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The influence of the river runoff in the artisanal fisheries catches in tropical coastal waters – The case of the Zambezi River and the fisheries catches in the northern Sofala Bank, Mozambique*

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ABSTRACT

The artisanal catches contributes significantly in the overall annual fish production in Mozambique, estimated to 115,000 - 140,000 tones, and thus of significant importance to livelihood of the coastal communities. However, the variation in fish production depends on several factors, among which the climatic factors, that need to be understood for sustainable fisheries management. The present study analyses the influence of the river runoff in coastal fisheries production, using the Zambezi Runoff (1996-2014) as a climatic indicator and the artisanal fisheries catches (2000-2014) as the indicator of fisheries production. The results obtained indicated that the artisanal catches in Sofala Bank were dominated by resident species in the region of fresh water influence (Engraulidae (53%), Clupeídea (10%), Sciaenidae (8%) and Sergestidae (7%)), by species that inhabit these regions at their earlier stage of life (Penaeidae (4%)) and by species that inhabit the vicinity and move to the region of fresh water influence for feeding (Trichiuridae (6%), Ariidae (4%), Carangidae (4%) and Hemulidae (2%)); The total annual catches were positively-linearly correlated with the total annual runoff (slope = 0.343, r^2 = 0.500, p = 0.005, n = 14). Further, the catches correlated better with both the wet season runoff (slope = 0.534, r^2 = 0.369, p = 0.021, n = 14) and the dry season runoff (slope = 0.773, r^2 = 0.389, p = 0.013, n = 15). The result is justified by the fact that most of the species caught (Engraulidae, Clupeídea, Sergestidae and Penaeidae) live in the region of freshwater influence, with one to two years life span and recruited to fisheries within the first year of their life. The present study emphasises the importance of the environmental/climatic factors such as river runoff in the fish production, and hence, on the need for the inclusion of the runoff variability in the fisheries management strategies.

Keywords: River runoff, climatic factors, fisheries production, sustainable fisheries.

RESUMO

Influência do escoamento de rios nas capturas de pescarias artesanais nas águas costeiras tropicais – o caso do Rio Zambeze e as capturas na zona norte do Banco de Sofala, Moçambique

As pescarias artesanais contribuem de uma forma significativa na produção pesqueira total de Moçambique, estimada em cerca de 115 000 -140 000 toneladas por ano, e por isso com impacto positivo na economia das comunidades costeiras. No entanto, a variação da produção pesqueira depende de muitos fatores, de entre eles os fatores climáticos, que devem ser com-

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preendidos para uma gestão sustentável das pescarias. No presente trabalho analisou-se a influência da descarga dos rios na produção pesqueira tomando como base o escoamento do Rio Zambeze (1996-2014), como variável climática e as capturas dos pescadores artesanais no Banco de Sofala (2000-2014), como indicador da produção pesqueira. Os resultados indicaram que a composição especifica das capturas artesanais no Banco de Sofala eram dominadas por espécies residentes nas zonas de influência de água doce (Engraulidae (53%), Clupeídea (10%), Sciaenidae (8%) e Sergestidae (7%)), por espécies que passam a parte inicial de sua vida em zonas de influência de água doce (Penaeidae (4%)) e por espécies que habitam na vizinhança de zonas de influencia de água doce e que se deslocam para estas zonas para se alimentar (Trichiuridae (6%), Ariidae (4%), Carangidae (4%) e Hemulidae (2%)); as capturas correlacionaram-se positivamente e significativamente com o escoamento total anual (tangente = 0,343, r^2 = 0,500, p = 0,005, n = 14). As capturas correlacionaram se bem tanto com escoamento da época chuvosa (tangente=0,534, r2=0,369, p=0,021, n=14) como com escoamento da época seca (tangente=0,773, r2=0,389, p=0,013, n=15). Este resultado se justifica pelo facto de a maioria das espécies nas capturas (Engraulidae, Clupeídea, Sergestidae e Penaeidae) habitarem zonas de influencia de água doce, com um ciclo de vida de um a dois anos, e serem recrutados para a pesca dentro do seu primeiro ano de vida. O presente estudo enfatiza a importância dos fatores ambientais/climáticos tais como escoamento dos rios na produção pesqueira e daí a necessidade de sua inclusão nas estratégias de gestão das pescarias.

Palavras-chave: *Escoamento do rio, fatores climáticos, produção pesqueira, gestão sustentável das pescarias.*

1. Introduction

Mozambican coastal waters are rich in fisheries and species diversity (Hoguane & Pereira, 2003). The total annual artisanal fisheries catches in tones were 65,535, 83,058, 104,069, 82,607 and 132,238 for the years 2007, 2008, 2009, 2010 and 2011, respectively (IIP annual reports). The artisanal fisheries catches contribute on average with about 87% of the total annual catch, as recorded in fish landings (Jacquet & Zeller, 2007). Most of the artisanal catches are directed to local market, and contribute significantly to the livelihood of the coastal communities and to local economy.

The relatively high productivity in coastal waters is mostly attributed to land based nutrients input into the coastal waters through the river or coastal rainfall leaching (Hoguane *et al.*, 2012), hence, the positive correlation between the river runoff and the coastal catches. There are several studies conducted relating the coastal productivity and river runoff. Loneragan (1999), studied the influence of the river runoff in coastal ecosystems in Queensland, Australia, and concluded that the higher the runoff the higher the production of commercial and recreational fish species. Maynecke *et al*. (2006) examined the relationship between the coastal freshwater runoff and the fisheries production, in same place, and found that 30% of the total variability in catch could be explained by freshwater flow into coastal waters. Conway *et al*. (2005) investigated the inclusion of the river runoff in the management of the natural resources, including inland waters, in East Africa, and discussed the complex interaction between climate, environment and social issues and reiterated the need to consider the runoff variability in the management of the natural resources. The scientific reasons of the positive relationship, often empirical, observed between the river runoff and the coastal fisheries reside in the fact that the river runoff and coastal water drain sediments and nutrients to the coastal waters, which in turn establish an appropriate shelter for the development of the larvae and juveniles and fertilize the coastal water for phytoplankton production, the foothold of the entire marine food web (Gammelsrød, 1992; Meynecke *et al*., 2006; Ayub, 2010).

In Mozambique, most of the studies conducted related to fisheries are mainly directed to surveys and stock assessment, and there are seldom studies relating the environmental issues and fisheries' production. Gammelsrød (1992) studied the effect of Zambezi Runoff and the shallow water shrimp production in Sofala Bank, and observed a positive correlation between the runoff and the shrimp catch; Hoguane *et al*. (2012) studied the relationship between the coastal rainfall and the artisanal catches in the northern Mozambique, and observed that the rainfall has a positive effect on coastal fisheries production.

According to Larkin (1996), further sustained by Garcia *et al.* (2003), the fisheries management measures should take into account the environmental factors such as river runoff. The present study examines the relationship between the Zambezi River, the largest river in Southern Africa, and one of the largest rivers in Africa, and the artisanal fisheries production in Sofala Bank. Considering the fact that the river is dammed, with two major hydroelectric dams, the Kariba dam in Zimbabwe and the Cabora Bassa dam, in Mozambique, the question remains whether the river is still tuned with ecological seasonal cycles.

2. Description of the study area

The Sofala Bank, with about 15,169 km^2 and 75 m average depth, located in between the Latitudes 16° 05' S and 21° 00' S, is the largest shelf in Eastern African coast (Figure 1) and the major fisheries zone in Mozambique (Gammelsød, 1992). The climate is subtropical humid with two distinct seasons: the summer or rainy season and the winter or dry season.

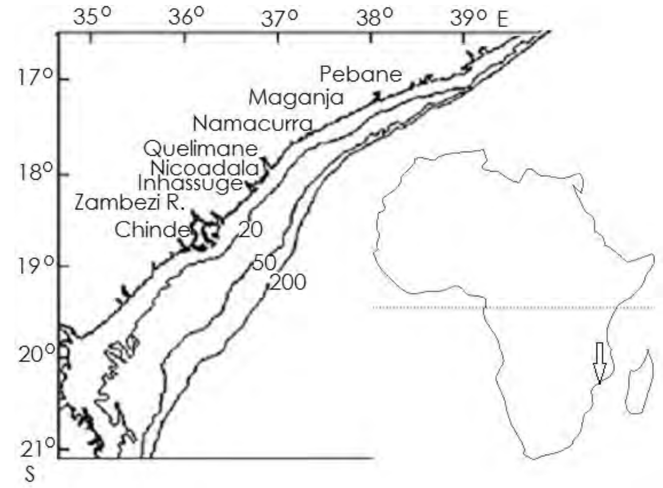

Figure 1 – Study area. Location map of the study area.

Figura 1 – Área de estudo. Mapa de localização da área de estudo.

The average air temperature varies between 24 and 29° C; the dominant winds are SE-trade. The tides are semi-diurnal with amplitudes of 0.4 to 4.5 m during the neap and spring tides, respectively. The shelf receives freshwater water from several rivers; being the Zambezi River the major, which discharge on average about 3,000 m^3s^{-1}, dominating the water masses in the Sofala Bank, consequently the water salinity in coastal waters, varies on average from 32 to 35, and could drop further during the rainy season (Gammelsrød, 1992). The width of the Zambezi plume, as described by Siddorn *et al.* (2001) and modelled by Nehama & Reason (in press), varies from 30 to 50 nautical miles, being wider nearest the delta, and its length is about 160 nautical miles, from the delta northwards (Figure 2).

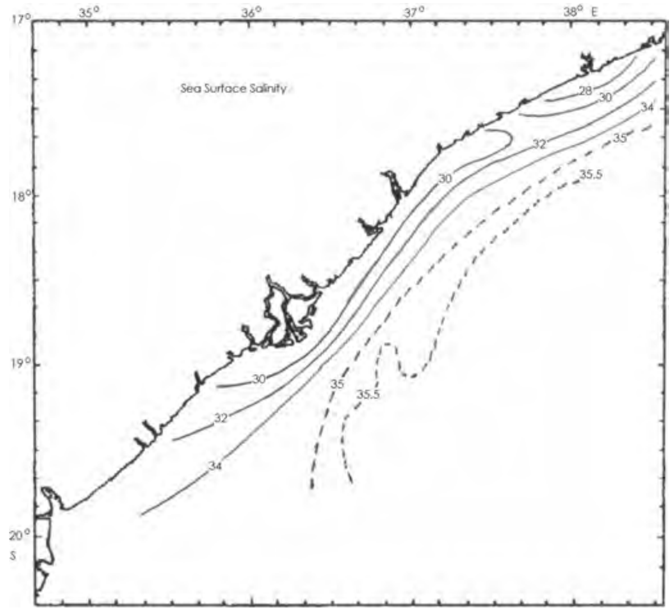

Figure 2 – Sea surface salinity distribution in Sofala Bank (Siddorn *et al*., 2001)

Figura 2 – Distribuição de salinidade de superficie no Banco de Sofala (Siddorn et al., 2001).

Table 1 – Annual artisanal catches (tons), from beach seine, recorded at the fish landings in coastal districts of Zambézia Province, northern Sofala Bank, during the period 2000-2014.

Tabela 1 – Capturas anuais (toneladas) de pescadores artesanais, através de arrasto à praia, registadas nos distritos costeiros da Província de Zambézia, zona norte do Banco de Sofala, durante o período 2000-2014.

District / Year	Pebane	Maganja	Namacurra	Nicoadala	Quelimane	Inhassunge	Chinde	Total
2000	16,894	5,561	648	2,487	682	-	-	**26,272**
2001	19,292	2,553	1,129	3,604	671	-	-	**27,249**
2002	11,739	5,755	1,036	3,246	477	-	-	**22,253**
2003	12,251	3,692	944	2,013	483	-	-	**19,383**
2004	11,905	4,043	1,161	2,649	831	-	-	**20,589**
2005	12,366	3,329	1,471	1,388	850	915	433	**20,752**
2006	20,228	4,301	1,102	1,307	1,207	998	632	**29,774**
2007	15,377	4,832	1,022	4,618	2,543	873	892	**30,157**
2008	14,099	4.166	2,006	5,664	4,295	1,678	564	**30,473**
2009	12,682	4,412	451	4,002	955	1,813	795	**25,110**
2010	7,453	3,224	690	1,431	238	1,140	807	**14,983**
2011	6,158	3,220	673	2,534	1,061	1,426	1,300	**16,372**
2012	7,503	1,968	635	1,541	1,984	904	732	**15,267**
2013	11,715	2,583	669	2,210	1,918	1,288	1,273	**21,656**
2014	10,066	2,978	1,009	1,639	1,856	1,055	1,264	**19,867**
Total	**189,728**	**56,617**	**14,646**	**40,332**	**20,051**	**12,089**	**8,693**	**342,156**

3. Data

The present study was based in monthly artisanal catch landing data, from the beach seine, undertaken in seven coastal districts of the Zambézia Province, namely, Pebane, Maganja da Costa, Namacurra, Nicoadala, Quelimane, Inhassunge and Chinde, located in the northern Sofala Bank, during the period 2000 - 2014 (Table 1), and the monthly Zambezi River runoff as measured in Station E-320, located in Tete Province, about 400 km upstream from mouth, during the period 1997 to 2014.

The year 2001 recorded extreme high runoff, during the wet season, and so considered abnormal, and consequently removed from the analysis. However, the dry season runoff of 2001 was considered. The catch data was kindly provided by the Institute for Fisheries Research (IIP), Zambézia Office, and the Zambezi River runoff data was kindly provided by The Zambezi River Basin Administration (ARA-Zambezi). The catch data was collected by samplers in each fishing centre, three days a week. During the sampling period a number of boats and of fishing gears used in the day was recorded and a random sample of 10 percent of the catch was selected for fish composition and biometric data analysis.

The overall monthly catch in a fishing centre was estimated considering the average daily catch and average number of boats and of active fishing gears recorded during the sampling periods, and 21 days, an average number of fishing days a month, based on the census carried by IDPPE in 2004. Since the recorded fishing effort of the artisanal fisheries, based on days of fishing, does not capture adequately the effort the total annual catch was then used as an indication of the fisheries production, as indicated by Hoguane *et al.* (2012). Hence, the total annual catch of the artisanal fisheries was correlated with the annual river discharge and then, sequentially, with the wet or rainy and dry seasons' runoffs, using a statistical package MINITAB.

4. Result and discussion

Figure 3 presents the Zambezi runoff, the total annual runoff (October-September), the rainy or wet season runoff (October-March) and the dry season runoff (May-August), measured in Tete Hydrological Station E-320, during the period from the hydrological year 1996/97 to 2010/14. The total annual Zambezi runoff varied from 41,000 to 84,000Mm^3, observed in the hydrological year 1996/97 and 2009/10, respectively; the wet season runoff varied from 26,000 and 46,000 Mm^3, recorded in the hydrological years 1996/97 and 2007/08, respectively and the dry season runoff varied from 12,000 and 32,000Mm^3 observed in the years 1997 and 2011, respectively.

Figure 4 presents the time series of the annual (Jan. – Dec.) artisanal annual catches, by the beach seine, recorded in Sofala Bank, during the period 2000 to 2014. The lowest catch was 20,000 tonnes observed in 2003 and the highest was 35,000 tonnes observed in 2010. The period between 2003 and 2005 was characterized by low catches and the period 2006 to 2010 was characterised by relatively high catches, with a minor reduction in 2009. Table 2 presents the dominant species in the artisanal catch in Sofala Bank as recorded during the period 2000 to 2014. The most dominant family species were Engraulidae with 53%, followed by Clu-

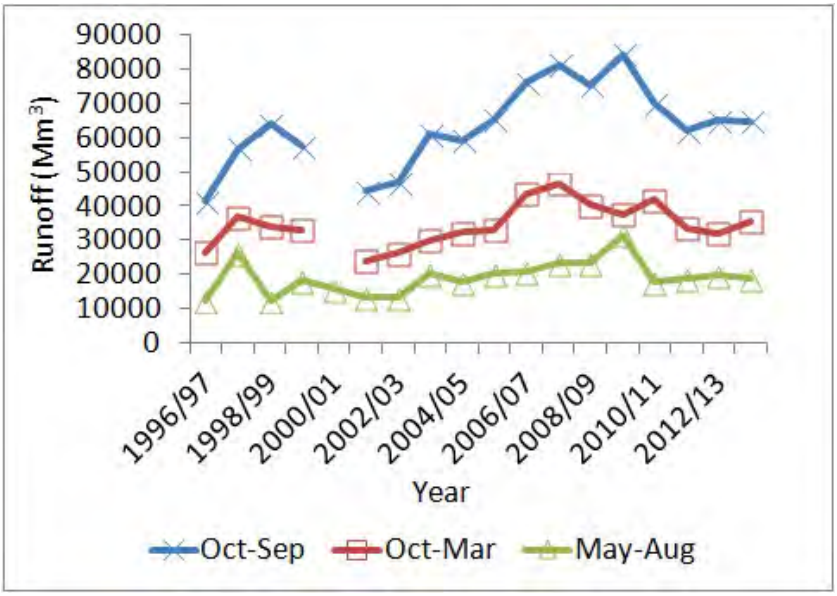

Figure 3 – Time series of the Zambezi total annual runoff (Oct.-Sep.), dry season runoff (Oct.-Mar.) and dry season runoff (May-Aug.), measured in Tete Hydrological Station E-320.

Figura 3 – Serie temporal do escoamento do Rio Zambeze total anual (Out.-Set.), do período húmido ou chuvoso (Out.-Mar.) e do período seco (Maio-Ago.), medido na Estacão Hidrológica de Tete E-320.

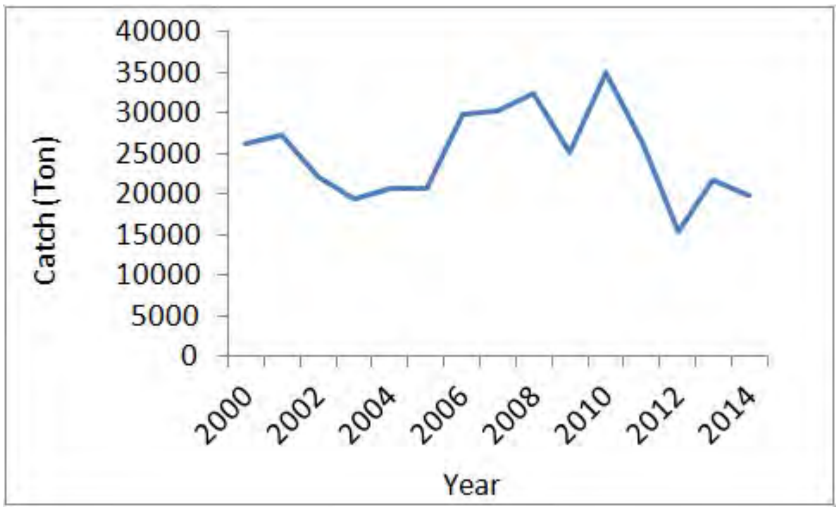

Figure 4 – Time series plot of the total annual (January-December) artisanal catches, by the beach seine, observed in Sofala Bank, during the period 2000 to 2014.

Figura 4 – Serie temporal das capturas artesanais totais anuais (Janeiro-Dezembro), capturadas por rede de arrasto à praia, no Banco de Sofala, durante o período de 2000 a 2014.

Table 2 – Dominant fish families caught by artisanal fisheries in Sofala Bank, using beach seine, during the period 2000-2014.

Tabela 2 – Famílias das espécies dominantes nas capturas dos pescadores artesanais no Banco de Sofala, capturadas por rede de arrasto à praia, durante o período 2000-2014.

Family	Total catch (Tons)(2000-2014)	Percentage (%)
Engraulidae	167,144	53
Clupeídea	31,537	10
Sciaenidae	25,229	8
Sergestidae (shrimp)	22,076	7
Trichiuridae	18,922	6
Ariidae	12,615	4
Penaeidae (shrimp)	12,615	4
Carangidae	12,615	4
Hemulidae	6,307	2
Ambassidae	3,154	1
Others	6,307	2

peídea with 10%, Sciaenidae (8%), shrimp of family Sergestidae (7%), Trichiuridae (6%), Ariidae (4%) Penaeidae (4%), Carangidae (4%), Hemulidae (2%), Ambassidae (1%) and non identified species (2%).

Figure 5 presents the time series plot of the total annual (January-December) artisanal catch by beach seine and the Zambezi River runoff, the total annual, the wet and the dry season, and the respective linear regression analysis. The best correlation was observed between the total annual (January-December) catches with the total annual (October-September) Zambezi River runoff (slope = 0.343, r^2 = 0.500, p = 0.005, n = 14), followed by the correlation of the catch with the wet season (October-Mar) Zambezi runoff (slope = 0.534, r^2 = 0.369, p = 0.021, n = 14). There was also a good correlation between the catch and the dry season (May-August) runoff (slope = 0.773, r^2 = 0.389, p = 0.013, n = 15). Stepwise regression analysis showed that any of the data sets, namely, total annual, wet season and dry season runoff can be used, as all are correlated. Even the dry and wet season runoff are correlated (r^2 = 0.339, p = 0.029), probably due to river regulation. Thus, the best linear regression equation predicting the total annual (January-December) catch (tons) as a function of the total annual (October-September) Zambezi River runoff (Mm^3) is as follows:

$$\text{Catch} = 0.343 * \text{Runoff} + 2255.4 \quad (1)$$

The entire coastal waters of Sofala Bank is dominated by freshwater (Figure 2), mostly from Zambezi River

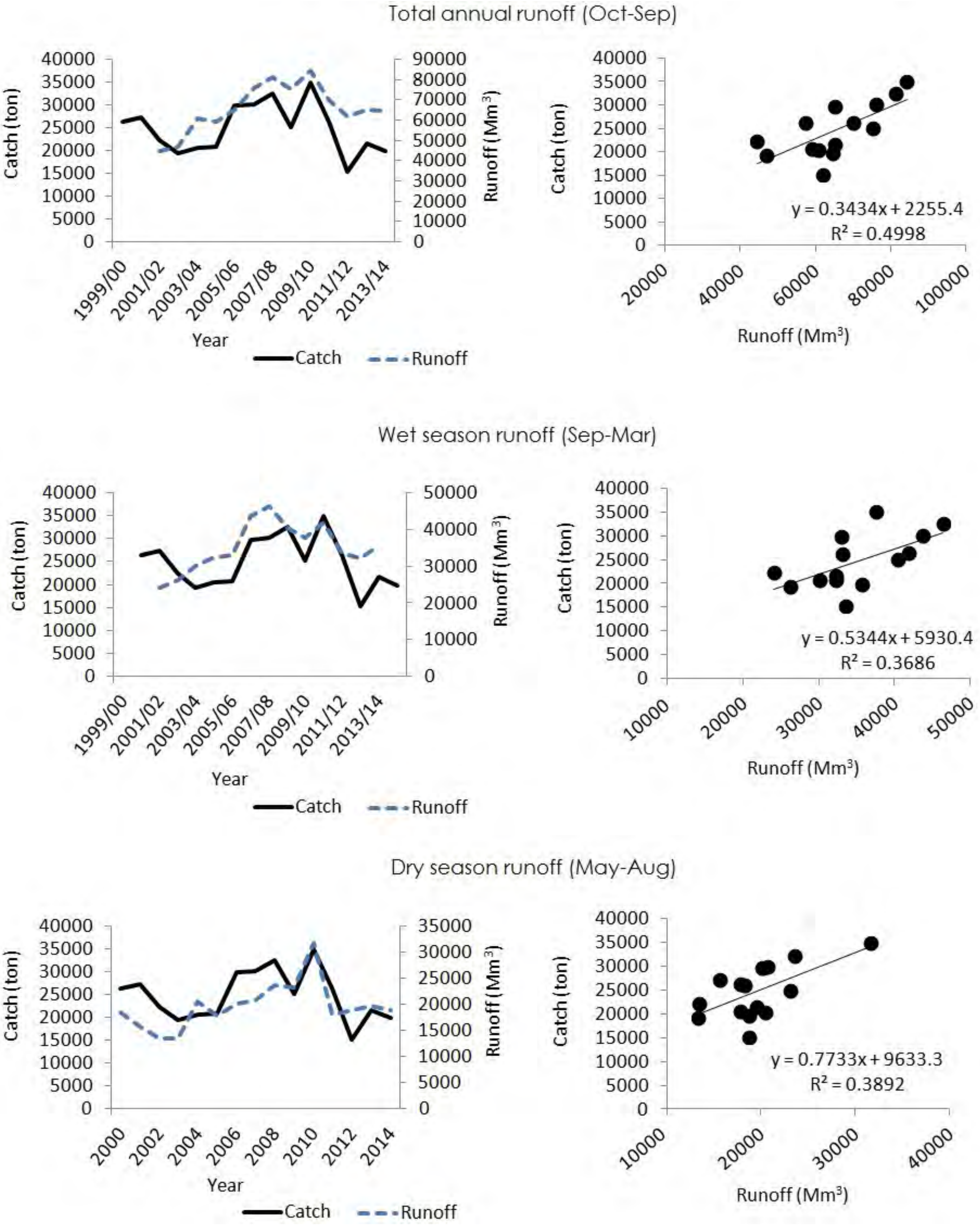

Figure 5 – Regression analysis of the annual artisanal catches (2000-2014) in Sofala Bank and the total annual Zambezi River runoff (1999/00-2010/14). .

Figura 5 – Resultados de regressão entre as capturas artesanais anuais (2000-2014) no Banco de Sofala e o escoamento anual do Rio Zambezi (1999/00-2010/14).

(Siddorn at al. 2001; Steen & Hoguane,1990; Sætre & Silva 1984; Nehama& Reason (in press)). Hence, the artisanal catches in Sofala Bank are dominated by estuarine species with the Engraulidae species totalling more than 50 % of the catch. The species from this family spawn at the shelf, in marine environment, and the eggs and larvae development occur in estuaries and mangrove creeks environment, with suitable shelter against predators and with abundant food (Hoguane et al., 2012; Ayub, 2010; Loneragan, 1999). The Clupeidae, the second abundant species, were represented mostly by species of sardines and hilsa, which tolerate low saline waters, and sometimes enter in the river for spawning and feeding (Nelson, 1998; Froese & Pauly, 2000). The species of shrimp Sergestidae, represented by species of genera Acetes and the shrimp of family Penaidae live in coastal waters during their adult stage, but the larval and juvenile phases are spent in estuaries and mangrove creeks (Simões *et al.*, 2013). The species of the family Sciaenidae are benthic species that inhabit both the freshwater as well as the marine environments (Johnson & Gill, 1998; Cisneros-Mata *et al.*, 1994). Lastly, the species of the families Trichiuridae and Carangidae inhabit marine environment, from the shelf break up to interface with estuarine environment, thus, their presence in the artisanal catches could be explained by temporary immigration into the region of freshwater influence for feeding.

The positive correlation between the Zambezi river runoff and the artisanal catches in Sofala Bank reiterates the importance of the Zambezi on coastal ecosystems, despite the regulation. This result found in this study falls in line with several studies in other places of the world with similar characteristics, as follows: Loneragan (1999) studied the effect of the runoff of the Logan River in southeast Queensland, Australia, and confirmed that high river discharge can have a strong positive effect on the production of commercial and recreational coastal fisheries. Binet *et al*. (1994) studied the influence of the Congo River runoff and the coastal ecosystems and found a positive correlation between the runoff and the catches of Pseudotolithus elongates. Gammelsrød (1992) found a positive correlation between the Zambezi runoff and the catches of Penaeidae shrimp in Sofala Bank.

The rational of the positive relationship between the river runoff and the coastal fisheries production reside in two major arguments: firstly, the provision of nutrients through the river runoff which fertilises the coastal waters, boosting the phytoplankton production as explained by several authors (Gammelsrød, 1992, Meynecke *et al.* 2006 and Ayub, 2010) and secondly, the turbidity associated with river runoff creates a suitable sheltering environment against predators which in turn increases the survival rate of the larvae and juveniles, as explained by several authors (Hoguane *et al*., 2012; Ayub, 2010; Loneragan, 1999). The good correlation between the wet season runoff and the catches could, in the similar way, be justified by the provision of food and shelter for juvenile brought by the freshwater from the river. However, the good positive relationship between the dry season runoff and the catches seems contradicting the argument that the river runoff should display a seasonal cycle, with high values during the wet season and low values during the dry season, to comply with ecosystems' seasonal dynamics as pointed out by several authors. Gammelsrød (1992) stated that the river flow regime in a regulated river should follow a natural pattern as much as possibly, i.e. with higher runoff during the wet season and low runoff during the dry season as to tune with the natural ecological cycles; and further stated that high runoff during the dry season may have a negative impact on the ecosystems health. Loneragan (1999) showed that the seasonal pattern of flow is equally important as the flow magnitude. Similar result was found by other authors (Binet *et al*., 1994).

While the river runoff regime is equally important as the runoff intensity, it should be emphasized, however, that the inflow of freshwater, both during the dry or wet season, supplies nutrients that fertilize the coastal water, providing food for fish. This would benefit all the species that spend their entire life in coastal waters or feed in these areas, regardless the season. Thus, the higher and the longer the freshwater supply the higher the primary production in coastal waters and the better for fish production. On the other hand, the dry season runoffs are likely to impact negatively the species which in the course of their life cycle would shift between estuaries and coastal waters, according to the river regime, as the penaeid shrimp studied by Gammelsrød (1992), which spawn in coastal waters and the development of the larvae and juveniles occurs in the sheltered estuarine and mangrove environments, then, the river regime should favour immigration of larvae, as passive drifters, from coastal water to estuaries and mangrove creeks, hence low flows, and conversely a flushing mechanism, through high flow, would be required to trigger the migration out the estuaries to fishing grounds. On the other hand, for those coastal species which do not undergo such migration, a continuous supply of nutrients by the river throughout the year would be beneficial. Similar result was found by Hossain *et al.* (2012) who studying the Fish diversity in Meghna river estuary reiterated the importance the estuaries as a suitable for spawning, development and growth of some species during their early life stage; Ramos *et al*. (2005) on studying fish larvae dynamics in the Lima River estuary reiterated the influence of the hydrodynamics on estuarine ichthyoplankton and, consequently, on the recruitment of marine coastal fish populations; Bardin & Pont (2002) studying the environmental factors controlling the fish immigration in estuarine draining into Mediterranean sea, where the most dominant species were *Pomatoschistus* spp., specie whose larvae and juvenile grow in estuaries, found that the availability of fish were mostly influenced by hydrographic conditions, mostly determined by river flow. Similar result was found by Dolbeth *et al*. (2007).

Correlation between the catches and the river runoff successively lagged by 1, 2 and 3 years (not shown), were performed, but the lagged correlations were always poorer than the non-lagged. The best correlation in the present study between the total annual (January-December) catches and annual (October-September) Zambezi Runoff, with no lag, is justified by the fact that most of the species of the catch Engraulidae, Sergestidae and Penaeidae, contributing with about 64% of the catch have a short time life cycle, from one to two years (Johnson & Gill, 1998; Cisneros-Mata *et al*., 1994), and recruited to fishing area within their first year of life.

Based on the regression analysis and taking advantage of the fact that the Zambezi River is regulated; the fish production in Sofala Bank could be enhanced by adequately tuning the dam for desired downstream runoff. Intuitively, higher runoff throughout the year may give a wrong impression that fish production would increase. Righteously, that would not be the case since the species that requires immigration to the estuaries during their earlier stage of life would require a pronounced seasonal river flow regime to flourish. Hence, the present study reiterate the need for a reduction in the river runoff during the dry season, to boost successful immigration of fish eggs and larvae to the sheltered estuarine and mangrove environments and an increase in river runoff during the wet season to stimulate the migration of juveniles to the coastal fishing grounds, as suggested by Gammelsrød (1992). For instance, a reduction in 25% of river runoff during the dry season, and a consequent re-allocation of the same amount during the wet season, may result in an increase of about 12% in the annual catch.

5. Concluding remarks

The species composition of the artisanal catches in Sofala Bank is dominated by estuarine species and those species living in the adjoining seas and that feed in estuarine environment. The artisanal catches are positively correlated with the Zambezi River runoff, and the runoff explains the variability of catches by 50%. The findings in this study reiterate the importance of the river runoff in the productivity of coastal ecosystems and, in particular, in fisheries production, hence, the call for the inclusion of the climate factors in fisheries management measures. Since the Zambezi River is regulated, fish production can be enhanced by managing the dams as to allow for increased flow, during the wet season and reduced flow, during the dry season.

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Solid waste management in coastal cities: where are the gaps? Case study of the North Coast of São Paulo, Brazil*

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ABSTRACT

Coastal cities are surrounded by important but fragile ecosystems that are under pressure from population growth, tourism and large commercial enterprises. These factors contribute to a complex solid waste management situation, which is exacerbated by lack of planning and sanitation infrastructure, common factors in cities in developing countries. The municipalities of the North Coast of São Paulo State were used as study cases to analyze public policies for solid waste management in the coastal zone, with wide seasonal variations in population and solid waste production. The analysis included planning, implementation, performance indicators and future prospects. The results revealed that some key issues that are critical to the development and improvement of solid waste management in these cities must be considered: (1) the main focus of the plans and future prospects is landfills; (2) only a few of the outputs and outcome indicators are related to MSW; (3) recycling is not well implemented; and (4) no indicators of the amount of waste recycled are established. Solid waste management in these municipalities should be strategically reframed in order to adopt more-sustainable alternatives for waste treatment, with outputs and outcome indicators to evaluate policy implementation. In addition, citizen (residents and tourists) should be encouraged in monitoring and implementing these policies.

Keywords: Solid Waste Management, Coastal Cities, Public Policies.

RESUMO

Gestão de resíduos sólidos em cidades costeiras: onde estão as lacunas? Estudo de caso do litoral norte de São Paulo, Brasil

Cidades costeiras estão cercadas por ecossistemas importantes e frágeis, pressionados pelo crescimento populacional, turismo e grandes empreendimentos comerciais. Estes fatores contribuem para uma situação complexa de gestão de resíduos sólidos, a qual é agravada pela falta de planejamento e infraestrutura de saneamento, comuns em cidades de países em desenvolvimento. Os municípios do Litoral Norte do Estado de São Paulo serviram como estudo de caso para analisar as políticas públicas voltadas à gestão de resíduos sólidos na zona costeira, incluindo o planejamento, implementação, indicadores de desempenho e perspectivas futuras. Os resultados indicam que algumas questões essenciais para o desenvolvimento e melhoria da gestão dos resíduos sólidos estão sendo negligenciadas: (1) o principal foco dos planos e perspectivas estão focados em aterros sanitários; (2) existem poucos indicadores de desempenho relacionados à gestão de resíduos sólidos; (3) a reciclagem não tem uma cobertura adequada nos municípios; e (4) não existem indicadores estabelecidos que quantifiquem o volume de resíduos reciclado. A gestão dos resíduos sólidos deveria ser estrategicamente reformulada nestas cidades, proporcionando alternativas mais sustentáveis para o tratamento de resíduos sólidos, com indicadores de desempenho que avaliem

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adequadamente o as políticas do setor e contribuam para o seu desenvolvimento. Além disso, a participação e engajamento dos cidadãos (residentes e turistas) deveriam ser incentivados, encorajando-os a colaborar na implementação das políticas e no seu controle.

Palavras-chave*: Gestão de Resíduos Sólidos, Cidades Costeiras, Políticas Públicas.*

1. Introduction

The increase of urban solid waste as well as the consumption of disposable items and the inappropriate ways in which this waste is collected and disposed of, lead to a worldwide crisis in urban solid waste management (UNHABITAT, 2010; Gray, 1997). Solid waste management is one of the most challenging problems faced by the world's municipalities (UNHABITAT, 2010). Coastal zones are even more exposed to this crisis due to the lack of appropriate landfill sites, wide seasonal population variations, extensive commercial enterprises and proximity to the marine environment with its fragile ecosystems.

1.1. Solid Waste Management and Marine Litter

The global population is concentrated in low-lying coastal zones, where approximately 2% of the earth houses 13% of its people, a proportion that is rapidly increasing (McGranahan *et al.*, 2007). In coastal cities, environmental features such as mangroves, estuaries, beaches and bays, coupled with population growth, tourism and pressure from commercial projects such as ports, harbors and offshore oil and gas exploration makes difficult solid waste management, already compromised by the lack of planning and basic sanitation infrastructures that is prevalent in developing countries (Jiang *et al.*, 2001; Li, 2003).

In the coastal zone, this situation leads to the proliferation of marine litter (Seco Pon & Becherucci, 2012), defined as any manufactured or solid waste from human activities that enters the marine environment, regardless of the source (land-based or marine-based), but excluding organic matter (e.g. food and plant waste) (Cheshire *et al.,* 2009). Marine litter causes harm to ecosystems and marine life and impacts economic and recreational activities in the marine environment, such as fishing, tourism and navigation (Cheshire *et al.,* 2009).

Land-based activities are the major source of marine litter, responsible for 80% of the marine litter collected in the marine environment (Balas *et al.,* 2001; Hetherington, 2005). Coastal cities have a responsibility to avoid generating marine litter, by implementing and conducting appropriate waste management procedures (UNEP & NOAA, 2011).

The second United Nations Conference on the Environment and Development, also known as the Earth Summit, Rio Summit and Rio-92, held in the city of Rio de Janeiro in 1992, was an international benchmark for waste management and protection of coastal zones. Agenda 21 of this convention established the priority objectives of protecting the oceans, seas and coastal zones, and reducing pollution from solid waste. The convention envisioned a serious international commitment to improving solid waste management, minimizing waste generation, maximizing reuse and recycling, promoting adequate disposal and treatment, and expanding waste services (UN, 1992).

In 2011, an international conference organized by the US NOAA (United States National Oceanic and Atmospheric Administration) and the UN (United Nations) published the Honolulu Strategy, a results-oriented framework of action with the overarching objective of reducing the impacts and amounts of marine litter over the next 10 years. The Honolulu Strategy is divided into three main goals that focus on reducing the amounts and impacts of marine litter from land-based and sea-based sources and the accumulation of marine litter in the marine environment (shorelines, benthic habitats and pelagic waters) (UNEP & NOAA, 2011).

1.2. Solid Waste Management on the Brazilian Coast

In Brazil, 24.6% of the inhabitants live in coastal municipalities (IBGE, 2011). Waste-collection coverage varies among municipalities, but is over 80% in all regions (North, Northeast, Southeast, South and Middle-west) (Astolpho & Gusmão, 2008). Nevertheless, half of Brazilian municipalities dispose of their waste in inappropriate areas (MMA, 2011), highlighting the urgency of pursuing alternative treatments for solid waste under the principles established in Agenda 21.

In Brazil, the federal law that establishes the National Plan for Coastal Management (PNGC), published before Agenda 21, had already defined the coastal zone as an area in need of changes in management (Lei nº7.661, 1988). A federal law regarding solid waste management was promulgated only in 2010, establishing the National Policy on Solid Waste (Lei nº 12.305, 2010).

