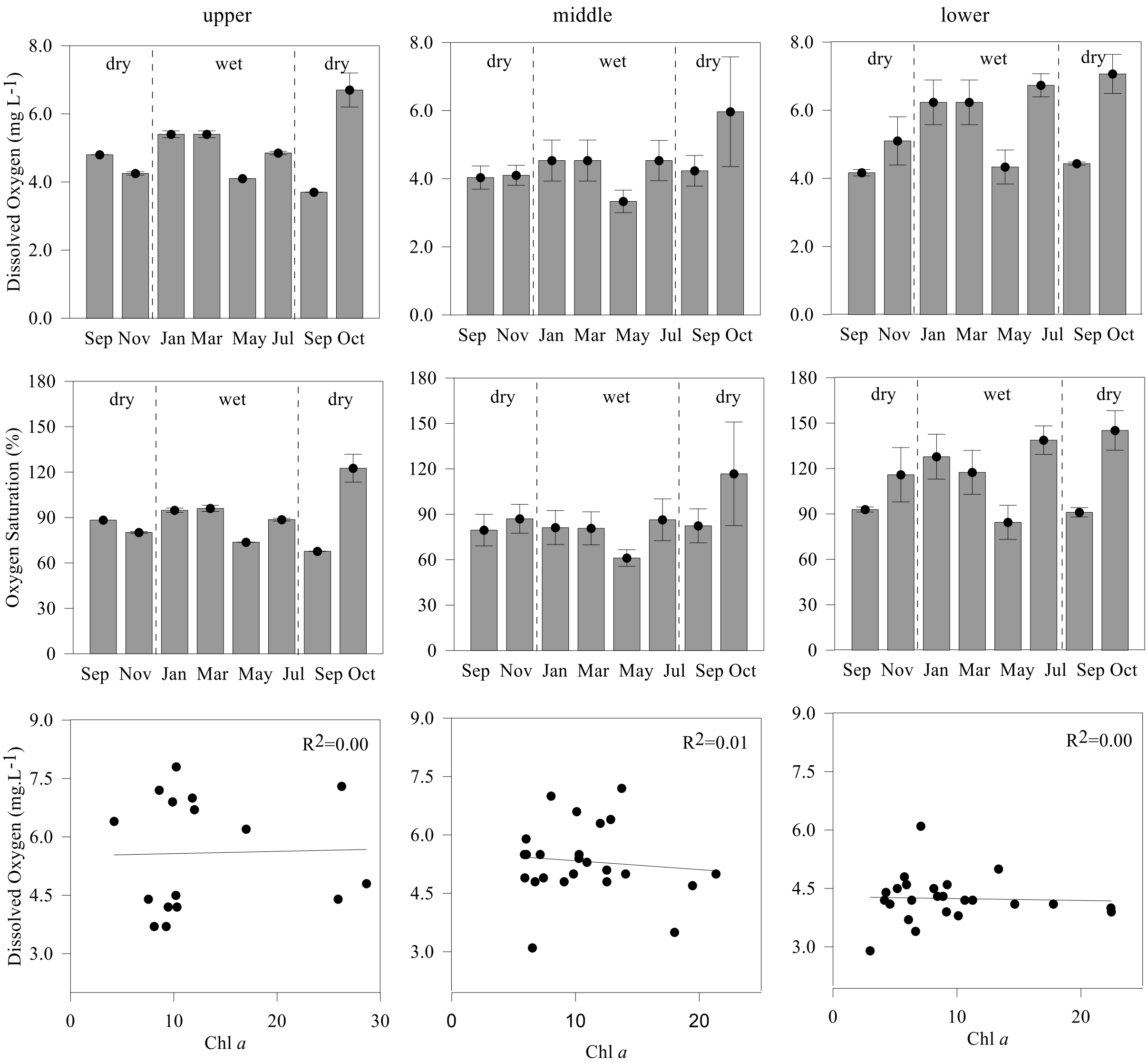

Figure 6.22: Physical and physical-chemical variables in the Caeté estuary between September 2010 and October 2011.

Dissolved nutrient concentrations appeared to be influenced directly by seasonal patterns, although significant seasonal variation was recorded only for phosphate (U = 140, p = 0.00). During periods of extreme and heavy rainfall when mean river discharge was as much as 40 $m^3.s^{-1}$ (January–May 2011), the effective transportation of dissolved nutrients from the upper sector to the mouth of the estuary was observed. Because of this process, dissolved nutrients (except ammonium) decreased in the upper estuary (with maximum values for Nitrite-NO_2^-: 0.3 µm; Nitrate-NO_3^-: 4.4 µm; Ammonium-NH_4^+: 2.8 µm; phosphate-PO_4^-: 0.2 µm, and Silicate-SiO_2: 30.7 µm) and increased in the lower estuary (with maximum values for NO_2^-: 0.8 µm; NO_3^-: 11.4 µm; NH_4^+: 2.7 µm; PO_4^-: 1.1 µm, and SiO_2: 147.3 µm) (Figure 6.23). No well-defined pattern was observed during the dry season, although the highest concentrations of dissolved nutrients were recorded in the middle sector of the estuary (with maximum values for NO_2^-: 4.8 µm; NO_3^-: 18.0 µm; NH_4^+: 4.5 µm; PO_4^-: 1.3 µm, and SiO_2: 234.0 µm), where the tide is amplified, favouring the outwelling of nutrients from the mangroves.

The low concentrations observed in the area of effluent input (upper sector) indicate that dissolved nutrients are not retained in the area where they are released, being transported toward the mouth of the estuary during the neap tide. The lower tidal prism recorded during this phase would favour the transportation of dissolved nutrients down the estuary, resulting in an increase in the concentrations in the middle and lower sectors. The correlation between salinity and dissolved nutrients was not strong ($R^2 \leq 0.71$), thus, there was not possible to observe the filtration capacity of the Caeté estuary (Figure 6.24).

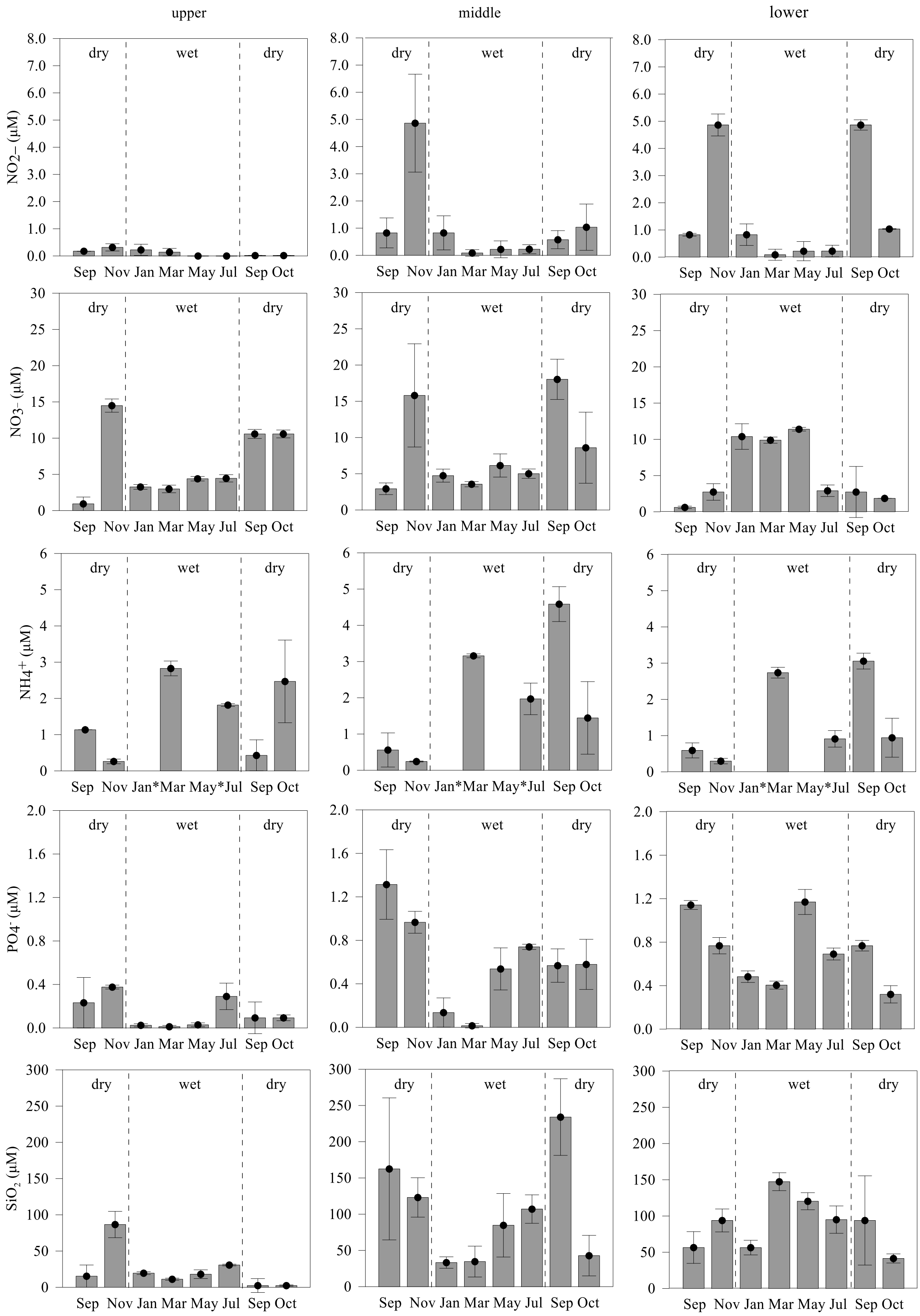

Figure 6.23: Dissolved nutrients in the Caeté estuary between September 2010 and October 2011. (*) Not sampled.