One of the tools of the PNGC is the Macrodiagnosis of the coastal and marine zones of Brazil, which combines socio-environmental information from the entire Brazilian coast. This diagnostic procedure uses data on the collection and disposal of urban solid waste, coupled with the average per-capita income and the existence of other sanitation services, to calculate the social risk indicator, given that residents of cities with poor sanitation services and infrastructure are more likely to encounter problems affecting their living conditions (Astolpho & Gusmão, 2008). Currently, 18% (75 of 395) of

Brazilian coastal municipalities are classed as "high" or "very high" social risk (Astolpho & Gusmão, 2008). Metropolitan regions with higher population densities tend to have higher social risk.

In southeast Brazil, for instance, almost half (33 of 68) of the coastal municipalities, including 8 of 16 in the State of São Paulo, are classed as high or very high social risk (Astolpho & Gusmão, 2008). These indexes reveal the vulnerable situation of coastal municipalities, even though they are not directly related to solid waste management.

In addition, several published studies have reported the occurrence of marine litter on beaches and other marine environments in Brazil. Araújo & Costa (2007) studied contamination by marine litter on an isolated beach in Pernambuco State. The main source of contamination was the Várzea do Una River, and the results indicated an exceptionally high level of contamination of the beach by plastics of urban origin, exposing the gravity of the basic sanitation situation in the urban centers of this river basin. Other studies also reported a high occurrence of marine contamination along the Brazilian coast, from the South to Northeast regions (Araújo & Costa, 2004; Ivar do Sul & Costa, 2007; Oigman-Pszczol & Creed, 2007; Cordeiro & Costa, 2010; Oliveira *et al.,* 2011). All these studies suggested that the waste mismanagement was one of the major causes of contamination.

1.3. Study Objectives

In order to analyze this issue closely and to increase understanding of the coastal zone of Brazil, the North Coast of the State of São Paulo was chosen for a case study. Despite their particularities, the municipalities of the North Coast of São Paulo have similar conditions to other coastal areas, including fragile environments; an economy based on tourism, especially vacation homes, with a marked seasonal variation in population; prospects for new projects that will conflict with existing activities; and the potential to produce marine litter.

This study analyzed the solid waste policies in these coastal municipalities. The following questions related to public policies for solid waste management were posed: Are there policies regarding solid waste? What are their main objectives and targets? How are the policies implemented? What are their main indicators for solid waste management assessment? Are the prospective future projects suitable for the area?

2. Research Method

2.1. Study Area

The North Coast of São Paulo is composed of three municipalities on the mainland, Caraguatatuba, São Sebastião and Ubatuba; and one island, Ilhabela (Figure 1). The region is an administrative unit of the State of São Paulo, for coastal management (Lei nº 10.019, 1998) and water resources (Lei nº 9.034, 1994), i.e., the North Coast has not only a physiographic identity but a management identity as well. This concept can also be applied to solid waste management.

The region has 11 federal, state and municipality Conservation Units, including one National Park, three State Parks, one Ecological Station, two Environmental Protection Areas and four Private Natural Heritage Reserves (CBHLN, 2011). The parks are fully protected areas where the main objective is to preserve nature, and only indirect uses of their natural resources are permitted. These areas comprise 76% of the entire area of the North Coast region (SMA, 2006). These numbers illustrate two important factors for the region. The first is tourism, which depends on the natural landscape; and the second is the limited space available for urban expansion and, as a result, for landfills and other solid waste management facilities.

2.1.1. Local Economic and Sanitation Context

The coast of São Paulo is the site of several large projects related to transportation (ports and roads) and offshore oil and gas exploitation. The State of São Paulo published a document titled "Strategic Environmental Assessment – Port, Industrial, Naval and Offshore Dimensions on the São Paulo Coast" that analyzed several ongoing and future projects in the area (ARCADIS, 2010). According to this document, if all the projects planned for the region were to be implemented within the next 15 years, the total cost could be 93 billon USD (209 billion BRL). The majority of these projects are located in the Central Baixada Santista (where the Port of Santos is located), where 92% of the total would be spent; 7% would be allocated to the North Coast, and less than 1% to the South Baixada Santista (ARCADIS, 2010).

Despite the small percentage of the total funds invested in the North Coast region, the contrast between the natural tendency for environmental protection and tourism and the possibility of increased urbanization is stark. Urbanization based on these large projects would compromise the environmental features and the natural situation of this coast.

These investments in the North Coast would be for infrastructure, such as the expansion of the Port of São Sebastião, construction of divided highways, and installation of oil and gas pipelines, among others. The municipalities have been conducting public hearings to discuss these new projects, including the environmental permitting process, installation and operation. These projects are likely to increase the population growth rate, putting pressure on the sanitation infrastructure.

The local economy is based mainly on services related to tourism activities, such as accommodation, food and

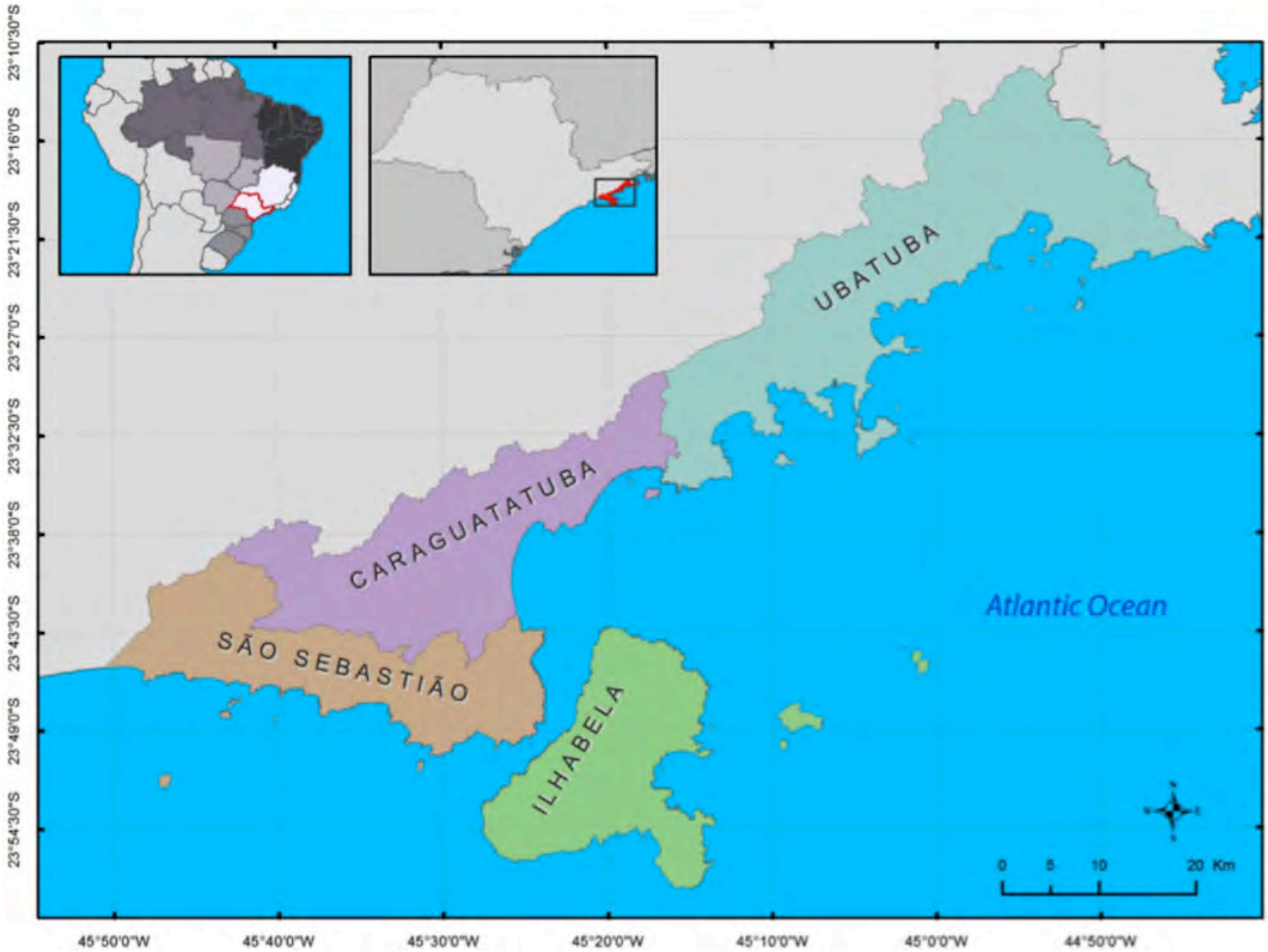

Figure 1 - Map of the North Coast of São Paulo State. Image: Mariana Corá.

Figura 1 - Mapa do Litoral Norte do Estado de São Paulo. Imagem: Mariana Corá.

transport. São Sebastião is the only exception; the royalties (taxes) that it receives from the Port of São Sebastião and the Almirante Barroso Transpetro Terminal provide it with the highest Gross Domestic Product (GDP) in the region (IBGE, 2010). The main source of tax revenue for the other municipalities is the service sector.

The permanent population of all municipalities of the North Coast is 290,429 inhabitants, but this number increases significantly during the summer high season (Table 1). As an indicator of this process, all the municipalities have a high proportion of non-occupied households (seasonal residences), especially Ubatuba, where 50% of the households fall in this category.

The sanitation situation varies widely among the municipalities, according to an assessment by IBGE (2010), Caraguatatuba has the highest proportion of households with adequate sanitation (88.7%). Ilhabela has the highest proportion of households classified as inadequate (32.2%). In São Sebastião the majority are considered semi-adequate (84%) and in Ubatuba more than half of the households have adequate sanitation (Table 1).

The local sanitation systems are deficient, and when overloaded may fail and themselves become a source of pollution. The region's solid waste collection coverage is good, with almost all households covered (99.5%) (CBHLN, 2011). However, the lack of regular collections leads the residents to discard their waste in vacant lots and waterbodies, increasing diffuse pollution (CBHLN, 2011).

2.2. Local Policies and Policy Implementation

Local policies were organized and analyzed, in order to identify the issues related to solid waste management and their approaches. Policy implementation was analyzed based on the Multiannual Plans (MAPs), Municipal Integrated Solid Waste Management Plans (MISWMPs) and Municipal Sanitation Plans (MSPs) when available.

The Multiannual Plans (MAPs) were analyzed through the identification of programs related to solid waste

Table 1 - Gross Domestic Product (GDP), population (permanent and temporary), occupancy rate of households and the sanitation situation in the municipalities of the North Coast of São Paulo State.

Tabela 1. Produto Interno Bruto (PIB), populacional (fixa e flutuante), taxa de ocupação dos domicílios e situação sanitária dos municípios do Litoral Norte do estado de São Paulo.

	Caraguatatuba	Ilhabela	São Sebastião	Ubatuba
GDP (in thousands, BRL)[1]	1,345.63	343.63	3,131.27	920.54
GDP per capita (in BRL)[1]	13,371.55	12,218.06	42,433.17	11,697.83
Permanent population in 2010[1]	100,840	28,196	73,942	78,801
Temporary population[2]	1,120,000 (annual)	100,000 (summer)	336,560 (annual)	Not specified
Occupancy rate of households[1]	43%	28%	38%	50%
Adequate Sanitation Situation[1]	88.7%	None	7%	52.8%
Semi-adequate Sanitation Situation[1]	11.3%	67.8%	84%	47%
Inadequate Sanitation Situation[1]	None	32.2%	9%	0.2%

Sources: 1- IBGE (2010). 2 – CBHLN (2011).

1 USD is equivalent to 2.2 BRL.

Sanitation Situation criteria: 1. adequate: there are drains connected to the network or general septic tank, water is provided by the water-supply system, and waste is collected directly or indirectly by cleaning services. 2. semi-adequate: at least one of the above services is classified as adequate. 3. inadequate: sewage enters a rudimentary sewage ditch, river, lake, the ocean or other sewer; water is obtained from wells, springs or other sources, and waste is not collected, but burned, buried or discarded into vacant lots, rivers, lakes or the ocean.

management, their indicators, and the resources invested. The MAP is a planning tool that must be prepared and approved for a period of four years. The plan organizes governmental actions, with programs oriented toward strategic goals defined for the period when the plan is in effect (Lei nº11.653). The municipal MAPs from 2010 to 2013 were analyzed with respect to budget items related to solid waste management, as well as the policy indicators used to evaluate these initiatives.

The Municipal Sanitation Plans (MSPs) and Municipal Integrated Solid Waste Management Plans (MISWMPs) analyzed were published after 2012, and the MISWMPs from Ubatuba and Caraguatatuba were published in 2014. The aspects considered in the analysis were (1) if the diagnosis in the plan considered the population growth during high season and the kind of solid waste collected and disposed of; (2) if the municipality had a well-established recycling program; (3) if the municipality established a target for the plan; (4) if the municipality had adequate performance indicators.

2.3. Data Analysis

The analyses were based on qualitative parameters, and a general profile was drawn for each municipality based on the public policies, MAPs, MSPs, and MISWMPs (when available).

The indicators were classified and analyzed according to Mosse & Sontheimer (1996) and Greene & Tonjes (2014), evaluating if they were inputs or process indicators, and discussing their weaknesses and strengths.

3. Results

3.1. Landfill Crises on the North Coast of São Paulo

Inappropriate disposal of solid waste is a chronic problem in the region. Caraguatatuba and São Sebastião had their landfills classified as inadequate for the first time by CETESB (Companhia de Tecnologia de Saneamento Ambiental, or Environmental Sanitation Technology Company of the state of São Paulo) since the classification process started in 1997; Ilhabela had its landfill classified as inadequate for the first time in 1998; Ubatuba had its landfill classified as inadequate in 2000 (CETESB, 2012).

In 2008, a newspaper article appeared, with the headline “Collapse in the waste sector affects North Coast”. The article described the sanctions on all the landfills of São Paulo’s North Coast, since all of them were classified as inadequate. As a result, the municipalities began to export their solid waste to private landfills in other municipalities (Tremembé and Santa Isabel), which requires trucks to travel 100 to 200 km through mountainous areas[1]. Consequently, the cost of waste transport and disposal has increased.

Ilhabela was the first municipality to export its solid waste, in 2004, to a private landfill in Tremembé; next, in 2005 São Sebastião also sent its waste to Tremembé; Caraguatatuba began to send waste to a private landfill in Santa Isabel in 2007; and Ubatuba also began to send

[1] Folha de São Paulo (2008) - Colapso na área do lixo afeta Litoral Norte. Cotidiano: São Paulo, p. C1, 30 Nov. 2008.

its solid waste to Tremembé in 2008. In 2011, São Sebastião began to send part of its waste to a landfill in Santos (also a coastal city) (CETESB, 2012). Caraguatatuba sent its waste to Tremembé after the landfill in Santa Isabel was closed in 2012[2].

The waste is transported on trucks that travel on the main roads, the Tamoios Highway (SP-99) and the Rio-Santos Highway (SP-55 or BR-101). Many stretches of these roads are dangerous, steep, with sharp curves and no shoulders, which increases the risk of accidents. A survey of newspaper reports of accidents involving waste trucks in the region indicated that they are infrequent. However, these accidents do cause traffic jams and leachate.

These risks are continuing, with no prospects for improvement in the short term, even though they generate environmental problems and burden municipal budgets. After the publication of the National Solid Waste Policy, several new concepts and principles regarding regulation of the sector entered into force, including reverse logistics, waste hierarchy (reduction, reuse, recycling and disposal) and shared responsibility, all of which were novel features of Brazilian legislation. Municipalities with cooperative management systems (a consortium among municipalities in order to co-manage) had priority in receiving federal funding. This sort of consortium might be a possible alternative for the North Coast.

The four North Coast municipalities have been studying alternatives for cooperation in waste management since 1999 (Kaslauskas, 2001). According to Kaslauskas (2001), the region has a shortage of suitable sites for landfills because of its geographical features and the presence of Conservation Units. One suggestion was to construct a landfill in Caraguatatuba to receive waste from all four municipalities. The landfill was also planned to house a triaging area for recyclable materials[3]. The bureaucratic requirements for an environmental permit for the landfill are being analyzed by CETESB.

3.2. Implementation

3.2.1. Multiannual Plans

The administration of Caraguatatuba presented three programs focused on solid waste management. These dealt with the recovery of degraded areas (former landfill areas), implementation of municipal recycling, and appropriate disposal of solid waste. The indicators adopted in the MAP were based on the amount of funds invested in the program (Table 2). The amount reserved for these activities corresponded to 0.40% of the expected budget for the period (2010-2013), according to the municipal MAP.

The administration of Ilhabela presented two programs for solid waste management, one to provide resources for exporting waste, and the other to promote environmental education. The indicators adopted in the MAP were based on the amount invested and the maintenance of the program (Table 2). The amount reserved for these activities comprised 5.23% of the expected budget for the period (2010-2013), according to the municipal MAP. Although some of this amount was reserved for other actions linked to environmental preservation, such as protecting conservation areas, the largest proportion was related to solid waste management.

The administration of São Sebastião presented one program focused on solid waste management. The program's objective was to keep the city clean through street sweeping, waste collection and waste treatment. The indicator adopted in the MAP was based on the degree of satisfaction of the residents (Table 2). The amount reserved for these activities corresponded to 4.0% of the expected budget for the period (2010-2013), according to the municipal MAP.

The administration of Ubatuba presented one program focused on solid waste management, with a very broad objective of environmental protection. However, it specified landfill maintenance, waste transshipping, recycling and collection. The indicator adopted in the MAPwas based on the percentage of the program that was implemented (Table 2). The amount reserved for these activities corresponded to 6.28% of the expected budget for the period (2010-2013), according to the municipal MAP.

The amounts indicated in the MAPs were not necessarily invested, because of cost-containment provisions in the annual budgets (Table 2).

The indicators presented in the MAPs are performance indicators, focused on the human and financial resources invested in the programs, known as input indicators (Mosse & Sontheimer 1996). For a plan focused on the allocation of financial resources this is a very important monitoring device. However, the MAPs did not adopted indicators regarding the outcomes related to solid waste management.

3.2.2. Municipal Sanitation Plans and Municipal Integrated Solid Waste Management Plans

According to the analysis of the MSPs and the MISWMPs, all municipalities conducted some sort of evaluation, considering the difference between the

[2] G1 (2012) - Cetesb suspende licença de aterro sanitário, em Santa Isabel, SP. Mogi e Suzano. 14 Nov. 2012. Available on-line at http://g1.globo.com/sp/mogi-das-cruzes-suzano/noticia/2012/11/cetesb-suspende-licenca-de-aterro-sanitario-em-santa-isabel-sp.html.

[3] Folha de São Paulo (2003) - Aterro único do litoral será em Caraguá. Folha Vale: São Paulo, p. C3, 23 Jan. 2003.

Table 2 - Programs related to solid waste management in the municipalities of the North Coast of São Paulo State, in the Multiannual Plans from 2010-2013 (Lei nº 1.768, 2009; Lei nº 773, 2009; Lei nº 2012, 2009; Lei nº 3287, 2009).

Tabela 2: Programas relacionados à gestão de resíduos sólidos nos municípios do Litoral Norte de São Paulo, nos Planos Plurianuais de 2010-2013 (Lei nº 1.768, 2009; Lei nº 773, 2009; Lei nº 2012, 2009; Lei nº 3287, 2009).

		Caraguatatuba	
Program	**Amount (in BRL)**	**Indicator**	**Objective**
Recovery of degraded areas	1,992,500.00	- Material and heritage management (amount invested) - Services and Support Management (amount invested)	Implement a municipal program for recovery of areas degraded by inappropriate disposal of solid waste, as well as degraded areas affected by unregulated land occupation, through specific programs.
Recycle Caraguá	1,717,500.00	- Collection and implementation of recycling cooperatives (amount invested) - Communication plan for the new collection system (amount invested)	Implement an official system of sorting waste prior to collection, and minimize budget impacts from export of solid waste; social support for residents who make their living by collecting recyclable materials, and also promote correct sorting methods for recycling.
Solid Waste Center	1,500,000.00	- Construction of the Center (amount invested)	Develop an appropriate site for disposal of urban solid waste with construction of a processing plant, in order to improve the quality of recyclable materials.
Total	5,210,000.00		
		Ilhabela	
Program	**Amount (in BRL)**	**Indicator**	**Objective**
Municipal Waste Collection	10,020,000.00	- General investments (monthly amount) - Unit Maintenance (monthly amount)	Provide for operational needs and enable export of waste.
Environmental Preservation	10,810,000.00	- General investments (monthly amount) - Unit Maintenance (monthly amount)	Develop projects on environmental education, cleaning and conservation of protected areas.
Total	20,830,000.00		
		São Sebastião	
Program	**Amount (in BRL)**	**Indicator**	**Objective**
Clean City	76,607,440.25	- Degree of satisfaction of inhabitants (%)	Keep the city clean through waste collection, street sweeping and waste treatment
		Ubatuba	
Program	**Amount (in BRL)**	**Indicator**	**Objective**
Environmental Protection	52,924,697.50	- Maintenance and expansion (%) - Equipment and durable goods (%) - Materials and services (%) - Human resources and costs (%)	Support maintenance of the administrative units with environmental policy development; preservation; and maintenance of the landfill, waste transshipping, manure control, recycling, collection from domiciles and hospitals.

1 Brazilian Real (BRL) is equivalent to 0.45 US Dollars.

mean amount of waste produced during the high and low seasons, and the classification of solid waste with respect to the type of material, organic matter or recyclable items.

The daily mean amount of waste produced during the low seasons increases by around 30% during the high seasons in Caraguatatuba and São Sebastião, around 20% in Ilhabela, and around 90% in Ubatuba (Table 3). During holidays this increase can be even greater; the maximum values recorded in these municipalities were 86% in Caraguatatuba, 185% in Ilhabela, 115% in São Sebastião and around 300% in Ubatuba (Table 3). As a result of the increase in waste production during high season, the costs of disposal increase in the same proportion, as well as the effort required in collection and street sweeping.

Selective collection is offered to some degree by all municipalities. However, only Ilhabela and São Sebastião have well-established recycling programs, while Caraguatatuba and Ubatuba are in the initial stages of the project (Table 3).

The main objectives of the MSPs and MISWMPs of all the municipalities were related to providing universal service of regular collections and increasing the reuse of waste (recycling and composting) (Table 4). Caraguatatuba also included targets related to reducing inappropriate waste disposal and implementing reverse logistics for electronic waste (Table 4). The indicators to monitor the outcomes of the targets proposed are both absolute indicators, i.e. direct figure, taken from input-output analysis (e.g. tons of waste produced, tons of waste disposed inappropriately), and indexed indicators, i.e. indicators expressed as a percentage with respect to the total (e.g. percentage of residences with regular collection service, percentage of reuse of total collected solid wastes).

The performance indicators proposed by the plans for overall monitoring are mainly indexed indicators (Table 5). An important indicator is related to the landfill conditions, known as "Landfill Quality Index" or IQR, in the Portuguese acronym. The IQR is measured by CETESB, and classifies a landfill according to its general conditions and pollution monitoring. The landfill lifetime estimation is also important because it is derived from the projected amount of waste produced and the capacity of a landfill.

Despite the importance of landfills, the other indicators proposed are very important, such as the "Residence Solid Waste Reuse Indicator", which could indicate the percentage of waste sent for recycling or composting. The "Selective Collection Indicator" considers the percentage of residents covered by the selective collection.

4. Discussion

One of the reasons for the worldwide crisis in solid waste management is the prevailing waste disposal method, landfills. The major reason for the dominance of landfills is that this is a relatively simple, inexpensive and familiar method (Gray, 1997). This method requires large areas prepared to receive the waste, but these areas have a limited lifetime, so that in the medium to long term it is not an effective strategy for waste management (Gray, 1997).

There are also economic reasons to avoid landfills; they are wasteful of natural resources. According to Gray (1997), landfilling not only buries materials that have

Table 3: Diagnostic data related to solid waste management in the municipalities of the North Coast of São Paulo.

Tabela 3: Dados diagnósticos relacionados à gestão de resíduos sólidos nos municípios do Litoral Norte de São Paulo.

	Caraguatatuba[1]	Ilhabela[2]	São Sebastião	Ubatuba
Maximum Amount of Waste Produced in holiday periods (tons/day)	200	80	250[6]	318[5]
Mean Amount of Waste Produced in High Season (tons/day)	139	33	150[6]	155[4]
Mean Amount of Waste Produced in Low Season (tons/day)	107	28	116[6]	80[4]
Mean landfill cost (BRL/tons/month)	200	156	156[6]	156[4]
Mean waste removal cost per month in High Season (BRL)*	834,000.00	140,400.00	702,000.00 [3]	725,400.00[4]
Mean waste removal cost per month in Low Season (BRL)*	642,000.00	48,204.00	542,880.00 [3]	374,400.00[4]
No. of trucks (High Season)	-	-	-	14[5]
No. of trucks (Low Season)	11	7	18[3]	9[5]
Selective Collection	No	Yes	Yes[3]	No[5]

*1 Brazilian Real (BRL) is equivalent to 0.45 US Dollars.

1- MISWMP Caraguatatuba; 2 – MISWMP Ilhabela; 3 – MSP São Sebastião; 4 – MISWMP Ubatuba; 5 - MSP Ubatuba; 6 – Jung, 2012

Table 4: Main objectives, targets and indicators used in the MSPs and MISWMPs.

Tabela 4: Principais objetivos, metas e indicadores usados nos Planos Municipais de Saneamento e nos Planos Municipais de Gestão Integrada de Resíduos Sólidos.

Municipality	Objective	Target	Indicator
Caraguatatuba[1]	Universal regular collection services	100% of the population served by the waste collection	Regular collection service
	Increase the reuse* of waste	60% of the waste will be reused in 2018	Residence solid waste reuse indicator
	Total treatment of waste	Reduce inappropriate disposal of waste by 70%	Amount of waste disposed inappropriately
		Implement reverse logistics for electronic waste	Businesses committed toreverse logistics
	Reduce waste production	Reduce waste production by 15%	Amount of waste produced
Ilhabela[2]	Universal regular collection services	100% of the population to receive waste-collection services	Regular collection service
	Increase the reuse of waste	60% of the waste will be reused in 2015	Residence solid waste reuse indicator
São Sebastião[3]	Universal regular collection services	100% of the population to receive waste collection services	Regular collection service
	Increase the reuse of waste	60% of the waste will be reused in 2018	Residence solid waste reuse indicator
Ubatuba[4]	Universal regular collection services	100% of the population with waste-collection services	Regular collection service
	Increase the reuse of waste	60% of the waste will be reused in 2020	Residences solid waste reuse indicator

1 - MISWMP Caraguatatuba; 2 MSP Ilhabela; 3 - MSP São Sebastião; 4- MISWMP Ubatuba.

* Reuse includes composting and recycling

some value and causes environmental problems (i.e. leachate, green gas emission, local impacts), it also means that fresh materials and energy are required, with all the environmental consequences and costs associated with resource exploitation, energy generation and manufacturing processes. There are also other problems related to landfills, including the shortage of suitable sites and rising costs imposed by the transport and landfill costs (Gray, 1997).

In many cities in developed countries, the landfill crisis started in the 1970s and continued during the 1980s and 1990s (Gray, 1997; Wagner, 2007; Sidique *et al.,* 2010). As a result, these cities have been changing the waste paradigm in recent decades. Most of them have established the waste hierarchy (i.e. reduce, reuse and recycle, in order of importance) as a guideline for waste management (Gray 1997; Wagner, 2007). In these countries, waste management is framed as a sustainability issue, and focuses on environmental impacts and benefits of the waste management strategies (Greene & Tonjes, 2014).

On the other hand, most developing countries still dispose of their solid waste in landfills that are not constructed to prevent soil and water contamination (UN-HABITAT, 2010). They also lack infrastructure and services related to waste management, as well as other sanitation sectors (water supply, sanitation facilities, drainage, urban roads, land management) (Abdrabo, 2008; Buenrostro & Bocco, 2003; Choguill, 1996). In other words, solid waste management in developing countries is mainly framed as a public health issue, instead of an environmental issue as well.

Brazilian Solid Waste Policy is attempting to introduce the practice of waste hierarchy in Brazilian solid waste management, to reduce the amount of waste sent to landfills. However, as the example of the North Coast of São Paulo showed, this is not an easy task. The main focus of the solid waste management plans and indicators on the north coast of São Paulo is related to landfills (e.g. Landfill Quality Index). For this reason, in the medium term, these municipalities' main strategy is to install a new landfill in Caraguatatuba.

Table 5: Main indicators proposed in the MSPs.
Tabela 5: Principais indicadores propostos nos Planos Municipais de Saneamento.

Solid Waste Management Indicators	Definition	Indicator Classification**
Street Sweeping Service Indicator	Considers the percentage of the total length of paved streets with sweeping service.	Indexed indicator
Regular Collection Service	Considers the percentage of residences with regular collection service.	Indexed indicator
Selective Collection Indicator	Considers the percentage of residences with selective collection.	Indexed indicator
Residence Solid Waste Reuse Indicator	Considers the percentage of reuse of total collected solid wastes.	Indexed indicator
Residence Solid Waste Final Destination Indicator	Considers the conditions of the landfill that receives the Municipal Solid Wastes.	—
Treatment and Final Disposal Saturation Indicator	Considers the remaining lifetime of the available landfill sites.	—
Industrial Solid Waste Reuse Indicator	Considers the percentage of reuse of total collected Industrial solid wastes.	Indexed indicator
Industrial Solid Waste Final Destination Indicator	Considers the conditions of the landfill that receives Industrial Solid Wastes.	—
Health Services Waste Management Indicator	Considers the conditions of the Health Services wastes treatment and disposal	—

* Reuse includes composting and recycling
** ISO14031

Appropriate disposal of waste is very important. Nevertheless, are the other management options in the waste hierarchy being adequately targeted and encouraged? The analysis of the targets and indicators suggested that the investments in other management options, such as reduction of waste production and recycling initiatives, were considered in the municipal plans and even have process indicators related to them. Nevertheless, only two of the four municipalities have well-established recycling programs; and reduction initiatives are cited only in the Caraguatatuba plan. This is very serious for municipalities that are passing through a landfill crisis, with wide seasonal changes in population. Reducing, composting and recycling should be considered at least as important as landfills.

One of the reasons for the more sustainable options in waste management not being strongly targeted, as noted by Moghadam *et al.* (2009), is because politicians give a low priority to solid waste management compared to other municipal activities. Zotos *et al.* (2009) noted that local authorities occupy a key position in supporting sustainable development, but the often fragmented local approach to problem-solving is frequently inadequate for designing and implementing large-scale projects.

The local authorities also give little attention to the role of the citizenry in managing solid waste. As noted by Guerrero *et al.* (2013), the operational efficiency of solid waste management depends upon the active participation of both the municipal agency and the citizens.

ticipation of both the municipal agency and the citizens. The participation of local people in decision-making is essential (Sharholy *et al.*, 2008). Administrators should involve the citizens more closely in the planning process, and also request their collaboration in reducing solid waste and in separating recyclable items at the source.

Another important issue is the wide seasonal population variation, which involves a huge increase in waste generation and the need to involve and properly inform tourists about the waste management routine, to encourage them to reduce, reuse and recycle.

5. Conclusions

The National Policy on Solid Waste mentions the need for integrated management, pressing the municipalities to prepare their Municipal Solid Waste Plans and search for cooperative solutions, adopt policies for waste reduction, recycling and composting, with only the non-recyclable refuse destined for landfills. However, the analysis of the North Coast showed that the main discussions, actions and indicators still focus on disposal. This situation reflects the difficulties faced by other coastal municipalities in Brazil, and is one of the main sources of pollution in watersheds and marine environments, due to the diffuse contamination caused by waste mismanagement.

The solid waste management situation in the cities of the North Coast of São Paulo is quite advanced compared to cities in other developing countries and even to other Brazilian cities. Waste is disposed in appropriate sites (landfills), nearly 100% of the population has a waste-collection service, and at least two municipalities (São Sebastião and Ilhabela) have a well-established recycling program. However, some key issues are critical to the development and improvement of solid waste management in these cities: (1) the main focus of the plans and future prospects is landfills; (2) there are only a few outputs and outcome indicators related to MSW-Municipal Solid Waste; (3) recycling is not well served; and (4) there are no established indicators regarding the amount of waste recycled.

A change in this picture will require reframing of the problem by the local and state administrations, as well as a change in commitment of public administrators and in the involvement of local residents, who must track the public investments and demand transparency from governments in the implementation, accountability, and use of proper indicators in the programs. Maintaining channels of communication with tourists is also a key point to encourage them to cooperate with the solid waste management routine. The engagement of the local residents in the municipal environmental councils should be encouraged, where they can propose changes in environmental policies, rethinking not merely the solid waste management issue, but also citizen participation.

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Long-term morphological evolution of urban pocket beaches in Montevideo (Uruguay): impacts of coastal interventions and links to climate forcing*

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ABSTRACT

Two pocket beaches, Ramírez and Pocitos (Montevideo, Uruguay) are analyzed to assessing their evolution (erosion/accretion) associated with human interventions and climatic forcings from 1927-2008. A multitemporal study was conducted using GIS, long series of aerial photos, satellite imagery, survey of historical background, and statistical analysis. Qualitative indicators of the stability of the beach area are proposed. The relevance of this methodology is analyzed on beaches whose fluctuations tend to mask their long-term evolution. Both beaches remain relatively stable but fluctuating since 1927, with slight loss of surface, especially in Ramírez. The influence of the following factors is discussed: i) human interventions; ii) ENSO events; iii) storm surges; iv) changes in beach area according to the Bruun rule and rising sea level in Montevideo. Although the four of them appear to have acted in different periods, the evidence is not conclusive regarding their relative quantitative importance. This article highlights the importance of using long series of remote sensing and historical analysis to interpret processes linked to inertia of the past in environments that have been modified from longstanding. The trend analysis of these two urban pocket beaches allows to infer that their resilience has not been affected yet, which would allow them to face not extreme climatic stressors. For the purpose of better management it is recommended to: i) conduct continuous monitoring; ii) minimize the actions of mechanized cleaning and sand losses by leakage or removal; iii) implement the reconstruction of natural structures such as primary dunes; and iv) apply the methodology explained in this paper in other Montevideo urban beaches to better understand the climate forcings.

Keywords: Remote sensing, sandy beaches, coastline *proxy* records, erosion/accretion, omega parameter, coastal management.

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RESUMO[§]

Evolução morfológica de longo prazo das praias urbanas de bolso de Montevidéu (Uruguai): impactos das intervenções costeiras e relações com as forçantes climáticas.

Duas praias de bolso, Ramírez e Pocitos (Montevideo, Uruguai) foram analisados para avaliar a sua evolução (erosão / acreção) associado a intervenções humanas e forçantes climáticas durante o período 1927-2008. Para tal, desenvolveu-se estudo multitemporal utilizando GIS, uma série longa de fotos aéreas, imagens de satélite, exame dos antecedentes históricos, e análise estatística. São propostos indicadores qualitativos da estabilidade da praia. A relevância da metodologia utilizada é analisada em praias cujas variações tendem a mascarar a sua evolução a longo prazo. Ambas as praias permaneceram, desde 1927, relativamente estáveis, embora com variações e ligeira perda de superfície, especialmente a praia de Ramirez. Neste artigo é discutida a influência dos seguintes fatores: i) intervenções humanas; ii) eventos de El Niño; iii) temporais; iv) mudanças na praia de acordo com a regra Bruun e elevação do nível do mar, em Montevidéu. Embora os quatro fatores referidos tenham atuado em diferentes períodos, as evidências não são conclusivas quanto à sua importância quantitativa relativa. O artigo destaca a importância da utilização de séries longas de sensoriamento remoto e da análise histórica na interpretação dos processos ligados à inércia do passado em ambientes que foram modificados desde há muito. A análise de tendências destas duas praias urbanas de bolso permite inferir que a sua resistência ainda não foi afetada, o que lhes permitiria enfrentar os estressores climáticos extremos. Com o objetivo de conseguir uma melhor gestão, recomenda-se: i) realizar monitoramento contínuo; ii) minimizar as ações de limpeza mecanizada e as perdas de areia por vazamento ou remoção; iii) implementar a reconstrução de estruturas naturais, como dunas primárias; e iv) aplicar a metodologia apresentada neste artigo noutras praias urbanas de Montevidéu para compreender melhor as forçantes climáticas.

Palavras-chave: *sensoriamento remoto, praias de areia, indicadores da linha de costa, erosão / acreção, parâmetros omega, gestão costeira.*

1. Introduction

Beach erosion is a serious world-wide problem; according to Bird (1985), at least 70% of sandy beaches are recessional. From the 1990s, this finding has driven to the achievement of long-term studies, in some countries taking advantage of the existence of high-resolution images (from *circa* 1930) and cartographic precision surveys (since the late nineteenth century). The relationship between trends and natural or induced events has allowed to understand the processes involved in each case, and develop baseline scenarios (i.e., Dias *et al.*, 2000; Ferreira *et al.*, 2006; Dolch, 2010; Baptista *et al.*, 2011; Klemas, 2011; Pilkey *et al.*, 2011; Sato *et al.*, 2011; Almeida, 2012; Freitas & Dias, 2012; Echevarría *et al.*, 2013; Ribeiro *et al.*, 2013; Splinter *et al.*, 2013).

Achieving integrated coastal management of beaches is a global aspiration because of their vulnerability, ecological and heritage value, and the mounting pressure on the ecosystem driven by the steady increase in the population settled in coastal areas over the past few decades (Brown & McLachlan, 2002).

Modification of coastal ecosystems and increased pressures on the resources that sustain their structure and function, should be seen as a global problem, as these ecosystems are of fundamental importance, providing various goods and services that directly contribute to socio-economic development defined by the Millennium Ecosystem Assessment (2005) as the direct or indirect benefits that humans obtain from ecosystems.

Thus, healthy and functional beaches provide various ecosystem services, which can be grouped into three main functions: provisioning, regulating and cultural. However, these ecosystems have been modified and adapted by direct or indirect human interventions, which ultimately affect the system's capabilities to provide these services and therefore support social welfare.

In this article, the concept of ecosystem services is the framework of our research and hypotheses. Therefore, the focus is on the surface of the beach and not only in the behavior of the coastline.

Despite the interest in beach conservation, management successes have been few, and since the 1980s widespread erosion of beaches (Bird, 1985) has increased due to Land Use Change (civil construction, real estate pressure, aggregate extraction), or simply by gradual depletion of circulating sand. These changes are enhanced by the effects of climate change such as rising sea levels, and increased frequency and intensity of storms (Nordstrom, 2004).

Causes of successive failures are multiple, but two can be highlighted: firstly the lack of knowledge of the long-term dynamics of each particular beach (Carter, 1988) and secondly, the multiplicity of jurisdictions and interests acting in this complex system. In Uruguay in particular, during the twentieth century, human interventions have changed the coastal morphology and dynamics, while in parallel the beaches began to show erosion and retreat of the coastline was observed (Panario & Gutiérrez, 2006).

According to Dias *et al.* (2012) in order to adopt corrective measures and an effective coastal zone management, it is essential to understand the current situation.

[§] Abstract and captions tranlation to Portuguese on behalf of the Editorial Board

This analysis focuses on two beaches, Ramírez and Pocitos at Montevideo, the capital city of Uruguay and home to a million and a half inhabitants. Both beaches have economic importance as areas for recreation, tourism, culture, and as iconic symbols. The intensity of use in both beaches led to a loss of their natural structure, leaving only sand surfaces bordered by a waterfront promenade, called "Rambla Costanera" or simply "La Rambla", which is the most popular ride in the city.

Because of their importance, these beaches have been certified for bathing, according to ISO 14001 standards by the municipal government of Montevideo (IdeM). These standards require the implementation of a continuous improvement process. Therefore, a retrospective analysis was performed in order to: i) depict the historical evolution; ii) project trends of erosion-accretion, taking advantage of the existence of a large number of remote sensing images; and iii) establish management recommendations.

The trends and drivers of the historical evolution of the beaches are analyzed from the extensive series of vertical aerial photographs since 1927, old maps, chronicles of physical and climatic databases over time using statistical indicators and various indicators of changes in the coastline. So the relevance of the method of long multi-temporal analysis (1927-2008) is tested on beaches whose fluctuations tend to mask long-term trends.

2. Study area and characterization

2.1. The Beaches

Ramírez and Pocitos are two urban pocket beaches located opposite each other, on a headland. They are oriented NNE-SSW, the former to the east side and the latter to the west side of the bow (Figure 1). This coast is a microtidal environment (amplitude less than 50 cm, Verocai *et al.*, 2015), wave-dominated (significant wave height [Hs]: 0.54 m; wave period [T] 5.66 s) and located in the middle region (brackish waters) of the Río de la Plata river estuary.

Ramírez is a dissipative beach with a convex profile bounded by two headlands (Figure 2a), a gentle slope (1.9°) that accentuates to the north end with a maximum of 2.7 degrees between 0.5 and 1.5 m water level amsl (meters above mean sea level reference = 0.91 m), with wet and dry sectors 10-15 and 65 m wide respectively, measured in its middle section, with a coastline of 500 m. As a particular feature, Ramírez exposes more than 100 m of additional beach during ebb, composed of sediments enriched with dense minerals.

Pocitos is also bounded by two headlands (Trouville and Kibón). It is a sandy beach convex toward the berm (Figure 2b), with a gentle slope (1.8°), which is accentuated to the north end (2.6° between water levels 0.5 and 1.5 m), concomitant with its northward evolution from a dissipative beach into an intermediate one. This beach has a wet area of 10 to 15 m width at its middle zone and a dry width of 65 m. The coastline is 1,427 m length. Both beaches are bounded by the wall of the waterfront, which is semicircular in Ramírez, and both lack the primary dune. The sediments of Pocitos and Ramírez beaches originate from different sources: estuarine sands and gravels, subrecent autochthonous alluvium, erosion of the crystalline basement debris and bioclastic material (shells). These sediments are partially re-transported by runoff, human action in mechanized maintenance, and wind action with sand losses to the mainland (roads).

2.2. Issues and Background

a. Ramírez Beach

Maps by the British Navy (years 1849 and 1883) and the French Navy (1867) indicate that Ramírez was wider and extended to the NW about 800 meters (about twice as long as by 2008), and seaward about 200 meters (twice the width remaining in its current location) (Figure 3). The survey of the IdeM (25/07/2007 manzanas.dwg, file) included cadastral references that are now located under water on this beach.

Ramírez beach was probably used as one of the primary sources of sand for construction of Old Montevideo and later the surrounding neighborhoods, as was subsequently Pocitos, once the expansion of the city reached its vicinity. In particular, in the early 1960s, according to MTOP/PNUD/UNESCO (1979) Ramírez was used as a source of sand to make an attempt to nourishment of Pocitos beaches.

Ramírez suffered significant erosion before 1927, leaving a surface enriched with sandy heavy minerals, which explains the slope of the beach. An area located to the NW was covered by the construction of the southern waterfront promenade, and the fill material was sand dredged from the offshore vicinities, which reduced the stock of nearshore sediment available in this area.

In photographic records of 1927 and 1929, a retreat of 200 meters had already occurred. The chart of the Military Geographic Service (published in 1929) based on surveys conducted in 1920, recorded this shoreline retreat with a configuration similar to the present. In turn, the image of 1927 presumably reflects the effect of extreme storm surges that occurred in 1923 and 1924, a feature clearly documented in the existing iconography. The storm surge of July 1923 was the strongest ever recorded since the beginning of measurements in 1898 (Verocai *et al.*, 2015) with a water level of 3.39 m amsl and an estimated return period of 821 years (MTOP/PNUD/UNESCO, 1979). The storm surge of

Figure 1 - Location of the urban pocket beaches Ramírez and Pocitos, metropolitan area of Montevideo, Uruguay.
Figura 1 – Localização das praias urbanas de bolso, Ramírez and Pocitos, na area metropolitana de Montevideo, Uruguay.

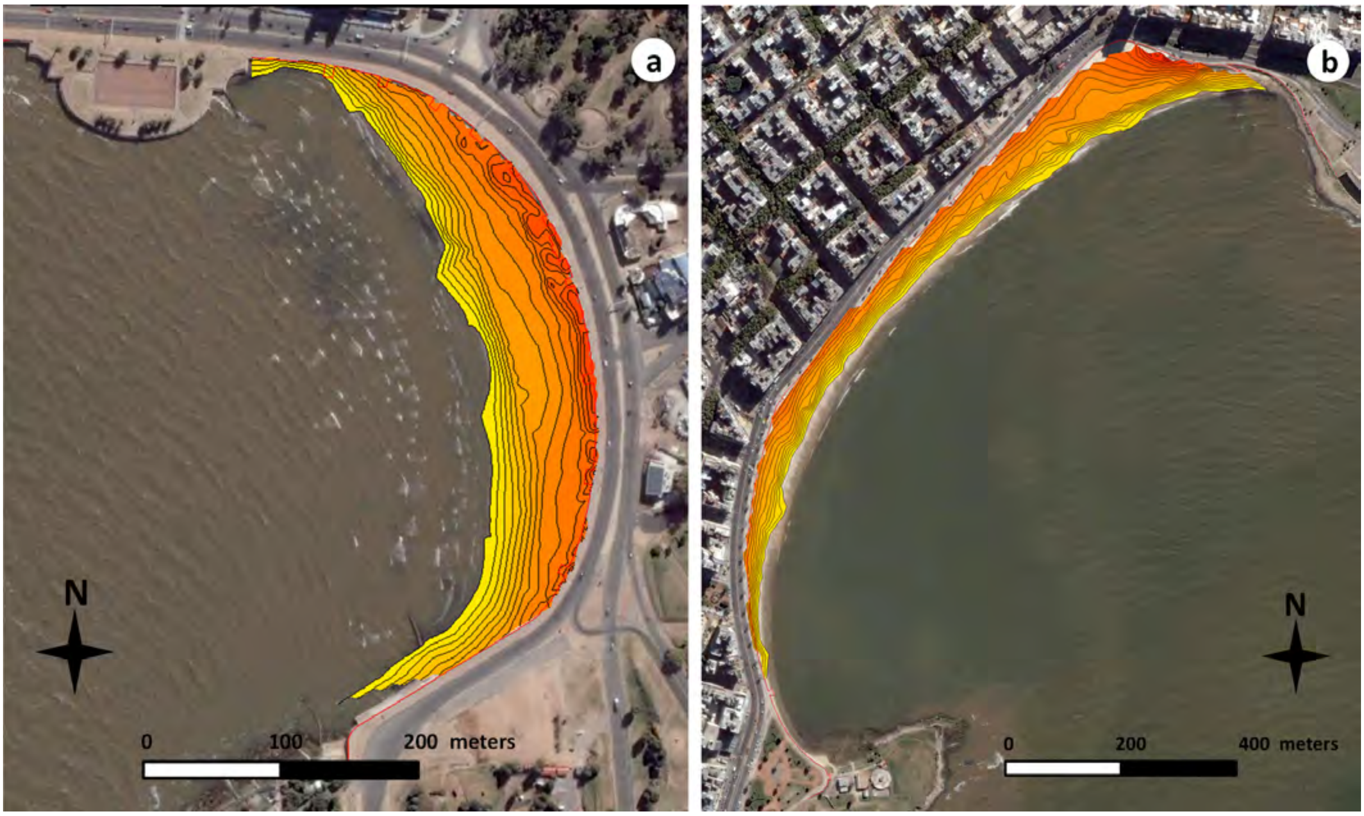

Figure 2 - Digital elevation models of (a) Ramírez and (b) Pocitos beaches. Contour interval is 20 cm.

Figura 2 – Modelos digitais do terreno das praias de (a) Ramírez e (b) de Pocitos. Equidistância: 20 cm.

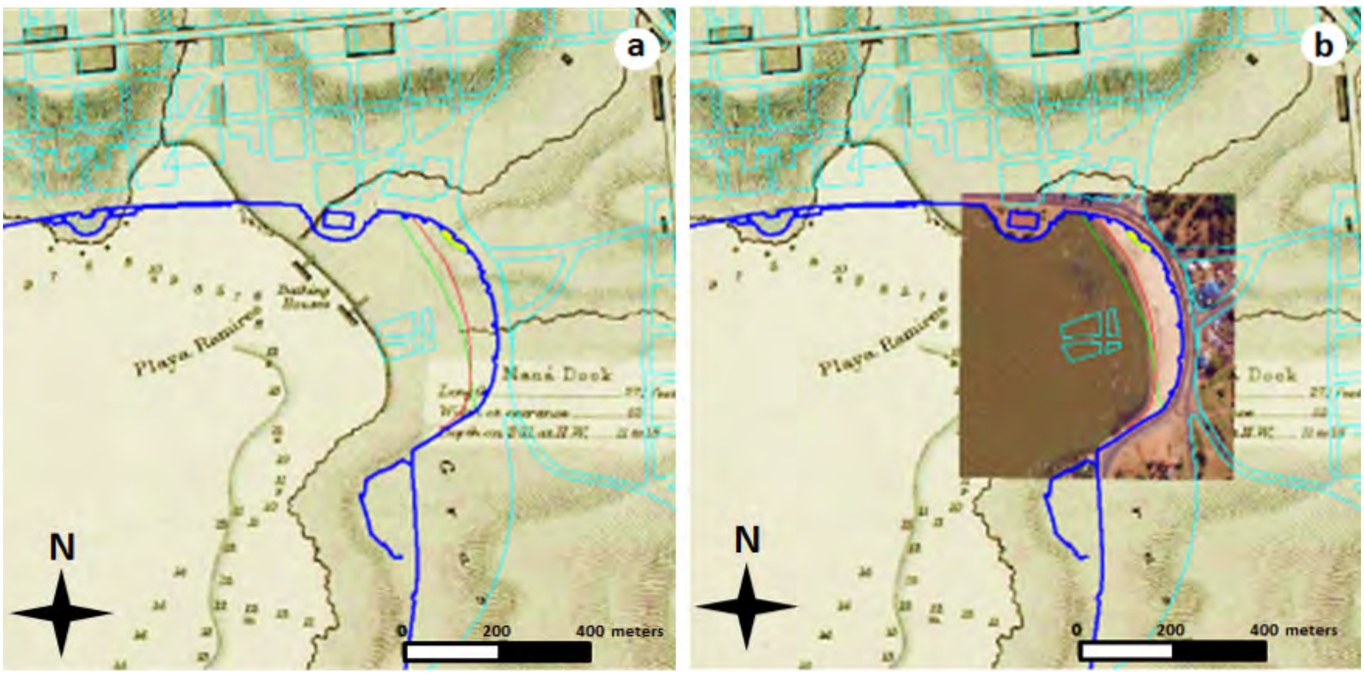

Figure 3 - a) Current location of the coastline of Montevideo overlapped over the old map of Montevideo (Royal Navy, 1849). The current urban blocks (turquoise), the waterfront (“La Rambla”, in blue), the coastline according to WDL-RM at 1927 (green) and 2008 (red). The location of some urban blocks is on the beach. b) The same composition, but with the superposition of the April 2008 image. Note in this case, the location of urban blocks under water.

Figura 3 – a) Localização actual do litoral de Montevidéu sobreposto a um antigo mapa de Montevidéu (Royal Navy, 1849). Os atuais blocos urbanos (turquesa), a beira-mar ("La Rambla", em azul), o litoral de acordo com WDL-RM em 1927 (verde) e em 2008 (vermelho). A localização de alguns blocos urbanos situa-se na praia. b) A mesma composição, mas com a sobreposição da imagem de Abril de 2008. Neste caso, alguns blocos urbanos situam-se debaixo de água.

January 1924 reached a water level of 2.19 m amsl (MTOP/PNUD/UNESCO, 1979; modified from the database of the Directorate of Oceanography, Meteorology and Hydrography of the Navy-SOHMA). The 1923 storm had winds of over 150 km/hour. This storm devastated the south coast of the city, which was reported by the press: "All the (South) Rambla has disappeared as well as the resorts of Ramírez and Pocitos" (El País Newspaper the day after the storm surge).

The cartographic documentation hiatus between 1886 and 1920 has not allowed generating a reconstruction of the rhythms of intense erosion process verified over that period, or specifying their causes.

The existence of a dune field is reflected in old place names (e.g., Road to the Dunes: "Camino a los Médanos"). The recirculation of this sand dune field originated from the mouths of the two creeks that existed on this beach. This recirculation was stopped early (late nineteenth century), when the waterfront promenade "La Rambla" was built, encircling the arc of the beach. This first layout of the waterfront at Ramírez beach, confined the beach to a well constrained arc. Such intervention modified the beach, dividing what was originally a functional unit, consisting of an arc of beach with the presence of a small tombolo near his its southern end. Subsequently, the northwest beach portion was filled, with the promenade (public walk), which was built gaining land to sea.

The arc of beach on the outside did not encompass the shape as was the original natural setting, because the new beach had a greater curvature. Since then the storm waves concentrate at both ends.

b. Pocitos Beach

The geomorphological changes documented in Pocitos beach have also been dramatic. Near the mid-nineteenth century there were dunes up to 10 meters high, and a beach prism several meters higher than the current situation (Ros, 1923; García-Moyano, 1969; Barrios-Pintos, 1971). These dunes were removed along with beach sand, to be used for construction (Ros, 1923; García-Moyano, 1969). This activity severely affected the amount for the beach sediment budget, to the extent that the foundations of houses were seen during an extreme low water event in the early twentieth century (Ros, 1923).

At the beginning of the twentieth century, three creeks flowed into this beach, but when the southern stretch of the waterfront was built in 1912, the creeks were encased and diverted. This original waterfront protruded into a section of beach and divided it into two sections (See Supporting Information SI.1c). At that time a large building ("Hotel de los Pocitos") was built on the beach, but was demolished in 1935, after being affected by the extreme storm surge in 1923. The 1927 photo shows only the Pocitos creek (See SI.1b), which in 1945 (See SI.1a) had also been encased and widened, cutting the recirculation of sand dune fields through its mouth. By 1950, the layout of "La Rambla" was rectified to its present form, and the surface of dry beach located in the NE sector was artificially extended.

Prior to the construction of "La Rambla", the beach was wider, from 40 to about 80 meters (based on an accurate survey conducted for the "Sanitation Project of the Pocitos Creek Basin", García, 1908). Also in that time, the prism of the beach was approximately two meters higher than present (Figure 4), whereas the prism now fluctuates around 60 cm thick above a layer of reworked Pleistocene sands. By the time of the photographic record of 1927, it had already occurred a widespread retreat of the coastline (See Supporting Information SI.2).

Despite the importance of beaches in the social imaginary for Uruguay, there is only one systematic study of beaches (MTOP/PNUD/UNESCO, 1979), which includes a reference to Pocitos and the recommendation for a refill of sand, and an article from Saizar (1997) which predicts its evolution using the Bruun's Rule.

3. Materials and methods

A multi-temporal analysis was undertaken, using remote sensing from 1927-2008, GIS techniques and historical information. A total of 23 and 21 aerial photographic surveys (1927-2008) were analyzed for Ramírez and Pocitos respectively (Table 1), obtained from the archives of the IdeM, the National Directorate of the Environment (DINAMA), the Military Geographic Service (SGM), and Google Earth satellite images. To better understand the long-term morphological changes, maps of the nineteenth and early twentieth centuries were also included, which have acceptable accuracy.

The series of aerial photographs was scanned at 1200 dpi, and the Google Earth images were downloaded in the best possible resolution. ArcGIS 10 was used for georeferencing, which was carried out using a detailed mapping of the wall of the waterfront surrounding both beaches made by the Department of Geomatics of the IdeM. This map was made by orthorectification and checkpoints from differential GPS with sub-meter relative accuracy, allowing to minimize errors between images. An accuracy of one pixels is assumed for the imaging georeferencing process. The UTM (Universal Transverse Mercator) Zone 21S projection and WGS84 datum was used.

Shorelines were digitized on screen using a constant scale of 1:3000 to standardize the procedure, according to Ciavola *et al.* (2003), Gutiérrez & Panario (2005) and Armaroli *et al.* (2006). The landward limit of the beach

Figure 4 - Contours digitized every 1 meter (made in 1906 for the “Sanitation Project of the Pocitos creek Basin”; García, 1908) superimposed on an image of 2007. The red line is the location of the current waterfront and the turquoise line shows the previous high tide high water level (PHTH-WL). Note the increased height and width of the beach shoreline in 1906 compared to 2007 (Source: Image-2007, IdeM).

Figura 4 – Linhas de nível digitalizadas a cada metro (feito em 1906 para o "Projeto de Saneamento da Bacia do riacho Pocitos"; García, 1908) sobreposta a uma imagem de 2007. A linha vermelha corresponde à localização do cais atual e a linha turquesa traduz o nível máximo da maré cheia (PHTH-WL). É de ressaltar a grande altura e largura da praia em 1906 comparativamente à de 2007 (Fonte: Imagem-2007, IdeM).

Table 1 - List of imagery. Image availability is highlighted in green.
Tabela 1 - Lista de imagens. A disponibilidade das imagens está realçada a verde.

Date *	Source	Original scale	Ramírez	Pocitos
1927, March 16	DINAMA	1/8.000		
1929, March 21	SGM	1/7.500		
1939	IdeM	1/5.000		
1942, November 25	DINAMA	1/7.300		
1945, January	IdeM	1/10.000		
1949	DINAMA	?		
1954, May 14	IdeM	1/15.000		
1954, May 17	IdeM	1/30.000		
1961, December 13	IdeM	1/15.000		
1961, December 21	IdeM	1/15.000		
1965, October 26	IdeM	1/10.000		
1966, January 26	SGM	1/20.000		
1970, July 21	IdeM	1/7.500		
1970, August 21	IdeM	1/7.300 y 1/10.000		
1970, December 07	IdeM	1/10.000		
1971, May 01	IdeM	1/10.000		
1975, January 29	IdeM	1/10.000		
1979, March 29	IdeM	1/10.000		
1983, February 12	IdeM	1/12.000		
1985, December	IdeM	1/10.000		
1991, May	IdeM	1/5.000		
1996, June	IdeM	1/40.000		
2000, September 22	Google Earth			
2001 August 09	Google Earth			
2002, September 21	Google Earth			
2003, October 23	IdeM	1/10.000		
2004, May 28	Google Earth			
2005, November 27	Google Earth			
2006, September 6	Google Earth			
2006, September 24	Google Earth			
2007, September 29	IdeM	1/10.000		
2007, December 8	Google Earth			
2008, April 30	Google Earth			
Totals of available imagery for each beach:			**23**	**21**

* Detailed dates of the images are not always available.
Abbreviations:
IdeM: municipal government of Montevideo;
DINAMA: National Directorate of the Environment;
SGM: Military Geographic Service.

was defined as the wall of "La Rambla", as it has historically functioned as the limit of the active littoral zone, defined here as the area where sediment exchanges between the beach and the nearshore occur.

Different proxy records were explored as indicators of coastline (Boak & Turner, 2005) in order to interpret the responses of the system, i.e., *i*) the previous high tide high water level - PHTH-WL (Boak & Turner, 2005; Moore *et al.*, 2006) and, *ii*) in order to evaluate the consistency of the results, the wet/dry line or run-up maxima - WDL-RM (Boak & Turner, 2005; Dolan *et al.*, 1978, 1980; Overton *et al.*, 1999). For the studied beaches, and in agreement with Boak & Turner (2005), both lines are clearly distinguishable from the other. The PHTH-WL is identified by the marks left by the tide (i.e. plant debris), and WDL-RM can be distinguished by the wet-dry sand contrast.

Due to the small size of the beaches and the multi-temporal evolution of the accretion and retreat of the coastline, a beach polygon (area) was drawn as proposed by Gutiérrez & Panario (2005) which is defined by each coastline proxy in each of the images and the corresponding landward limit. This procedure allows reducing uncertainty, since the surface is equivalent to infinite transects (method commonly used for these studies), and ultimately, the beach area is the parameter of greatest socio-economic, ecological and management interest.

It was calculated the percentage difference between the largest/smallest area for Ramírez and Pocitos beaches from 1927 to 2008 and their current areas.

An artifact called "*landward limits of the beach in 1927*" (L27) was used in Pocitos beach, where the landward limit of the beach was defined on the basis of its configuration in 1927, in order to know the trend, regardless of public works that expanded their area (creek diversion and re-alignment of the coast). A second artifact called "*landward limits of the beach in 2008*" (L08) was used, where the landward limit is the current (2008) spatial configuration.

The analysis included the long-term fluctuations of the beach area, especially the reductions, which were evaluated against freshwater and sea levels increases in the Río de la Plata river estuary produced by the great floods of the rivers Paraná and Uruguay (combined or separated), the time-series of severe storm surges, and the occurrence of El Niño Southern Oscillation (ENSO) El Niño and La Niña anomalies. Data for sea-level and storm surges at Montevideo (brackish waters) and river flow at the middle Río de la Plata river estuary are provided for the studied period (1928-2008) by the Uruguayan *Servicio de Oceanografía, Hidrografía y Meteorología de la Armada* (SOHMA) and the Argentinean *Instituto Nacional del Agua y el Ambi*ente (INA) respectively.

Mineralogical analysis of the subaerial and subacuatic sediments of Ramírez and Pocitos beaches was conducted.

For Ramirez beach the Dean´s dimensionless parameter Ω (Hb / wf . T) was calculated where Hb is the significant wave height, wf is the sediment fall velocity and T is the wave period, applied as proposed by Wright & Short (1984).

A simple regression statistical analysis is performed using R-CRAN statistical (R Core Team, 2013) software to calculate the model parameters of sand surface evolution. The assumption of normality and randomness was previously evaluated (See Supporting Information SI.I and SI.II). The Anderson-Darling test for normality was conducted on the surfaces value series and a run test was applied with PAST 1.96 (Hammer *et al.*, 2001).

The run test analysis is a non-parametric test for values obtained in time sequence to analyze randomness of events. The data set was transformed by subtracting the average, to obtain positive and negative numbers. This test was used because the data are not continuous by nature, since the flights were not planned for the systematic survey of the morphological evolution of beaches and that despite their statistical significance, the small magnitude of the changes could introduce uncertainty about the randomness of trends.

4. Results and discussion

4.1. Evolution of Ramírez beach

To analyze Ramírez beach, the start date was set at the date of the first image available (1927), when the arc of beach was similar to the current one.

Using a first series of 16 images (1927-2007), the evolution of the coastline according to PHTH-WL and WDL-RM indicators showed a weak significant trend of loss of surface ($p < 0.19$) (Figure 5a and 5b). Then, with a second series of 23 images (1927-2008), the analysis was completed (Figure 5c) and, given the similarity of results obtained, WDL-RM was the only one used as the proxy because it was best expressed in the time-series resulting in a tendency to a significant surface loss with $p < 0.02$. Some of the early records were removed (Figure 5d), based on the assumption that the image of 1945 (there are no records between 1927 and 1929) was shaped more like the present form. Before 1927, the most intense storms ever recorded occurred in Montevideo in 1923, and after the image of 1929, a prominent structure was built in the north end that changed the circulation patterns of sand sediment; hence the images of 1927 and 1929 were excluded.

Since 1927, there was an increase in the area of the arc of the beach until 1961 (maximum increase), possibly recovered from the impact of storm surges of 1923 and 1924. Since 1945, the beach has had the current con-

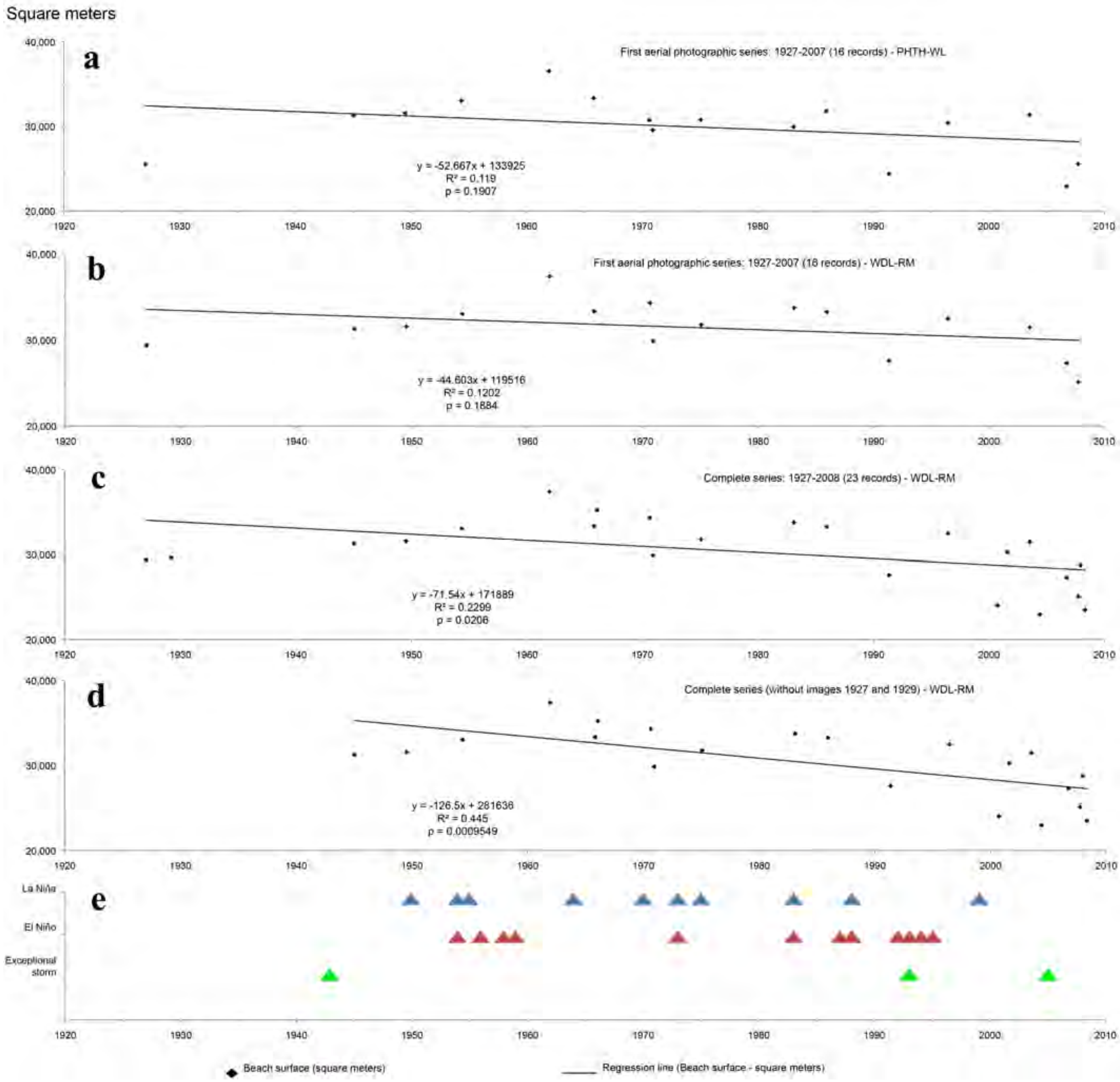

Figure 5 - Historical development of Ramírez beach arc from 1927-2008. a) First series of photos (16 entries) using the previous high tide high water level (PHTH-WL). b) the same series, using wet/dry line or run-up maxima (WDL-RM). The trend line indicates a weak decline of beach surface but sustained over time and statistically significant at 81%. c) all the 23 registers were used with WDL-RM. The trend line indicates a reduction of the beach surface statistically significant at 98%. d) Post-1945 records using WDL-RM are highly significant at $p < 0.001$. e) Series of ENSO anomalies and extreme storm surges show some degree of association with erosion-accretion of the beach surface. Blue triangle represent La Niña events, red triangle El Niño events, and green triangle the extreme storms.

Figura 5 - Desenvolvimento histórico do arco da praia de Ramírez no período 1927-2008. a) Primeira série de fotos (16) considerando a linha da maré cheia anterior à foto (PHTH-WL). b) A mesma série, considerando a linha praia seca / praia molhada ou o run-up máximo (WDL-RM). A linha de tendência revela um pequeno declínio da superfície da praia, mas persistente ao longo do tempo e estatisticamente significativo (81%). c) Conjunto dos 23 registros considerando em todos a linha praia seca / praia molhada ou o run-up máximo (WDL-RM). A linha de tendência indica uma redução da superfície de praia estatisticamente significativa em 98%. d) Os registos pós-1945 utilizando WDL-RM são altamente significativas para $p < 0,001$. e) As séries de anomalias ENSO e de temporais extremos apresentam algum grau de associação com a erosão-acreção da superfície da praia. Os triângulos azuis representam eventos de La Niña, os triângulos vermelhos os eventos de El Niño, e os triângulos verdes os temporais extremos.

figuration and the evolution of its surface areas shows a highly significant ($p < 0.001$) negative trend (Figure 5d and see Supporting Information SI.III). The randomness of the process was ruled out by the runs test (Figure 6). Descriptive statistics (See SI.IV) for the series of 16 images (1927-2007) was analyzed for the full set of 23 images (1927-2008), and the complete series using post-1945 images. The coefficient of variation (CV = 12.69%) of beach surface areas shows little variability in the data and it is further reduced by removing from the analysis the photos prior to 1945 (CV = 13.24%). From the analysis of the multi-temporal evolution of Ramírez, and depending on the considered period, a decrease in the surface area of 126 m^2/year was recorded (from 1945-2008).

Ramírez behaves as a dissipative beach in typical sea conditions because it is characterized by a large area of low slope, surf and spilling breaking waves. However, the Dean´s dimensionless parameter Ω classifies Ramírez as an "intermediate" sandy beach (46cm / [2cm.s x 4.4s] = 5.2). The Ω parameter determines the threshold values or transition from reflective to intermediate or from dissipative to intermediate beach type. Dean (Ω) values "less than 1" are associated with reflective beaches, values between "1 and 6" are intermediate states and those "over 6" are typically dissipative beaches. The apparent contradiction of this result, may explain its relative stability, despite suffering significant losses due to wind transport towards the waterfront.

The convex transverse profile is characteristic of an intermediate beach as established by the parameter Ω. However, the geological control exerted by the shore platform in the surf zone, determined that under normal conditions the beach behaves as dissipative, whereas it behaves as intermediate under storm surge conditions according to its convex profile and the value of Ω. Here, storm surge is defined as an increase in coastal water level caused by the action of wind blowing over the sea surface (wind setup) (DECCW, 2010).

During low water conditions, the coastline of this beach retreats 200 m and exposes an area of abrasion enriched in dense minerals. Therefore, the relative stability of this beach would be supported by a slow recovery of the profile due to sediment transport from the plain of abrasion to the sub-aerial beach. The analysis of the series of images indicates that Ramírez lost a beach area of 5,791.5 m^2 (19.7%) from 1927 to 2008. This loss is relatively consistent with the observed 11 cm sea level rise (SLR) at Montevideo in the last 100 years (Bidegain *et al.*, 2005; Magrin *et al.*, 2007; Nagy *et al.*, 2013, 2014a; Verocai *et al.*, 2014), and the consequent reduction of 5,600 m^2 obtained by Saizar (1997) applying the Bruun Rule (where the shoreline retreat is equal to the ratio of rising sea level with the tangent of the angle of the beach).

In addition, the difference between the current state and the best/worst case scenario of each beach in the time-series was analyzed. The percentage difference between the largest observed area and its current area was -37.1%, whereas the percentage difference between the smallest observed area and its current area was only 2.3% (Table 2).

Table 2 - Calculated percentage difference for Ramírez and Pocitos between the largest/smallest area for each beach from 1927 to 2008 and their current areas. From this figure the distance between the current state and the best/worst case scenario of each beach is analyzed.

Tabela 2 - Diferença percentual calculada para Ramírez e Pocitos entre a maior / menor área de cada praia entre 1927 e 2008 e suas áreas atuais. A diferença entre o estado atual e os pior e melhor cenários de cada praia foi analisada com base nestes dados.

	Ramírez	**Pocitos**	
		L27	**L08**
	%	**%**	**%**
Difference with the largest beach area ever registered	-37.1	-42.2	-32.6
Difference with the smallest beach area ever registered	2.3	0.2	0.0

Nevertheless, this calculation assumes a linear steady SLR from 1927-2008 which was not been the case;

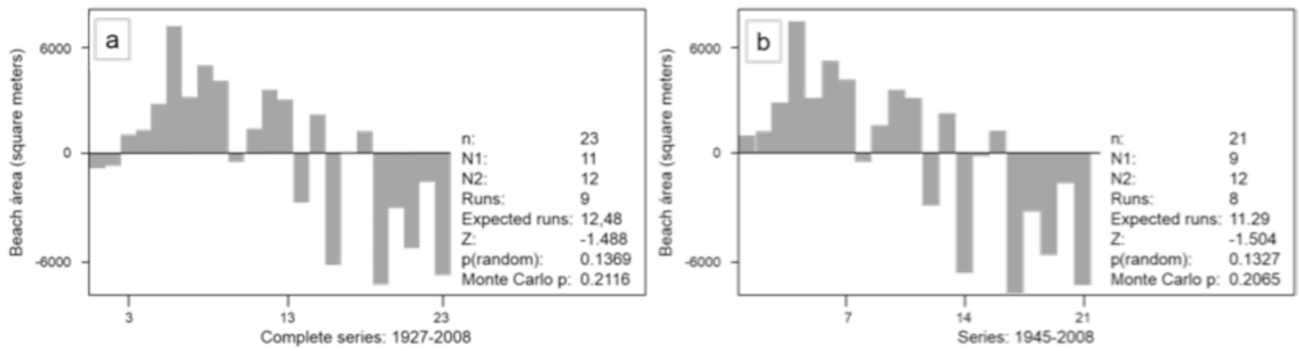

Figure 6 - Run test results for Ramírez beach. a) all the 23 registers were used with WDL-RM; b) post-1945 records.

Figura 6 - Resultados do teste para a praia de Ramírez. a) considerando a totalidade dos 23 registros, com WDL-RM; b) considerando apenas os registos pós-1945.

more than half of the observed SLR occurred between 1961-2003 (Nagy *et al*., 2005). Thus, there is not that good fit between morphological changes and SLR when shorter periods are considered.

4.2. Evolution of Pocitos beach

The analysis of the series of images of Pocitos also begins in 1927, the year of the first photographic record. Unlike Ramírez, Pocitos is oriented eastward which made it less vulnerable to the extreme storm surge in 1923, associated with very strong (> 100 km/hour) and persistent (over 24 hours) Southwest Wind (data collected for the old *Servicio Meteorológico del Uruguay*). The trend analysis of Pocitos beach was performed using the two artifacts L27 and L08 for the wet/dry line or run-up maxima (WDL-RM) as a proxy of the coastline. The first trend analysis was performed with a series of 15 images from 1927-2007 (Figure 7a and 7b). This series does not show significant changes in the surface area of exposed sand, but for the L27 limit it suggests a marginally significant retracement trend ($p = 0.1$) (Figure 7a and see Supporting Information SI.Va) of the beach area.

The coefficient of variation (See Supporting Information SI.VI) of beach surface area (series of 15 images: 1927-2007) indicates little variability in the data using L27 (CV = 14.82%), which is further reduced by analyzing the series using L08 as landward limit (CV = 10.21%). To deepen this analysis and confirm or exclude the evidence shown in the previous analysis, a set of 21 images was analyzed from 1927 to 2008. The linear regression trend line indicates a reduction of the beach surface statistically significant ($p < 0.04$) for L27 (See SI.Vc), while the trend is not significant for L08 (See SI.Vd), even indicating a very slight upward trend of beach area (+6 m^2/year). This would confirm that the effect of the artificial extensions might have masked the loss of surface area (Figure 7c and 7d). The coefficient of variation of beach surface area (series of 21 images: 1927-2007) indicates little variability in the data (L27 CV = 15.33% and L08 CV = 10.94%) (See SI.VIc and SI.VId).

For both series (15 and 21 images) the runs test does not rule out that the behavior of the advance and retreat of the coastline is of a random type, considering that the value of the test is very close to 0.2 at the edge of the range from which it is considered random (Figure 8a to 8d). The Pocitos dry-beach surface area has increased by 24,000 m^2 from 1927 to date due to the expansion work done by the IdeM. Likewise, what was done in Ramírez, assuming that the present configuration of the beach begins in 1954, images of 1927, 1945 and 1949 were removed from the analysis. Then, the beach surface area loss was not statistically significant for L27 and L08. This result would indicate that the surface area of the beach shows a relatively stable system after human intervention began (Figure 7e and 7f).

Such relative stability can have several causes: a) likewise Ramírez, Pocitos also has an abrasion plain located on its southern area (end of Trouville) and much of its current relative stability may be due to slight drift transport from the South to the North, which is reinforced by aeolian transport in the same direction; b) due to its location, the beach is relatively protected from the SW storms, the primary cause of wind-related coastal erosion. Furthermore, fluctuations in the beach match its natural dynamics and/or human intervention, including beach sand filling from Ramírez in the early 1960s.

The descriptive statistics of the series of 18 images from 1954 were also analyzed (See Supporting Information SI.VIe and SI.VIf) when the coast had already been rectified and the beach had a configuration similar to the present. The coefficient of variation of beach surface for L27 decreases (CV = 14.77%) when compared to the test performed with the full set of 21 images, probably because since 1954 the beach has had a conformation similar to the present. However, when the analysis is performed for the series of 18 images using L08 as landward limit (CV = 11.49%), this ratio increases due to increases in the beach surface area and the various modifications made by the local government (IdeM).