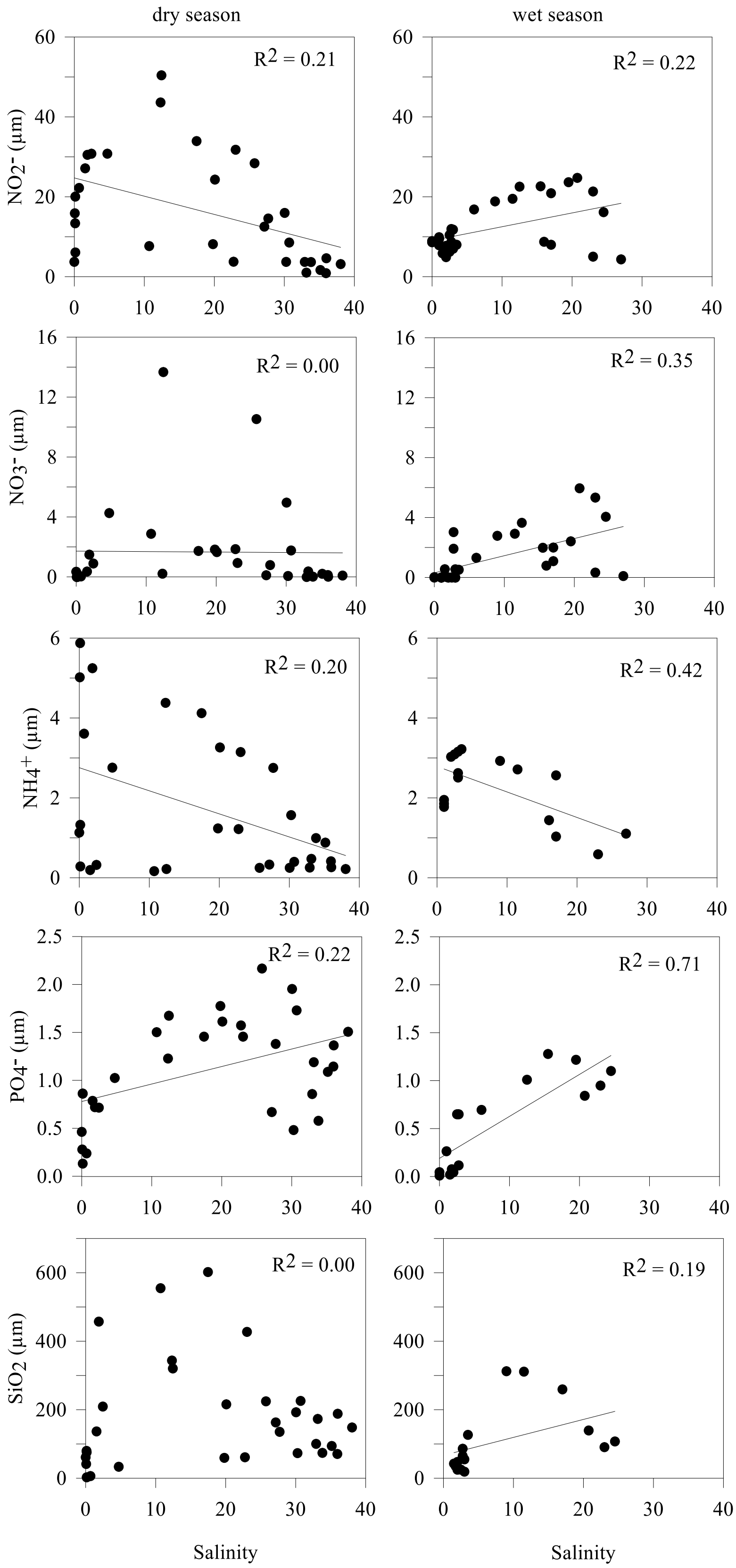

Figure 6.24: Mixing diagrams along the salinity gradient of the Caeté estuary.

During the neap tides, eutrophication was less intense than that observed during spring tides. Karydis index reported a predominance of mesotrophic conditions in the Caeté estuary (Figure 6.25). During the dry season, when the dilution and transportation of nutrients towards the mouth of the estuary are less intense (low fluvial discharge), the trophic conditions deteriorated in the upper and middle sectors of the estuary. In the wet season (high discharge), on the other hand, the more effective transportation of nutrients from the upper sector to the mouth of the estuary resulted in an increase in the trophic status of the lower estuary. According to the TRIX, the water of the Caeté was good and eutrophication medium (Figure 6.25).

The DIN values recorded during the present study indicate the active nitrification of the estuary. The concentrations of the more oxidated forms of nitrogen (nitrate and nitrite) were higher during the dry season, when the estuary's waters were more oxygenated (Figure 6.26). During the period of reduced oxygenation (wet season), however, the concentrations of ammonium (the least oxidated form of nitrogen) increased, corresponding to 50% of the total inorganic nitrogen. Once again, high concentrations of ammonium were recorded in the upper sector, adjacent to the sources of pollution.

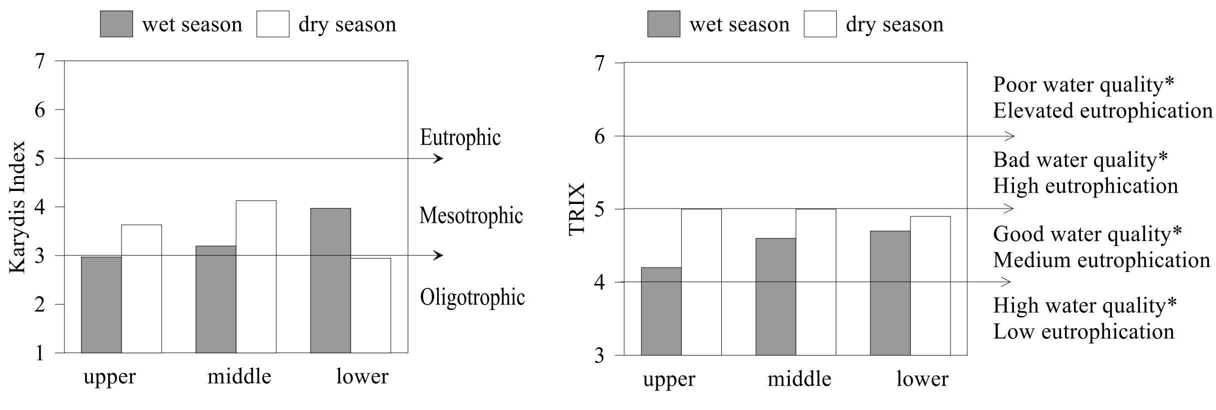

Figure 6.25: Trophic status of the Caeté estuary during the wet and dry seasons. (*) This classification has been discussed in the Chapter 8.

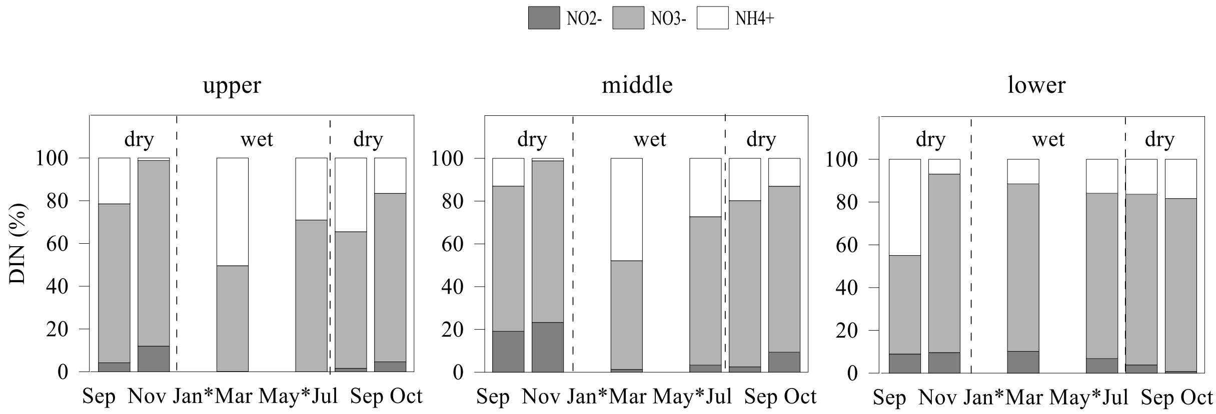

Figure 6.26: Dissolved inorganic nitrogen concentrations in the Caeté estuary between September 2010 and October 2011. (*) Data not collected.

The molar DIN:DIP ratios recorded during the present study indicated an excess of nitrogen only in the upper estuary during almost all months, with values ranging from 15:1 to 133:1 (Figure 6.27). In the middle sectors, the ratios were balanced (except in March 2011), while in the lower estuary, they were low. The DSi:DPI ratio indicated an excess of silica over phosphate in all sector, especially during the period of high fluvial discharge (wet season).

Peaks of chlorophyll *a* were recorded more frequently during the wet season, when the concentrations of nutrients (except ammonium) declined in the upper and middle sectors, indicating that the reduction in the availability of nutrients does no limit phytoplankton growth. In broad terms, the values decrease between the upper estuary (values frequently above 10.0 $mg.m^{-3}$) and the lower sector (values are typically below 10.0 $mg.m^{-3}$) (Figure 6.27).

In addition to dissolved nutrients, rainfall also appears to contribute to the dilution and transportation of faecal coliforms from upper estuary. As result, slight increase in concentrations in the middle and lower sectors of the estuary during the period of increased fluvial discharge, between January 2011 and May 2011 (Figure 6.27). The contamination of the upper sector was consistently high, however, with 90% of the samples returning values of over 1100 MPN/100 ml. As described in Chapter 5, sources of contamination – household and urban effluent outlets, and the fishing fleets – are concentrated in this sector. The best conditions were observed in the lower estuary, where anthropogenic impacts are reduced (Figure 6.27).

The correlation matrix indicated that most of the parameters analyzed (except nitrate) were correlated positively with salinity (Table 6.8), although chlorophyll *a* presented a negative relationship, decreasing during the dry season, when salinity increased. The chlorophyll *a* correlations were also correlated positively with nitrate, which may be assimilated by the phytoplankton, increasing its biomass.

The other correlations observed here (silicate *vs.* ammonium and silicate *vs.* phosphate) may also be accounted for by the increase in the biomass of the phytoplankton (which are made up of frustules that contain silica) during the periods when these nutrients (ammonium and phosphate) are most abundant (Table 6.8).

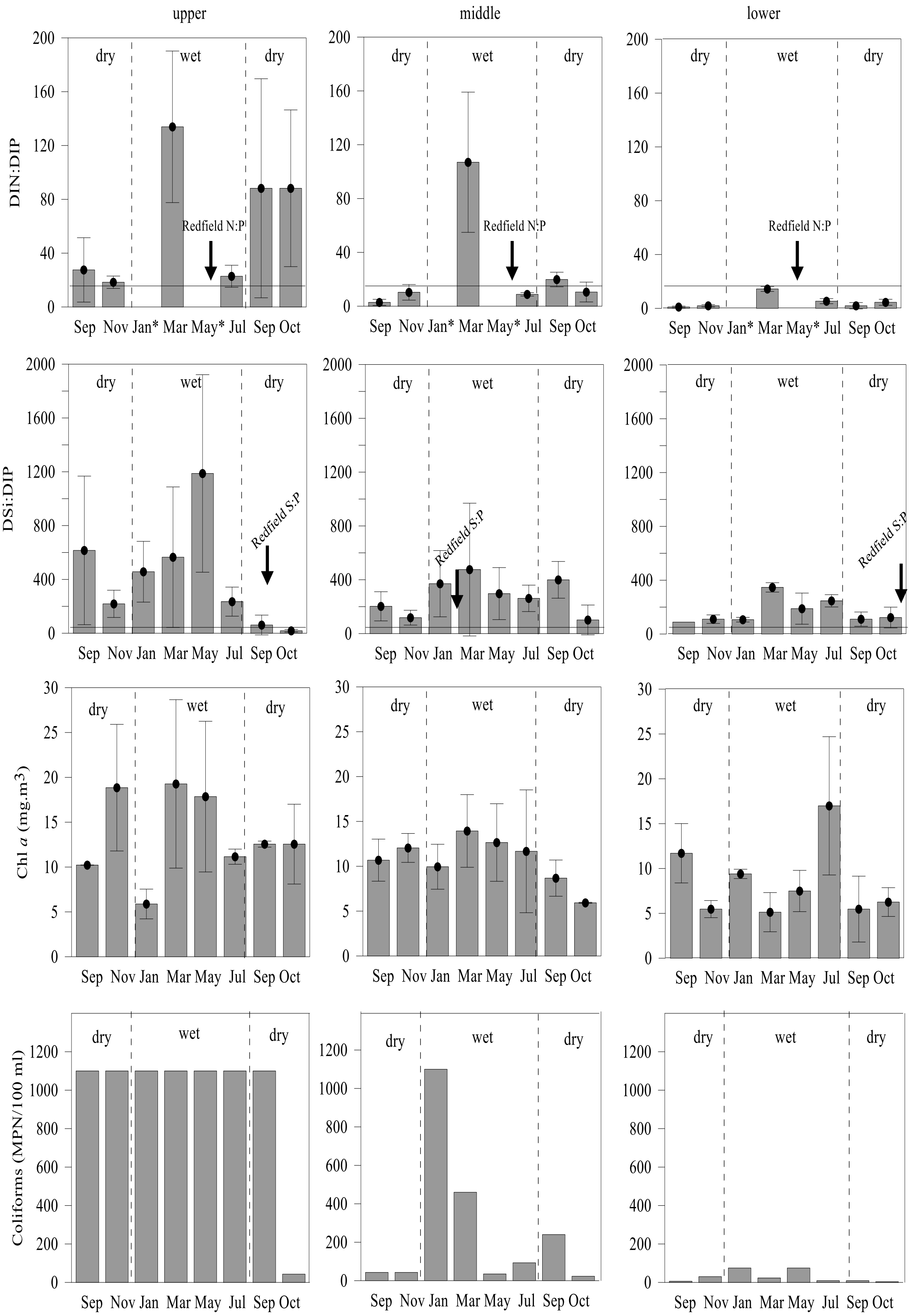

Figure 6.27: Redfield ratios, chlorophyll *a* and faecal coliforms concentrations recorded in the Caeté estuary between September 2010 and October 2011. (*) Not collected.

Table 6.8: Spearman correlation matrix for the variables monitored during the neap tide periods.

	Sal	pH	Nitrite	Nitrate	Ammonium	Phosphate	Silicate
pH	**0.49******						
Nitrite	**0.21***	-0.02					
Nitrate	-0.17	0.02	**0.35*****				
Ammonium	**0.21***	0.17	**0.40*****	**0.52*****	0.51		
Phosphate	**0.58******	**0.29****	**0.57******	0.02	0.37		
Silicate	**0.33*****	0.19	**0.53******	0.04	**0.44******	**0.59******	
Chl *a*	**-0.20***	0.13	-0.09	**0.21***	0.19	-0.12	0.00

Significant correlations in bold

Significance level * = p < 0,05; ** = p < 0,001; *** = p < 0,0001; **** = p < 0,00001

6.3 Comparative analysis between phase I and phase II

This comparative analysis encompasses the hydrological data obtained during the flood tide cycle in the oceanographic campaigns of phases I (spring tides) and II (neap tides).

The lowest rainfall rates were recorded in phase I (2006-2007) when the rainfall rate recorded in the dry season was only 40% of that recorded during the same period in 2010, and only 18% of the total rainfall recorded during the wet and dry seasons of 2011. However, wind speeds (10% increase in the occurrence of winds of 8.0 m s^{-1}), current velocities (peaks twice as high) and the tidal prism (40% greater) were all more pronounced during phase I.

The increase in the tidal prism observed during phase I favoured the intrusion of saline waters into the estuary, causing an increase in salinity and pH in this phase. The reduced rainfall, and consequently, the lower discharge of the Caeté, may also have favoured this process. In both phases, in fact, peaks in salinity and pH were recorded during periods with low or absence of rainfall, when the discharge of the Caeté was reduced (Figure 6.28). Dissolved oxygen also peaked during phase I, coinciding with the greater wind and current velocities observed during this period, although no clear seasonal pattern was recorded (Figure 6.28).

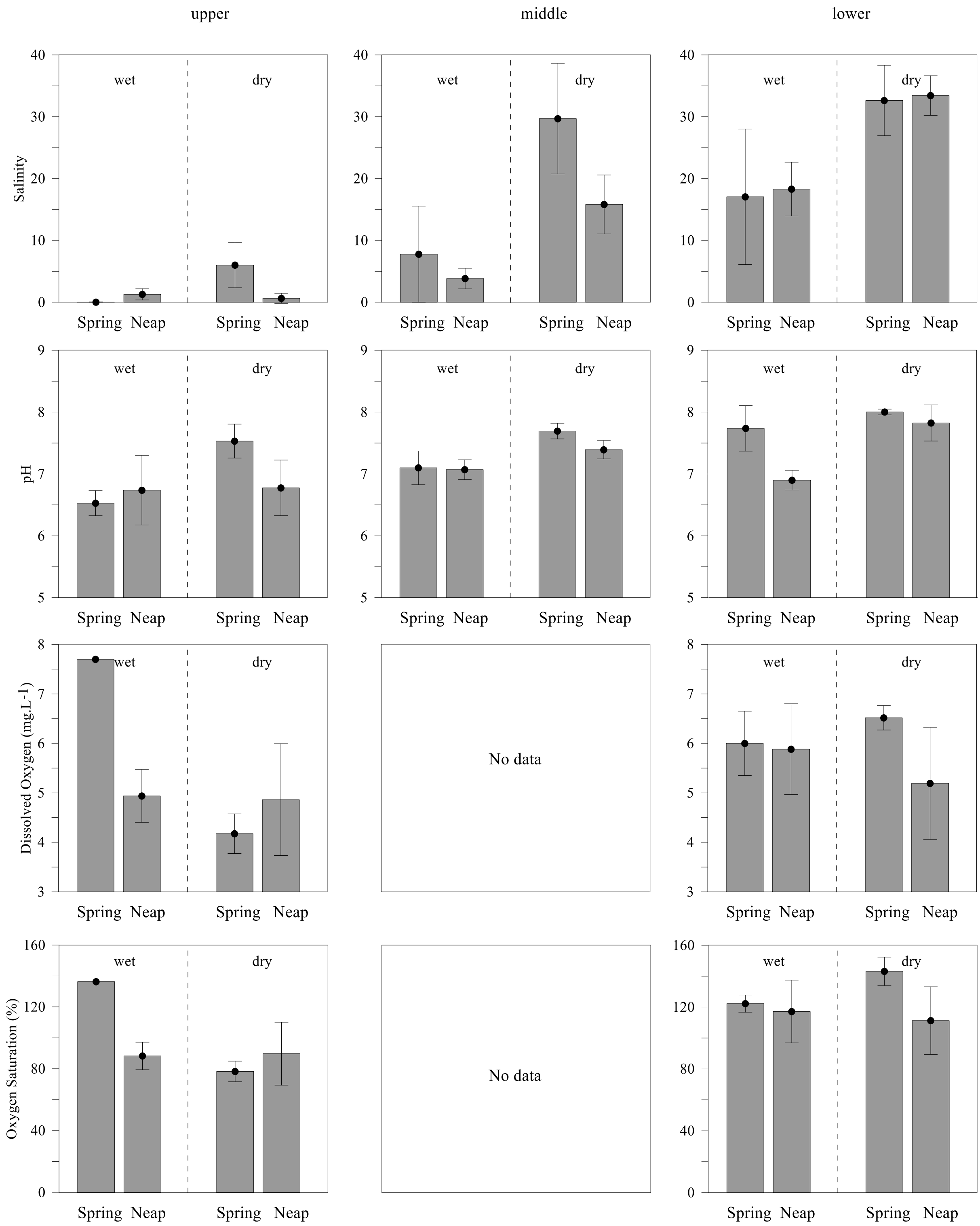

Figure 6.28: Physical and physical-chemical variables in the Caeté estuary during spring and neap tides.

High concentrations of dissolved nutrients were recorded during both phases, indicating a highly productive environment. There was an increase in these concentrations during the dry season in the upper and middle sectors. During the phase II the concentrations of nitrogenous nutrients (nitrate and ammonium) and silicate were higher. The decrease in the tidal prism and the lower current velocities recorded during this phase may have favoured the accumulation these dissolved nutrients (Figure 6.29).

Phosphate was the only nutrient that varied significantly between phases, with higher concentrations being recorded during spring tides ($F = 8.88$, $p = 0.05$ This reflects the contribution of marine waters which act as a phosphate source for the estuary, as showed by the salinity *vs.* phosphate diagram (Figure 6.11) and would account for the higher concentrations recorded in the upper and middle sectors during the dry season, when the marine intrusion increases (Figure 6.29). In addition, the predominantly alkaline conditions ($pH > 7.0$) recorded during the spring tides favour the release of the phosphorus absorbed by the sediments into the water column.