Runs test was applied to this series of 18 images (1954 to 2008), and to the two approaches (L27 and L08). The test infers that the advance and retreat of the coastline is random for the level of significance set for both L27 and L08 (Figure 8e and 8f), while the coefficients of variation of the data are kept low for both cases (L27 CV = 14.77% and L08 CV = 11.49%). The figure obtained by applying the Bruun Rule, with the parameter calculated by Saizar (1997) for beaches of Montevideo, is 15,982 m^2 in Pocitos which is intermediate between the current (L08), and which would have been observed without human intervention (L27). Also, the estimated regression loss would be negligible for L08 (470 m^2) and 10,328 m^2 for L27 for 1927-2008 which represents 0.8 and 16.9% respectively.

The loss of sand in Pocitos from 1927-2008 was estimated at 5,257 m^2 (8.6% of the surface area) using the L08 artifact, which includes all interventions that increased the surface of the beach; instead, the L27 artifact, that restricts the analysis to the original surface of the beach in 1927, estimated a loss of 25,756 m^2 or 42.2% (1927-2008). Despite the relative stability of the coastline, the beach prism suffered a significant reduction from the earliest available detailed map (Figure 4). Such reduction could be explained by the permanent leakage of sand towards the waterfront, from where the sand has been definitively removed whit mechanized cleaning by the IdeM, during the entire analysis period.

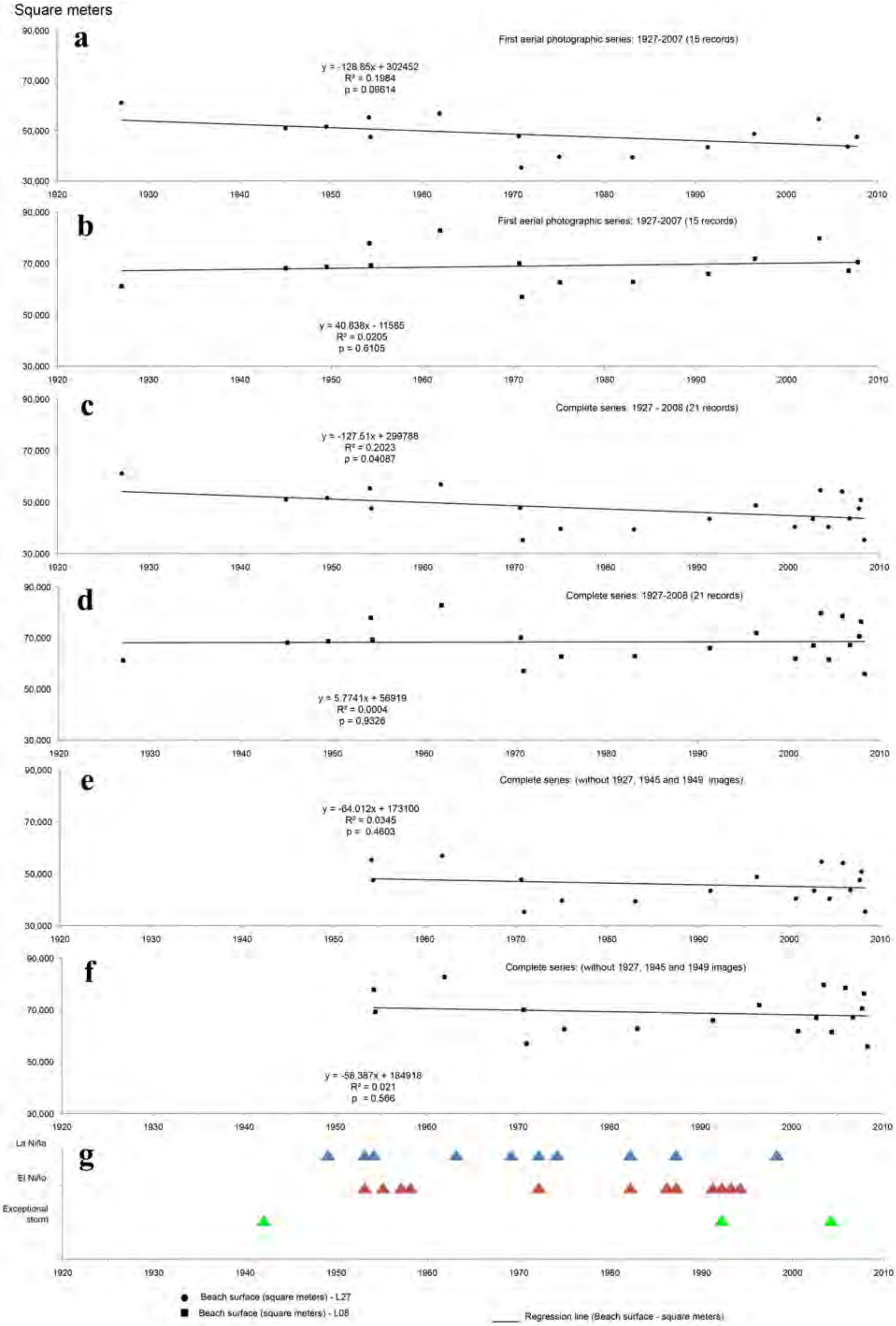

Figure 7 – See caption in the next page

Figura 7 – Ver legenda na próxima página

Figure 7 - Historical trend-line of Pocitos beach arc from 1927-2008 using WDL-RM. In a), c) and e) the artifact (L27) "*landward limits of the beach in 1927*" is used, while in b), d) and f) the artifact (L08) "*landward limits of the beach in 2008*" is used. In a) and b) the trend-line of the first series of 15 photos shows a weak but sustained decline over time in beach area, significant at 90% in a), and not significant in b). In c) and d) all 23 records of this beach are used. The beach area reduction is statistically significant at 96% when the L27 limit is used, but not significant when using the L08 limit, even indicating a very slight upward trend of the beach area. In e) and f) the post-1954 records are used. The trends are not statistically significant for any of the limits, although a slight loss of area was observed. g) Series of ENSO anomalies and extreme storm surges show some degree of association with erosion-accretion of the beach surface. Blue triangle represent La Niña events, red triangle El Niño events, and green triangle the extreme storms.

Figura 7 - Tendência histórica da linha do arco da praia de Pocitos no período 1927 a 2008 usando WDL-RM. Em a), c) e e) foi utilizado o artefato (L27) "limite terrestre da praia em 1927", enquanto que em b), d) e f) se utilizou o artefato (L08) "limite terrestre da praia em 2008". Em a) e b) a linha de tendência da primeira série de 15 fotos revela pequeno mas persistente declínio ao longo do tempo da área de praia, significativa a 90% em a), e não significativa em b). Em c) e d) foram utilizados todos os 23 registros desta praia. A redução de área de praia é estatisticamente significativa em 96% quando o limite L27 é utilizado, mas não é significativa quando se usa o limite L08, mesmo indicando uma ligeira tendência de aumento da área de praia. Em e) e f) foram utilizados apenas os registros pós-1954. As tendências não são estatisticamente significativa para qualquer um dos limites, embora se tenha observado uma ligeira perda de área. g) As séries de anomalias ENSO e de temporais extremos apresentam algum grau de associação com a erosão-acreção da superfície da praia. Os triângulos azuis representam eventos de La Niña, os triângulos vermelhos os eventos de El Niño, e os triângulos verdes os temporais extremos.

However, the percentage difference between the largest observed area compared with the photographical records shows differences of -42% for L27 and -32.6% for L08 suggesting that beyond the statistical results, the current state of the beach shows the highest percentage loss of surface compared to previous states. Moreover, the percentage difference between the lower recorded area compared to the photographical record was 0.2% for L27 and L08 for 0.0%, since 2008 coincides with the lowest record (Table 2).

Therefore, the analysis of the series of 21 images of Pocitos beach from 1927-2008, shows that the dry surface area of this beach has increased, although the same considerations that were made to Ramírez are valid, compounded by the fact that Pocitos beach has in some areas less than 0.60 m of sand thickness. Therefore, the apparent stability of this beach can relate mainly to a continuous "dry beach construction" by the IdeM (Figures 7c and 7e). So, without human intervention Pocitos beach should have suffered a significant reduction.

4.3. Behavior of the ensemble of case studies

For pocket beaches, especially if they are subject to human intervention, a different analysis than the one usually used for a wide beach is required. Pocket beaches may have significant responses to severe climate events; however, trends show spatial changes of small magnitude in the medium term. Ramírez and Pocitos have almost opposite orientations (the former to the West and the latter to the East), different depth gradients and divergent drifts, and although they have a similar mineralogical composition, they are two separate beaches, and independent of the other urban beaches of Montevideo (Figure 1). Therefore, it is particularly important to analyze the causes of the similarities in behavior over the years.

The existence of a relationship between the floods of the Paraná and Uruguay rivers, individually and combined, with the Río de la Plata level at Montevideo was explored, since floods trigger sea level fluctuations (Bidegain *et al.,* 2005; Nagy *et al*., 2005) and according to recent studies (Nagy *et al*., 2013, 2014b, 2015), these fluctuations may be in the range of 10-20 cm. This influence of river inflow on SLR is explained by the local effect of a close mouth of a great river (Nicholls *et al*., 2011) such as the Río de la Plata (Nagy *et al*., 2014b). Thus the possibility of a receding shoreline cannot be ruled out. However, the comparison between these flood events and the behavior of the middle estuary beaches, contrary to expected, shows that the period when the beaches show increased recovery coincide with major flooding and higher sea levels at Montevideo.

A series of subsequent images to the extreme Southern storm events (1923 and 1924) was analyzed that produce positive anomalies in sea level (storm surges), finding three events with increases in water/sea level of 2 m amsl or more, which coincide with the shoreline retreats observed in 1943, 1993 and 2005. Storm surges over 2 m amsl are those exceeding the prism of the beaches studied in most of its surface. These beaches have very little area above 1.84 m amsl which is the height of the biennial extraordinary high tide, and 2.11 m amsl with an estimated return period of 10 years (MTOP/PNUD/UNESCO, 1979). Therefore, since the current major impacts occur when water level increases 2 m amsl, and the observed SLR is 0.11 m amsl, a future SLR of only 0.20 m or less, would be sufficient to reach a critical point.

Unfortunately, the available discontinuous series of images and the low number of simultaneous occurrence of ENSO years 1-2 years before them precludes any robust statistical inference. However, the results presented

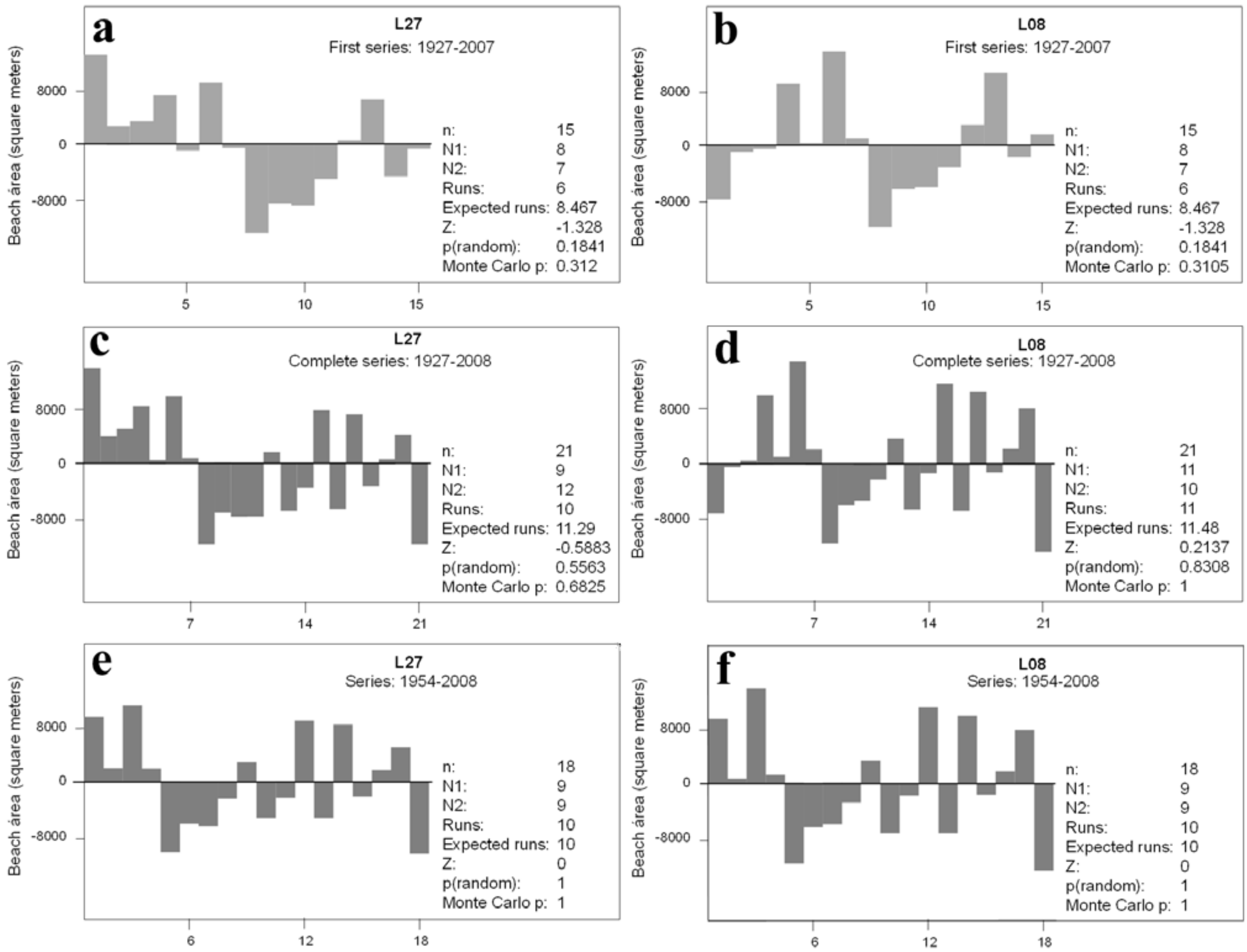

Figure 8 - Run test results for Pocitos beach. L27: a) First aerial photographic series: 1927-2007 (15 records); c) Complete series: 1927-2008 (21 records); e) Complete series (without 1927, 1945 and 1949 images). L08: b) First aerial photographic series: 1927-2007 (15 records); d) Complete series: 1927-2008 (21 records); f) Complete series (without 1927, 1945 and 1949 images).

Figura 8 - Resultados do teste para a praia de Pocitos. L27: a) Primeira série fotográfica aérea: 1927-2007 (15 registros); c) Série completa: 1927-2008 (21 registros); e) série completa (sem imagens de 1927, 1945 e 1949). L08: b) Primeira série fotográfica aérea: 1927-2007 (15 registros); d) Série completa: 1927-2008 (21 registros); f) série completa (sem imagens de 1927, 1945 e 1949).

here support the hypothesis of the existence of some degree of relationship between the occurrence of strong to moderate La Niña events of long duration-and shoreline retreat, which were analyzed according to the historical series of ENSO events (Severov *et al.*, 2004) and, conversely, recoveries during El Niño events (Figure 5 and 7). In the same way, Ortega *et al.* (2013) in analyzing two ocean sandy beaches of Eastern Uruguay, plotted the values of wind speed anomalies for the area and the sedimentary balance of sands. The trend line from 1985-2009 and the distribution of outliers (anomalies) suggests a similar pattern of coincidence between ENSO events and sedimentary balance. The apparent correlation with ENSO events needs further research.

5. Conclusions

The examples presented in this article show how dependent on the magnitude of the changes, the time-scale of the analysis and the frequency of records, are the conclusions. Thus, in urban pocket beaches, it is crucial to have numerous aerial photos and satellite images over long time intervals in order to make reliable analysis of the morphological evolution.

Since the discontinuous time-series of records can not match ideally with the occurrence of human interventions and climate events, it is important to obtain as many records as possible.

Ramírez and Pocitos beaches seem to be relatively stable but fluctuating from 1927 (first aerial photographic record available) to 2008. Both beaches are shown to be resilient to sporadic water/sea level rises. For Pocitos, this was true only after the end of heavy human intervention affecting this beach in the first half of the twentieth century which left the beach very vulnerable. However, the risk might increase again if the frequency of extreme events increases under likely future climate change scenarios.

In addition to the diverse human interventions explained along this article and the observed 11 cm sea level rise, some of the fluctuations observed in the 81-year period of analysis seem to be associated with years with atmospheric circulation anomalies related to ENSO or extreme storms with an increase in sea level of more than two meters above the historical mean sea level.

Therefore, a better understanding of the medium-term trends in regional atmospheric circulation will allow estimating likely beach evolution under climate change and, in particular in pocket beaches, of the expected sea level rise, in order to provide a basis to planning better adaptations to the threats and impacts associated with these trends.

Understanding the evolution of urban beaches subjected to long term human interventions such as Pocitos and Ramírez of Montevideo, requires a historical analysis to determine both the effects of the inertia of the past, and to determine when the beaches acquired a dynamic setting similar to the present, in order to have scenarios of future developments. Keeping the desired state of resilience of these beaches under both climatic and human pressures requires a thorough understanding of trends and variables that affect their states of balance-imbalance.

6. Management recommendations

To an effective coastal zone management it is crucial to understand the roots of the conflicts and issues that influence the littoral at Present (according to Dias *et al.*, 2012).

Therefore, it would be a wise practice the recovery of natural structures, like primary dune and seed of psamophyl native grasses and other pioneers species as a way of recovering beach prism to prevent the reflection of waves from the armored road.

From the knowledge generated by this research, we believe that in order to analyze long-term morphological changes and improve the prognosis of the future evolution of these beaches, it would be desirable that the local government conduct the following actions:

- Keep track of trends in these beaches. This will make it possible to assess the resilience of both beaches regarding restoration measures. But fundamentally, it will reveal the evolution of the beaches facing the gradual sea level rise and storm surges.
- Control sand loss by building fences to prevent its loss by the stairs to the beach.
- Replenish sand extracted in cleaning.
- Redistribute the already existing sand aimed at increasing prism height beach.

Moreover, the implementation of a monitoring of the evolution of beach prism would allow the agencies in charge of coastal management to contrast the effectiveness of the measures taken, considering not only the time factor but also some variables involved and/or affected by the intra-annual variability.

Will the studied pocket beaches keep stable under a plausible and likely climatic scenario for the near future of a La Niña event ("erosive Southwestern winds") and a storm surge (+ 2.3 amsl) with a slight SLR of only +5 cm?

Therefore, our results suggest the importance of continuing the analysis of the evolution of these and other urban beaches of Montevideo, to better understand the suggested relationship between climate forcings, i.e., ENSO and fluctuations in the beach area.

Knowing the morphological responses of these beaches will allow better coastal management and climate adaptation.

Appendix

Supporting Information associated with this article is available on-line at **http://www.aprh.pt/rgci/pdf/rgci-553_Gutierrez_Supporting-Information.pdf**

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Reanalysis of marine-coastal indicators assessed by national and multi-national organizations for the integrated coastal zone management[*]

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ABSTRACT

The progressive occupation of coastal zones led to consolidation of the Integrated Coastal Zone Management (ICZM) as a shared management process that aims to improve population life quality, to conserve biological diversity and coastal productivity. This ICZM view follows the premises of sustainable development, established in 1992 by the United Nations Conference on Environment and Development – environmental conservation, economic growth and social equality. In this Conference, countries were invited to produce indicator systems, as a follow-up towards sustainable development. At world level, the Intergovernmental Oceanographic Commission (IOC) prepared in 2006 a handbook of indicators to support the ICZM, titled *A Handbook for Measuring the Progress and Outcomes of Integrated Coastal and Ocean Management (ICAM Handbook)*, incorporating socioeconomic, ecological and political dimensions as the base to analyzis. The present work reanalyzes marine-coastal areas indicators related to the ICZM, included by ten selected organizations in its official publications and websites about sustainability (or sustainable development). Seven sources are national: SayDS (Argentina), INE (Spain), INEGI (Mexico), DEFRA (United Kingdom), IBGE (Brazil), APA (Portugal) and Statistics Canada (Canada); and three, multinational – The GEO Project, REDESA and ILAC. The analysis has the list of ecological indicators suggested by the *ICAM Handbook* as a reference. The results showed that a few number of indicators are related to marine-coastal areas (less than 15%), giving the total number of indicators for each analyzed source. Most of the ecological indicators suggested by the *ICAM Handbook* are not considered by the selected organizations in its systems of sustainability indicators. The research aims to contribute to the improvement of the sustainability indicators systems, especially those maintained by the IBGE in Brazil, and to alert researchers and policy-makers to the importance of the natural environment as essential to the support of life, and to the conservation of biological diversity and productivity in marine-coastal areas.

Keywords: sustainable development, integrated coastal zone management, marine environment, indicators.

RESUMO

Reanálise dos indicadores marinhos e costeiros para gestão integrada da zona costeira, contemplados por organizações nacionais e multinacionais.

A progressiva ocupação de zonais costeiras levou à consolidação do Gerenciamento Costeiro Integrado (GCI) como um processo de gestão compartilhada que visa a melhoria da qualidade de vida da população e a conservação da diversidade biológica e da produtividade costeiras. Essa visão de GCI segue as premissas do desenvolvimento sustentável, estabelecidas na Conferência das Nações Unidas em Ambiente e Desenvolvimento, realizada em 1992 no Rio de Janeiro: conservação ambiental, crescimento econômico e igualdade social. Nessa mesma conferência, os países foram incentivados à produção de

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sistemas de indicadores, como forma de acompanhamento do rumo ao desenvolvimento sustentável. Em nível mundial, a Comissão Oceanográfica Intergovernamental elaborou em 2006 um manual de indicadores para apoio ao GCI, que inclui as dimensões socioeconômica, ecológica e política como base de análise, intitulado: "Manual para Mensuração do Progresso e dos Resultados do Gerenciamento Oceânico e Costeiro Integrados" (em inglês: "A Handbook for Measuring the Progress and Outcomes of Integrated Coastal and Ocean Management"), adiante referido como Manual ICAM. O presente trabalho tem como objetivo reavaliar indicadores marinhos costeiros relacionados com o GCI, incluídos por dez organizações selecionadas, nas suas publicações e websites oficiais sobre sustentabilidade (ou desenvolvimento sustentável). Sete fontes de dados são nacionais: SayDS (Argentina), INE (Espanha), INEGI (México), DEFRA (Reino Unido), IBGE (Brasil), APA (Portugal) e Statistics Canada (Canada); e três multinacionais: Projeto GEO, REDESA e ILAC. A análise tem a lista de indicadores ecológicos sugeridos pelo Manual ICAM como referência. A partir dos resultados, observou-se que, do total de indicadores de cada uma das dez fontes analisadas, há poucos indicadores relacionados às áreas costeiras e marinhas, com percentuais que não chegam a 15%. Grande parte dos indicadores ecológicos sugeridos no Manual ICAM não são considerados nas fontes analisadas. O trabalho visa contribuir para o aperfeiçoamento dos sistemas de indicadores de sustentabilidade, especialmente aquele mantido no Brasil pelo IBGE, e alertar aos pesquisadores e tomadores de decisão para a importância do meio natural como essencial ao suporte à vida e à conservação da diversidade biológica e da produtividade em áreas costeiras e marinhas.

Palavras chaves: *desenvolvimento sustentável, gerenciamento costeiro integrado, ambientes costeiro e marinho, indicadores.*

1. Introduction

The United Nations Conference on the Environment and Development (UNCED), held in Rio de Janeiro, dated on 1992, encouraged the participating countries to produce indicators to monitor their progress towards sustainable development, which is understood as economic growth coupled with environmental conservation and social equality.

It is noteworthy that in 1996, the Group of Experts on Scientific Aspects of Marine Protection (GESAMP) incorporated this vision that reconciles economic growth with environmental conservation and quality of life into the definition of the ICZM process: *The goal of ICM is to improve the quality of life of human communities who depend on coastal resources while maintaining the biological diversity and productivity of coastal ecosystems. Thus, the ICM process must integrate government with the community, science with management, and sectoral with public interests in preparing and implementing actions that combine investment in development with the conservation of environmental qualities and functions*. (GESAMP, 1996: iv)

Some researchers reaffirm the importance of the inclusion of at least three of the dimensions (environmental, economic and social) included in the sustainable development strategy, in the treatment of some coastal issues (Malone *et al.,* 2014; Ye *et al.,* 2014; Cooper, 2011; Gallagher, 2010; Peng *et al.*, 2006; Pickaver *et al.,* 2004; Shi *et al.*, 2004; Polette & Silva*,* 2003; Vandermeulen, 1998; Thia-Eng *et al.*, 1997).

In Europe, the progress of implementation of the ICZM was evaluated by Pickaver *et al.* (2004), that showed the absence of an ICZM strategy, which includes the marine environment and that "has been produced which takes into account both the interdependency and disparity of natural processes and human activities" (Pickaver *et al.*, 2004: 456). In the other hand, the evaluated strategies incorporate "the precautionary principle and an ecosystems approach, and (…) treats coastal areas as distinct and separate entities" (Pickaver *et al.*, 2004: 456).

The importance of a holistic and integrated view in the analysis of the ICZM aspects is highlighted by Ye *et al.* (2014: 113), that argue that "the linkages and interdependencies of socio-economic, governance and coastal environmental dynamics have been rarely analyzed through evaluation".

Thia-Eng *et al.,* (1997) describe the necessity of an integrated vision in the adoption of a strategy to the prevention and management of marine pollution and the rapid economic development in Xiamen, China. The same authors list the issues that have to be included in the environmental profile of the coast of Xiamen (Thia-Eng *et al.*, 1997: 239). Notes that there is an integration between the natural environment and the anthropogenic activities:

- *Natural environment and its relation to development*
- *Marine resources and their development status*
- *Urban socioeconomics and status of ecological environment*
- *Status of coastal water quality*
- *Characteristics of marine ecosystems problems*
- *Status of marine environmental legislation*
- *Status of marine environmental management*

In other work, dated on 2006, Chinese researchers investigate the socioeconomic benefits of the ICZM, using the improvements in the ICZM process in Xiamen (China) as a case study. Conclusions show that the obtained results demonstrate the improvement of the ICZM process in Xiamen is contributing to an economic development with nature conservancy of the region: (…) *indicate that the ICM program in Xiamen has led to an impressive increase in net socioeconomic* *benefit from its marine sectors. The difference in the present values of total net benefit from 1997 to 2001 between the two policy regimes amounts to around 9 billion yuan. (...) The efforts to improve environmental quality and to conserve natural resources have resulted in a notable increase in environmental benefits. Furthermore, various external costs have declined in the Xiamen area.* (Peng *et al.*, 2006: 107)

Cheong (2008: 1090) indicates the importance of the dissolution of the limits between natural and social scientists in order to achieve a *new direction in coastal management*, which can be obtained through the sustainability science, which *has emerged out of this interdisciplinary, (…) combining the areas of sustainable development and environmental science*".

Ignacy Sachs (1990; 2002), a recognised Polish eco-socioeconomist, proposed eight dimensions for represent the sustainability: social, economic, ecological, territorial (before named, geographical), cultural, environmental, national politics and international politics. These dimensions can be combined when using the systems approach, which was borned with Ludwig von Bertalanffy (2006) in the Biological Sciences and spreads to many others scientific areas, until arrive to the environmental systems modelling, which is frequently used in the resolution of various types of environmental and socioeconomic problems (Christofoletti, 2010).

Shi *et al.* (2004: 336) argue that the systems approach has to be used to ensure the sustainable development of the coastal zone and that the national sustainability indicator system developed to Shangai municipality (and Chong Ming Islands), China, includes five sub-systems: *survival, development, environment, social and intelligence supporting systems*. In the same way, Gallagher (2010) defends the adoption of the management systems approach in order to achieve the coastal sustainability. The same author affirms that the ICZM plans and processes are based in the three golden principles of the sustainable development: sustainable economic growth, natural conservancy, and social equality.

Taussik (2007: 612) shows that the ICZM process in development in England is using the spatial planning approach, in order to *ensure the sustainable balanced development of the European territory which respects its diversity*. The same author explains that spatial planning is a term that can be applicable in a wider way, in other words, referring to aspects observed in a spatial or geographical dimension. The tools that use this approach frequently include zoning techniques and temporal controls.

For example, still according to Taussik (2007: 612), with respect to the marine-coastal areas, the following issues have a spatial dimension: *new development, nature conservation, coastal defence and shoreline management; the regulation of minerals on and off shore; and fisheries*. All these activities and related interests can cause conflicts and the ICZM is strategically important to resolve the conflicts present in coastal regions, in order to promote the proper management of their natural resources, as highlighted by Asmus *et al.* (2006: 52, our translation): *The integrated coastal management arose from the need to manage the natural resources of the coastal zone in a sustainable manner. These regions have great commercial, industrial and touristic interest. Hence, the depletion of natural resources becomes evident in several respects, such as increased urban and industrial population (compared to the cluster population), overfishing, massive exploitation of mineral resources, among other equally important issues. The Integrated Coastal Management can be defined as a continuous and dynamic process by which decisions and actions are made for the sustainable use, development and protection of coastal areas and maritime resources.*

The global increase of coastal population density, development of various industrial plants and port facilities, hotel network and fishing activity expansion, require determining whether the sustainability indicator systems maintained by national and multinational organizations incorporate all aspects of coastal and marine areas, taking into account all parameters and indicators listed. The health of coastal ecosystems and the population should be closely monitored to allow effective measures that can be taken to safeguard natural resources and individuals.

Seven countries with consolidated and internationally recognized official statistics agencies and which have developed their own sustainability (or sustainable development) indicator systems (or lists), were also included in the analysis. Among them there are four American institutions:

- Argentina – Secretariat of Environment and Sustainable Development (Spanish acronym: SayDS);
- Brazil – Brazilian Institute of Geography and Statistics (Portuguese acronym: IBGE);
- Mexico – National Institute of Statistics, Geography and Informatics (Spanish acronym: INEGI); and
- Statistics Canada (Canada);

and three European institutions:

- Spain – National Statistics Institute (Spanish acronym: INE);
- Portugal – Portuguese Environment Agency (Portuguese acronym: APA); and
- United Kingdom – Department for Environment, Food and Rural Affairs (English acronym: DEFRA).

Three multinational initiatives were also selected because of its international recognition and, sometimes, because it corresponds to the region of which Brazil is part:

- Latin American Network of Experts on Social and Environmental Statistics in Latin America and the Caribbean (Spanish acronym: REDESA);
- Caribbean Initiative for Sustainable Development (Spanish acronym: ILAC); and
- Global Environment Outlook Project (GEO Project).

The Canadian National Round Table on the Environment and the Economy (NRTEE), a committee of experts, which function as an independent policy advisory agency to the Government of Canada, was established in 1988. The NRTEE report, dated on 2003 and titled *The State of the debate on the Environment and the Economy: Environmental and Sustainable Development Indicators for Canada*, was prepared with the cooperation of the Statistics Canada and the Environment Canada. Economic indicators included in this report are supplemented by indicators related to the human capital and the natural capital (NRTEE, 2003).

According to the natural capital model, the condition of sustainability is the maintenance over time of a stock or natural capital assets (or the total stock of capital artificial, natural and human) (Martínez, 2001). The indicators related to the human capital presents in the cited NRTEE report adopts metrics referred to the socioeconomic dimension (NRTEE, 2003) and, in the same way, following the strategy for the conservation of the stocks, in order to achieve the sustainability.

The Argentinean SayDS, the Brazilian IBGE, and the Mexican INEGI follow the guidelines of the regional project of the *Comisión Económica para América Latina y el Caribe* (CEPAL) (in English: Economic Commission for Latin America and the Caribbean, ECLAC), titled *Evaluación de la Sostenibilidad en América Latina y el Caribe* (in English: Sustainability Assessment in Latin America and the Caribbean) (Spanish acronym, ESALC).

The first consultative meeting of the ECLAC, with representatives of countries, was held in Santiago, Chile, dated November 29, 2001, reported in the *Informe del Seminario Indicadores de Desarrollo Sostenible en América Latina y el Caribe* (CEPAL, 2001). This ECLAC project follows the view of the socio-ecological model, a holistic approach, which consider two components: one, human, and other, ecological (CEPAL, 2001). This model follows the strong sustainability, concept in which different types of capital are not necessarily interchangeable (Gallopín, 2003).

Three European national organizations, the Spanish INE, the Portuguese APA and the DEFRA, from the United Kingdom, follow the European Union Sustainable Development Strategy (EU-SDS), published in the report titled *A Sustainable Europe for a Better World: A European Union Strategy for Sustainable Development*, published by the Commission of the European Communities (EC, 2001).

The EU-SDS follows the sustainable development vision, present in official documents derivate from the United Nations Conference on Environment and Development (UNCED), also known as the Rio Summit, Rio Conference, and Earth Summit. According with this vision, the economic growth has to be accompanied by the environmental conservation and the social equality, in order to achieve the sustainable development.

All three selected multinational initiatives (REDESA, ILAC and Geo Project) also follow the recommendations of the UNCED, dated on 1992.

REDESA was created in 2001 by the Division of Statistics and Economic Projections of ECLAC to promote and strengthen the production of social and environmental statistics in the countries of the region. REDESA also acts as a coordinating organization and holding meetings with representatives of the countries concerned to improve the methodology for the collection and processing of data and encouraging the exchange of information and experiences among experts and institutions.

ILAC was proposed by the Forum of Ministers of Environment of Latin America and the Caribbean during the Johannesburg Summit, held by the United Nations in South Africa, in 2002. ILAC objectives are similar to REDESA, but it focuses more specifically on the institutional arrangements, as well as financial and political mechanisms to implement Agenda 21 in the region.

Initiated in 1995 by the United Nations Environment Program (UNEP), the GEO Project aims to meet the recommendations of Agenda 21, regarding the formulation of indicators for assessing the progress towards sustainable development.

Although these organizations follow the United Nations or regional strategies to reach the sustainable development, the list of indicators formulated and maintained by them have different configurations, regarding the aspects: objectives; conceptual model; form of development and disclosure of the indicator system; architecture; selection criteria; geographical coverage and how the indicators are presented (on press reports, on the Internet and on others medias) (Souto, 2011).

Regarding on the indicators schemes applied to the marine-coastal areas and that follow the three sustainable development principles, titled *A Handbook for Measuring the Progress and Outcomes of Integrated Coastal and Ocean Management* (hereinafter, *ICAM Handbook*) is the only intergovernmental document that guides the development of indicators to support ICZM.

The *ICAM Handbook* was published by the Intergovernmental Oceanographic Commission (IOC), with the overall goal of contributing to the sustainable development of coastal and marine areas by promoting a measurable and adaptable, results-oriented approach to coastal management (IOC, 2006).

To meet this goal, the *ICAM Handbook* presents a wide range of ecological and socioeconomic indicators and metrics for assessing the ICZM process itself, providing a framework for the countries to adopt and adapt according to their regional characteristics (IOC, 2006). The *ICAM Handbook* also describes eight country case studies, including results and lessons gained from these experiences. Thus, the *ICAM Handbook* is considered an appropriate reference for sustainability assessments in coastal and marine areas as it covers the main topics of sustainable development (environmental, social, economic and political-institutional) and proposes to use indicators to assist the diagnosis and monitoring of the ICZM process, given the complex reality of coastal zones worldwide, which aggregate a wide variety of resources, types of use, stakeholders, interests and conflicts.

Ye *et al.* (2014: 113) argue that the *ICAM Handbook* is an useful reference, but the same authors alert, citing other authors, that *there are still no widely accepted methodologies or common criteria for assessing ICM performances due to the complexity and heterogeneity of assigned ICM programmes in different regions* (…). However, these authors also argue that the *ICAM Handbook* adopts the holistic and integrated vision (Ye *et al.*, 2014: 113). It functions like a suggestive list of indicators, parameters and aspects to be considered in the moment of formulation of the ICZM indicators in the three levels of approach: local, regional and national.

The present work reanalyzes marine-coastal indicators related to the ICZM, included by the ten selected organizations in its official reports and websites about sustainability (or sustainable development). The analysis used the list of ecological indicators suggested by the *ICAM Handbook* as a reference (IOC, 2006). In the results, this work presents the main themes and the gaps, related to the marine-coastal areas, present in the analyzed sources. Additionally, this work aims to contribute with others producers of official statistics, highlighting the importance of the marine-coastal indicators to improve the ICZM processes in its countries.

Specifically for the official publication published by the IBGE, titled *Indicadores de Desenvolvimento Sustentável: Brasil* (in English: Sustainable Development Indicators: Brazil), this work seek also to contribute to its improvement, by suggesting parameters related to marine-coastal areas, which should be included in this publication.

2. Material and methods

The sustainability indicators included in the ten analyzed sources (official reports and websites) of national and multinational organizations, selected for this work, were compared with the list of ecological indicators presented in the *ICAM Handbook* (IOC, 2006, p.38), adopted as reference, in order to evaluate qualitatively what are the issues included in the analysed publications. A survey of the parameters used by each selected organization that have specific relevance to the marine-coastal areas was performed, and the results are presented in tables, which demonstrate the issues related to marine-coastal included by them.

The indicators from the national level were surveyed from the sources expressed at Supporting Information.

3. Results and discussion

The marine-coastal areas are under-represented in all the analyzed lists (or systems) of indicators. Table 1 presents the result of comparison between the organizations on the number of ecological indicators (absolute and approximate percentage) related to marine-coastal areas, as noted in the sources consulted; and yet, the total indicators contained in each observed source.

It is noteworthy that the DEFRA publication, from United Kingdom, which has the highest number of indicators (124 in total), has the lowest percentage of participation of marine-coastal areas (about 0.8%). On the other hand, the multinational GEO Project, with the lowest number of indicators (21 in total), has the highest percentage (about 14.3%) of indicators related to the marine-coastal areas. Among national initiatives, IBGE has the largest percentage (5.5%) and DEFRA has the lowest percentage of participation of marine-coastal areas (0.8%). There is no visible difference between sources from American countries and from European countries. And there is no difference also between countries considered on economic development or economically developed. Thus, the representation of the marine-coastal areas in the indicators schemes for the sustainability (or the sustainable development) seems to be independent of the economic development level and the geographic localization of the country.

Table 2 presents the indicators related to the marine-coastal areas, according to the analyzed sources. Most of the indicators related to marine-coastal areas, included in the analyzed sources, are related to fishing activity, but the parameters are distinguished, according to the subject (e.g., operationalization of the fishing activity, volume of fish production, environmental and sustainability aspects of the fishing activity). The *ICAM Handbook* presents the indicator of incidental mortality (by catch), which is essential for the conservation of

Table 1 - Comparison between organizations. Absolute numbers and percentage of indicators related to the marine-coastal areas and total number of indicators listed.