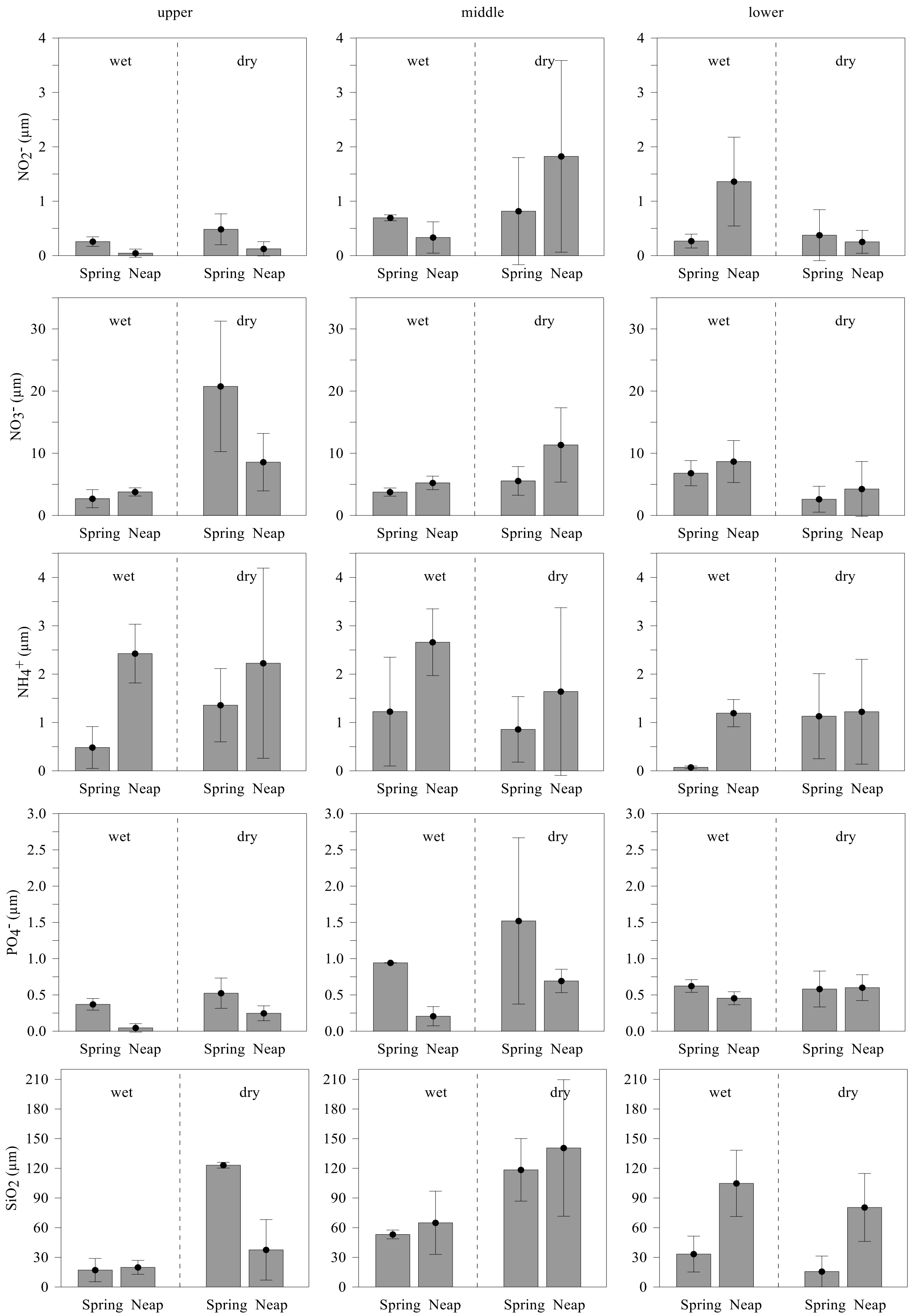

Figure 6.29: Dissolved nutrient concentrations recorded in the Caeté estuary during spring and neap tides.

In general terms, the trophic indices did not vary systematically between spring and neap tide periods. Only the Karydis index indicated a marked increase in eutrophication in the upper estuary during the dry season (Figure 6.30). In the other sectors, the estuary was mesotrophic to oligotrophic. The upper and middle sectors presented more intense trophic conditions (meso and eutrophic) during the dry season, when nutrient transportation towards the coast is reduced. In the lower sector when nutrient transportation was reduced, oligotrophic conditions were observed, and during the wet season, when the fluvial discharge increases, the trophic state become mesotrophic.

The TRIX index reflected similar seasonal and spatial patterns within the estuary, with a predominance of bad water quality and high eutrophication during phases I and II, although slightly better conditions were observed during the neap tides of the wet season (Figure 6.30). This index, based on the concentrations of nitrogen, phosphate, and saturated oxygen, reflects the pattern observed previously for these variables.

In both phase the dissolved inorganic nitrogen (DIN) was constituted primarily of nitrate, followed by ammonium (Figure 6.31). The relative scarcity of nitrite (unstable form of inorganic nitrogenous) indicates that nitrification and denitrification were occurring during flood phase in both monitored phases.

The DIN:DIP ratios indicated a deficit of nitrogen during the spring tides in all sectors of the estuary, whereas an excess of nitrogen was observed in the middle and upper sectors in the neap tides during the wet season (Figure 6.32). An excess of silicate was recorded in all both phases in all sectors throughout the study period. Again, an excess was observed during neap tides, mainly in the wet season (Figure 6.32).

In general, the chlorophyll *a* concentrations were highest during the neap tides (except for the middle sector during the dry season and the lower sector during the wet season), coinciding with the period when ammonium was most available for assimilation by the phytoplankton. During the spring tides, the increased intrusion of marine waters, generally characterized by lower productivity, may have contributed to the lower values recorded (Figure 6.32).

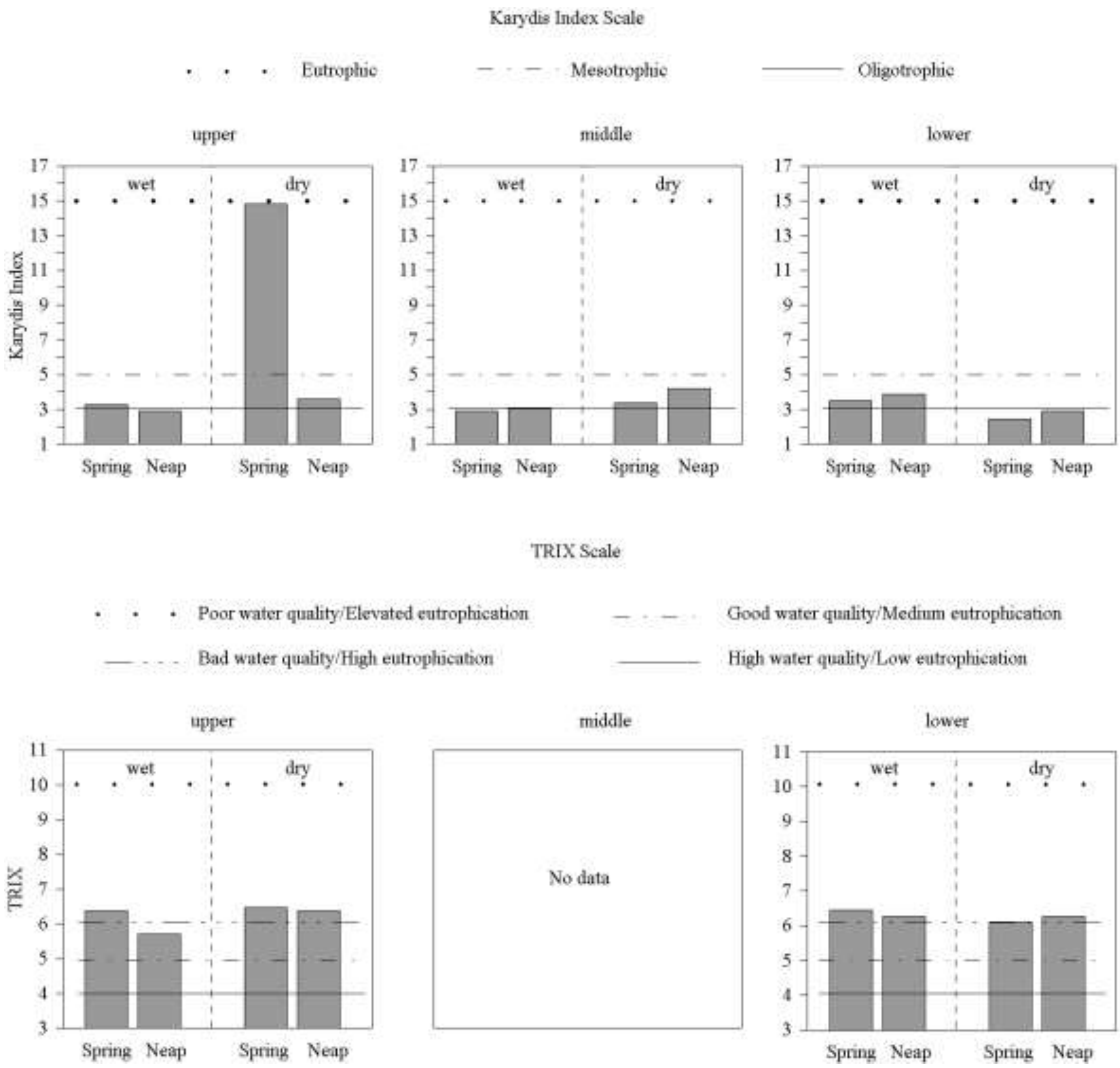

Figure 6.30: Trophic status of the Caeté estuary during spring and neap tides. (*) This classification has been discussed in the Chapter 8.

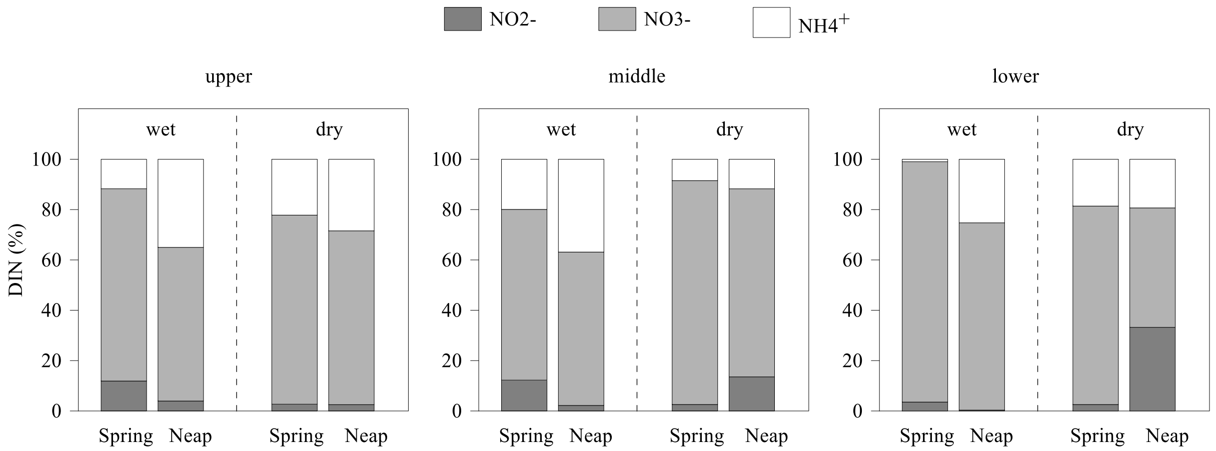

Figure 6.31: Dissolved inorganic nitrogen concentrations in the Caeté estuary during spring and neap tides.