Tabela 1 – Comparação entre organizações. Números absolutos percentuais de indicadores relacionados às áreas costeiras e marinhas e número total de indicadores listados.

Indicators	GEO Project [1]	REDESA [2]	ILAC [3]	SayDS (2010)	IBGE (2010)	Statistics Canadá (2007)	INEGI (2000)	INE (2000)	APA (2009)	DEFRA (2010)
Total number of indicators listed	21	87	54	72	55	73	113	121	59	124
Number of indicators related to the marine-coastal areas	3	5	1	2	3	1	2	3	2	1
Approximate percentage (%) of indicators related to the marine-coastal areas	14.3	5.7	1.8	2.8	5.5	1.4	1.8	2.5	3.4	0.8

[1] GEO Data Portal/GEO Core Indicators (http://geodata.grid.unep.ch/extras/indicators.php).
[2] CEPALSTAT (http://www.cepal.org/en/datos-y-estadisticas).
[3] UNEP (2005).

fish stocks, but has not been included in the indicators set of any selected organization.

Table 2 also reveals that only Argentinian and Portuguese sources consider biomass indicators. The *ICAM Handbook* suggests a number of other production and reproduction indicators, which should be considered by the organizations: quality of habitats, secondary productivity, stages of life, reproductive parameters, average generation time and spawning survival rates.

Regarding the load of pollutants in coastal and marine areas, Statistics Canada considers the estimated total load of phosphorus, while Spanish INE, the mercury concentrations in fish and shellfish/ molluscs. The *ICAM Handbook* suggests monitoring the levels of pollutants and contaminants in the water and not just the bioaccumulation of toxic compounds, as well as the diseases and abnormalities of the species.

Swimming suitability, an indicator considered only by the Brazilian IBGE, is covered in the *ICAM Handbook,* under the subject "Water Quality".

Surprisingly, the resident population of coastal areas is considered only by the Brazilian IBGE and the Mexican INEGI. The distinction that must be made is that the index adopted in Brazil follows the absolute values of the resident population while Mexico monitors population growth. In the *ICAM Handbook,* this indicator appears in the list of socioeconomic indicators, but it is inserted in this survey to show that few of the evaluated organizations consider important to monitor the population in coastal areas.

The urbanization of the coastal areas grows continuously around the world, given the facilities for maritime trade, the attraction for the coastal environmental services and other reasons. It becomes, therefore, necessary to consider the coastal population indicator in sustainability (or sustainable development) indicators schemes of countries that have maritime boundary since the pressure of intense human occupation on these areas often leads to environmental problems.

The GEO Project presents "Change in glacial mass" indicator, which is not covered in the *ICAM Handbook,* but it became important in the global discussions due to the current process of global warming. This indicator can be adopted by countries with permanent ice cover (permafrost) in order to contribute to the evaluation of the overall effect of global warming.

REDESA and ILAC have an indicator to monitor the surface of protected marine-coastal areas. REDESA includes the surface of marine-coastal areas as an absolute measure, while ILAC includes as a percentage in relation to the total marine-coastal area. The *ICAM Handbook* considers this aspect in the evaluation section of the legislation for the ICZM. It is mentioned in this survey, since this aspect acquires paramount importance with the increasing development of economic activities in coastal and marine areas.

The protection of these areas becomes fundamental to ensure the preservation of important ecological sites (*e.g.,* nesting and feeding areas, species migration routes, among others).

Table 2 - Indicators related to the marine-coastal areas, included by the analyzed organizations.

Tabela 2 - Indicadores relacionados às áreas costeiras e marinhas, incluídos pelas organizações analisadas.

Indicators	GEO Project [1]	REDESA [2]	ILAC [3]	SayDS (2010)	**IBGE (2010)**	Statistics Canada (2007)	INE (2000)	INEGI (2000)	APA (2009)	DEFRA (2010)
Total indicators	3	5	1	2	3	1	3	2	2	1
Population growth in coastal areas								x		
Population residing in coastal areas					x					
Swimming suitability					x					
Changes in glacial mass	x									
Load of total phosphorus estimated from the main direct point sources (marine and continental)						x				
Level of mercury in fish and shellfish							x			
Percentage of protected coastal marine areas in relation to total coastal marine areas			x							
Surface of protected marine areas		x								
Total volume of aquaculture production		x								
Biomass and reproductive biomass evolution				x						
Spawning biomass and crayfish recruitment evolution									x	
Spawning biomass and hake recruitment evolution									x	
Number of vessels engaged in fishing		x					x			
Number of species with restrictions		x								
Marine catches (fish, crustaceans and mollusks)	x									
Depletion of world fish stocks	x									
Fishing catches outside biosafety boundaries							x			
Extraction of main/major fish		x								
Maritime and continental fish production					x					
Relationship between maximum allowable catch and land-ings				x						
Fishing maximum sustainable yield								x		
Sustainability of fishing stocks in the country neighboring areas										x

[1] GEO Data Portal/ GEO Core Indicators (http://geodata.grid.unep.ch/extras/indicators.php);
[2]CEPALSTAT (http://websie.eclac.cl/sisgen/ConsultaIntegrada.asp?IdAplicacion=1); [3]UNEP (2005).

REDESA and the Brazilian IBGE presents indicators related to the aquaculture activity. REDESA includes the "Total aquaculture production" and IBGE presents "Marine and continental fish production". There is a pressing need to develop indicators, which monitor the quality of aquaculture because, when poorly managed, this type of activity can result in severe environmental damage, such as eutrophication of water bodies, siltation, and introduction of invasive species.

The array of all the indicators of these sources are fully described in Souto (2011). Below, the list of the key results acquired in the present work resumes the key points observed.

Key results

(1) The systems (or lists) of sustainability (or sustainable development) indicators, maintained by the analyzed sources, national or multinational, still need to

improve the participation of the indicators related to marine-coastal areas;

(2) Some of the gaps identified in this work could be considered, in order to promote the rational use of marine-coastal living resources;

(3) The level of participation of indicators related to marine-coastal areas seems to be independent of the geographic localization of the country or its level of economic development;

(4) In a generally way, there is not also a maritime mentality in the analyzed official discussions and reports about sustainability (or sustainable development). This is a major shortcoming since the marine-coastal areas become increasingly important in the world scenario;

(5) ICAM Handbook must be better used by the researchers and the policy-makers, to improve the ICZM processes and to include more metrics related to marine-coastal areas;

(6) Only one of the schemes analyzed follows the systems approach. The Argentinian SayDS try to combine dimensions, in order to better understand its related aspects;

(7) The source with the highest total number of indicators (DEFRA) is the source with the lowest percentage of inclusion of marine-coastal indicators (about 0.8%). The inverse situation occur with the source from Geo Project, which has the lowest total number of indicators, but presents the highest percentage of inclusion of marine-coastal indicators (about 14.3%).

4. Conclusions

The present work sheds light on some characteristics of the analyzed sustainability (or sustainable development) indicator systems (or lists), formulated by some of the most important national and multinational organizations worldwide. The ecological indicators list presented in the *ICAM Handbook* was used as a reference to the reanalyses of the selected sources, including official publications and websites.

The presented reanalysis is important to verify the level of coverage of the issues related to marine-coastal areas in national (or multinational) official reports on indicators of sustainability (or sustainable development). These areas are essential in the processes of formulation, implementation and maintenance of these lists (or systems) of indicators, in order to fully reach the sustainable development, which is based on the economic growth with environmental conservation and social equality.

The evaluated organizations have incipient coverage of relevant aspects to the marine-coastal areas, in a general way, which must be monitored to provide information to the ICZM process, in order to achieve the targets towards the sustainable development. The lack of such indicators hampers and probably prevents the development of management plans aimed at conservation of biological diversity and productivity in marine-coastal areas, part of the ICZM goals, as presented by GESAMP (2006).

In addition, most ecological indicators suggested in the *ICAM Handbook* are not included in the official publications and websites selected to this work. These indicators relate to important aspects regarding conservation of biological diversity and productivity of marine-coastal ecosystems. This can include, such critical factors as diversity of communities, populations, species or even genetic variability; abundance (in number and density) of marine organisms; trophic interactions; health and species distribution; habitat quality; and oceanographic characteristics (related to sedimentation, physical processes and system changes).

In Brazil, supervising many of these aspects still requires an institutional organization that enables parameter monitoring, in order to improve the knowledge of the Brazilian marine-coastal areas, regarding the ecological dimension of sustainability. So, will be possible to improve its sustainable development indicators list. The same institutional problem occur with others countries belonging the Latin America and Caribbean region. Martínez (2001) also cites the following challenges to the development of this type of list (or system) in this region: *i)* the involved costs to keep it; *ii)* the insufficiently recognition of the importance of this type of list (or system) to the decision-making processes; *iii)* the methodological aspects and problems, since the sustainability (or the sustainable development) is a concept which still needs a worldwide accepted definition.

The environment is paramount within the ICZM process since it is the means to support life and fundamental to the development of economic activities. Given the size of the Brazilian coastal and maritime zones, and the diversity of natural resources in those waters, the monitoring of these aspects is of strategic importance for the country in the international relations background.

The marine-coastal areas shelters a notable diversity of mineral deposits, live resources, sources of energy, all of them important to any country's sovereignty. In the words of Moraes (2007, p.28, *our translation*): "Seaside, an unusual place, a rare and strategic localization".

Future researches on the institutional arrangements and legislation of countries, related to the marine-coastal areas, may reveal the reasons for the lack of information related to these areas in the official sources of sustainability indicators.

In addition, the future examination of national legislation for the sustainability (or sustainable development) and for environmental issues in the countries, could provide other conclusions, regarding on the importance of the marine-coastal areas in the production of its official statistics and in the policy-making process. And could collaborate to confirm the results acquired in this work, of which the representation of the marine-coastal areas in the sustainability (or the sustainable development) indicators systems (or lists) seem to be independent of the economic development level and the geographic localization of the country.

This work aims at contributing to the improvement of the analyzed systems (or lists) of sustainability (or sustainable development) indicators, highlighting the international standards in this issue, as well as to alert researchers and policy-makers to the importance of the natural environment as essential to the support of life, of the conservation of biological diversity, and of the productivity in the marine-coastal areas.

Appendix

Supporting Information associated with this article is available on-line at http://www.aprh.pt/rgci/pdf/rgci-535_Souto_Supporting-Information.pdf

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Shallow-water hydrothermal vents in the Azores (Portugal)*

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ABSTRACT

The impact of global warming has been a major issue in recent years and will continue increasing in the future. Knowledge about the effects of ocean acidification on marine organisms and communities is crucial to efficient management. Island environments are particularly sensitive to externally induced changes and highly dependent on their coastal areas.

This study summarises the published information on shallow-water hydrothermal vents of the Azores. These environments were reported to exhibit high metal concentration and acidified seawater due to the diffusion of acidic volcanic gases (mainly CO_2) and a considerable temperature range. In some vents a water input with lower salinity was reported. These conditions result in a depletion of some of the species but can also enhance a diversity gradient between the "unique" shallow marine hydrothermal ecosystems and the surrounding common coastal marine environment, potentiating the co-existence of a high variety of metabolisms and so biodiversity. Metal content on species from vent areas was reported to be associated with volcanic activity and signs of organism's chronic stress seemed to result in modifications on their morphometry and internal composition. Species able to survive at vent conditions are indicated as potential sentinels for studying the effects of increasing temperature and acidification on marine organisms and as bioindicators of metal accumulation studies at the Azores.

Further information on CO_2 flux, metals concentration in the sediments and seawater and on the geochemistry of fluids from active shallow-water hydrothermal systems is needed. Also, research on the productivity of shallow-water vent areas at the Azores and on food chains and interactions between trophic levels at these environments is recommended as it will contribute to a better knowledge of metal bioavailability, accumulation and biomagnification. This research should be complemented by investigations directed to the venting periodicity and episodicity and metal deposits resulting from hydrothermalism. This would increase the value of the Azorean vents as natural laboratories to the implementation of multidisciplinary research aimed at contributing to predict and/or to infer about ocean acidification effects on marine organisms and communities.

Keywords: Temperature; Acidification; Submarine degassing; Volcanic gas; Hydrothermal system.

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RESUMO

Fontes hidrotermais de superfície nos Açores (Portugal)

O impacte do aquecimento global é atualmente um assunto de grande interesse e que continuará a aumentar no futuro. O conhecimento sobre os efeitos da acidificação dos oceanos nos organismos e comunidades marinhas é fundamental para uma gestão eficiente. Os ambientes insulares são particularmente sensíveis às mudanças externamente induzidas e muito dependentes das suas áreas costeiras.

Este estudo resume as informações publicadas em fontes hidrotermais de superfície dos Açores. Nestes ambientes foram reportadas elevadas concentrações de metais, água do mar acidificada devido à difusão de gases vulcânicas ácidas (principalmente CO_2) e um intervalo de temperatura abrangente. Em algumas fontes foi relatada uma entrada de água com baixa salinidade. Estas condições resultam na depleção de algumas das espécies, mas também podem induzir um gradiente de diversidade entre os ecossistemas hidrotermais marinhos de superfície "únicos" do ambiente costeiro marinho comum circundante, potenciando a coexistência de uma elevada variedade de metabolismos e assim a biodiversidade. A concentração de metais em espécies de fontes hidrotermais foi reportada sendo associada à atividade vulcânica e os sinais de stress crónico dos organismos parece resultar em modificações na sua morfometria e composição interna. Espécies capazes de sobreviver em fontes hidrotermais de superfície são indicadas como potenciais indicadores para estudar os efeitos do aumento da temperatura e da acidificação em organismos marinhos e como bioindicadores de acumulação de metal em estudos nos Açores.

É necessário maior conhecimento sobre o fluxo de CO_2, a concentração de metais nos sedimentos e na água do mar e sobre a geoquímica de fluidos de sistemas hidrotermais de superfície ativos. Para além disso, a investigação sobre a produtividade em áreas de fontes hidrotermais de superfície nos Açores, nas cadeias alimentares e interações entre níveis tróficos nestes ambientes é recomendada, pois irá contribuir para um melhor conhecimento da biodisponibilidade, acumulação e biomagnificação de metais. Esta investigação deverá ser complementada por investigações dirigidas à periodicidade e sazonalidade das fontes hidrotermais de superfície, assim como aos depósitos de metais resultantes do hidrotermalismo. Isso aumentaria o valor das fontes hidrotermais de superfície dos Açores como laboratórios naturais para a realização de investigação multidisciplinar que visa contribuir para prever e/ou para inferir sobre os efeitos da acidificação dos oceanos nos organismos e comunidades marinhas.

Palavras-chave: *Temperatura; Acidificação; Desgaseificação submarina; Gases vulcânicos; Sistemas hidrotermais.*

1. Introduction

The Azores archipelago comprises nine volcanic islands (Fig. 1), located in the North Atlantic Ocean where the Eurasian, American and African lithospheric plates meet at a triple junction (Searle, 1980), between latitudes 36º 55' N and 39º 45' N and the longitudes 24º 45' W and 31º 17' W (Instituto Hidrográfico, 2000). It extends for more than 480 km along an Northwest-Southeast trend (Morton *et al.*, 1998) and occupies an area of about 2344 km^2 (Instituto Hidrográfico, 2000).

The main tectonic features are the Mid-Atlantic Ridge (MAR) that crosses the archipelago between the islands of Flores and Faial, the East Azores Fracture Zone (EAFZ), which extends E–W from the MAR to Gibraltar including the Gloria Fault, and the Terceira Rift (TR), which trends NW–SE from the MAR to the island of Santa Maria (França *et al.*, 2003; Cruz & França, 2006). On account of this complex tectonic setting, seismic and volcanic activities are frequent throughout the archipelago (França *et al.*, 2003; Ferreira *et al.*, 2005; Viveiros *et al.*, 2010).

Present-day volcanic activity in the Azores is marked by highly active fumarolic fields, hot springs and soils diffuse degassing phenomena (Ferreira *et al.*, 2005), where degassing areas are related to hydrothermal systems (Ferreira, 1994) and anomalous CO_2 fluxes are mainly controlled by tectonic structures and by the geomorphology of the volcanic complex (Viveiros *et al.*, 2010).

A striking feature of these islands, as a result of their volcanic nature, is the presence of active deep sea and shallow-water hydrothermal activity caused by diffuse degassing from submerged soils (Cruz, 2003; Ferreira *et al.*, 2005). Organisms associated to hydrothermal activity are chronically exposed to extreme environments characterized by "natural thermal pollution", high metal concentrations (Cunha *et al.*, 2007; Cunha *et al.*, 2008; Wallenstein *et al.*, 2009a; Couto *et al.*, 2010; Dionísio *et al.*, 2013; Wallenstein *et al.*, 2013), either in the form of particles or associated with gases from volcanic emissions (Hansell *et al.*, 2006), as well as acidic seawater due to the diffusion of volcanic gases (Cruz & França, 2006).

The terrestrial volcanic systems have been well-studied, both because of the long history of devastation caused by their eruptions and because of their geothermal potential (Ferreira, 1994; Cruz *et al.*, 1999; Ferreira & Oskarsson, 1999; Cruz, 2003; França *et al.*, 2003; Ferreira *et al.*, 2005; Cruz & França, 2006; Viveiros *et al.*, 2008; Cruz *et al.*, 2010; Viveiros *et al.*, 2010).

The shallow submarine parts of the volcanic system have received relatively little attention, and are poorly studied when compared to some of the mid-ocean ridge systems (Bachraty *et al.*, 2009). Shallow-water venting extends from the intertidal down to more than 200 m in depth and is, in general, typically characterized by free gas release and water efflux (Dando *et al.*, 1995). At the Azores shallow-water vents occur along the islands and in seamounts (see Fig. 1). A detailed discussion of the

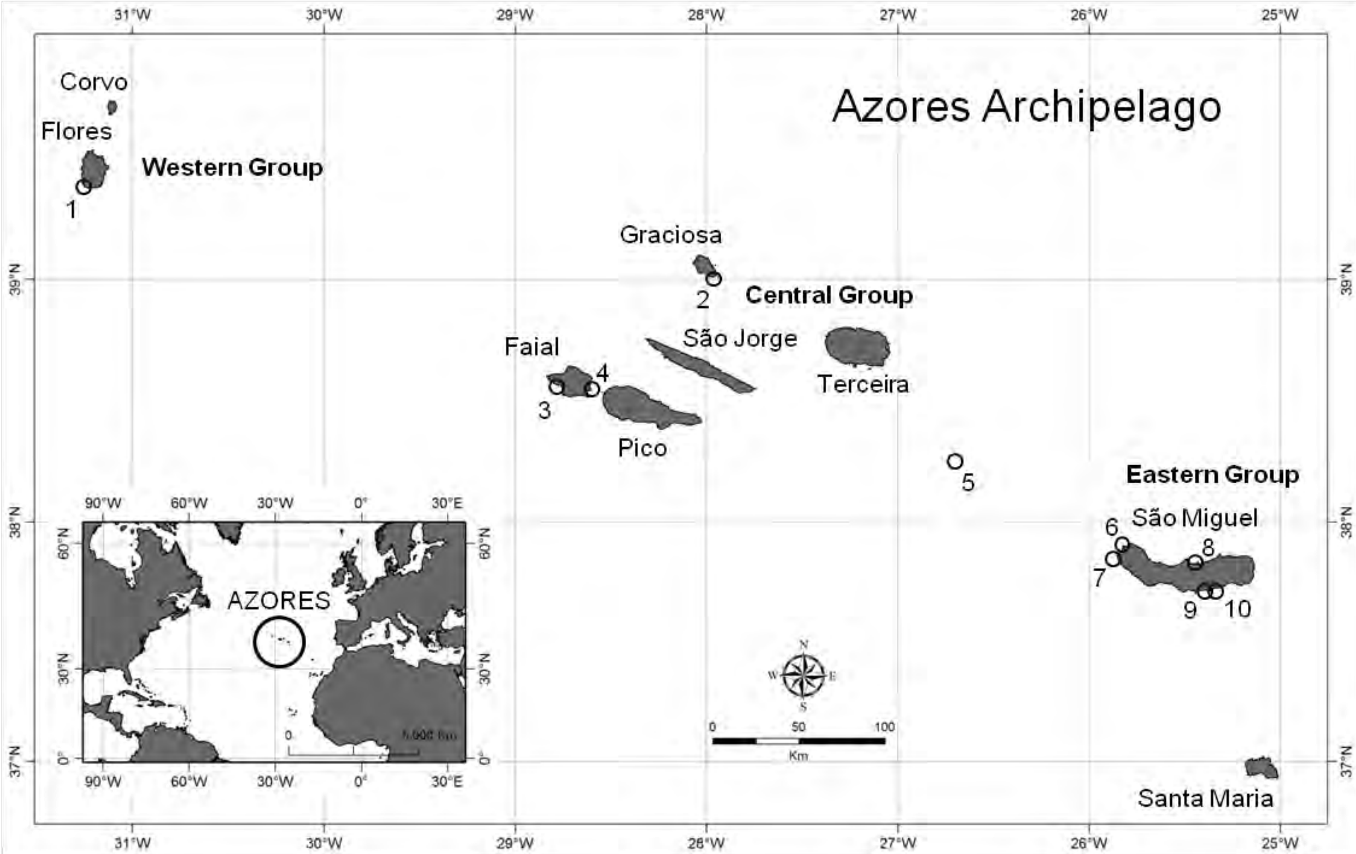

Figure 1 - Azores archipelago, showing the known shallow-water hydrothermal vents locations: (1) Lajedo; (2) Carapacho; (3) Varadouro; (4) Espalamaca; (5) D. João de Castro Bank; (6) Mosteiros (Beach); (7) Ferraria; (8) Porto Formoso; (9) Ribeira Quente (Lobeira); (10) Ribeira Quente (Beach).

Figura 1 - Arquipélago dos Açores com a localização das fontes hidrotermais de superfície conhecidas: (1) Lajedo; (2) Carapacho; (3) Varadouro; (4) Espalamaca; (5) Banco D. João de Castro; (6) Mosteiros (Praia); (7) Ferraria; (8) Porto Formoso; (9) Ribeira Quente (Lobeira); (10) Ribeira Quente (Praia).

differences between shallow-water and deep sea hydrothermal vent ecosystems is given by Tarasov *et al.* (2005). Temperatures at shallow vents, due to the lower boiling point, are not as high as in the widely-studied deep sea vents, which can exceed 277°C (Desbruyéres *et al.*, 2001). Primary production at shallow depths is mainly generated by photosynthesis, while at deep-sea vents it is generated by chemoautotrophic or methanotrophic microbes (Tarasov *et al.*, 2005).

In order to increase knowledge and better understand the functioning and the processes occurring at these peculiar systems, different types of studies, with different aims and methodologies, have been published in a variety of scientific journals. This review, aimed at congregating the dispersed published information on shallow-water hydrothermal vents at the Azores, summarises the current published information on those systems since 1985.

2. Hydrothermal areas

Degassing areas in the Azores are related to hydrothermal systems (Ferreira *et al.*, 2005). Active shallow-water hydrothermal vent fields are found at the islands of Flores, Faial, Graciosa, São Miguel and at D. João de Castro Bank

D. João de Castro Bank is one of the best studied sites. It is the remains of an island formed by a submarine eruption in 1720 (Daussy, 1830; Agostinho, 1941; Oliveira, 1943) that disappeared in 1722 (Daussy, 1830). Back then the hydrothermal activity was already reported by navigators (Daussy, 1830; Agostinho, 1941; Oliveira, 1943) but only in 1941 the exact location of the bank was definitively established (Oliveira, 1943). This is one of the few Azorean vents that is not near any island shore, lying 36 nautical miles away from Terceira and 40 miles away from São Miguel islands (Santos *et al.*, 2001).

The majority of the other known vents in the Azores are located near or in the islands shores and are variable in shore height, depth, substratum composition and exposition (Table 1). Even vents at the same island or at the same area can have different physical and chemical conditions. Some, e.g. Ferraria, Varadouro, Lajedo and Carapacho are known by their thermal baths. On São

Table 1 - Shallow-water hydrothermal vent sites studied in the Azores.
Tabela 1 - Fontes hidrotermais de superfície estudadas nos Açores.

Local	Island	GPS Coordinates	Depth (m)	Seafloor	References
D. João de Castro Bank	-	N 38° 13' 59″ W 26° 37' 59″	18-45	Rock	Aguiar & Costa, 2010; Ávila, 1997; 2007; Ávila *et al.,* 2004; 2007; Boury-Esnault & Lopes, 1985; Cardigos *et al.*, 2002; 2004; 2005; Cardigos, 2002; 2006; Colaço *et al.,* 2006; D'Udekem d'Acoz & Wirtz, 1999; MBL, 2009; Mohandass *et al.*, 2012; Raghukumar *et al.*, 2008; Santos *et al.*, 1996; 2001; 2010; Sobrinho-Gonçalves & Cardigos, 2006
Lajedo	Flores	N 39°22′58″ W 31°15′11″	Intertidal	Rock	Aguiar & Costa, 2010; MBL, 2009
Espalamaca	Faial	N 38°32′44″ W 28°36′10″	5-50	Sand	Aguiar & Costa, 2010; MBL, 2009; Munaro *et al.*, 2010
Carapacho	Graciosa	N 39°00′45″ W 27°57′32″	Intertidal	Rock and Boulders	Aguiar & Costa, 2010; MBL, 2009
Varadouro	Faial	N 38°33′51″ W 28°45′35″	Intertidal	Rock and Boulders	Aguiar & Costa, 2010; MBL, 2009
Mosteiros (Beach)	São Miguel	N 37°53′12″ W 25°49′26″	Intertidal	Sand	Aguiar & Costa, 2010; MBL, 2009
Ferraria	São Miguel	N 37°51′30″ W 25°51′07″	Intertidal	Rock	(Aguiar, 1999; 2005; Aguiar & Costa, 2010; Albuquerque *et al.,* 2002; Carvalho *et al.*, 2009; 2011; Cruz *et al.,* 2010; Cunha *et al.*, 2008; Freire, 2006; MBL, 2009; Moore *et al.*, 1995; Vedel & Depledge, 1995; Wallenstein *et al.*, 2009a; 2009b; 2013; Weeks *et al.*, 1995
Ribeira Quente (Lobeira)	São Miguel	N 37°43′26″ W 25°19′09″	6-8	Rock and Sand	(Aguiar, 1999; 2005; Aguiar & Costa, 2010; Dionísio *et al.,* 2013; MBL, 2009; Mendes, 2008; Zillig *et al.,* 1990; 1991
Ribeira Quente (Beach)	São Miguel	N 37°43′46″ W 25°18′30″	Intertidal	Sand	(Aguiar, 1999; 2005; Aguiar & Costa, 2010; Ávila *et al.,* 2007; Cunha *et al.,* 2008; Huber *et al.,* 1986; Manaia & Costa, 1991; Manaia *et al.,* 1994; MBL, 2009; Nunes *et al.,* 1992; Segerer *et al.*, 1991
Porto Formoso	São Miguel	N 37°49′18.8″ W 25°27′25.2″	Intertidal	Boulders	(Aguiar & Costa, 2010; Couto *et al.,* 2010; 2012; Wallenstein *et al.,* 2009a; 2013

Miguel Island, the vent sites Mosteiros, Ferraria, Ribeira Quente and Porto Formoso are in intertidal areas used by locals for leisure.

Only two studies have been published on habitat mapping of Azorean hydrothermal vent fields. Santos *et al.* (2001) presented bathymetric maps and a general characterization of the D. João de Castro bank. Munaro *et al.* (2010) mapped the shallow-water hydrothermal vent site of Espalamaca.

Seven of the Azorean vent sites are located within areas subjected to some environmental protection, either within the Island Park delineation (e.g., Ferraria and Carapacho) or within the Azores Marine Park domain (e.g., D. João de Castro Bank). D. João de Castro seamount was classified as a Special Area of Conservation (SAC) and as a sensitive habitat under the "Submarine structures made by leaking gases". Espalamaca degasification low temperature hydrothermal field is also integrated in a larger protected area designated Baixa do Sul, recently classified as a SAC and integrated in the Faial's Natural Park (Aguiar & Costa, 2010).

Lagedo (Flores), Carapacho (Graciosa), Ferraria (S. Miguel) and Ladeira da Velha (S. Miguel) were previously classified as Important Bird Areas (IBAs) and now Ferraria, Mosteiros, and Ladeira da Velha (Porto Formoso) on S. Miguel Island, as well as Espalamaca (Faial) are classified as Protected Areas for Resources Management within the framework of the respective Island Park premises (Aguiar & Costa, 2010). Carapacho (Graciosa) and Lagedo (Flores) are classified as Protected Areas for Habitat or Species Management. The marine hydrothermal site of Varadouro (Faial) and Ribeira Quente (S. Miguel) are not included within the respective Islands Park limits (Aguiar & Costa, 2010).

However, these protection figures were not established to value and protect the hydrothermal ecosystems, but to protect other coastal systems and organisms (Aguiar & Costa, 2010). In fact, there aren't clear indications of the uses and restrictions of the shallow marine hydrothermal sites. This information, however, should be provided and complemented with management plans for each area.

3. Hydrothermal fluids

3.1. Gas composition of fluids

Data on the gas composition of shallow submarine hydrothermal vents in the Azores is only available for D. João de Castro Bank (Cardigos *et al.*, 2005). Although there is no gas flux evaluation, the authors reported that the major gas component was CO_2 (90%), with lesser H_2S (9-36 ppm), H_2 (19-21749 ppm), CH_4 (0.0-84.2 ppm) and the presence of He (Santos *et al.*, 1996; Cardigos *et al.*, 2005).

3.2. Water fluxes and solutes

Water fluxes are formed by the venting of meteoric and seawater, which composition has been altered as a result of interactions with the sediments by elevated temperatures and the entrainment of interstitial waters by the rising fluids. Rising gas bubbles can initiate water circulation within the sediment, so that the released water is recharged by overlying water (O'Hara *et al.*, 1995; Dando *et al.*, 1999). Reports on this matter are restricted to D. João de Castro Bank and indicate flow rates of venting water of 773 and 787 mL/min in September 1999 (Cardigos *et al.*, 2005). This work is an important milestone for shallow-water hydrothermal vent studies in the Azores as it provides information on water chemistry from shallow-water hydrothermal vents and a physical characterization of the vent surroundings. It distinguishes two main types of vents: "white" vents (due to the presence of a white bacterial mat, mainly an attached form of *Beggiatoa* TREVISAN) and "yellow" vents (due to an amorphous material bordering the vents with no evidence for crystalline mineral phases), characterized by different physical and chemical properties (Cardigos *et al.*, 2005).

Further research on the subject is restricted to the collection of physical and chemical data from several vents performed in the course of the International Census of Marine Microbes (ICoMM), and made available online (MBL, 2009).

Available data on temperatures at the fluid outlets and other physical and chemical parameters of shallow submarine vents in the Azores revealed that they are very variable [Supplementary Information - Annex I] and for same cases, different from the surrounding seawater environment (e.g. pH) (Instituto Hidrográfico, 2000).

Vents at the same island or at the same area have different physical and chemical parameters. This represents one of the characteristics of shallow water hydrothermal vents: their singularity (therefore unreplicated). Each vent is associated to a specific substratum type and depth, and the physical and chemical properties of the fluid can be quite variable (Melwani & Kim, 2008). Even the temperature range can be of considerable magnitude (Vedel & Depledge, 1995; Wallenstein *et al.*, 2013). The majority of the data concerns to physical data, revealing the need for more studies regarding chemical water analysis and dissolved gases (*e.g.* CO_2).

4. Biota

4.1. Microorganisms

Microbial investigations on the shallow hydrothermal vents at the Azores were mainly directed to bacteria (Huber *et al.*, 1986; Zillig *et al.*, 1990; Manaia & Costa, 1991; Segerer *et al.*, 1991; Zillig *et al.*, 1991; Nunes *et al.*, 1992; Manaia *et al.*, 1994; Aguiar, 1999; 2005; Albuquerque *et al.*, 2002; Cardigos, 2002; Cardigos *et al.*, 2004; 2005; Raghukumar *et al.*, 2008; MBL, 2009; Aguiar & Costa, 2010; Zinger *et al.*, 2011; Mohandass *et al.*, 2012) with the selective isolation of chemosynthetic and thermophilic bacteria (see Table 2). A few studies were devoted to Fungi and Protists (Colaço *et al.*, 2006; Raghukumar *et al.*, 2008).

Huber *et al.* (1986) described an anaerobic, extremely thermophilic eubacterium (*Thermotoga maritime* HUBER), isolated from geothermally heated sea floors in Ribeira Quente (SE coast of São Miguel island), representing a new genus and a new species. Segerer *et al.* (1991) described the bacteria genus *Stygiolobus* SEGERER from the same location, pointing that "it may be that the genus *Stygiolobus* is a very rare and possibly even an endemic genus in the Azores". Zillig *et al.* (1990) isolated and described the metabolism and phylogeny of a hyperthermophilic bacteria from a moderately active submarine hydrothermal area also at Ribeira Quente, at a depth of about 9 m, 200 m away from a steep, rocky shore from São Miguel Island that was later classified as *Hyperthermus butylicus* ZILLIG (Zillig *et al.*, 1991).

Manaia & Costa (1991) described the phenotypic characteristics of several bacterial isolates from the same area, demonstrating a relationship, at a low similarity level, between the marine and the terrestrial bacterial strains, suggesting that the exchange of these halotolerant strains between nearby marine and terrestrial hot springs is probably frequent.

The isolation and characterization of *Rhodothermus* ALFREDSSON strains from shallow marine hot springs at Ribeira Quente was performed by Nunes *et al.* (1992). Later, Manaia *et al.* (1994) studied the halotolerant *Thermus thermophilus* (ex Oshima &

Table 2 - Microbial species isolated from hydrothermal sites in the Azores.
Tabela 2 - Espécies microbianas isoladas em locais com atividade hidrotermal nos Açores.

Species	References
Bacteria	
Thermotoga maritime Huber	Huber *et al.*, 1986
Hyperthermus butylicus Zillig	Zillig *et al.*, 1990; 1991)
Stygiolobus azoricus Segerer	Segerer *et al.*, 1991
Rhodothermus Alfredsson	Nunes *et al.*, 1992
Thermus thermophiles (ex Oshima & Imahori) Manaia	Manaia *et al.*, 1994
Albidovulum inexpectatum Albuquerque	Albuquerque *et al.*, 2002
Beggiatoa sp. Trevisan	Cardigos, 2002; 2006; Cardigos *et al.*, 2004; 2005
Alcaligenes faecalis Castellani & Chalmers *Bacillus flexus* (ex Batchelor) Priest *et al.* *Bacillus licheniformis* (Weigmann) Chester *Bacillus subtilis* (Ehrenberg) Cohn *Brevibacterium casei* Collins *et al.* *Halomonas* sp. Vreeland *et al.* emend. Dobson & Franzmann *Micrococcus luteus* (Schroeter) Cohn *Pseudoalteromonas* sp. Gauthier *et al.* emend. Ivanova *et al.* *Staphylococcus arlettae* Schleifer *et al.* *Staphylococcus cohnii* Schleifer & Kloos *Staphylococcus succinus* Lambert *et al.* *Yersinia* sp. Loghen	Mohandass *et al.*, 2012
Fungi	
Aspergillus sp. Micheli *Cladosporium* sp. Lindau	Raghukumar *et al.*, 2008
Protists	
Ulkenia sp. Gaertn	Raghukumar *et al.*, 2008

Imahori) Manaia. These extreme thermophile and halotolerant species indicate a specific capacity of adaptation to the extreme environment (Manaia & Costa, 1991) that can promote speciation even to Genus level (Huber *et al.*, 1986; Zillig *et al.*, 1990; Segerer *et al.*, 1991; Zillig *et al.*, 1991; Albuquerque *et al.*, 2002).

After the analysis of several bacterial isolates recovered from the marine hot spring of Ferraria by Albuquerque *et al.* (2002) the new species *Albidovulum inexpectatum* Albuquerque was proposed.

Aguiar (1999) made a preliminary characterization of intertidal and subtidal microbial communities, complemented with a study on the microbial ecology of Azorean hot springs (Aguiar, 2005). This later work report that microbial communities are very different between sites and that a more continuous sampling effort is necessary to better understand the nature of the microbial community composition in these shallow-water marine vents.

Mohandass *et al.* (2012) studied the bacterial diversity and their adaptations to the shallow-water hydrothermal vents and reported specific physiological changes that are likely to be adaptations to that environment. These authors alerted to their potential use in biotechnological applications. Specific physiological changes were also reported to other groups like Fungi and Protists (Colaço *et al.*, 2006; Raghukumar *et al.*, 2008)

According to Albuquerque *et al.* (2002), the water temperature of the vents drops very rapidly in contact with seawater and it is likely that the organisms colonize the geothermal aquifer or the porous lava before the hydrothermal water is released into the seawater. The extreme occurrence of *Bacillus* sp. found at D. João de Castro Bank was related to the ability of these organisms to form spores, thus enabling them to withstand a wide range of environmental conditions like temperature and pH (Mohandass *et al.*, 2012).

4.2. Fauna and flora

Different approaches have been made to the study of the fauna and flora of the Azorean vents (Table 3) but, in general, these organisms are similar to those of other coastal and seamount areas of the archipelago (Cardigos *et al.*, 2005).

Ávila (1997) published a list of the marine molluscs collected at 30 m depth at D. João de Castro Bank. D'Udekem d'Acoz & Wirtz (1999) published a list of animal species identified at the same area and commented that the studied area was "impoverished" when compared to other sites at similar depths, probably due to the "toxic environment" of the vent. A similar comment was made by Ávila *et al.* (2004) when comparing marine molluscs composition between shallow-water hydrothermal vent sites with other sites at similar

Table 3 - Taxonomic groups studied at shallow-water hydrothermal vents in the Azores.
Tabela 3 - Grupos taxonómicos estudados em fontes hidrotermais de superfície nos Açores.