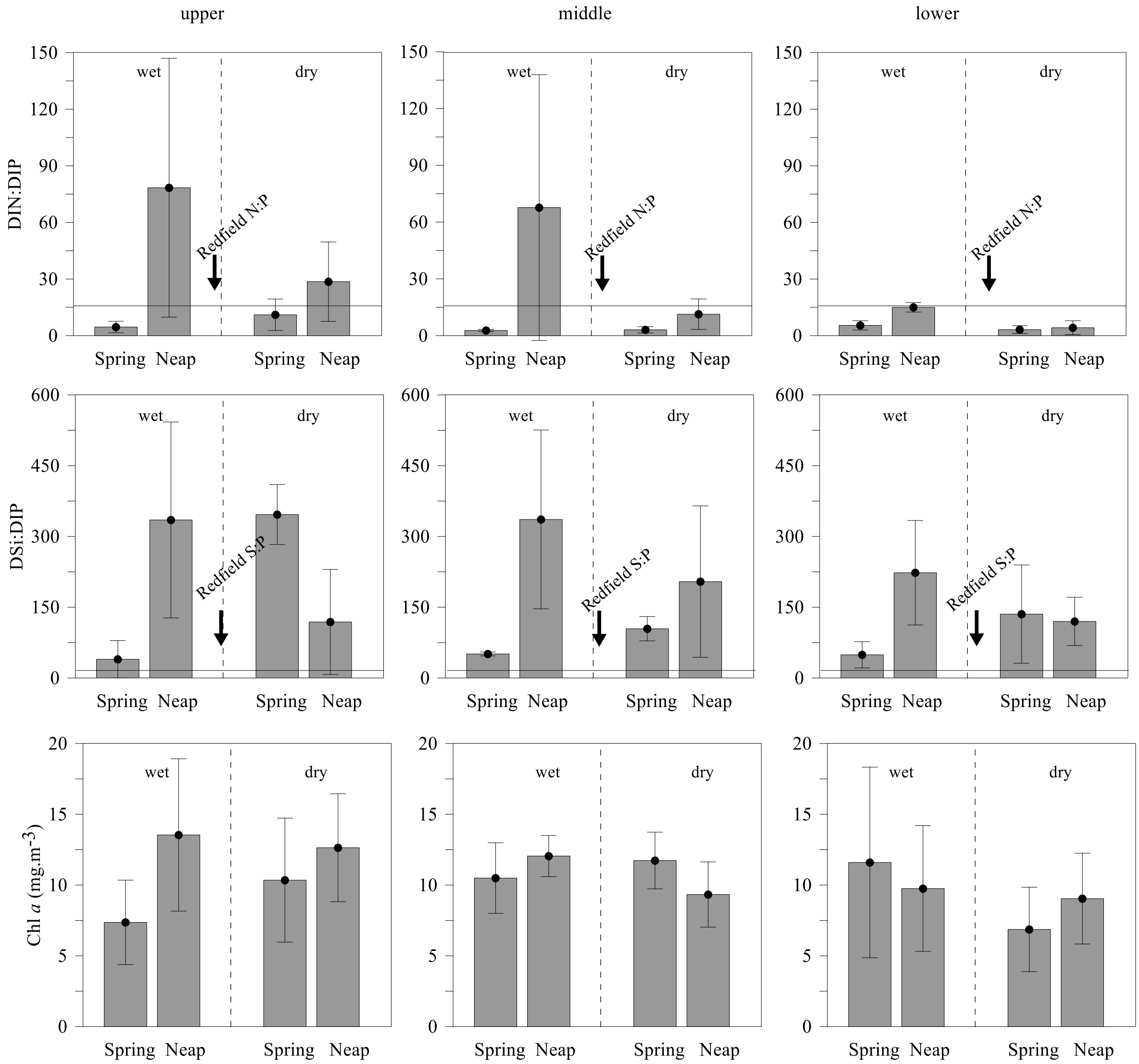

Figure 6.32: Redfield ratios and chlorophyll *a* concentrations in the Caeté estuary.

The faecal coliform concentrations were highest during the neap tides, principally in the upper and middle sectors, which are more affected by anthropogenic impacts (Figure 6.33). During this phase, the lower salinity of the estuary may favor the survival of the coliforms, although no marked seasonal pattern was observed.

From this comparative analysis, it is possible to affirm that the increase of the tide and, consequently, a greater marine intrusion registered during phase I support the increase of salinity, pH and phosphate. The lower level of rainfall registered in this phase also contributed to the increase in salinity and pH, while higher winds and currents velocities supported highest levels of oxygen. Other monitored variables such as nitrate, ammonium and chlorophyll *a* decrease in this phase, due to the dilution from marine waters. Faecal coliforms also decrease in this phase, probably due to low tolerance to high salinity.

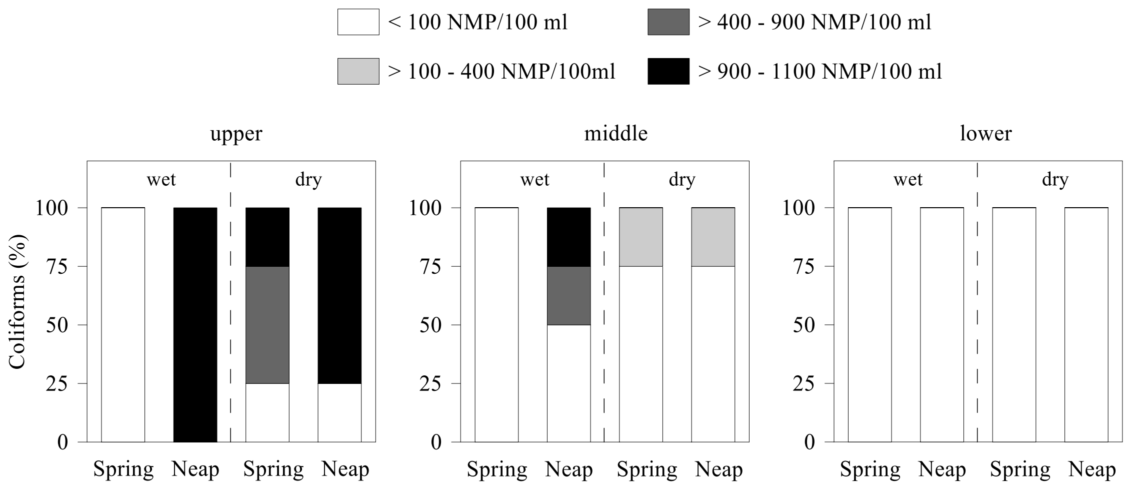

Figure 6.33:Coliform concentrations recorded in the Caeté estuary.

CHAPTER 7

FUTURE SCENARIOS FOR THE CAETÉ ESTUARY

In this section, the potential future scenarios for the Caeté estuary are described, based on the anthropogenic and natural processes, which may contribute to the quality of the water of this estuary. To main scenarios are considered: the first one is related to the evolution of population in the area and consequent increase in the production of sewage. The second scenario, considered the occurrence of climatic events such as droughts related to variations in the sea surface temperature (SST) in the tropical Pacific (El Niño-Southern Oscillation - ENSO), and in the tropical Atlantic (Northern Atlantic Oscilation - NAO and Atlantic Multidecadal Oscilation - AMO), or a combination of both processes, all of which may result in a decrease in local precipitation rates and consequently in river discharge.

7.1 Population projections and effluent production up until 2050

According to the IBGE (2015) and Guimarães et al. (2009) surrounding the Caeté estuary has a population of 80,800 inhabitants, which 90% live in the Bragança city, in the margin of either the Caeté estuary (in the Centro, Aldeia and Riozinho neighbourhoods), or the Cereja River (Taíra, Cereja, Padre Luiz I and II, and Vila Sinhá neighbourhoods). In addition, other smaller communities (Maranhaozinho, Fazendinha, Camutá, Vila q Era, Bacuriteua, Caratateua, Vila dos Pescadores and Urumajó) located in the middle and lower sectors have approximately 8,259 inhabitants (Guimarães et al., 2009; IBGE, 2015).

In the Brazilian state of Pará – where the Caeté estuary is located – the mean population growth rate is 10% per decade, while in the town of Bragança, it is 20% (IBGE, 2015). Considering the mean growth rate of Pará, the population of the Caeté estuary will reach 118,416 inhabitants by 2050, although if the population continues to grow at the current rate of Bragança, it will reach 167,712 inhabitants by 2050 (Figure 7.1).

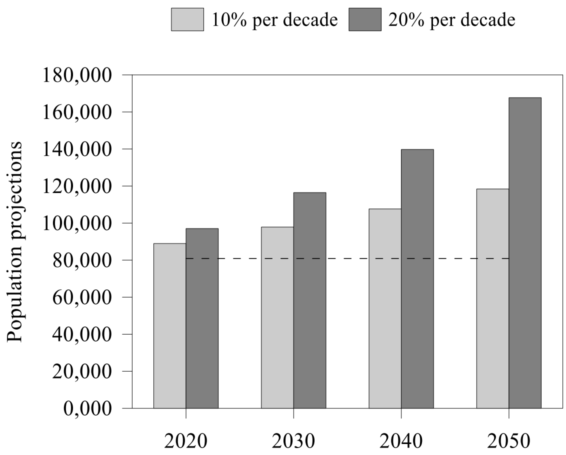

Figure 7.1: Estimated population growth in the area of the Caeté estuary from 2020 to 2050. The dashed line indicates the population in 2010.

To predict the impacts of this growth process, it was assumed that each inhabitant produces at least 150 l of effluents per day, which contain 1.0 g of nitrate, 4.5 g of ammonium, 1.7 g of phosphate and a minimum of 100 billion faecal coliforms (ABNT, 1982; Von Sperling, 2007). From this, the total amount of effluents produced by the local population, taking into account a population growth of 10 and 20% per decade in the region, will increase to 17,762 m^3 or 25,156 m^3, respectively, per day by 2050. Of this total, 90% is produced at the most urbanized area (upper sector), which releases about half of the total effluents discharged into the Caeté and Cereja rivers. As described in the Chapter 5, the middle and lower sectors are characterised by low population density with a total population of 7,672 and 587 respectively (Guimarães et al., 2009; IBGE, 2015).

Tables 7.1, 7.2, 7.3 and 7.4 show the total amount of dissolved nutrients and fecal coliforms produced and/or released in all three sectors. In the upper sector, it is estimated that half of the effluents produced (corresponding to the neighbourhoods on the margins of the Cereja and Caeté rivers) reach the estuary. In all the sectors, it was assumed that the total amount of effluents produced by the communities reaches the estuary, considering that it is the major body of water draining most of the settlements.

Assuming that current pattern of waste treatment and the climatic and physical features of the estuary are maintained (tidal currents favouring the transportation of effluents and strong tidal prism favouring the renewal of the estuary’s waters), and that management measures are not implemented, future impacts on the Caeté estuary will be conditioned primarily by settlement patterns. If, for example, the current spatial pattern of settlement persists in the future, with 90% of the population settling in the upper estuary, the negative impacts of effluent discharge will continue to predominate in the upper estuary, especially if urban development expands into areas that are currently unoccupied on the margins of the Cereja and Caeté rivers. In this case, it seems likely that the high concentrations dissolved nutrients and high trophic levels recorded in the present study (Chapter 6) will continue to prevail in the upper sector.