Taxonomic Group	**References**
Algae	*Ávila et al., 2004; Cardigos, 2002; Cardigos et al., 2004; 2005; Colaço et al.*, 2006; Couto *et al.*, 2010; Santos *et al.*, 1996; Wallenstein *et al*., 2009a; 2009b; 2013
Porifera	Boury-Esnault & Lopes, 1985; Cardigos *et al*., 2004; 2005; Cardigos, 2002; Colaço *et al*., 2006; D'Udekem d'Acoz & Wirtz, 1999; Santos *et al*., 1996)
Bryozoa	Cardigos *et al*., 2004; Cardigos, 2002; Santos *et al*., 1996
Cnidaria	Cardigos, 2002; Cardigos *et al*., 2004; 2005; d'Acoz & Wirtz, 1999; Santos *et al*., 1996)
Ctenophora	Cardigos, 2002; Cardigos *et al*., 2004; 2005; d'Acoz & Wirtz, 1999)
Annelida	Cardigos, 2002; Cardigos *et al*., 2004; 2005; d'Acoz & Wirtz, 1999; Santos *et al*., 1996; Colaço *et al*., 2006
Arthropoda	Cardigos, 2002; Cardigos *et al*., 2004; 2005; d'Acoz & Wirtz, 1999; Santos *et al*., 1996; Dionísio *et al.,* 2013; Moore *et al*., 1995; Weeks *et al*., 1995)
Echinodermata	Cardigos, 2002; Cardigos *et al*., 2004; 2005; d'Acoz & Wirtz, 1999; Santos *et al*., 1996;
Diatoms	Colaço *et al*., 2006; Raghukumar *et al*., 2008
Mollusca	Ávila, 1997; 2007; Ávila *et al*., 2004; 2007; Cardigos, 2002; Couto *et al*., 2012; Cunha *et al*., 2008; d'Acoz & Wirtz, 1999; Santos *et al*., 1996; Vedel & Depledge, 1995)
Tunicata	Cardigos *et al*., 2004; Cardigos, 2002; d'Acoz & Wirtz, 1999)
Pisces	Cardigos *et al*., 2004; Cardigos, 2002; d'Acoz & Wirtz, 1999; Santos *et al*., 1996; Sobrinho-Gonçalves & Cardigos, 2006)
Reptilia	Cardigos, 2002; Cardigos et al., 2004
Aves	Cardigos, 2002; Cardigos et al., 2004
Mamalia	Cardigos, 2002; Cardigos et al., 2004
Meiobenthos	Mendes, 2008

depths. Further research by the same authors (Ávila *et al.*, 2007) revealed differences not only in terms of presence/absence, but also in species densities with a lower number of species and lower densities at the studied hydrothermal vents sites.

A comparative study between meiobenthic communities affected by hydrothermal activity and a control site without such influence (Mendes, 2008), concluded that the hydrothermal site has more or less the same composition as non-hydrothermal sites but with lower abundances.

Recently, Wallenstein *et al.* (2013) gave an account of the habitat characteristics and associated intertidal seaweed communities subjected to shallow-water hydrothermal activity in the Azores. Seaweed communities were found to be species poor and to have a disproportionally larger number of filamentous early successional species. The authors pointed to the remarkable ecological resemblance between the studied communities and those affected by an acid mine drainage in the UK. Their study suggested that hydrothermalism could be a useful scenario for pollution studies under conditions of ocean warming and acidification.

5. Vent effects on the biota

Moore *et al.* (1995) and Vedel & Depledge (1995), analysed the copper (Cu) and zinc (Zn) concentrations on, respectively amphipods and limpets living on hydrothermal vents. Moore *et al.* (1995), analysing the whole body concentration, found a general increase of Cu and Zn concentrations in four species of talitroid amphipods, remaining to be shown whether this is a species characteristic, or an effect resulting from the volcanic origin of the islands. Vedel & Depledge (1995) found that the essential trace metals, Cu and Zn (important cofactors in the functioning of many enzymes), occurred at significantly higher concentrations in the tissues of limpets from the thermal vent population, consistent with the higher enzymic concentrations found in organisms as result of metabolic adaptive responses to high temperatures. These later authors examined intraspecific differences in thermal tolerance in different populations of marine snails and limpets from rocky shores and from the vicinity of a thermal vent and verified that there was a tendency for a greater thermal tolerance in individuals from the hot spring site.

Cunha *et al.* (2008), in a study aimed to evaluate the bioavailability of metals in the Macaronesian endemic limpet *Patella candei gomesii* DROUET living close to shallow-water hydrothermal vents, reported modifications in the organisms morphometry, higher metal concentrations (Cs, Co Cu, Mn, Rb, and Zn), and more prevalent apoptotic nuclei. Abnormal shells on limpets living at intertidal hydrothermal vents were also found by (Couto *et al.*, 2012) as a result of the higher acidity of the vent locations, providing evidences that limpets are sensitive to such environmental changes and therefore have an enormous potential to be used as sentinel organisms of ocean acidification.

Trace metal bioavailability evaluation on barnacles (*Chthamalus stellatus* POLI) by Weeks *et al.* (1995) revealed high levels of Zn and Cd in the organisms from the Ferraria vent.

Colaço *et al.* (2006), in a study aimed at evaluating trace metal concentrations in species of macroalgae and sponges and the tolerance of microorganisms (protists and bacteria) to trace metals, produced baseline data on metal content for the studied organisms and concluded they were well adapted to the metal enriched waters of the study site (D. João de Castro).

Wallenstein *et al.* (2009a) compared the accumulation of a selected pool of chemical elements by common intertidal macroalgae from three distinct situations acting on rocky shore locations around São Miguel Island: pristine shores, urbanized coasts, and coasts subjected to shallow-water hydrothermal activity. Results revealed that the algae from the hydrothermally active had higher concentrations of the metals Mn, Rb and Zn, indicating these organisms could be used as bioindicators of heavy metal enrichment. A subsequent research by the same authors (Wallenstein *et al.*, 2009b), studied the effect of exposure time on the bioaccumulation of certain elements by *Cystoseira abies-marina* (GMELIN) AGARDH specimens subjected to shallow-water hydrothermal activity and concluded that this species could be used as a tool to monitor water quality in the Azores. High levels of metal accumulation (Zn, Rb and Mn) and morphometric changes were also reported by Couto *et al.* (2010) for the calcareous alga *Corallina elongata* ELLIS ET SOLANDER from shallow vents.

6. Conclusions and directions for future research

Research on shallow-water hydrothermal vents confirmed that organisms that live in such environments as hydrothermal vents are chronically exposed to ‘‘natural thermal pollution”, high metal concentration (Hansell *et al.*, 2006), as well as to acidified seawater adjacent to hydrothermally active areas due to the diffusion of acidic volcanic gases (mainly CO_2) (Cruz & França, 2006). In some of the shallow vents a water input with lower salinity was reported (Dando *et al.*, 1995; Dando *et al.*, 1999; Biasi *et al.*, 2004) (see Table 2). In Ladeira da Velha a freshwater input (small stream) is visible running from land to the seawater (Couto *et al.*, 2010; Couto *et al.*, 2012). Extreme environments can result in a depletion of some of the species present in the surrounding areas, except the ones that exhibit some tolerance to extreme conditions (Melwani & Kim, 2008), which is reflected in differences on species number and abundances (D'Udekem d'Acoz & Wirtz, 1999; Ávila *et al.*, 2004; Ávila *et al.*, 2007; Mendes, 2008).

Research has also documented that organisms can develop physiological adaptations in extreme environments (Manaia & Costa, 1991; Vedel & Depledge, 1995; Cardigos *et al.*, 2006; Raghukumar *et al.*, 2008; Couto *et al.*, 2010; Mohandass *et al.*, 2012). Metal content on species from vent areas was reported to be associated with volcanic activity (Cardigos *et al.*, 2005; Colaço *et al.*, 2006; Cunha *et al.*, 2008; Wallenstein *et al.*, 2009a; Wallenstein *et al.*, 2009b), and the species able to survive at those conditions are indicated as potential useful bioindicators for metal accumulation studies at the Azores (Cunha *et al.*, 2008; Wallenstein *et al.*, 2009b; Couto *et al.*, 2010; Couto *et al.*, 2012). Calcareous organisms (e.g. coralline algae, corals, echinoderms or molluscs, among others), chronically exposed to conditions that promote the dissolution of their calcified structures/ components were indicated as potential sentinel species for studying the effects of increasing temperature and acidification on marine organisms (Hall-Spencer *et al.*, 2008; Marshall *et al.*, 2008; Martin *et al.*, 2008; Couto *et al.*, 2010; Couto *et al.*, 2012). These findings are particularly important in recent times when ocean acidity is becoming a major concern (Hall-Spencer *et al.*, 2008; Marshall *et al.*, 2008; Martin *et al.*, 2008; Riebesell, 2008; Riebesell *et al.*, 2010).

Available data on the fluid analysis (Cardigos *et al.*, 2005; Cruz & França, 2006) (see Annex I [Supplementary Information / Informação Suplementar]), is insufficient and further information is needed on metals concentration in the sediments and seawater and on the geochemistry of fluids from active shallow-water hydrothermal systems. Particle and fluid fluxes, especially CO_2 flux, which has implications on acidity, also deserve attention.

Research on the productivity of shallow-water vent areas at the Azores and on food chains and interactions between trophic levels at these environments will contribute to a better knowledge of metal bioavailability, accumulation and biomagnification. This research should be complemented by investigations directed to the venting periodicity and episodicity and metal deposits resulting from hydrothermalism.

The signs of chronic stress reported for some organisms from the studied shallow-water hydrothermal vents (Colaço *et al.*, 2006; Cunha *et al.*, 2008; Mendes, 2008; Raghukumar *et al.*, 2008; Couto *et al.*, 2010; Couto *et al.*, 2012; Mohandass *et al.*, 2012) seems to result in modifications on their morphometry and internal composition that can promote speciation (Huber *et al.*, 1986; Zillig *et al.*, 1990; Segerer *et al.*, 1991; Zillig *et al.*, 1991; Albuquerque *et al.*, 2002). The ways or tools that organisms found in order to survive in extreme environments should be explored by biotechnology.

In conclusion, a review of the available published information made in the present study reveals that, despite all what has been done, a deeper knowledge is needed, encompassing a better characterization, of the vents and organisms living there, complemented by accurate maps. This would establish a baseline for the urgently needed effort that should be done to create specific protection figures to all Azorean shallow marine hydrothermal ecosystems and their surroundings. This would increase the value of the Azorean vents as natural laboratories to the implementation of multidisciplinary research aimed at contributing to predict and/or to infer about ocean acidification effects on marine organisms and communities.

Appendix

Supporting Information associated with this article is available on-line at http://www.aprh.pt/rgci/pdf/rgci-584_Couto_Supporting-Information.pdf

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Evaluation of trophic state in the Palo Verde estuary (Colima, México), action to regulating agricultural activities*

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ABSTRACT

The agricultural zones subjected to fertilizer use and inland runoff of nutrients leads to accelerated eutrophication with negative effects on coastal ecosystems and therefore significant negative economic impacts. The Palo Verde estuary (PVE) is a shallow estuary (0.4–1.5 m depth) located in the lower area of the sub-basin of the Armería River, in Colima, México. The PVE forms a temporary connection with the sea during unusual extreme meteorological events, but it is otherwise isolated. Freshwater inputs are restricted to discharges from nonpoint sources, such as agricultural runoff, torrential streams, and seasonal input from the Armería River. Farming is practiced along the boundaries of the PVE and involves an area of ~34.36 km^2 such that the estuary is under considerable anthropogenic pressure. The PVE has been recognized as a RAMSAR site (no. 1985), due to the biological, ecological, and socio-economic importance, but the estuary has been the focus of very few environmental studies, and there is a need to demonstrate, quantify and predict the effects of human activities on these interrelated components in space and time. We describe subsidies to agricultural sector the agricultural and activities within the drainage basin through stakeholder's engagement, also assessing the trophic status of the estuary with a trophic state multivariate index (TRIX) and proposing different ecosystem-based management (EBM). Actions intended to improve and control the use of agrochemicals (fertilizers N and P) in order to preserve ecosystem services.

Keywords: Palo Verde Estuary, Eutrophication, Ecosystem-based Management, Agrochemicals.

RESUMO §

Avaliação do estado trófico no estuário do Palo Verde (Colima, México), acção para a regulação das actividades agrícolas

As zonas agrícolas sujeitas ao uso de fertilizantes e a escorrência de nutrientes vindas do interior levam à aceleração da eutrofização com efeitos negativos nos ecossistemas costeiros e consequentemente a impactos económicos negativos signi-

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ficativos. O estuário de Palo Verde (PVE) é um estuário pouco profundo (0.4-1.5 m de profundidade) localizado na área inferior da sub-bacia do Rio Armería, na Colima, México. O PVE forma uma ligação temporário com o mar durante eventos meteorológicos extremos pouco invulgares, mas em caso contrário encontra-se isolado. As entradas de água doce restringem-se às descargas provenientes de fontes não pontuais, tais como os escoamentos agrícolas, ribeiras torrenciais e as contribuições sazonais do Rio Armería. A agricultura é praticada ao longo das margens do PVE e envolve uma área de ~34.36 km^2, de tal modo que o estuário encontra-se sob uma pressão antropogénica considerável. O PVE foi reconhecido como um sítio RAMSAR (n.º 1985) de importância biológica, ecológica e socio-económica, mas o estuário tem sido foco de muito poucos estudos ambientais, e é necessário demonstrar, quantificar e prever os efeitos das actividades humanas sobre estes componentes inter-relacionados no espaço e no tempo. Nós descrevemos os subsídios ao sector agrícola, a agricultura e actividades dentro da bacia de drenagem através do engajamento das partes interessadas, avaliando também o estado trófico do estuário com um índice multivariado do estado trófico (TRIX) e propondo diferentes gestões baseadas no ecossistema (EBM). Acções destinadas a melhorar e controlar o uso de agroquímicos (fertilizantes com N e P), a fim de preservar os serviços dos ecossistemas.

Palavras-chave: *Estuário do Palo Verde,* Eutrofização, Gestão com base nos Ecossistemas, Agroquímicos.

1. Introduction

Estuaries are transition zones between inland and open waters (González *et al*., 2006). The unique ecological and hydrodynamic characteristics account for the complexity of these environments but also their fragility (Coelho *et al*., 2007; Taner *et al*., 2011; Jennerjahn, 2012; Alves *et al*., 2013; Jennerjahn and Mitchell, 2013). However, estuaries also provide numerous goods and services to humanity. The economic importance of these ecosystem services (MEA, 2005) has been evaluated using a wide range of methods and econometric techniques (Stolk *et al*., 2006; Espino *et al*., 2013; Arocha *et al*., 2013; Valdez *et al*., 2014). In addition, estuaries have pedagogical potential, as a model for sustainable development (Costa *et al*., 2013).

Among the multifarious anthropogenic activities that impact estuaries (e.g., their touristic, urban, industrial, agricultural functions), agriculture is perhaps the most important, as it is responsible for the direct and indirect discharge of untreated water rich in fertilizer derived nitrogen (N) and phosphorous (P) (Ongley, 1997; Carpenter *et al*., 1998; Esqueda & Rivera, 2004, Espejo, *et al*., 2012).

The agricultural activity as a nonpoint pollution source is the main culprit producing the eutrophication of surface waters; currently, it is the most widespread water quality problem in many nations (Carpenter *et al*., 1998) and thus a cause for reduction in ecosystem services (Verdugo *et al*., 2007). Eutrophication is the result of over-enrichment of nutrients, such as the P and N present in synthetic fertilizers. These nutrient inputs increase primary productivity; thus, eutrophication is a process and not a trophic state (Nixon, 1995), that causes changes in the state trophic of the ecosystems, converting those that are nutrient poor (oligotrophic) to a state of over-enrichment (hypereutrophic) (USEPA, 1995).

While eutrophication is a natural process in coastal ecosystems (USEPA, 1995; Bricker *et al*., 2003), its additional negative associations as a byproduct of anthropogenic activities date back to the middle of the twentieth century, when the "green revolution" resulted in the excessive use of fertilizers in agriculture (Nixon, 1995; Cloern, 1999). Several studies have provided evidence of the contribution of incorrect synthetics fertilizer use to eutrophication (Correll, 1998; Sims *et al*., 1998; Sharpley *et al*., 2003; Siu *et al*., 2007; Espejo *et al*., 2012; Kroger *et al*., 2013).

In Mexico, agriculture is promoted through agricultural policies, including the application of agrochemicals, through the SAGARPA (Secretariat of Agriculture, Livestock, Rural Development, Fisheries and Food). Although implementation of these policies and programs (SAGARPA, 2014) is important to improve agriculture in Mexico, mexican farmers are not provided with the appropriate training. Consequently, agrochemical subsidies and inadequate training are the driving force exerting pressure on coastal ecosystems (Espejo *et al*., 2012).

Several models and indexes have been developed as tools to evaluate eutrophication in marine environments and other coastal-adjacent areas (Franco *et al*., 2010), such as the multivariate trophic index TRIX (e.g., Penna *et al*., 2004; Coelho *et al*., 2007; Silveira & Ojeda, 2009; Alves *et al*., 2013). A model used as tool support to communicate information is the Pressure-State-Response (PSR) framework, originally proposed by the Organization for Economic Co-operation and Development (OECD, 2001). This model has been used to organize data on environmental and societal characteristics, relations, and effects (Morais & Abessa, 2014) and because easily adjusted (OECD, 2001; Vázques-González *et al*., 2014). Therefore, in this study, we integrated data obtained from interviews, sample analysis, and TRIX into a modified (Driver-Pressure-State-Response) DPSR model approach followed the methodological arrangement suggested by OECD (2001).

The actions described herein as “response” are focused on regulating the actual agricultural practices and overuse of fertilizers and thus field´s over-enrichment and increased run-off (pressure) to support and improve decision-making for a sustainable PVE.

2. Materials and Methods

2.1. Study area

Palo Verde estuary (PVE) is located in the Armería, Colima State, Mexico (Fig. 1). At its northwest end, it is open to the Cuyutlán Lagoon, while to the southeast it communicates with the Pacific Ocean through a natural sandbar opening that results from the increased hydraulic pressure exerted by the large volumes of water flowing through the estuary or during the occurrence of extreme weather events. The PVE serves as a biological flyway of resident and migratory birds of the Mexican Pacific region (Mellink & López, 2009). The PVE's flora and fauna are protected under Mexican environmental regulations (FIR, 2009; NOM-059-SEMARNAT-2010), as part of the estuary's recognition as a RAMSAR Site (no. 1985) (RAMSAR México, 2009). Along its main axis it is approximately 4 km long and of varying width, with an estimated total area of ~734,968 m^2.

Along its boundary, there are three ejidos (in México ejido is a portion of land for public use like livestock and agriculture among others) and a small private property farmed (Fig. 1). Regional farming practices include both monoculture and polyculture of crops such as banana, coconut, lemon, and other seasonal crops in an area of approximately ~34.36 km^2. In addition to continental runoff discharges, the PVE is subjected to sedimentation problems. Thus, during the dry season (December to June), its volume is reduced and its water level declines, although both have been attenuated by an artificial floodgate.

3. Conceptual DPSR framework

The PSR framework, originally proposed by the Organization for Economic Co-operation and Development (OECD, 2001) considers that human activities exert *pressure* on the environment that affect both the quality and the quantity of natural resources and therefore their *state*. The *response* of society is to make the necessary changes through environmental as well as general economic and sectorial policies and through changes in awareness and behavior. Specifically, we used DPSR framework to analyze the main driving forces that encourage on the PVE according to scope our work, the pressures exerted on it, and its current trophic state, and to intent simplify communication between of decision-making, because all blame cannot be laid on the decision makers if the information is deficient (Lundberg, 2013). Thus, in this study, we integrated data obtained from interviews, sample analysis, and TRIX into a modified DPSR model approach, followed the methodological arrangement suggested by OECD (2001) to communicate the main message, and to help facilitate of possible responses to managers. The DPSR indicators are described beneath.

3.1. Drivers

The "Drivers" indicators are largely economic and socio-political (industrial or agricultural development, trade, regulations, subsidies, and others) that promote or

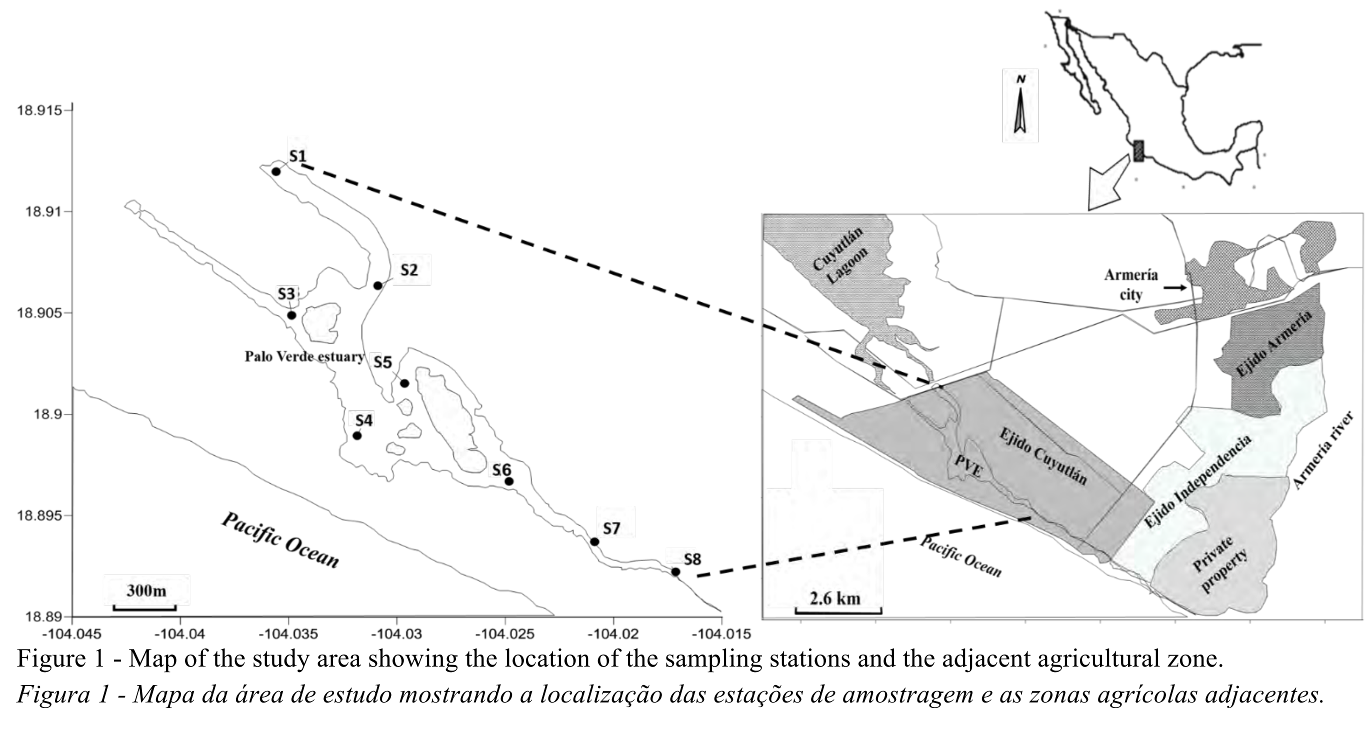

Figure 1 - Map of the study area showing the location of the sampling stations and the adjacent agricultural zone.

Figura 1 - Mapa da área de estudo mostrando a localização das estações de amostragem e as zonas agrícolas adjacentes.

influence environmental pressures in the absence of effective pollution abatement (Ærtebjerg *et al*., 2001; OECD, 2001). Nevertheless, in addition to subsidies, the inadequate agrochemicals training are the driving promote pressure on coastal ecosystems (Espejo *et al*., 2012). Thus, to propose work it, "Drivers" indicator to refer to federal subsidies of federal and municipal farming programs in order to synthetic N and P fertilizers acquisition, the lack of training agrochemical programs for farmers, and the lack of knowledge regarding regulations/measures referent to agrochemicals used on the agriculture area (ejidos) to lead it their inappropriate application.

3.2. Pressure

The issue of eutrophication, "Pressure" indicator, is human activities related to agriculture and emissions of N and P in water and soil, runoff from excessive commercial derivate of synthetic fertilizer use (OECD, 2001). Thus, this "Pressure" indicator is represented by agricultural activities in the adjacent zone (fertilizers N and P) that input to PVE trough continental runoff.

In our model both, the empirical data presented and analyzed stems from qualitative approach structured interviews, a method with a flexible structure, i.e. allowing new questions to be brought up during the interview depending on the answers from the former questions (Soriano, 1995; Sampieri *et al*., 2008). The interviewees represent a selection of key informants; commissioner and committee (12 persons). Commissioner and committee consisted mainly of the ejidos: Armería, Independencia, Cuyutlán and small-property owners (Fig. 1). The information of the current situation of subsidies and amount of approximate agrochemical used was for each ejido.

Thus, the structured interview to key informants consisted of 26 open- and closed-ended questions grouped in three sections: a) agricultural activities (7 questions related with: crop types, years of farming practice, time and alternative economic activities). b) farming capacity and agrochemical use (15 questions related with: main types of fertilizers employed, frequency of application/seasonal use, average amount used, training programs on the use of agrochemicals received, knowledge of the effects of the overuse of agrochemicals), and c) agricultural subsidies (4 questions related with: type of subsidies: cash, equipment, agrochemicals, and type and frequency).

In addition we dialogue with authorities (5 persons): Municipality's Director of Rural Development, Direction and Head of the Center for Rural Development Support, State Council of Lemon Producers (citrus production, COEPLIM), the State Council of Coconut Producers (COECOCO), and the Colima State Plant Health Committee (CESAVECOL) that represents the authorities. Also was taken in account the opinion of different stakeholders agricultures suppliers (5 persons), there were the five main regional distributors. They validated information about of fertilizer foremost trade. Information on the recommended doses of agrochemicals was obtained from the Technological Reports of the Development Rural Secretary Mexican National Institute for Forestry and Agricultural Research (SEDER). All interviewed were divided into three groups (Table 1).

3.3. State

The core set indicators in the issue of the eutrophication are the concentration of N and P and BOD/DO (OECD, 2001). However, in this work "State" indicator is integrate of the concentration of dissolved inorganic nitrogen (DIN: nitrate-NO_3^-, nitrite-NO_2^-, ammonia-NH_4^+), dissolved inorganic phosphorus (DIP) (both in μML^{-1}), dissolved oxygen (DO, in mgL^{-1}) and chlorophyll-a (Chl-a, in mg/m^{-3}), and information obtained integrated TRIX used to characterize the trophic state of the PVE.

The TRIX (proposed by Vollenweider *et al*., 1998) was used to measure the trophic state because it consists of a set of aggregated indicators, which reduces the number of measurements and parameters that normally would be required to describe a coastal lagoon environment. In addition, the measurement data can be easily communicated, thus providing an "exact" description of a particular situation, as recommended by the OECD (2001). The TRIX considers four state variables: those directly expressing productivity: Chl-a and oxygen [absolute value of the percentage of DO saturation, (abs|100%|=% O_2)], and nutritional factors: DIN (NO_3^-, NO_2^-, NH_4^+) and DIP. The values are provided in Table 2. The parameters were integrated into the following formula:

$$\text{TRIX} = (\log_{10}\text{-}a \times a\%O_2 \times \text{DIN} \times \text{DIP}+k/m \qquad (1)$$

where: k = 1.5 and m = 1.2 are constants.

3.3.1. Sampling and laboratory analysis

A series of samplings were conducted in the PVE with adequate temporal and spatial coverage such that representative conditions in the estuary with respect to depth, inputs from agricultural runoff, and sediment accumulation zones were included. Eight stations were selected. Their geographical positions were registered with GPS devices (Garmin eTrex). The stations were grouped in three zones with respect to depth: Stations 1, 2, and 3 corresponded to the northern zone (S-NZ: S1, S2, S3), with an average depth of 1m. Stations 4, 5, 6 made up the shallower central zone (S-CZ: S4, S5, S6), with a depth of 0.5m. Stations 7 and 8 comprised the southern zone (S-SZ: S7, S8), with an average depth of 0.8m. In addition, geomorphologic characteristics were considered.

Table 1 - Presentation of the groups of interviewed and the organizations and institutions they represent.

Tabela 1 – Apresentação dos grupos de entrevistados e das organizações e instituições que eles representam.

Group of interviewed	Organization	www-page
Commissioner and committee	Armería ejido, Independencia ejido, Cuyutlán ejido and Small-property owners	
Authorities	Municipal Director of Rural Development	http://www.armeria.gob.mx
	Direction and Head of the Center for Rural Development Support	
	COEPLIM	www.coeplim.gob.mx
	COECOCO	www.coecoco.gob.mx
	CESAVECOL	www.cesavecol.gob.mx
Agricultures suppliers	Hermanos Gómez Fertilizer	www.fertigomez.com.mx/
	Cazares Fertilizer	
	Ducor-Dupont fertilizer	www.ducor.com.mx
	Tepeyac Fertilizer	
	FERMAN Fertilizer	www.ferman.mx/

Table 2 - Values and levels of eutrophication in the TRIX scale for water quality assessment (take from Penna *et al*., 2004).

Tabela 2 – Valores e níveis de eutrofização na escala do TRIX para a avaliação da qualidade da água (retirado de Penna et al., 2004).

Trophic scale	State	Conditions
2-4	High	• Water poorly productive • Low trophic level
4-5	Good	• Water moderately productive • Mean trophic level
5-6	Bad	• Poor water moderate to highly productive • High trophic level
6-8	Poor	• Water highly productive • Greatest trophic level

Samples were collected during three periods: the dry season (March: dry), the beginning of the rainy season (July: Inter D-R) and the heavy-rain season (September: rainy). These periods have been identified as transition phases that strongly influence the ecological behavior of coastal systems (Espinosa *et al*., 1994) and are similar to those considered by other authors (Romero *et al*., 2004; Espino *et al*., 2008).

Superficial water samples for dissolved inorganic nutrient (DIN and DIP), and Chl-a determinations were taken at a depth of 0.2m from the surface using 50-mL and 1-L bottles, respectively. The samples were stored under cold, dark conditions until used in a laboratory colorimetric analysis. DIN and DIP were analyzed using a segmented flow autoanalyzer (Skalar San Plus II) according to the methods of Strickland & Parsons (1972).

Temperature (T), dissolved oxygen (DO) and salinity (S) were determined *in situ* with the Geoscientific field multiparameter instrument YSI85. Depth was determined with the Speedtech Depthmate portable sounder model SM-5. Rainfall data were obtained of Estación: Armería - Municipio: Armería from the Agroclimatological Armería Station of the National Network of Workstations of INIFAP.

Water samples for Chl-a determinations were filtered through Whatman GF/C glass-fiber filters. Pigment was extracted with 90% acetone and measured in a spectrophotometer (Perkin Elmer LAMBDA 35 UV/Vis) following the methods of Strickland & Parsons (1972).

3.3.2. Statistical analysis

The statistical analysis was focused to "State" indicator. Thus, prior to data normality testing, the homogeneity of variance was tested using Cochran, Hartley, and Bartlett's test. Significant differences in eutrophication levels between collection periods and between the samples, collection zones were determined using a one-way ANOVA. Multiple comparisons were performed using Tukey's HSD. Spearman's correlation test was used to evaluate the correlation between the state variables (i.e. Chla, DO, DIN and DIP) and the overall eutrophic state determined with TRIX. All statistical analyses were carried out using the software package Statistic 8.

3.4. Response

The "Response" indicators refer to individual and collective actions and reactions, intended to: mitigate, adapt to or prevent human-induced negative effects on the environment; halt or reverse environmental damage already inflicted; preserve and conserve nature and natural resources (environmental expenditure, environment-related taxes and subsidies, and others) (OECD, 2001). Thus, "Societal response" is considered herein as a corresponding "Response" action proposal (Fig. 2).

4. Results

4.1. Drivers

The absence of government programs regarding education on the use and application of fertilizers was reported in all the interviewees. There was also a lack of awareness about the fertilizer themselves and the doses recommended in the Technological Package of the SEDER (2005). Only recommendations came from the CESAVECOL and the supplier, but only at the time, the fertilizers were acquired. The respondents said that 15% of they were familiar with the municipality's regulations regarding plant health. Lemon producers indicated that, since 2013, they have received increased attention and assistance from government organizations as CESAVECOL and FIRA (Trust Funds for Rural Development) in efforts to combat pests (Huanglonbing: "yel-

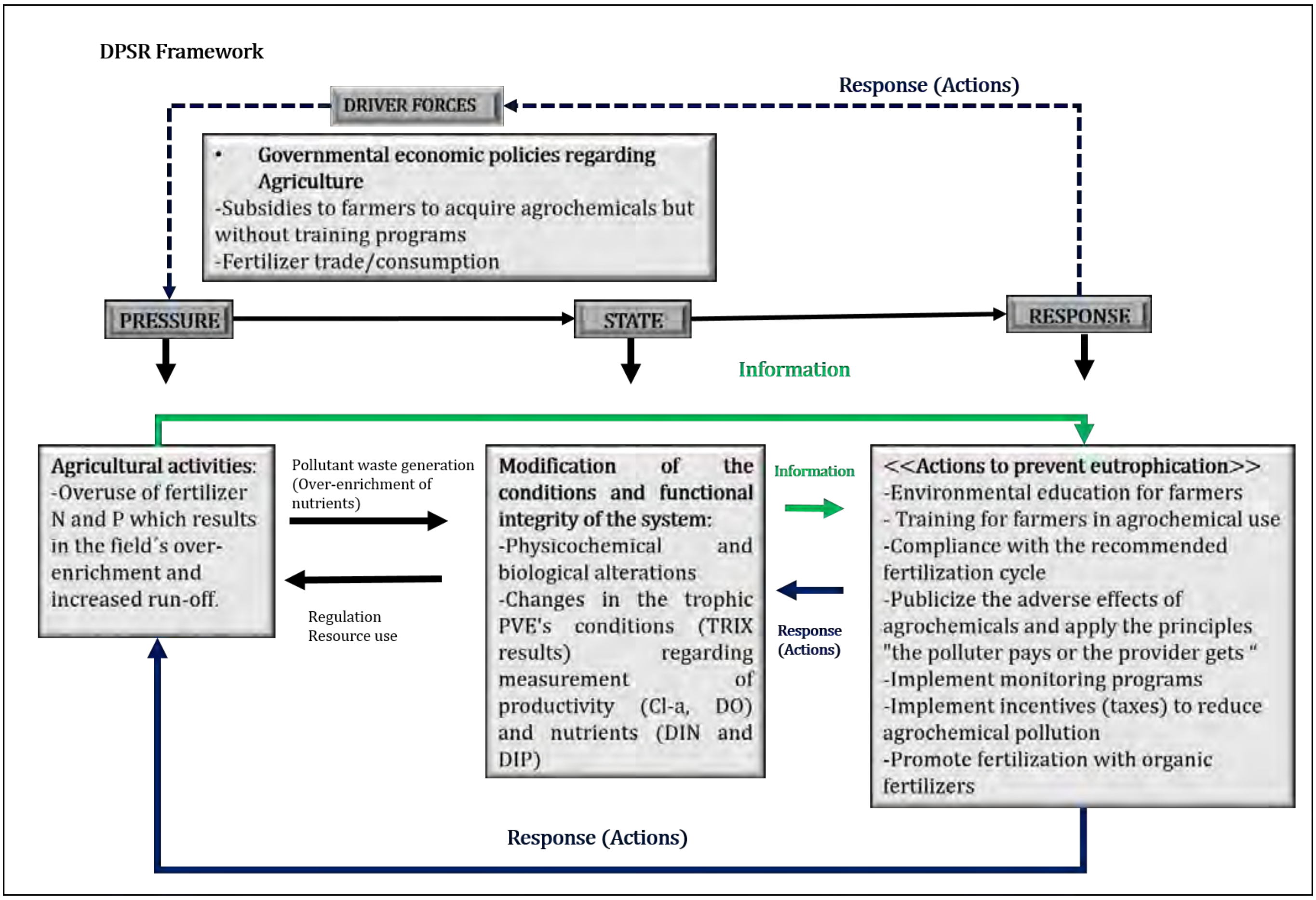

Figure 2 - Flow diagram explaining the indicators integrated in the PSR framework (modified from the OECD, 2001, and from Tenorio *et al.*, 2013). Dark gray boxes: The indicators drivers, pressure, state, and response. Light gray boxes: The actions of each of the indicators.

Figura 2 - Fluxograma explicando os indicadores integrados no quadro PSR (modificado a partir de OECD, 2001, e de Tenorio et al., 2013). Caixas cinzentas escuras: Os indicadores condutores, pressão, estado, e respostas. Caixas cinzentas claras: As acções de cada um dos indicadores.

low dragon") in the region. The authorities informants validated information about the lack of training agrochemical formals programs for farmers.

According to the respondents, in 2013, the farmers received cash for the purchase of agrochemicals (the amount of money was not specified). In 2014, they received 14 bags of fertilizer (ammonium sulfate) from SAGARPA, who later also gave them $1,100.00 MNX/hectare (ha)/farmer (equivalent to ≈ US $ 84) for the acquisition of nitrogen-phosphorus-potassium (NPK) fertilizer (formulation: 20-10-10) through the Agriculture Development Program in its "Agroincentivos" section. The subsidies ranged from ≈ USD $84 to USD $260 per farmer. The municipality's Director of Rural Development, Direction and Head of the Center for Rural Development Support validated information about subsidies to farmers.

4.2. Pressure

According to the interviewed, 560 parcels of land (Garcia, *et al*., 2013) are managed by 495 farmers, who practice both monoculture and polyculture, including banana, coconut, lemon, and other seasonal crops. Subsidies for farmers are awarded annually.

Respect to the fertilizers used in the agricultural lands, SEDER (2005) recommended N and P, and agrochemical suppliers confirmed these fertilizers as more trade. Thus, the interviewees said that 47% most producers applied sulfates, 35% applied phosphate, and nitrogen fertilizers, and 37% using either of these fertilizers for the lemon crop, monthly or quarterly (1–3 kg /tree). The quantity, frequency, and application period recommended by the SEDER (2005) depends on tree age and the number of trees per hectare and ranges between 1 and 2kg/tree per fertilization cycle. Coconut crop fertilizer (ammoniac sulfate) is annually applied in 43% of the ejidos. Distributors of agricultural supplies confirmed the high demand for fertilizers (N, P, and sulfates).

In addition, pluvial precipitations have consequences over continental runoff from the agricultural zones to the PVE. According to the data registered by Agroclimatological Armería Station, the rainy season in 2014 started in May and lasted until November of the same year. During March, there was no rainfall but values in June reached 245 mm. Rainfall was heaviest in September, with 458 mm.

4.3. State

4.3.1. Physicochemical water quality

A comparison (Tukey HSD test) of the physicochemical variables (T, DO, DIP and DIN) showed spatial variation between zones (Table 3), except Chl-a and salinity not showed differences statistical ($p > 0.05$). Statistically, temporal significant differences between periods are indicated in Table 4, with the exception of DO and DIN statistical test, not showed differences between periods.

A correlation was observed between chlorophyll a and TRIX, which justify the median values, since this index

Table 3 - Show differences between variables by zones and period (Tukey HSD test).

Tabela 3 – Apresentação das diferenças entre variáveis por zona e período (teste Tukey HSD).