In order to mitigate the impacts from population growth on the Caeté estuary, management measures can be adopted. In the Caeté estuary, one important measure that would help mitigate the effect of contamination by sewage is the construction of an efficient sewage treatment plant that would minimise the direct discharge of untreated sewage into the estuary. With effective treatment of domestic effluents, the total amount of dissolved nutrients and faecal coliforms released into the Caeté estuary could be reduced considerably by 2050, whatever the growth of the local population over the intervening period (i.e., 10% or 20%). In addition to a sewage treatment plant, other approaches (e.g., overland-flow or evapotranspiration systems) could be used to reduce impacts, principally in the communities along the middle and lower estuary, where population density is considerably lower.

Overall, this scenario indicates that over the coming decades, the amount of effluents produced by the communities located along the margins of the Caeté estuary will tend to increase, resulting in the discharge of increasing amounts of sewage into the estuary. In addition to population growth in itself, settlement patterns in each sector of the estuary will influence overall patterns of impact. It is important to note, however, that this impact may be reduced considerably through the installation of sewage treatment plants appropriate to the reality of each local community.

Table 7.1: Total amount of effluents, dissolved nutrients, and faecal coliforms produced by the total population of the upper Caeté estuary from 2020 to 2050 based on a population growth rate of 10%.

	Effluents ($m^3.day^{-1}$)		**Nitrate ($ton.day^{-1}$)**		**Ammonium ($ton.day^{-1}$)**		**Phosphate ($ton.day^{-1}$)**		**Min Coliform (day)**	
	produced	released	produced	released	produced	released	produced	released	produced	released
2020	11,98	5,99	0,008	0,004	0,359	0,180	0,136	0,068	8,0E+13	4,0E+10
2030	13,18	6,59	0,009	0,004	0,395	0,198	0,149	0,075	8,8E+13	4,4E+10
2040	14,50	7,25	0,010	0,005	0,435	0,217	0,164	0,082	9,7E+13	4,8E+10
2050	15,95	7,97	0,011	0,005	0,478	0,239	0,181	0,090	1,1E+14	5,3E+10

Table 7.2. Total amount of effluents, dissolved nutrients, and faecal coliforms produced by the total population of the upper Caeté estuary from 2020 to 2050 based on a population growth rate of 20%.

	Effluents ($m^3.day^{-1}$)		**Nitrate ($ton.day^{-1}$)**		**Ammonium ($ton.day^{-1}$)**		**Phosphate ($ton.day^{-1}$)**		**Min Coliform (day)**	
	produced	released	produced	released	produced	released	produced	released	produced	released
2020	13,07	6,54	0,009	0,004	0,392	0,196	0,148	0,074	8,7E+13	4,4E+10
2030	15,69	7,84	0,010	0,005	0,471	0,235	0,178	0,089	1,0E+14	5,2E+10
2040	18,82	9,41	0,013	0,006	0,565	0,282	0,213	0,107	1,3E+14	6,3E+10
2050	22,59	11,29	0,015	0,008	0,678	0,339	0,256	0,128	1,5E+14	7,5E+10

Table 7.3: Total of effluents, dissolved nutrients, and faecal coliforms produced by the total population in the middle and lower sectors of the Caeté estuary, and the values projected for future decades, based on a population growth rate of 10%.

	Effluents ($m^3.day^{-1}$)		**Nitrate ($ton.day^{-1}$)**		**Ammonium ($ton.day^{-1}$)**		**Phosphate ($ton.day^{-1}$)**		**Min Coliform (day)**	
	produced	released	produced	released	produced	released	produced	released	produced	released
2020	1,31	0,66	0,0009	0,0004	0,039	0,020	0,015	0,007	9,0E+12	4,5E+12
2030	1,45	0,72	0,0010	0,0005	0,043	0,022	0,016	0,008	9,9E+12	5,0E+12
2040	1,59	0,80	0,0011	0,0005	0,048	0,024	0,018	0,009	1,0E+13	5,5E+12
2050	1,75	0,87	0,0012	0,0006	0,052	0,026	0,020	0,010	1,2E+13	6,0E+12

Table 7.4: Total of effluents, dissolved nutrients, and faecal coliforms produced by the total population in the middle and lower sectors of the Caeté estuary, and the values projected for future decades, based on a population growth rate of 20%.

	Effluents ($m^3.day^{-1}$)		**Nitrate ($ton.day^{-1}$)**		**Ammonium ($ton.day^{-1}$)**		**Phosphate ($ton.day^{-1}$)**		**Min Coliform (day)**	
	produced	released	produced	released	produced	released	produced	released	produced	released
2020	1,43	0,72	0,0010	0,0005	0,043	0,022	0,016	0,008	9,9E+12	4,9E+12
2030	1,72	0,86	0,0011	0,0006	0,052	0,026	0,019	0,010	1,1E+13	5,9E+12
2040	2,06	1,03	0,0014	0,0007	0,062	0,031	0,023	0,012	1,46E+13	7,1E+12
2050	2,48	1,24	0,0017	0,0008	0,074	0,037	0,028	0,014	1,7E+13	8,5E+12

7.2 Effects of climatic events

Considering that rainfall is the principal source of freshwater for the Caeté River, during intense drought events the discharge of the river will be significantly affected. These events may occur due to an increase in the SST in the Pacific (El Niño) and Atlantic oceans (NAO or AMO). This favours the subsidence of the air masses over the Amazon basin and may result in negative rainfall anomalies (see Chapter 3).

Independently of the exact trigger mechanism (El Niño, NAO or AMO), drought events provoke a reduction in rainfall rates in the Bragança region. An analysis of the long-term rainfall data for the Bragança region (1974–2011, except for 1981, 1983 and 1989) indicates that, during drought events, rainfall rates may be as much as 40% lower than during “normal” years. Figure 7.2 shows that the rainfall anomalies caused by drought events are more pronounced during the wet season when rainfall typically exceeds 200 mm per quarter. The opposite pattern is recorded during the dry season, when the effects of drought events tend to be less pronounced. It is important to note that the relationship between drought events and rainfall rates may vary considerably, given that the intensity and duration of these events in a given year will determine rainfall patterns.

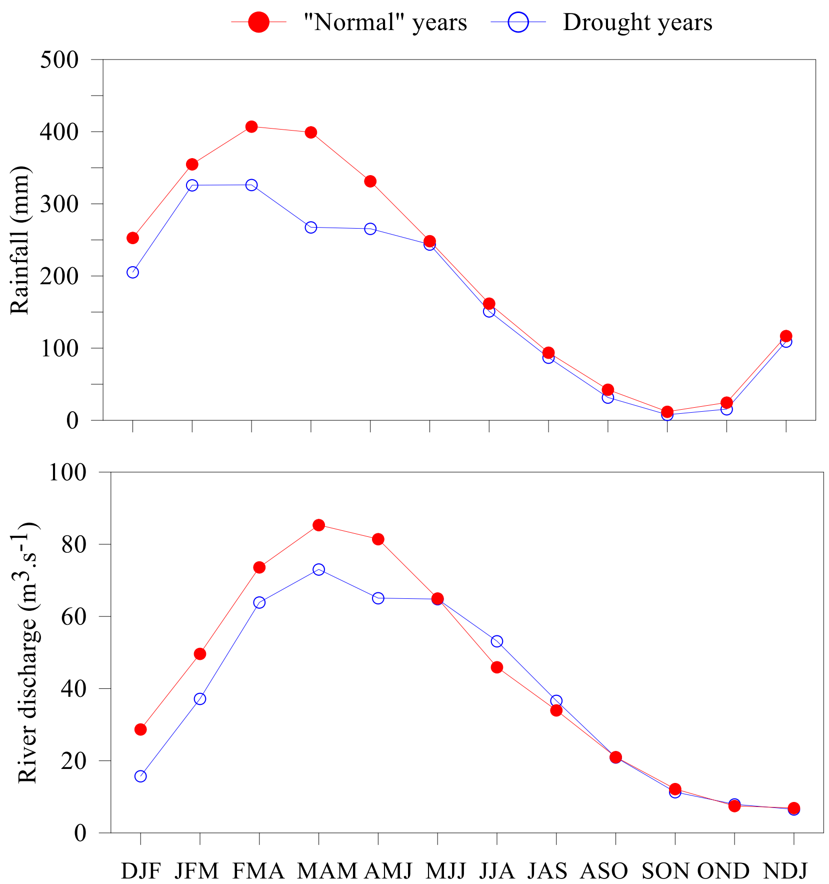

Figure 7.2: Mean rainfall recorded per quarter (3 months) during normal and drought years for the period between 1974 and 2011 (except for 1981, 1983 and 1989).

As described in the Chapter 6, the results obtained in this study have shown that a reduction in rainfall rate may to decrease the fluvial discharge on the Caeté estuary. The effects of reduced fluvial discharge may include:

> *(i) Reduced transportation of dissolved nutrients*: during “normal” years in the Caeté estuary, dissolved nutrient concentrations and associated eutrophication follow seasonal patterns. During the wet season, when fluvial discharge increases, these parameters tend to decrease in the upper estuary, but increase in the lower estuary. As discussed in Chapter 6, this reflects the increase in the velocity of the ebb currents (to around 1.0 $m.s^{-1}$), which favours the transportation of contaminants from the upper to the lower estuary (a displacement of around 41 km, see Chapter 6, Figure 6.6). During dry season, by contrast, when fluvial discharge is reduced, ebb current velocities decrease

(usually < 1.0 m.s^{-1}), and the transportation of effluents released into the upper sector of the estuary to its lower reaches is greatly reduced (maximum displacement of around 25 km). The dissolved nutrients tend to be retained in the upper sector, leading to an increase in eutrophication. In this case, during drought events, the reduced in the fluvial discharge could to affect the transportation of effluents from the upper to the lower estuary, which lead to eutrophication of waters. On the other hand, the reduction of eutrophication observed in the upper sector during the wet season in "normal" years (Chapter 6, Figure 6.12 and 6.25) may be greatly reduced or absent during drought events.

(ii) Reduced dilution of dissolved nutrients: the concentrations of dissolved nutrients recorded in the upper sector during periods of high fluvial discharge decreased, such as observed during wet season of 2006. During the dry season, by contrast, when fluvial discharge decrease, dissolved nutrient concentrations tend to increase (Figure 7.3). Given this, the flow of freshwater is considered to be an important mechanism for the dilution of the effluents released into the estuary. Thus, the reduction in fluvial discharge recorded during drought events may greatly reduce the capacity of the freshwater to dilute the effluents discharged into the upper estuary, contributing to the eutrophication of this sector, similar to that observed in the dry season of "normal" years (Chapter 6).