		Dry (March)			Inter D-LL (July)			Rain (September)		
	Zone	**N**	**C**	**S**	**N**	**C**	**S**	**N**	**C**	**S**
T °C	**N**	-	0.630	**0.007**	-	0.871	**0.005**	-	0.231	**0.014**
	C		-	**0.014**		-	**0.006**		-	0.076
	S			-			-			-
DO	**N**		0.280	**0.008**	-	-	-	-	-	-
	C			**0.030**		-	-		-	-
	S						-			-
DIP	**N**	-	-	-	-	**0.002**	**0.006**	**-**	**0.012**	**0.012**
	C		-	-		-	0.788		-	0.886
	S			-			-			-
DIN	**N**	-	-	-	-	**0.003**	**0.001**	-	0.114	**0.044**
	C		-	-		-	0.182		-	0.541
	S			-			-			-

Highlight black correlations are significant at p <.05000. - Not difference

Table 4 - Show differences variables considered between periods (Tukey HSD test).

Tabela 4 – Apresenta as diferenças das variáveis consideradas entre períodos (teste Tukey HSD).

Variables	T°C			Salinity			DIP			Chla		
Periods	**Dry**	**Inter D-LL**	**Rain**	**Dry**	**Inter D-LL**	**Rain**	**Dry**	**Inter D-LL**	**Rain**	**Dry**	**Inter D-LL**	**Rain**
Dry	-	**0.000**	0.071	-	**0.025**	**0.031**	-	**0.01**	0.82	-	0.103	**0.018**
Inter D-LL		-	**0.000**		-	0.994		-	**0.00**		-	0.675
Rain			-			-			-			-

Highlight black correlations are significant at p <.05000. - Not difference.

is more connected to primary productivity. A minor correlation was also observed between the TRIX values and the temperature (Table 5); with this parameter, which relation with ambient temperature and serving to growth of phytoplankton biomass and as a response result of increase of chlorophyll a availability light.

Table 5 - Spearman correlations between considered variables and TRIX index of all periods.

Tabela 5 – Correlações de Spearman entre as variáveis consideradas e o índice TRIX para todos os períodos.

	DIP	DIN	Chla	T	DO	Sal	TRIX
DIP	1.00	**0.82**	-0.16	-0.35	0.15	-0.12	0.15
DIN		1.00	-0.03	0.03	**0.42**	0.12	0.12
Chla			1.00	**0.58**	-0.36	**0.50**	**0.68**
T				1.00	0.01	**0.69**	**0.47**
DO					1.00	0.13	-0.31
Sal						1.00	**0.62**
TRIX							1.00

Highlight black correlations are significant at p <.05000.

The oscillations in superficial water temperature were: 23.5–28.5° C (dry), 28–33.9° C (Inter D-R), and 27–29.2° C (rainy). The minimum values were always at S-SZ and the maximum values at S-NZ (Fig. 3: red circles). Statistically significant differences ($P < 0.05$) were determined for Inter D-R vs. dry and rainy seasons (Tukey HSD; $P < 0.05$). A spatial gradient for temperature was observed according to the distance of the sampling sites, with higher values in S-NZ (S1) and lower values in S-SZ (S8).

Salinity did not follow a defined spatial gradient along the PVE, but there were statistically significant differences ($P < 0.05$) between periods. Minimum values were measured at S-SZ (S7 and S8: 0.4 and 0.7, respectively) during the dry season. Salinity values in the shallower S-CZ (shallower) reached a maximum (1.2) during the Inter D-R and rainy seasons (1.1) whereas at S-NZ the values were more homogenous (0.9) during the three sampling periods (Fig. 3: black triangles). During this study, the PVE did not have a communication with the ocean because of the persisting sand barrier.

DO concentration in the PVE varied from 0.28 to 6.46 mg/L^{-1} (3.2–81.6% oxygen saturation). During the dry period, DO was in the range of 0.3–5.42 (2–77.3% oxygen saturation); in the Inter D-R, 0.22–5.5 mg/L (2.8–70.2% oxygen saturation); and in the rainy period, 0.22–5.53 mg/L^{-1} (2.8–70.2% oxygen saturation) (Fig. 3: blue circles). Hypoxia occurred at S-SZ (DO ≤ 2 mg/L^{-1}) during all sampling periods.

The Chl-a concentration showed the greatest seasonal variation at S-SZ, with an average > 10 mg/m^3 most of the year, except during the dry season, when it was < 4 mg/m^3. Chl-a reached a peak at S3 (47.5 mg/m^3) during the rainy period but was lowest at S1 (0.14 mg/m^3) during the dry period (Fig. 3: green circles). A one-way ANOVA showed significant differences ($P < 0.05$) between the rainy period and the dry period (Tukey HSD; $P < 0.05$).

A comparison of the superficial DIN and DIP concentrations showed an increased spatial tendency from S-SZ towards S-NZ during all sampling periods, but mainly during the rainy season (Fig. 4). Maximum DIN values were consistently recorded at S-NZ during all periods (dry: 14.7–20.72 µM L^{-1}, Inter D-R: 13.8–15.45 µM L^{-1}, rainy: 15.70–21.93 µM L^{-1}). The same pattern was observed for DIP (Fig. 4), with maximum values measured at the NZ during all three sampling periods (dry: 6.20–8.29 µM L^{-1}, Inter D-R: 4.39–4.61 µM L^{-1}, rainy: 8.04–9.95 µM L^{-1}). The exception was at S7, where the values of DIN and DIP during the dry period were higher than those of the other stations (14.34 µM L^{-1} and 7.28 µM L^{-1}, respectively). Differences between the zones during all periods were more obvious in summer ($P < 0.05$).

The level of eutrophication increased gradually from 3.5 to 5.0 during the study period. During the dry period the eutrophication level and water quality were characteristic of a poorly productive system, with a low level of eutrophication (3.61: March) whereas during the rainy period eutrophication increased (4.92: September),

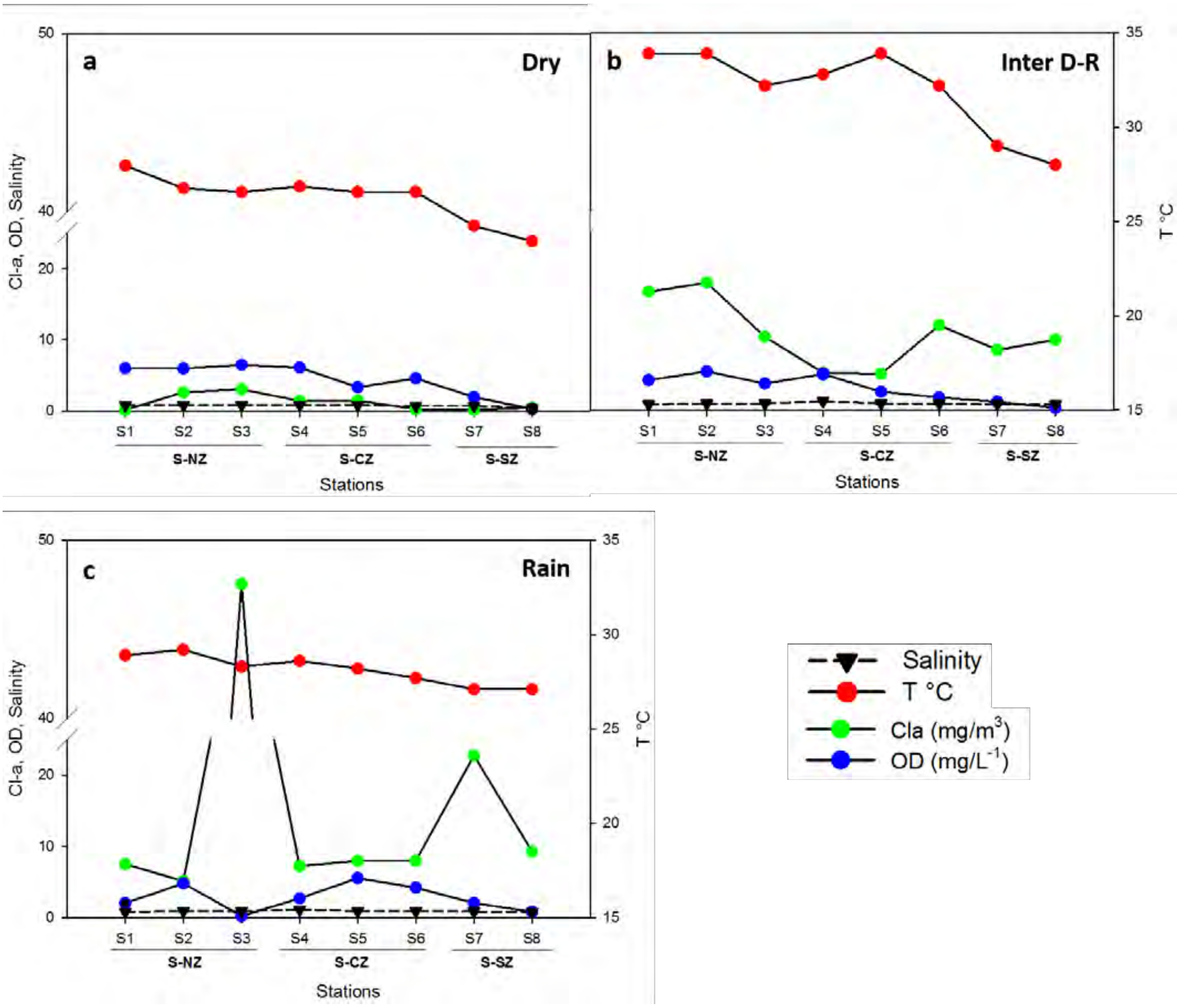

Figure 3 - Seasonal variation in the physicochemical parameters of the water (temperature, salinity, dissolved oxygen) and in the chlorophyll-a concentration at the sampling stations. a) Dry (March), b) Inter D-R (July), and c) rainy (September).

Figura 3 – Variação sazonal dos parâmetros físico-químicos da água (temperatura, salinidade, oxigénio dissolvido) e na concentração de clorofila-a nas estações de amostragem. a) Seco (Março), b) Entre S-C (Julho), e c) Chuvoso (Setembro).

although water quality was acceptable and the water was also moderate-highly productive (Fig. 5a). However, a high eutrophication level (5.34) was reached at most of the stations at S-NZ, although the water remained moderate-highly productive (Fig. 5b). Eutrophication at S-NZ was also reflected in the TRIX value.

4.3.2. Response

The driver indicators demonstrate the existence of subsidies to agricultural sector that has not been accompanied by government actions to improve agrochemicals use, to reduce the generation of polluting waste or nutrient supply. There are also deficits in the implementation of environmental regulations aimed at improving agrochemical use in agricultural activities and a lack of knowledge regarding the doses for diverse crops as recommended in the Technological Report of the SEDER (2005).

Pressure indicator showed the fertilizer N and P use in agricultural activities and the emission and input of nutrient through continental runoff to PVE. State indicators, (high nutrients concentrations) which reveal an eutrophication process in progress confirmed this. Thus, the analysis of DPS indicators allows suggesting management actions as response to improve trophic conditions of the PVE. Actions to be implemented can be, environmental education and training for farmers in agrochemical use, compliance with the recommended fertilization cycle, publicize the adverse effects of agrochemicals and apply the principles "the polluter pays“

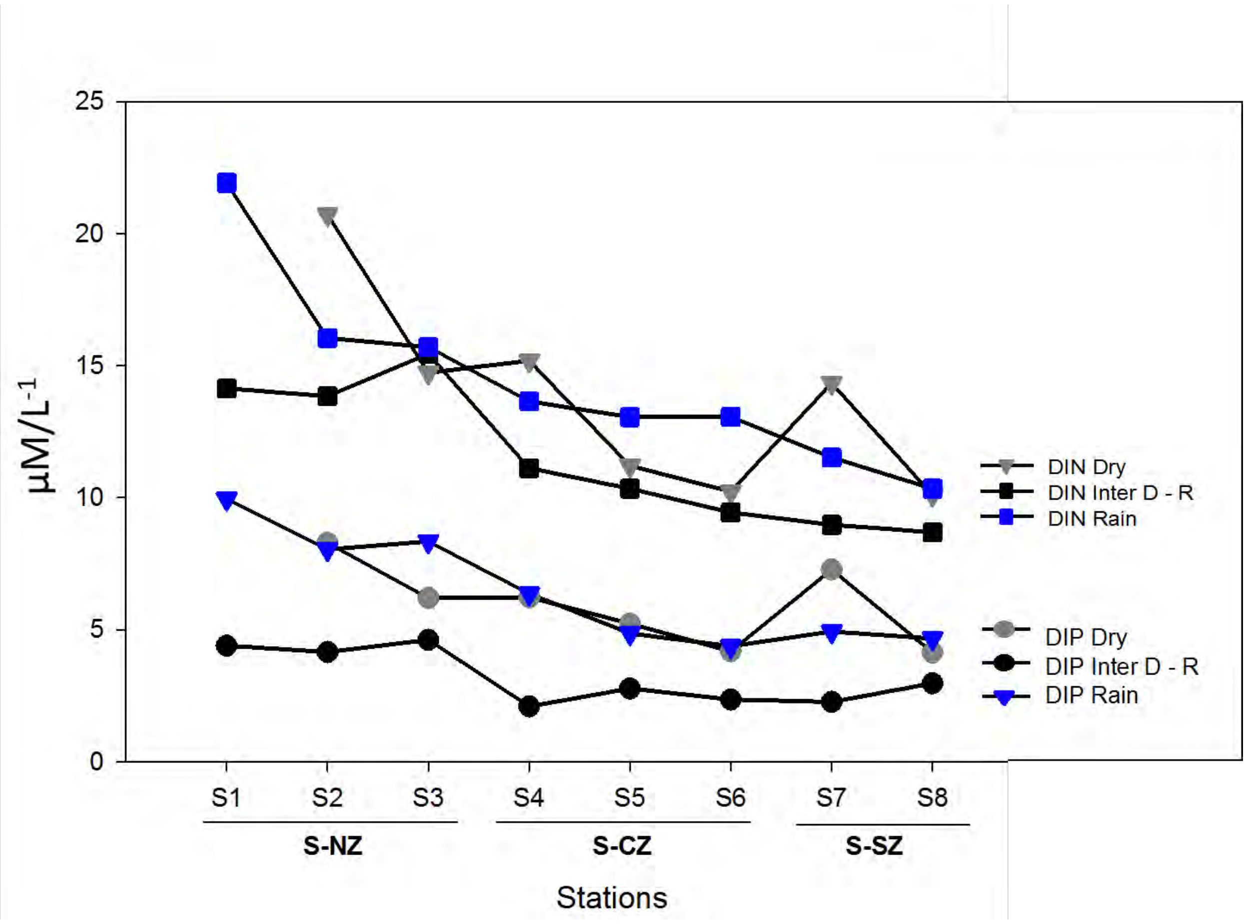

Figure 4 - Seasonal variation of nutrient concentrations at the sampling stations. DIN: dissolved inorganic nitrogen: (NO^{3-}, NO^{2-}, NH_4^+; in µM L^{-1}). DIP: dissolved inorganic phosphorus (in μML^{-1}). Dry (March), Inter D-R (July), and rainy (September).

Figura 4 – Variação sazonal da concentração de nutrientes nas estações de amostragem. DIN: azoto inorgânico dissolvido: (NO^{3-}, NO^{2-}, NH_4^+; em µM L^{-1}). DIP: fósforo inorgânico dissolvido (em μML^{-1}). Seco (Março), Entre S-C (Julho), e Chuvoso (Setembro).

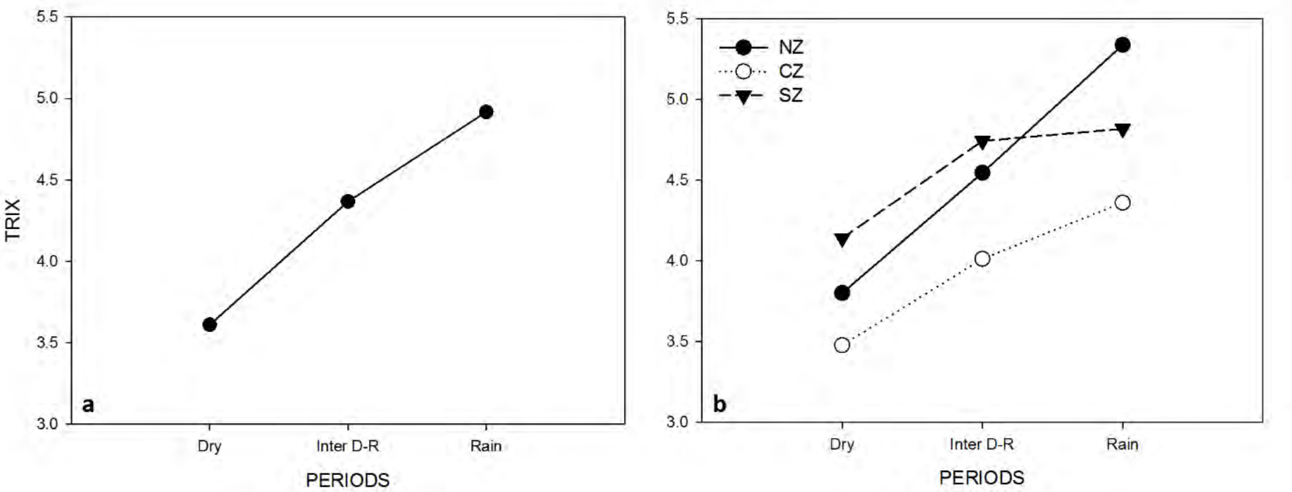

Figure 5 - a) Seasonal variations in the trophic state index (TRIX). b) Seasonal variation in TRIX at the three zones. NZ: northern zone, CZ: central zone, SZ: southern zone.

Figura 5 - a) Variações sazonais no índice do estado trófico (TRIX). b) Variação sazonal do TRIX em três zonas. NZ: zona norte, CZ: zona central, SZ: zona sul.

or "provider gets", implement monitoring programs and incentives as taxes to reduce agrochemical pollution and promote fertilization with organic fertilizers (Fig. 2). These actions would be needed to avoid the pollution loads from diffuse agricultural sources, which are an issue in many countries, and implies integration considerations in agricultural sectorial policies trough of an integrated management based on the ecosystem approach, and thereby preserving its ecosystem services as explain to OECD (2001).

5. Discussion

According to Espejo *et al*., (2012), the subsidies are a driver to overuse of agrochemicals, also the absence of strict penalties for polluting the water generate environment pollution due the delegation of the responsibility to farmers and to the agrochemicals suppliers, who "provides" technical assistance, but finally, farmers do not consider that it is their responsibility to oversee water quality. Further, in opposition to the belief of the majority of Mexican economists, is documented that our country, relative level of subsidies to its agriculture is similar to those in the United States of America and Canada, its main commercial partners Estrada & Bustos, (2006), which puts into context the amount of fertilizer used in our México.

Respect to pressure detected in PVE, the use of N and P are recommended because are basic nutrients to play role in nutrition of the plants (Correll, 1998; Kroger *et al*., 2013). However, importance, its generate waste and is recognized that intensity of use of N and P fertilizers in agriculture, reflected through apparent consumption in tons of active ingredients (N and P per km^2 of agricultural land) represents potential pressure on the environment in the absence of effective pollution abatement (OECD, 2001). As shown by Siu *et al*., (2007), 20–40% of N fertilizer is lost as ammonium in coastal systems through continental runoff. Whether a similar process occurs in the PVE remains to be determined. However, although qualitative information about the use of agrochemicals was obtained through interviews; exact information about amount used was difficult to estimate because neither farmers nor the authorities haven´t a precise record agrochemical applications. Nevertheless, is possible that applied doses can easily exceed the doses recommended in the Technological Report of the SEDER (2005), confirmed by high nutrients concentrations registered in the PVE. Thus, the overuse of agrochemicals results not only in unnecessary costs to farmers but also in excess inputs of inorganic nutrients into the PVE.

The seasonal and spatial variations of physical, chemical and biological parameters in PVE are determined by variations in rain and other freshwater contributions, mainly nonpoint agricultural continental runoff. The intermediate site (S-CZ) remained fairly stable and thus differed from the two other zones. During all periods, the gradient between the zones was maintained, with highest values consistently in the S-NZ and lowest values in the S-SZ. At the S-NZ, a floodgate between PVE and basin IV of the Laguna of Cuyutlán reduces flow. In addition to restricting flow, the floodgate causes the retention of water that generates nutrient accumulation. Results about prolonged exposure to nutrients and photosynthetically active radiation in water systems, have shown that promotes biological activity (Bonilla *et al*., 2005), this sequence of events would explain the high values of nutrients, Chl-a, DO, and temperature at S-NZ.

The conditions of the PVE were those of an oligohaline environment. Salinity did not follow a spatial gradient along but statistical differences ($P < 0.05$) between periods were observed. During the study period, there was no communication with the ocean, which prevented the establishment of optimal estuarine conditions. Thus, the system showed a seasonal pattern of salinity corresponding to period 2 as described by Arancibia *et al*., (2014), in which due to the disconnection from the sea freshwater inputs predominate and are greater than evaporation, such that salinity decreases to as low as 5. In the PVE, the seasonal patterns of the physicochemical and biological parameters resulted mainly from continental runoff during rain and namely from the input of groundwater during the dry season.

The hypoxic conditions recorded in S-SZ during all periods were likely due to the rapid consumption of oxygen by bacteria in their degradation of suspended organic materials (USEPA, 1995; Zink *et al*., 2004). The presence of suspended organic material in this zone can be attributed to: a) the turbulence, and thus the resuspension of sediments, caused by the propellers of motor boats (Kelty & Bliven, 2003) carrying eco-tourists and the motor boats of fishermen, which constantly transit through this zone and b) continental runoff during the Inter D-R and rainy seasons, which causes material inputs and high turbulence, increasing the oxygen demand and decreasing the DO content of the system.

Coinciding with the hypoxic conditions in the PVE were minimum values of Chl-a, most likely due to resuspension of the sediments. Concentrations in the S-SZ can probably be explained by the presence of phytoplankton as *C-* and *CR-strategists*, defined as mixing-dependent opportunistic-invasive species with high growth rates that proliferate in permanently mixed systems (Reynolds, 1984; Sommer, 1993; Huszar *et al*., 1998; Bonilla *et al*., 2005). These species are favored by the shallowness of the PVE's waters. Furthermore, S-SZ forms a channel approximately 5m in width, with low solar radiation exposure due to the height of the resident mangroves, which prevent the penetration of light and therefore of photosynthesis and primary production, despite the available nutrients.

On the other hand, similar hypoxic conditions (<-2 mg/L^{-1}) were reported by Romero *et al*., (2004) during the same seasonal periods in a lagoon system adjacent to an important agricultural area in southern Mexico. There, continental runoff was shown to cause material inputs and high turbulence, increasing the oxygen demand. This could have happened in S-NZ where concentrations of DIN and DIP increased during the rainy season due to adjacent agricultural inputs, which may have been magnified by the interruption of the flow due to the floodgate and autochthonous processes of remineralization of nutrients due to degradation of organic matter in this area of PVE. Several authors (Espinoza *et al*., 1996; Newton *et al*., 2003; Coelho *et al*., 2007) have reported that in coastal lagoons increases in DIN and DIP can be attributed to continental runoff, such that nutrient concentrations are an indicator of the proportion of the surrounding agricultural land area.

The concentrations of Chl-a in the PVE were higher than those reported by Avalos *et al*., (2013) for Cuyutlán lagoon system located at 4 km, who classified this lagoon as a eutrophicated system according to the OECD's definition (1982). Chl-a values in PVE were higher than the threshold of 8–25 mg/m^{-3}proposed by the OECD (1982) for a eutrophic system. Moreover, the values of DIN and DIP exceeded the 16 and 1.1µM L^{-1} proposed by the Crouzet *et al*., (1999) as the maximum permitted level of nutrients in areas of coastal/marine water transitions. In line with both the OECD and Crouzet, *et al*., (1999) values, the PVE is a eutrophic estuary.

The DIP concentrations measured in the PVE were above the mean range (0.01–5.0 µM L^{-1}) in 69% (27) of 39 coastal lagoons in Mexico (19 in the Gulf of Mexico and 20 in the Mexican Pacific Ocean) that maintain different hydrological regimens, including terrigenous entrainment (Espinoza *et al*., 1996). Their analysis showed that coastal lagoons with high concentrations of phosphates (> 5 µM L^{-1}) are characterized by higher trophic states and greater anthropogenic pressure like agriculture.

In this study, the eutrophication level was determined by the integration of Chl-a, DO, DIN, and DIP values in the TRIX, which showed oligotrophic to eutrophic conditions in the PVE and the good to bad water quality characteristic of moderate to highly productive waters. High productivity was mainly found at S-NZ during the rainy period. The results are consistent with the levels of agricultural activity in the area of the PVE, which increase nutrient loads from continental runoff, as in similarly impacted areas (Coelho *et al*., 2007; Silveira & Ojeda 2009; Alves *et al*., 2013).

DIP was the nutrient most closely linked to eutrophication of the PVE, together with Chl-a and to a lesser extent DIN, coinciding with those reported by Penna *et al*., (2004). During the dry period (March), the conditions in the PVE corresponded to a poorly productive system with a low level of eutrophication. By contrast, during the rainy period, there was a slight shift to a higher eutrophication level, with acceptable water quality and moderate-highly productive water. The higher eutrophication level at S-NZ was presumably related to the moderate-highly productive water and its prolonged exposure to continental drainage, together with the influence of the seasonal variations in continental contributions.

In the absence of previous data from scientific monitoring, the TRIX proved to be an important tool for assessing the eutrophic state of PVE. The results from studies conducted in the coastal region of Mexico using the TRIX and other models (Silveira & Ojeda, 2009) were similar to those obtained in this work, with the worst trophic conditions determined at sites with the greatest influence of anthropogenic activities. In addition, the results of the TRIX corresponded well with those derived from others models.

Based on the highest TRIX value (6.43), Alves *et al*., (2013) reported that the worst water quality was associated with the wastewater of major continental downloads, in an area of the studied estuary that was farthest from marine influences. Similar conditions were observed in this study, with seasonal rain causing major continental runoff that accelerated eutrophication of the system.

During the study period, tendency significant spatial and temporal eutrophication occurred, as reflected in the values typically used to assess coastal ecosystems. Thus, the cumulative driver-pressure-state indicators showed a spatial and temporal deterioration that resulted in modified conditions and a negative influence on the functional integrity of the PVE. These changes can be attributed to improper handling of fertilizer, and the lack of understanding of ecosystem functioning by the farmers who use the fertilizer supported by economic policies that promote agricultural development but which are not accompanied by training programs.

A eutrophicated water body represents ecological, economic, and social costs (Bricker *et al*., 2003; Savage *et al*., 2010; Junior *et al*., 2013). Accordingly, actions aimed at preventing eutrophication are desirable because they are ultimately less costly than ecological and economic rehabilitation and restoration (Lizárraga *et al*., 2009). The conservation of ecosystems and sustainable management of resources requires scientific knowledge that can be used as a tool to detect environmental trends. Of equal importance is communication of that knowledge so that it can be used as a baseline for decision making (Lomelí, 2004; Lizárraga *et al*., 2009; Costa *et al*., 2013; Arancibia *et al*., 2013; Arancibia *et al*., 2014). Thus, the analysis "State indicator" offer the understanding system functioning, which is basic for sustainable management of coastal ecosystems and system functioning can be serve as a management tool in the management implications (Arancibia *et al*., 2014). According with these authors, the ecosystem-based management (EBM) has emerged as an approach that reflects the relationships among all ecosystem components, including the influence of humans, and the environment in which they live, and ultimately combines ecology and human dimensions in an integrated way that is transdisciplinary ecosystem management.

Thus, our study of the current trophic status of PVE shows that it is not necessary to restrict agricultural activities in the surrounding region. Nevertheless, there is much to be gained by coupling these activities with others that do not endanger the PVE. As mentioned by Estrada & Bustos, (2006) rather than to increase agricultural subsidies, Mexico should invest considerably more in investigation, education capacitation, among others.

Therefore, the proposed management options should be multiple and progressive: first awareness on possible impacts of too much fertilizer, then training on best practices for using fertilizers. This may be achieved providing environmental education to farmers to facilitate an integrated perception of the environment and its rational use, with benefits for social development and the environment. The assimilation of knowledge and modification of behaviors will ensure the preservation of resources as established by the General Law of Ecological Equilibrium and Protection of Environment (LGEEPA, 2015). According to Cortinas de Nava (2000), the implementation of training can provide the knowledge necessary for the proper handling and use of agrochemicals, which in addition to preventing and mitigating environmental risks reduces production costs, which is of obvious interest to local farmers.

It is also important to involve agrochemical suppliers in training and programs for farmers so that a mutual understanding regarding good agrochemicals practices is established. As shown by Espejo *et al*., (2012), the promotion of accountability by providers of agrochemicals contributes to the rational use of agrochemicals. By monitoring the implementation of the recommended dose in the fertilization cycle, as proposed by the SEDER (2005), the effectiveness of fertilization and the need for actions to improve it can be evaluated. By applying the principle, "the polluter pays" or "the provider gets" and strict monetary fines for violating regulations regarding agrochemical use, will radically change the perception that water polluting can continue without fear of punishment.

Equally importance is the needs to upgrade agrochemical programs to farmers, as there are offered incentives to reduce agrochemical use; these incentives could include taxation rather than the subsidization of agrochemicals. Although from the environmental point of view, it would be reasonable, to tax the agrochemicals from the perspective of farmers would be unacceptable, but this would motivate them to change to organic fertilizers (Espejo *et al*., 2012; Ahodo & Svatonova, 2014).

In addition, the implementation of continue monitoring program in the PVE will generate awareness about the conditions leading to ecosystem eutrophication. It results can serve as a reference for decision-makers, because should be noted that the feasibility of the proposed alternatives and of others will change with time; thus, any plan must be dynamic and able to respond to changing interests, conditions in situ, and potential problems that may emerge regardless of whether a given alternative has been implemented consistently and has reached its goal like have been proposed by Cohen *et al*., (2011).

6. Conclusions

The assessment of current conditions using both the TRIX and the PSR framework in the PVE offered a fast and practical approach to identify the main drivers that exert pressure (changes) on the PVE and to devise possible solutions (Fig. 2). The main driver identified in this study was inadequate economic policies that promote the acquisition of agrochemicals, without appropriate training programs regarding their use and therefore maintain their improper application by farmers in the agricultural area adjacent to the PVE.

The inadequate fertilizer used in the agricultural activities generate residues, which exerting pressure through continental runoff representing a constant potential risk to eutrophication of the system. State indicator showed tendency serious spatial and temporal eutrophication during the study period. The response actions discussed herein are intended to improve and control agrochemicals use, by changing their mode of use. We do not claim that our proposed action is the one most suitable to the PVE, but it is certainly worthy of serious consideration and a preliminary test of its effectiveness.

In a first approximation, our comprehensive study of coastal systems provides: a) a baseline to interested users and local policy-makers for managing the PVE and b) a support to description of the environment regional system that identifies sources of pressure. The results of this study allow for focused and efficient management strategies to prevent human-induced negative effects on the environment, thus promoting the preservation and conservation of the PVE and its natural resources.

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Water mass characteristics in a shallow bank highly influenced by river discharges: the Sofala Bank in Mozambique

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Abstract

Hydrological data collected between 2003 and 2007 were analysed in order to describe the water masses of the Sofala Bank in Mozambique Channel, a region under the influence of outflow from the Zambezi River. The data analysis consisted in the visual inspection of temperature and salinity combined with the analysis of variance for unbalanced data. Four water masses were identified, which differ in their location, temperature, and mainly salinity. These water masses are: (i) LSSW-low salinity shelf water that occurs at the upper 15m and within 40 km from the coastline; (ii) WOSW- warmer oceanic surface waters that occurs throughout the bank at depths not exceeding 70m; (iii) DOW- deep oceanic waters that occur from the sub-surface layer to the seabed; and (iv) HSSW- high salinity shelf water that occurs offshore from 40 km at depths greater than 15m. In general, the water masses are well oxygenated with the lower limit of oxygen being 13, 7 and 5.7 mL/L for the LSSW, WOSW, and the HSSW, respectively. Fluorescence levels are low and almost homogeneous in the LSSW, but it varies with depth in the other oceanic waters. The presence of four different water masses in the Sofala Bank is likely to have ecological and management implications.

Keywords: Water mass, Sofala Bank, Zambezi, Dissolved Oxygen, Fluorescence.

Resumo

Características das massas de água num banco pouco profundo altamente influenciado por descargas fluviais: o Banco de Sofala, em Moçambique.

Dados hidrológicos colhidos entre 2003 e 2007 foram analisados com o intuito de descrever as massas de água que ocorrem no Banco de Sofala no Canal de Moçambique, uma região sob influência das descargas do Rio Zambeze. A análise desses dados consistiu na inspecção visual da temperatura e salinidade combinada com a análise de variância para dados de tamanhos diferentes. Foram identificadas quatro massas de água, que se diferenciam pelo local de ocorrência, temperatura, e principalmente salinidade. As massas de água são: (i) LSSW- águas costeiras de baixa salinidade que ocorrem nos primeiros 15m de profundidade e a 40 km da costa; (ii) WOSW- águas superficiais oceânicas de alta temperatura que ocorrem em todo banco a uma profundidade máxima de 70m; (iii) DOW- águas oceânicas profundas de baixa temperatura que ocorrem desde a camada sub-superficial até ao fundo; e (iv) HSSW- águas da plataforma com salinidade elevada que ocorrem a partir dos 40 km da costa a uma profundidade não inferior a 15m. No geral, as massas são bem oxigenadas, sendo o limite inferior de oxigénio de 13, 7 e 5.7 mL/L para a LSSW, WOSW, e a HSSW, respectivamente. Os níveis de fluorescência são baixos e a distribuição é quase homogénea para LSSW, mas variável em profundidade nas águas oceânicas. A presença de quatro massas de água diferentes no Banco de Sofala tem provavelmente implicações ecológicas e de gestão de recursos.

Palavras-chaves: *Massas de água, Banco de Sofala, Zambeze, Oxigénio Dissolvido, Fluorescência.*

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1. Introduction

The knowledge of water mass characteristics is important for the understanding of marine and coastal ecosystems, and the behaviour or marine organisms. In particular, coastal waters often receive many land-derived contaminants that alter the manner in which services that includes fisheries, tourism, harbours, and others, can be provided to coastal communities. The water mass characteristics are more variable at the coast because of the influence of tidal currents, river runoff, local topography, seasonal climatic forcing, and the variable circulation patterns. Therefore, evaluating some fundamental hydrological properties of water masses in the coastal zone is a difficult task, mainly because of the dynamic complexity of these environments. In order to quantify properties of interest for the coastal zone management, researchers rely on assessing tracers for the mixing between different water masses and their transports. These tracers have to be readily measurable and often include temperature and salinity (Silva, 1984; Gammelsrod and Hoguane, 1995; Machaieie, 2012), as well as nutrients and trace elements (Ferreira *et al.,* 2010; Santos *et al.,* 2008; 2011).

Traditionally, a water mass is defined as a sizeable portion of water associated with a particular range of temperature (T) and salinity (S) values, which can be identified through a curve in a T-S diagram. Changes in salinity of seawater have remarkable impacts on marine organisms that must actively regulate their salt tolerance in order to maintain the body fluids in movement and also the ionic concentration different from of the surrounding environment (Pickard & Emery, 1990; Malauene, 2005). The temperature of the water influences many physical, chemical and biological processes in the marine environment; it controls the setting where biological processes occur and determines the concentration of gases dissolved in seawater, including oxygen and carbon dioxide. Metabolism takes place faster in warmer water than in colder ones, and it only takes place within tolerable range of temperature. Temperature also is a major abiotic factor influencing the distribution of marine species (Lalli & Parsons, 1997).

Sofala Bank is one of the most important ecological regions along the Mozambique coast on the western Indian Ocean, and a host for most of the mangrove and fishery resources of the country (Hoguane, 2007). The water masses in the Sofala Bank are characterized by the presence of (i) low salinity shelf water due to the strong influence of freshwater discharge from numerous rivers, the Zambezi River being the most important of all; (ii) oceanic water resulting from the mixing of equatorial and subtropical water masses transported by eddies in the Mozambique Channel; and (iii) high salinity shelf water formed by elevated evaporation in the mangrove swamps along the coast. Several studies allowed this characterization to be drawn, including the work of Brinca *et al.* (1983, 1984), Silva (1984), Gammelsrød & Hoguane (1995), Hoguane (1997), and Machaieie (2012). According to these studies, the ranges of salinity for these three water masses are as follow, less than 34.8, between 34.8 and 35.4, and greater than 35.4 respectively.

The Zambezi River outlet is located in the Sofala Bank, on the western margin of the Mozambique Channel, around 18.7^{o} S. The bank constitutes an offset in the coastline between 17- 20^{o} S, and is characterized by an estuarine environment with a large range of salinity variability. There are records of salinity as low as 20.0 in extensive regions of the bank taken during the rainy season, when the salinity near the shelf break was slightly above 35.0 (IMR, 1978; Lutjeharms, 2006). The hydrodynamics of the channel is dominated by a number of highly variable anticyclonic eddies propagating poleward. These remarkably large eddies (>300 km wide) are formed roughly every 8 weeks (i.e., 6 s 7 eddies per year) in the northern part of the channel, following a pulse in the volume transported westward by the South Equatorial Current (Backeberg & Reason, 2010). The frequency of these mesoscale features decreases in the central and southern parts of the channel to 4 per year (Schouten *et al.,* 2003), likely induced by anomalies emanated from the western coast of Madagascar (Huisman, 2006). Based on the transport estimates reported in the literature, deRuijter *et al.* (2002) and Asplin *et al.* (2006) have suggested that the poleward residual current at 15^{o} S carries about 5 Sv (1 Sv = 106 m^3s^{-1}), a significant contribution to the global thermohaline circulation. The existence of large anticyclonic eddies in the offshore region implies a modified poleward (equatorward) current along the Mozambique (Madagascar) side of the channel. According to Lutjeharms (2006), these currents induce cyclonic lee eddies when moving past a shelf offset, as it is believed to be the case in Angoche, (i.e., north of the Sofala Bank) and Delagoa Bight. Amongst other characteristics, the lee eddies are known to drive a significant upwelling at the shelf edge, which is likely to be an intermittent feature given the variability of the poleward current and lee-eddy generation.

Although there is an agreement amongst researchers on the existence of different types of water in the Sofala Bank, a great deal of problems directly associated to these water masses still remains unsolved. That includes knowing the secondary characteristics of the water masses, such as their horizontal and vertical distribution, the typical concentrations of dissolved oxygen and fluorescence, the impact of these watermasses on the general and shelf circulation, the origin and fate of these watermasses, the associated stratification and mixing, the watermass impacts on local biogeochemical processes, and the temporal variations of watermass distributions. In this paper we limit ourselves at documenting the horizontal and vertical distribution, as well as the distribution of dissolved oxygen and fluorescence, using field data measured onboard several research vessels between 2003 and 2007.