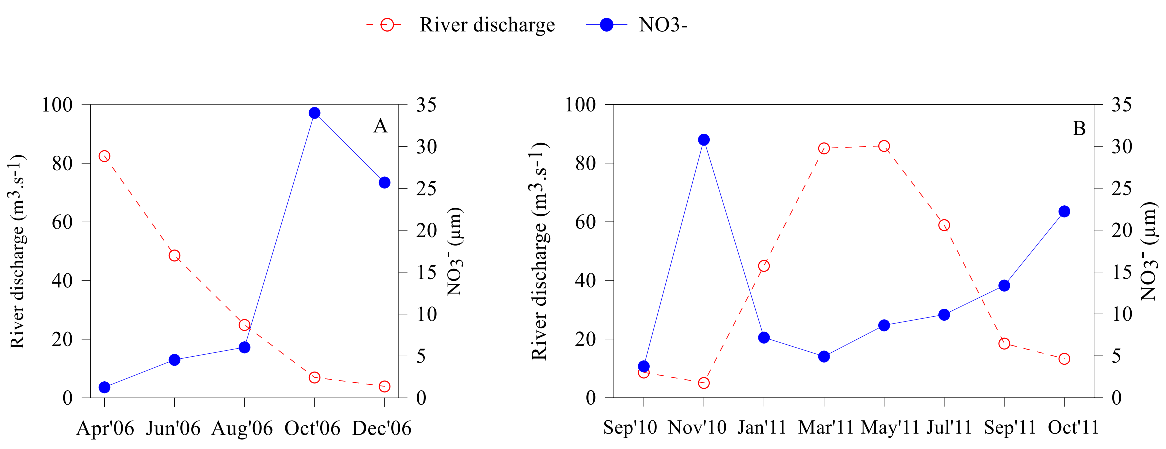

Figure 7.3: The relationship between river discharge and nitrate concentrations observed during monitoring phases I (A) and II (B).

(iii) Increase of dissolved nutrient input from mangrove outwelling: the reduced fluvial discharge recorded during the dry season may favour the incursion of tide into the estuary. The increase of tidal range support the flooding of mangrove area, mainly during equinoctial spring tides. This contributing to the mangrove outwelling and may result in a further increase in the concentrations of dissolved nutrients into the water column as observed in phase II in the middle estuarine sector (Chapter 6). The same could be occur during drought events due to the reduced fluvial discharge.

Overall, then, drought events may act as an important regulator of water quality in the Caeté estuary, with negative consequences for the quality of the estuarine waters through an increase in their trophic status and bacteriological contamination. The poor conditions observed during dry season in the upper estuary may also arise during the wet season, when the effects of drought events may be more pronounced.

DISCUSSION

AND CONCLUSIONS

CHAPTER 8

DISCUSSION AND CONCLUSIONS

In this chapter, the results presented in the preceding chapters are discussed in the context of regional and global patterns, based on the systematic revision of the literature consulted during the compilation of this thesis. To conclude, the principal findings of the study are compiled and summarized to provide a succinct overview of the results.

8.1 Discussion

Estuaries are highly complex and dynamic ecosystems, whose physical and chemical processes are influenced primarily by freshwater runoff and adjacent marine waters (Duarte et al., 2001; Potter et al., 2010). In the Amazon region, this dynamic is accentuated by annual precipitation of over 2000 mm – which is typical of only 7% of the world's surface (Corlett and Primark, 2011) – and a macrotidal regime, which determines the characteristics of the interaction between the river and the sea.

In the Caeté estuary, the peak fluvial discharge, which occurred during the wet season (up to 103 $m^3.s^{-1}$), resulted in negligible salinity and low pH values. The peak in salinity in the upper estuary recorded during the wet season (March, 2011, neap tide) was probably due to the water reaching the salt crystals that form in the area surrounding the upper estuary, where salinity may reach values of 50–100 (Cohen and Lara, 2003). In the other sectors, the marine intrusion is the principal factor determining the increase in salinity and pH of the estuary waters, principally during the dry season, when the fluvial discharge decreases, to less than 50 $m^3.s^{-1}$.

The formation of a halocline in the water column (May 2011) resulted in a weak stratification of the waters of the middle estuary. Weakly stratified estuaries are associated with string tidal currents, which enhance vertical diffusion (Boer et al., 2006). The Caeté estuary and its smaller creeks are known to be a well-mixed environment (Cohen et al., 1999; Cavalcante et al., 2013). However, the reduction in current flow observed on the slack tide during periods of high fluvial discharge and reduced tidal intrusion resulted in a weak vertical stratification (Cavalcante et al., 2013).

The intensification of tidal forcing leads to an increase in vertical turbulence, which breaks down the stratification of the water. In many estuaries in Europe, North America, and Oceania, local macrotidal regimes provoke the turbulent mixing of waters and advection through tidal incursion (Uncles et al., 2002; Audry et al., 2007). In the Caeté estuary, turbulent mixing and strong currents (up to 2.0 m/s) support the resuspension of the fine particles from the bottom into the water column. In addition, increasing rainfall levels and the resulting freshwater runoff also support an increase in turbidity in macrotidal estuaries (Uncles et al., 1992), such as those data recorded in January 2011 at the Caeté estuary.

The high dissolved oxygen concentrations recorded in the lower estuary contrasted with the low chlorophyll *a* values registered in this sector. This indicates that photosynthetic activity was not the primary source of the oxygen in these waters. In this estuary, the wind speed and turbulence may be the principal driving of gas exchange, as observed in other aquatic environments around the world (Alli et al., 2011; Ho et al., 2011) as well as in the Amazon region (Sousa et al., 2009; Pereira et al., 2012).

In May 2011, weaker mixing (reduced stratification) resulted in lower oxygen concentrations in the estuary, similar to those observed by Lin et al. (2008) and Wetz et al. (2011) in estuaries in the United States. Shivaprasad et al. (2013) found that the stratification induced by the discharge of freshwater determined the depletion of oxygen in the bottom layer. When stratification persists, there is an increasing probability of a shift from hypoxic to anoxic condition in the intruding frontal system.

In general, the input of nutrients into estuaries peaks during the period of maximum fluvial discharge, as observed in the Nile, Patxunt, Cochin and Neuse estuaries (Paerl et al., 2002; Nixon et al., 2003; Qasim et al., 2003; Boynton et al., 2008; Wetz et al., 2011). This is because large amounts of terrestrial nutrients and other substances are displaced to the river through surface runoff, atmospheric deposition, and groundwater discharge. In the Caeté estuary, the fluvial discharge contributes to the dilution of the effluents released into the water in the upper estuary. This pattern may be accentuated during La Niña events, with the opposite tendency being observed during El Niño events (see Chapter 7).

An analysis of the data from the Caeté estuary indicates that a mean discharge of 45.0 $m^3.s^{-1}$ is the threshold for converting the river flow into an efficient mechanism of effluent transport. This transport increase during the wet season, when runoff is at its highest level, and then decrease during dry season. A similar situation was observed in the Nile estuary when fluvial discharge decreased by 90% (Wetz and Yoskowitz, 2013), and in the Hudson River, where nutrient loads increased during periods of reduced flow (Howart et al., 2000).

The increased capacity for the dilution of sewage effluents observed during the wet season may be related to the low levels of human activities in the hydrographic basin as a whole (other than those observed in Bragança, in the estuary proper), which would not be expected to have a significant effect on the quality of the basin's waters. In a previous study, Gorayeb et al. (2008) demonstrated that dissolved nutrient levels in the fluvial sector of the Caeté basin are very low (NO_3< 2.0 µm, NO_2 < 0.2 µm, PO_4 < 0.2 µm). This pattern, associated with the diluting effects of the increased freshwater discharge (i.e., increased precipitation during the wet season), together with the strong ebb currents and prolonged ebb tide, results in the effective dilution of the effluents discharged into the upper sector, with its water quality increasing as a consequence. In this context, it is important to note that changes in land use within the basin, resulting from the ongoing occupation of the available farmland in the area surrounding the estuary, will eventually lead to a surplus of nutrients, as observed in estuaries in north-eastern Brazil (Noriega and Araújo, 2009).

The high nitrate concentrations and low concentrations of nitrite and ammonium recorded throughout the Caeté estuary confirmed an active nitrification process, principally during the spring tides when dissolved oxygen concentrations reached supersaturated levels. This indicates that the ammonium is being oxidated by anaerobic bacteria, which is common in well-oxygenated environments, like those on the Amazon Coast (Sodré et al., 2011; Costa et al., 2013a). Pamplona et al. (2013) obtained similar results in the in the Quatipuru estuary, which is 40 km from the Caeté, and located within an area of mangrove forest. By contrast, studies in estuaries associated with mangroves in the United States and north-eastern Brazil (Childers et al., 2006; Barboza et al., 2013; Silva et al., 2015) found that NH_4^+ was the dominant type of DIN, a situation also recorded by Dittmar and Lara (2001) in an earlier study of the Caeté estuary. As ammonium is an indicator of pollution, and is produced by the incomplete degradation of organic nitrogen (Brinzeiet al., 2005). The high values observed on the Bragança waterfront are associated with the sources of contamination identified in this area. Fish processing plants and sewage outlets are important sources of ammonium in these environments (Islam et al., 2004).

The high concentrations of phosphate observed in the lower estuary reflect an association with marine processes. During the dry season (low fluvial discharge), in addition, phosphate concentrations exported from the mangroves of the Caeté estuary increased approximately eightfold (Dittmar and Lara, 2001), and the high hydrodynamic energy observed during this period results in the re-suspension of fine particles and the desorbed phosphorus associated with the bottom sediments, as observed on the Amazon continental shelf (Fox et al., 1986). The phosphate concentrations decrease during the wet season, primarily in the upper estuary. Low salinity may also contribute to the adsorption and precipitation of the phosphate to the bottom sediment, causing them to sink in the water column (Kadiri et al., 2012).

The high concentrations of dissolved nutrients observed in the upper sector of the Caeté Estuary were not expected for the Caeté basin, a region with low population density and minimal industrial development. The values recorded in the present study were more similar to those found in densely-populated Brazilian estuaries, such as that of Recife, which has 190 inhabitants per km² (see Flores Montes et al., 2011), or in more heavily industrialized zones. However, similar values have been recorded in other estuaries dominated by mangrove systems, such as the Kaw, Taperaçu, Curuça, and Quatipuru estuaries (Lam-Hoai et al., 2006; Costa et al., 2013a, 2013b; Pamplona et al., 2013).

The 8900 km² of mangrove surrounding the Caeté estuary is its primary natural source of nutrients, with the outwelling of nutrients and organic matter from the forest supporting a natural eutrophication process (Dittmar and Lara, 2001). The 5.0 g m^{-2} $year^{-1}$ of Nitrogen recorded in the present study far exceeds the values recorded in mangrove forests in other regions of the world, such as Conn Creek in Australia, with 1.2 gN m^{-2} $year^{-1}$ (Ayukai et al., 1998) and Lobos Bay in Mexico, with 1.8 gN m^{-2} $year^{-1}$ (Carrillo et al., 2009).

In coastal environments, which are less productive than estuaries, an increase in nutrient concentrations is generally associated with anthropogenic impacts (Jiao et al., 2015).

Given this, trophic indices based on nutrient concentrations, e.g., the TRIX, which was developed for the analysis of the Adriatic Sea in Italy (Vollenweider et al., 1998) and the Karydis index, which is based on the nutrient concentrations found off the coast of Greece (Karydis et al., 1998), relate eutrophication to low water quality. In the specific case of the Caeté estuary, a naturally eutrophic environment, the classification of water quality as poor or bad would be inadequate, especially given the low population density of the middle and low sectors.

In addition to the natural source of nutrients, the Caeté estuary receives the input of effluents from the local population, mainly at the upper sector. Due to the lack of water treatment plants, these effluents are not processed adequately (as recommended by resolution nº 274/2000 of the Brazilian National Environment Council, CONAMA) before being discharged into the estuary. Guimarães et al. (2009), Pereira et al. (2010), and Monteiro et al. (2011) all concluded that these effluents are the principal impact on the waters of the Caeté estuary. The Cereja River is another important source of pollution for the upper estuary, with domestic, commercial, and hospital effluents being discharged directly into its waters, which flow into the upper Caeté estuary (Guimarães et al., 2009).

No evidence was found in the region of any systematic seasonal variation in population dynamics or associated economic activities that might have a significant influence on the amount of sewage being discharged into the estuary during different periods of the year. In other words, anthropogenic pressures on the environment can be considered to be essentially stable over the course of the year. Population pressures and unregulated development in coastal basins are the primary source of environmental problems in estuarine systems (Gibbes et al., 2014; Birch et al., 2016). As shown in Chapter 7, the current problems of the Caeté estuary will tend to become more widespread in the future if no effective measuresare implemented to control the amount of effluents being discharged into its waters. Natural processes such as droughts may further impact the quality of the estuarine waters by increasing bacteriological contamination and the trophic status of the aquatic environment.

In addition to the input of nutrients, the quality of the water of an estuary is influenced by its capacity for the assimilation, transport, and dilution of these substances. A review of 79 estuaries found that the most significant problems, such as toxic blooms or eutrophication, are found in the systems with the slowest flushing times (Bricker et al., 2008). This indicates a reduced potential for nutrient retention, which would make the estuary less susceptible to long-term nutrient enrichment and eventual eutrophication. The decrease in nutrient levels in the area of discharge (upper sector) during the wet season indicates that the Caeté estuary is able to assimilate the effluents released into this sector during this period. The longer ebb phase in this sector may also help to minimize the impact of sewage effluents.

Diatoms are the second most abundant phytoplankton group in the Caeté estuary (Matos et al., 2011). These organisms require compounds of phosphorus and silica for the formation of their cell structure (Hildebrand, 2008). While the Redfield index indicates that phosphate are the limiting nutrient in the Caeté estuary, the high chlorophyll *a* concentrations recorded during periods of intense phosphate uptake (wet season, spring tides) indicate that this parameter is not affected by phytoplankton growth, as observed in the estuaries of north-eastern Brazil (Noriega and Araújo, 2009). Given this, the seasonal variation in nutrient concentrations does not appear to be a factor limiting optimum phytoplankton growth at any time of the year, because in general it is high the local availability of dissolved nutrients. High concentrations of suspend matter in the water column (primarily in the upper and middle estuary) did not appear to influence photosynthetic activity in the Caeté estuary, because the high photosynthetic activity (high chlorophyll *a* values) was observed in those sectors.

In general, estuarine waters support the development of faecal coliforms (Maillin et al., 2004). In the Caeté estuary, the intrusion of seawater and the long distance to the sources of contamination contribute to the low concentrations of these bacteria observed in the middle and lower sectors. However, high concentrations (above 1100 MPN/100 ml) were recorded in the upper sector, in the vicinity of the urban settlement, which is the primary source of effluents. The concentrations recorded in the present study exceed the limits established by CONAMA (resolution nº 357/2005) for the conservation of aquatic environments, which is the primary objective of the Caeté-Taperaçu Extractive Reserve. The concentrations were equally prejudicial for other uses, with those recorded in the upper estuary during the dry season being up to five times higher than the maximum values recommended for human use.

Overall, then, the patterns observed in the waters of the Caeté estuary are the result of a balance between the natural dynamics of the system (mangrove outwelling, tidal and river discharge) and human inputs (effluent discharge). The constant discharge of untreated sewage into the upper estuary throughout the year is considered to be a primary source of dissolved nutrients and faecal coliforms. The higher fluvial discharge recorded during the wet season contributes to the dilution and transport of the material released from sewage outlets. This effect may be intensified during La Niña events due to the increase in rainfall and the resulting intensification of the river discharge. The opposite pattern was observed during the dry season, when the river discharge decreased, and in particular during El Niño events, which may provoke a significant reduction in rainfall levels throughout the Amazon basin. During these events, the dilution and transport of effluents within the estuary becomes less effective, and the material is concentrated in its waters.

In addition to the anthropogenic input, natural sources of nutrients, such as mangrove outwelling, may also contribute to an increase in concentrations. This input increases during spring tides, especially the equinoctial spring tides, which favour the flooding of the mangroves. All these factors contribute individually to the eutrophication of the estuary's waters, and their combined effect, when occurring simultaneously, intensifies the process considerably.

8.2 Conclusions/Final considerations

The results obtained in this study allow us to conclude that unplanned settlement and unregulated economic activities in the town of Bragança have placed increasing pressure on the Caeté estuary, impacting the quality of its waters, especially in the most urbanized sector of the river. This unplanned urban development, which includes the lack of a public sewage treatment system and inadequate refuse disposal, and the absence of any effective controls or regulation of human activities in the region constitute the principal anthropogenic pressure that drives the alterations of the quality of the water of the Caeté estuary.

The different types of land use and occupation observed around the estuary may also have distinct implications for the quality of the water in its different sectors. The concentration of the population and economic activities in the upper sector of the estuary, combined with the influence of the port, applies considerable pressure in this sector, with a considerable potential risk of exporting the effects downstream. As expected, in the more urbanized sector (upper estuary) more negative impacts were observed in the quality of the water. For example, the high concentrations of faecal coliforms found in the upper sector reflect the influence of the human presence (e.g., sewage effluents), and its potential contribution to the eutrophic status of the estuary. In the middle and lower sectors, the concentrations of faecal coliforms were much lower. This confirms the first hypothesis proposed in this study.

The eutrophication of the middle and lower sectors observed during spring tides may be considered a natural process, given that the low coliform concentrations in these sectors indicate a significant decrease in the influence of anthropogenic impacts. While there is a high natural level of nutrients in the estuary, when the anthropogenic input is added, it will contribute synergistically to the negative impacts on the quality of the environment in the estuary (measured by its nutrient concentrations). This occurs typically during periods when the estuary is more susceptible to the retention of the nutrients, that is, during the dry season.

The location of the Caeté estuary within the world’s second largest continuous tract of mangrove forest contributes to the nutrient balance of its waters through the inundation of the marginal mangroves during spring tides. This flooding results in the release of nutrients from the mangrove sediments into the water column, which increases the nutrient content of the water, contradicting the second hypothesis proposed in this study. A reduced nutrient input was recorded during neap tides, by contrast, possibly due to a reduction in the outwelling from the mangrove. During this period, a medium eutrophication or mesotrophic status was recorded in the estuary.

The climatic and hydrodynamic conditions of the region contributed to a reduction in the impact on the estuarine environment caused by the activities of the local population, especially during the wet season (when rainfall levels and fluvial dischargewere both high). During this season, the transportation, dilution, dispersion and/or advection of suspended particles are all more efficient and water quality is better (less eutrophic) in the areas most impacted by anthropogenic activities, once again, contradicting the pattern predicted by the second hypothesis.

However, the Caeté basin has a low population density overall, and low levels of industrial development, so human pressures can still be considered to have only a moderate impact on the estuary. However, the high concentrations of nutrients and chlorophyll *a* observed in the upper sector are inconsistent with the levels expected for a region with limited industrial development and low population density, although the values recorded in the middle and lower sectors were typical of the estuaries of the Amazon region.

Given that the local population is expected to grow by 10–20% per decade, which will exacerbate human impacts in the study area, it will be necessary to implement a monitoring program to evaluate ongoing pressures and their resulting impacts on the estuary before the effects become irreversible. It is essential that the measures adopted to resolve this problem take into account the natural characteristics of the region, such as the high productivity of its aquatic environments, as well as the occasional drought events caused by variations in the sea surface temperature in the tropical Pacific or Atlantic oceans, or a combination of both processes.

In addition to this monitoring, an action plan will be needed to prevent any further increase in anthropogenic pressures on the estuarine environment. The problems observed during the present study may be mitigated by a number of simple measures, including (i) the provision of an efficient urban cleaning system; (ii) the regulation of the disposal of residues from local markets, medical facilities, and ice factories; (iii) the construction of an effective public sanitation system for the treatment of sewage, and (iv) stricter controls on the input of waste water into the Caeté estuary.

8.3 Further research questions

During the development of the present study, a number of challenges were identified for the improvement or extension of the database established for the Caeté estuary:

- The application of more detailed procedures for the calculation of the input of nutrients into the Caeté estuary from the local mangroves and anthropogenic sources;
- The continuation of the monitoring of hydrological variables to provide a reliable time series for the establishment of a trophic index appropriate for the

Amazon region. The results of this monitoring would be improved by the inclusion of biotic variables, which have been shown to be good indicators of water quality;

- Once the first empiric knowledge about the functioning of the Caeté estuary has been provided, the application of a numerical modeling approach to predict the microbiological and trophic status of the Caeté estuary under different conditions of fluvial discharge, tidal range and current dynamics.

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APPENDIX A

APPENDIX A

Participation in seminars and congresses

Monteiro, M.C., Jiménez, J.A., Pereira, L.C.C. 2016. The Trophic Status of an Amazonian Estuary Under Anthropogenic Pressure (Brazil). 14**th** International Coastal Symposium, , Sydney, Australia.

Monteiro, M.C., Jiménez, J.A., Pereira, L.C.C. 2013. Anthropogenic and climate induced controls on the water quality an estuary in the Amazon. 53th ECSA Conference: Estuaries and coastal areas in times of intense change, 2013, Shangai, China.

Monteiro, M.C., Jiménez, J.A., Pereira, L.C.C. 2013. The Environmental status of the Caeté Estuary (Amazon Coast, Brazil). 53th ECSA Conference: Estuaries and coastal areas in times of intense change, Shangai, China.

Monteiro, M.C., Jiménez, J.A., Pereira, L.C.C. 2012. Human influence on the water quality of the Caeté estuary (Amazon, Brazil). 50th ECSA Conference: Today's science for tomorrow's management, Venice, Italy.

Monteiro, M.C., Gorayeb, A., Guimarães, D. O., Costa, R.M., Pereira, L.C.C., Jiménez, J.A. 2011. Presence of bacteriological indicators of contamination in the hydrographic basin of the Caeté river. Conference Environmental Health, Salvador, Brasil.

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