2. Study Site

The Sofala Bank (Figure 1) extends from Angoche at 17° S to Nova Mambone at 21° S covering the whole coastal zone of the central Mozambique. The bank is about 20 miles wide and the area is approximately 50.000 km^2. The climate along the bank is marked by a cold, dry season (April to October) and a hot, wet season (November to March). The northern part of the Sofala Bank is strongly influenced by the East African monsoon system, therefore the surface ocean circulation patterns is different from the other regions of the bank. The morphology of the coastal zone in Sofala Bank is characterized by flat terrain with an almost continuous fringe of mangroves. The seabed in the central and northern Sofala Bank is flat, and most of the industrial fishing fleets operate in this region. The water column in this region has very low salinities at the shore due to the influence of the freshwater from the Zambezi River, which discharges over 3000 m^3/s on average per year Gammelsrød, 1992; Siddorn *et al.,* 2001; Scodanibbio & Mañez, 2005). The Zambezi annual runoff has remarkably reduced since 1978, following the regulation of the river by Cahora Bassa dam, but it is still large enough to seasonally flood the low-lying areas. The brackish water moves over the oceanic water to a distance of 50 km and a depth not exceeding 15 m. Near the Zambezi mouth, the less saline water stretches from the surface to the seabed, presumably because of the shallow nature of the bank and the combined effect of wind and tides (Lutjeharms, 2006; Nehama, 2012).

The southern Sofala Bank (20° to 21°S) is characterized by sand waves believed to be caused by the strong tidal currents, except close to the shore where the semi-industrial fleet and artisanal fishery operate with trawl-

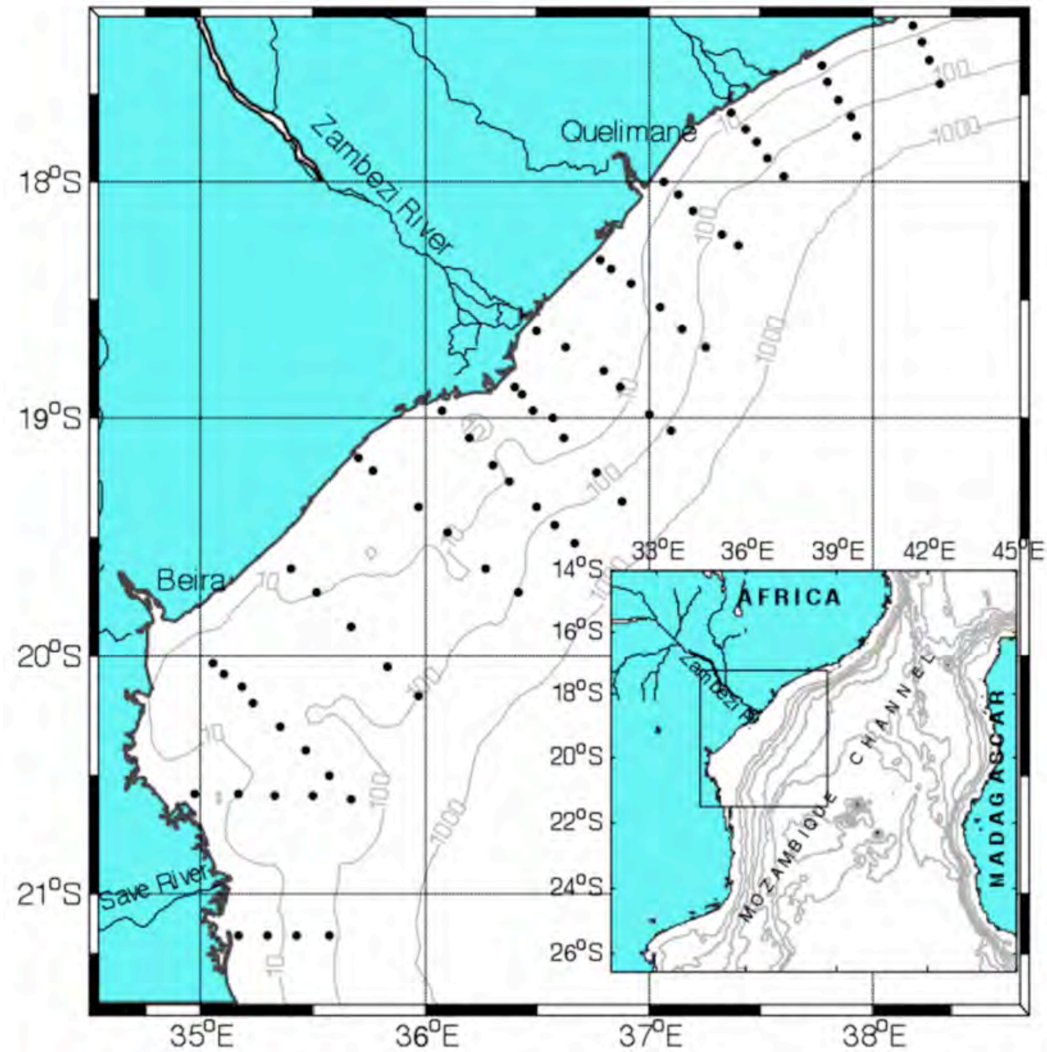

Figure 1 - Map showing study area including sampling sites

Figura 1 - Mapa que ilustra a área de estudo incluindo as estações de colheita de dados ing nets and beach seine, mainly targeting the shallow water shrimp (Machaieie, 2012). A large coastal area in this region is subjected to inundation by oceanic water. The salinity exceeds 36.5 as a result of extreme evaporation and evapo-transpiration in the mangrove swamps (Brinca *et al.,* 1983; Silva, 1984). This portion of high salinity water was observed over the entire water column in shallow waters at a distance of 80 km from the shoreline (Brinca *et al.,* 1983).

The Sofala Bank is known for its high productivity, which is caused mainly by the input of terrigenous nutrients through the Zambezi River, and also the extensive mangroves that provide shelter (nursery) for important fisheries and shellfish. The main fish species are Scads (*Decapterus russelli*), occurring in abundance at depth of 20 to 90 m; *Carangoides malabaricus* that occurs between 10 and 100 m deep; anchovies (*Stolephorus spp*), which occurs between 20 and 60 m deep; sardines (*Pellona ditchela* and *Thryssa vitrirostris*) occurring at depths less than 20 meters; *Leiognathus equulus*, *Insidiator Secutor*, *Etrumeus teres* and *Hilsa kelee* that occur near the coast and in estuaries (Saetre & Silva, 1979; Brinca *et al.,* 1983; Machaieie, 2012).

3. Hydographic data and methods

In this study, hydrographic data measured by a CTD probe were analysed. The data was collected on cruises conducted by the Mozambican National Institute for Fisheries Research (IIP), between the years 2003 and 2007 in Sofala Bank, using vessels from the semi-industrial shrimp fishery fleet. For each year, the hydrographic measurement covered 73 stations (Figure 1) over a period of about 15 days, and these stations were interspersed with sampling of shrimp recruitment. The design of the station network allowed for a minimum distance between stations of 5 km, and the furthermost station in each transect was located along the 100 m isobath, which in some cases corresponds to a distance from the coast of above 100 km. The probe (CTD seabird 19plus) was in many occasions coupled to other sensors, namely turbidity (D&A OBS), dissolved oxygen (Beckman/YSI) and fluorescence (Wetlab wetStar), except for cruise conducted in 2003 that had only the standard probe sensors (temperature, salinity and pressure). At each station, the sampling started as close as possible to the surface, and subsequent readings were taken every half a second and averaged every 2 dbars.

The density of water at each station was calculated after landing using the Equation of State established in 1980 (UNESCO, 1983) and the atmospheric pressure. Distances between stations was determined using a Matlab code specifically designed for that purpose, which uses simple geometry principles, and stations located along a line crossing the shoreline

The data analysis consisted of visual inspection of the salinity and temperature properties of all dataset, combined with one-way analysis of variance (ANOVA) for unbalanced data following the description in Chambers (1992).

4. Results

The water masses are described and discussed here in terms of a vector with two components, salinity and temperature. Figure 2 presents the water types observed around Sofala Bank from 2003 to 2007. Based on this T-S diagram one can identify four water masses with different properties. For the sake of simplicity and clarity these water masses will be called **A**, **B**, **C**, and **D**. The water mass **A** corresponds to water with salinity below 32.5 and temperatures ranging from 27.5 to 31.5° C, which is within the limit for a tropical estuarine plume with strong influence of freshwater discharges (Simpson, 1997; and the references therein); The water mass **B** has salinity levels between 32.5 and 36.5 and similarly high temperatures (between 26.5 and 31.5° C); While the water mass **C** presents high salinity values varying in a narrow range (34.5 and 35.5) and have low temperatures (14 to 26.5° C); The water mass **D** has high salinity levels (over 35.5) and highly varying temperatures (15 – 27.5° C).

Analysis of variance (ANOVA) was carried out to verify whether significant differences exist among the salinity and temperature of the four water masses. The one-way ANOVA results showed that all physical properties listed in table 1 have significant differences ($p < 0.01$) between the four water types, with the mean salinity increasing while mean temperature decreased from water type A though D. Specifically, the Tukey's test identified significant differences ($p < 0.01$).

To examine the variability of water masses in terms of their cross-shelf location, the distance of sampling station in relation to the coast was calculated suing the latitude and longitude coordinates, and then all dataset was grouped into water types and inspected. Figure 3 presents the across-shelf distribution of the four water masses, showing the salinity against the location of occurrence at the coast. As can be seen, water masses **A, B** and **C** can be found from the coast to 140 km offshore. The water mass **D** is not present near the coast and it extends offshore from 40 km. The maximum salinity values (>36.5) occur between 80-100 km from the coast.

Figures 4 and 5 present the variations of the dissolved oxygen and fluorescence for each water mass as a function of distance to coast. Data for water mass **D** is missing because this water mass only appeared in the 2003 dataset, and coincidentally, oxygen and fluorescence were not recorded in that year. Similarly,

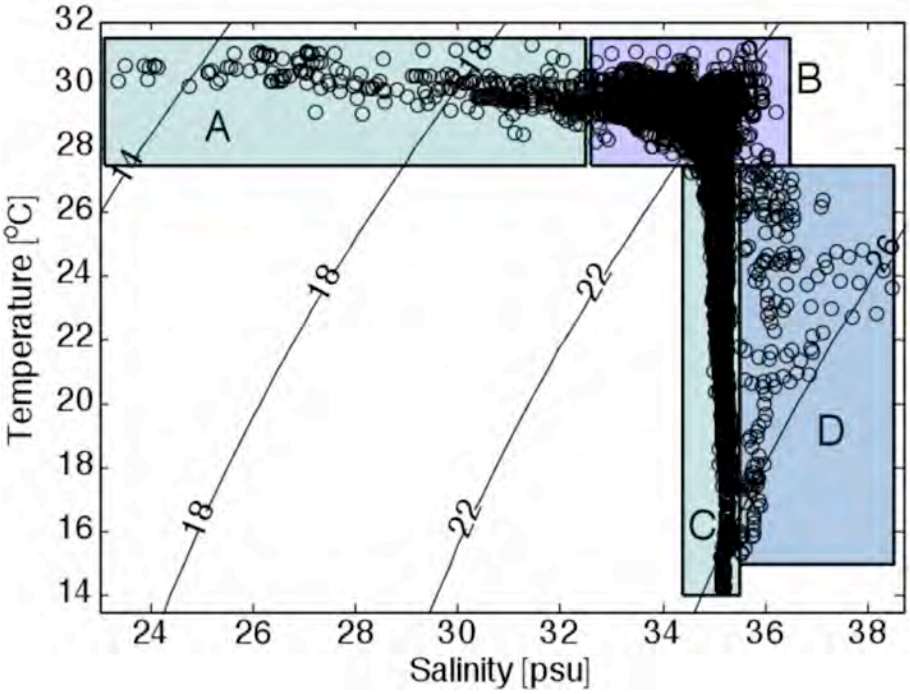

Figure 2 - TS diagram for all samples, depicting four water masses.

Figura 2 - Diagrama TS para todas amostras, ilustrando quatro distintas massas de água.

Table 1 - Average values of the variables for each water mass and results of one-way ANOVA, for critical $p < 0.01$, and Tukey test for unbalanced data between water masses. The significant values ($p< 0.01$) are in bold.

Tabela 1 - Valores médios dos parâmetros para cada massa de água e resultados da analise de variância para um valor crítico de $p<0.01$, e o resultado do teste de Tukey entre as massas de água para dados não uniformes. Os valores significantes ($p<0.01$) aparecem em negrito.

Parameter	**Type A**	**Type B**	**Type C**	**Type D**	**F calculated**	***p* value**
Salinity (psu)	29.05	34.72	35.14	36.18	**5112.00**	**0.00**
Temperature (°C)	29.96	29.00	23.44	22.75	**4797.00**	**0.00**
Depth (m)	3.90	14.66	64.87	59.40	**3132.00**	**0.00**
Distance (km)	31.04	60.05	65.78	102.79	**203.80**	**0.00**
Oxygen (mL/L)	16.70	16.72	13.55	15.73	**865.70**	**0.00**
Fluorescence (mg/m^3)	1.88	1.72	2.03	2.83	**26.88**	**0.00**

the data points in figures 4 and 5 are relatively lower than those presented in Fig.3 because the dissolved oxygen and fluorescence sensors were turned off in some cruises. As can be seen, the distribution of both dissolved oxygen and fluorescence differs considerably in the recorded water masses; however, there is no clear trend for the relationship of these two parameters with the distance to shoreline. The water mass **A** has very high values of dissolved oxygen (13-20 mL/L) and low values of fluorescence (1-4 mg/m3), while for the masses **B** and **C** the range of values is greater for oxygen (7 to 21.6 mL/L) and fluorescence (0.01 to 11 mg/m3).

In order to investigate the vertical distribution of water masses, the data for each water mass were grouped according to their properties and plotted against depth. Figures 6, 7 and 8 illustrate the variation in salinity, dissolved oxygen, and fluorescence of each water mass, respectively. Water masses **A** and **B** are located in the upper 18 m and 70 m of the water column, respectively. This pattern suggests that these masses either move over denser water, or are distributed throughout the water column in shallow areas. The water masses **C** and **D** are not present in the first few meters at the surface, and they can only be found from the 5 m or 15 m depth towards the seabed, respectively. The region of maximum salinity (> 36.5) in the water mass **D** is located between the 30 m and 65 m depth. Dissolved oxygen has its maximum and minimum values at the surface in the water masses A and B, and the range slightly decreases with depth. The dissolved oxygen in

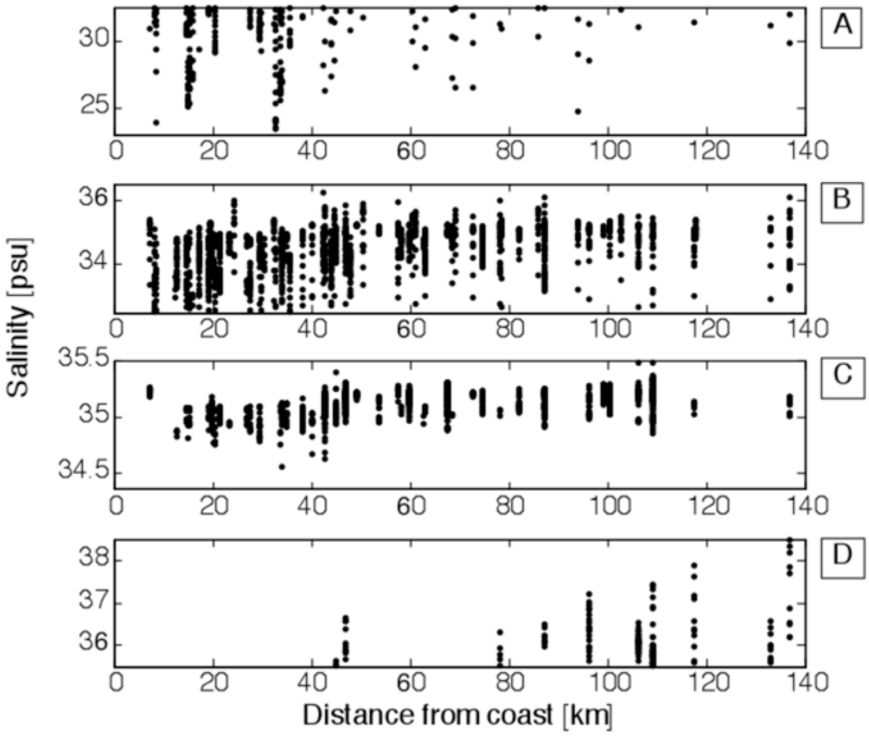

Figure 3 - Variation of salinity with across-shelf distance for water masses **A**, **B**, **C** and **D.**

Figura 3 - Variação da salinidade em função da distancia para as massas de água A, B, C e D.

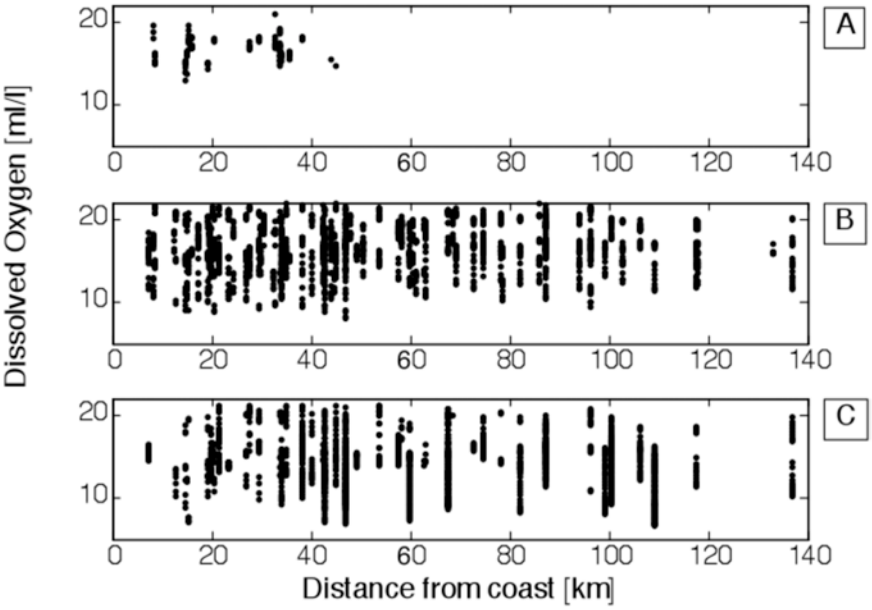

Figura 4 - Variation of dissolved oxygen with across-shelf distance for the water masses **A**, **B**, and **C.**

*Figura 4 - Variação do oxigênio dissolvido em função da distancia para massas de agua **A**, **B**, e **C**.*

the water mass C is low near the surface, a maximum value occurs between 20 m and 50 m depth, and it tends to a minimum value at location deeper than 100m. On the other hand, the fluorescence decreases with depth in general, and the maximum value occurs between 20 and 50 m depth.

5. Discussion

Based on the T-S diagram presented in Figure 2, four water masses that are mainly different in their salinity were identified in the Sofala Bank. The salinity has a greater impact on the description of water masses (Duxbury and Duxbury, 1997), given that it is the factor influencing the seawater density the most in the tropical regions with strong freshwater influence, as opposed to temperate regions where the strong seasonal heating cycle controls the density variations (Simpson, 1997). Low salinity (23-32.5) shelf waters having high temperatures (27-31ºC) were recorded over the Sofala Bank. The occurrence of this water mass is consistent

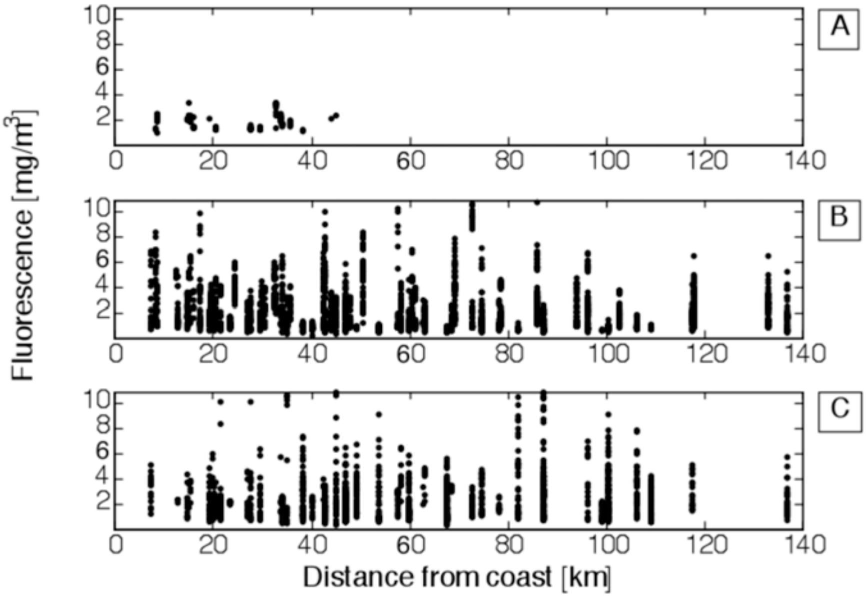

Figure 5 - Variation of fluorescesce with the across-shelf distance for water masses **A**, **B** and **C.**
Figura 5 - *Variação da fluorescência com a distância para massas de água* ***A, B*** *e* ***C****.*

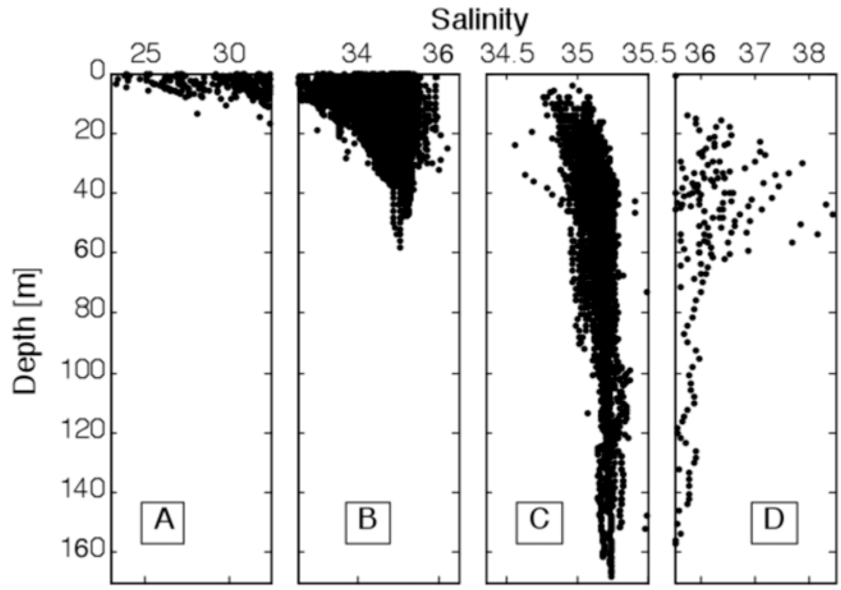

Figure 6 - Vertical distribution of salinities in water masses **A**, **B**, **C**, and **D** based on data collected between 2003 and 2007.

Figura 6 - Variação vertical da salinidade das massas de água ***A, B, C*** *e* ***D*** *no Banco de Sofala, a partir dos dados do cruzeiro do IIP no período de 2003 a 2007.*

with the known physical characteristics of the study site, given that the Sofala Bank is a recipient of fresh-water discharges from a number of rivers, including the Pungwe, Buzi and Zambezi rivers. The latter contributes a great deal in terms of buoyancy input to the coastal ocean. According to the results presented here, the low salinity shelf water is limited to the upper 15 m of depth and spreads horizontally beyond 100 km from the coast. It covers the regions surrounding the river mouths (Silva, 1984; Machaieie, 2012), and the area of the plume Zambezi River (Nehama, 2012).

The water masses identified in this study are comparable with those previously described by Silva (1984), Gammelsrod & Hoguane (1995), and Machaieie (2012). These authors observed only three water masses in the Sofala Bank region area, namely: low salinity shelf water (LSSW) with high temperatures, which is comparable to the water mass **A**; oceanic water (OW) with relatively high salinity and low temperatures that matches the water mass **C**; and high salinity shelf water (HSSW) that matches the mass **D**. According to Siddorn *et al.* (2001), the water mass **B**, absent in these two earlier studies, refers to the oceanic surface water not influenced by the freshwater discharges, yet having higher temperatures than the water mass **C**. This water mass can be found over the entire breadth of the bank

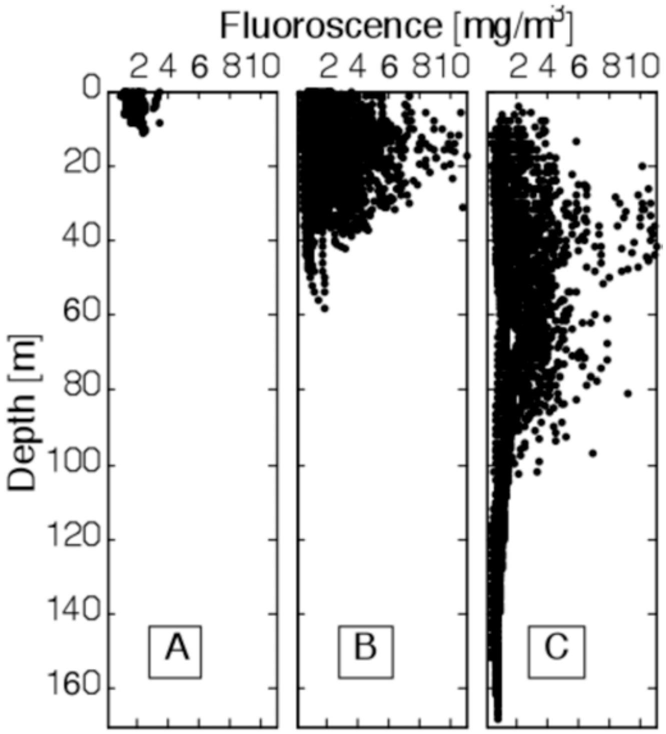

Figure 7 - Vertical distribution of dissolved oxygen in three water masses.

Figura *7 - Distribuição vertical do oxigénio dissolvido em três massas de água.*

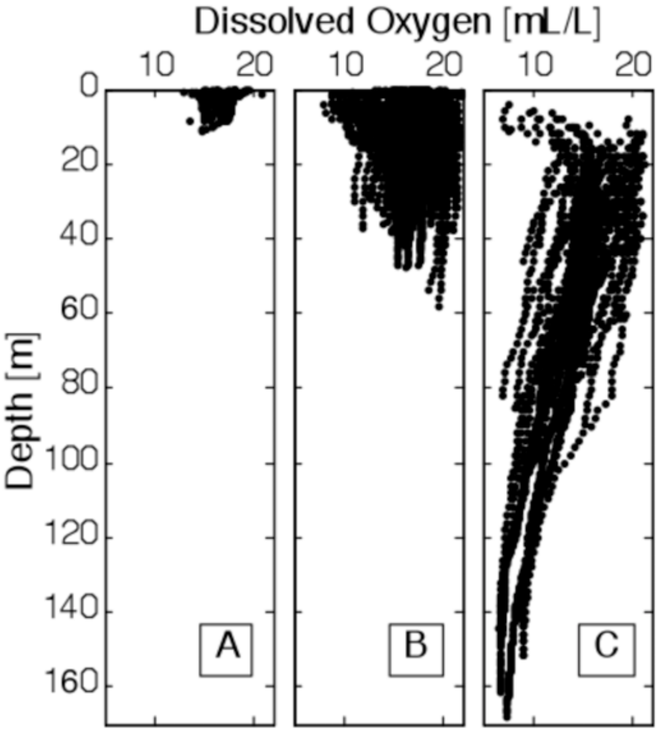

Figure 8 - Vertical distribution of fluorescence.

Figura 8 - *Distribuição vertical da fluorescência.*

(0-140 km) and is limited to the upper 70 m of the water column. In those earlier studies, the type C water was considered to be part of either type A or type C water, however, the ANOVA results indicated that the water samples A, B, C, and D all came from different groups. Brinca *et al.* (1983) and Silva (1984) reported the occurrence of high salinity (> 35.4) shelf water along the coast around latitude 20º 20 S over the entire water column. In this study, high salinity water (> 36.5) presented in Figure 3-D was found beyond 80 km from the coast, at about 50 m depth (Figure 6-D). It is believed though, that we are dealing with same water mass, where the differences in location could have been induced by some form of natural variability in time and space. In that report, the authors (Brinca *et al.,* 1983) argued using simple transport calculations that the occurrence of this water mass could not be justified only by the increased evapotranspiration rates estimated for the mangrove areas. Additional hydrographic measurements taken in 2003 and presented in this study reinforce the idea that the origin of these hypersaline waters still needs to be determined.

The entire region of the Sofala Bank is in general well oxygenated, with values around 20-22 mL/L of dissolved oxygen at the surface and 5-7 mL/L at greater depths. No clear pattern of the variation of both dissolved oxygen and fluorescence with distance to the coast was found. This suggests that for a fixed depth the four identified water masses cannot be distinguished by their content of dissolved oxygen. Moreover, this pattern indicates that any activity of respiration or oxidation of organic material occurs homogeneously in the whole bank. The oxygen concentration was never lesser than 12 mL/L in the water mass A, which is noticeably influenced by the rivers. A typical vertical profile of dissolved oxygen in the open ocean is one which high values occur near the surface because the atmosphere is the main source for oxygen (Pickard & Emery, 1990). Super-saturation can occur in this layer due to the additional input of oxygen from photosynthesis. The profiles of dissolved oxygen presented here display the typical decrease in concentration with depth, and also point to a great variability for a given depth or distance to coast, which in turn highlights the need for further analysis. Santos et al. (2008) analysed abiotic parameters within the extent of the Amazon River plume and found dissolved oxygen in concentrations of about 5 mL/L corresponding to saturated to supersaturated environments. Provided that a direct comparison with those measures cannot established, it can only be speculated that the concentrations of dissolved oxygen reported for Sofala Bank presented in Figures 4 and 7 might be above the limit of saturation. In general, higher values of fluorescence were observed below the sub-surface layer and the stations where depth exceeds 100m, the fluorescence at the seabed is about 10% that of the surface. This type of distribution pattern has been observed before in other parts of the Mozambique Channel (Langa, 2011), and is related to nutrient distribution and light penetration.

There are great examples in the literature of physical control to recruitment of various species, as a consequence of the transport of water with particular characteristics from the shore or towards the shore. For instance, Parnell (2001) used the recruitment of different species to associate larval species with particular estuarine water, and Farrell *et al.* (1991) found large recruitment in the intertidal region associated with the advection of warm, clear, and low-salinity water into nearshore region. The presence of four different water masses in the Sofala Bank has ecological and management implications that still needs to be thoroughly investigated. There is a clear linkage between the runoff and shrimp catch rates (Gammelsrod, 1992; Hoguane, 1997), which has direct implications on the management of shrimp resources. We still need to understand whether the variations and transport of the three other oceanic water masses cause changes in the living resources in the bank.

6. Conclusions

Four water masses were identified along the Sofala Bank, namely, low salinity shelf water, (< 32.5 psu and 28-31º C), surface warmer oceanic water (32.5-35.8 psu and 27.5-31° C), deep oceanic water (34.5-35.5 psu and 15-27.5º C), and high salinity shelf water (>35.5 psu). The variance of the water masses was tested statistically using ANOVA and Tukey test and a significant difference was found ($p < 0.01$). The direct influence of river runoff as evidenced by the presence of low salinity waters in the shelf is limited to a narrow strip of around 50 km and to the upper 15 m of the water column, which in some cases correspond to entire water column. The high salinity shelf water extends offshore from 38 km at a depth greater than 15 m. All water masses are generally well oxygenated and the lower limit of dissolved oxygen decreases with depth but is homogeneous over the bank's breadth. This lower limit corresponds to 13, 7 and 5.7 mL/L for the low salinity shelf water, surface oceanic water, and high salinity water, respectively. Fluorescence is in general low and almost uniform over the low salinity shelf water, but in the two oceanic waters (i.e., having high and low temperatures) it presents low values at the surface and higher values immediately below the surface layer. The presence of four different water masses in the Sofala Bank is likely to have ecological and management implications.

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Modelling the thermal effluent of a near coast power plant (Sines, Portugal)*

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ABSTRACT

The present work is focused on the dispersion of a thermal effluent, produced by the Sines power plant, Portugal, along coastal waters. This facility intakes a yearly average around 40 m^3/s of seawater, for the required cooling process, which is subsequently discharged back to the ocean at a 10 ºC increase in temperature. A three-dimensional hydrodynamic local model was nested into a regional model and set up to simulate the transport of the thermal effluent during two distinct periods, August and October 2013, respectively featuring dominant north and south wind. The simulations were performed for both situations, with and without the thermal discharge, where the later provides baseline scenarios. Obtained model results closely followed the existing field data. The temperature increase is shown to decay from 10 ºC near the outlet vicinity to 2 ºC at a distance of 2 km from the outlet for both scenarios. Even though the main driving force of this phenomenon is the wind, tidal conditions also have additional influence on thermal plume dispersion near the discharge area. In the north wind scenario the plume extends away from the coast while under south wind dominance the plume is contained near the coast, extending towards the inlet. As a consequence there is a positive feedback under south wind dominance, which is caused by the intake of already warm water from the thermal plume itself. Consequently, south wind dominance is the most unfavorable scenario for both coastal environment and the operational efficiency of the power plant.

Keywords: Thermal discharge; Three-dimensional model; Coastal hydrodynamics; Water temperature

RESUMO

Modelação de um efluente térmico numa zona costeira (central termoelétrica de Sines, Portugal)

Este artigo tem como objetivo estudar a dispersão do efluente térmico da central termoelétrica de Sines (Portugal) na zona costeira. Esta central retira em média 40 m^3/s de água do oceano Atlântico que após o processo de refrigeração é restituída à fonte através de dois canais, com uma temperatura de 10º C acima daquela que tinha na zona de captação. De modo a estudar o transporte deste efluente térmico foi implementado um modelo hidrodinâmico tridimensional acoplado a um modelo regional. Foram simulados e analisados dois cenários de ventos diferentes, vento predominante do quadrante norte e vento predominante do quadrante sul. Para cada tipo de vento são comparados os resultados para a situação com e sem descarga. Os resultados obtidos com o modelo evidenciam a anomalia térmica, observável nos dados de campo, mostrando um aumento variável entre 10º C, na região próxima à descarga, até 2º C a cerca de 2 km da mesma área, para ambos cenários. Contudo, enquanto que no cenário de vento norte se observa uma pluma térmica estreita, ao longo da costa, no caso do vento sul observa-se uma pluma mais confinada à região da saída do efluente. O vento sul é o cenário mais desfavorável à eficiência da

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central uma vez que nesta situação a pluma é direcionada para zona de captação. Assim conclui-se que o vento tem um papel preponderante na dispersão do efluente térmico. Os resultados do modelo mostram ainda que a maré também influência a dispersão, sobretudo na zona junto à descarga.

Palavras-Chave: *Efluente térmico; Modelo tridimensional; Hidrodinâmica Costeira; Temperatura da água*

1. Introduction

Coastal areas are often used as a disposal environment for thermal effluents originating from the cooling processes in thermal or nuclear power plants. Studies providing information on thermal effluent behavior in receiving environments can contribute to efficiently manage such discharges, mitigating impacts on relevant environmental and economic values (Abbaspour *et al.*, 2005). The changes caused by the effluents of power plants on ambient water temperature and, consequently, their impact on the aquatic biota has been studied for decades (e.g., Takesue & Tsuruta, 1978; Kelso & Milburn, 1979; Hester & Doyle, 2011; Coulter *et al.*, 2014).

Reported values show that power plants can cause temperature increases that range from 1-2° C up to 15º C, in both rivers and seawater (Takesue & Tsuruta, 1978; Kelso & Milburn, 1979; Madden *et al*., 2013; Stewart *et al*.,2013; Coulter *et al*.,2014;). Since temperature is an essential environmental variable, affecting the metabolic rate of organisms and the levels of dissolved oxygen (Langford, 1990; Agarwal, 2005; Coulter *et al*., 2014), any disturbances in ambient temperature has the potential to disrupt the marine environment (e.g. Martinez-Arroyo *et al*., 2000; Poornima *et al.,* 2005; Chuang *et al.,* 2009; Choi *et al.,* 2012). Therefore, the forecast of the thermal plume transport and dispersion in the receiving water body is critical to assess its environmental exposure.

There are several methodologies to study thermal plume behavior, ranging from physical models (El-Ghorab, 2013), to in *situ data* analysis (e.g. Jan *et al.,* 2004; Hunt *et al.,* 2010) to the use of numerical models (e.g. Bedri *et al.,* 2013). The latter option allows the continuous representation of the environmental system in space and time, and with fewer information requirements and reduced resources when compared to the other options (Jones *et al.,* 2007).

A common practice to discharge thermal effluents consists of open channels with free surface flow and along the water column, such as the examples provided by Abdel-Latif *et al.* (2007) and Fossati *et al.* (2011). Open channels are more cost effective when compared with submerged point or multiport diffusor systems, although this type of diffusors can provide an increased initial mixing (Kim & Cho, 2006).

In the open channels systems the effluent is released at lower velocities, originating a buoyant plume, similar to plumes caused by natural geophysical phenomena such as tributaries and rivers. Thermal plumes spread from the outlet depending on transport and mixing mechanisms controlled by environmental conditions, with wind stress acting as a major driving force (Lentz & Largier, 2006).

This work presents a methodology based on the implementation of a three-dimensional numerical model to study the dynamics of a thermal plume originated by a power plant located at the Portuguese west coast. A reference scenario without the effluent was used to compare with other scenarios where the effluent is present, for simulations with distinct wind conditions. The differences between the reference and the other scenarios were then quantified and discussed, highlighting the less favorable conditions for plume dispersion.

2. The case study

The Sines thermal power plant is located on the west Portuguese coast, as shown in Figure 1. This thermal power plant has a total installed capacity of 1192 MW. On yearly average, 40 m^3/s of cooling water go through the intake structure (Direcção de Produção Térmica da EDP, 2012) and, after flowing through the condenser system, are discharged back to the ocean by two open channels, along the water column, which depth is around 4.5 m. The discharge structure is located approximately 400 m to the south of the water intake.

Coastal hydrodynamics, particularly in what concerns superficial currents and waves, is conditioned by dominant wind patterns. Furthermore, wind is also responsible for the vertical movements caused by upwelling phenomena in this area (Barton, 2001; Santos *et al.*, 2011). During a typical year, 80% of wind observations exhibit north wind dominance (See Supporting Information I), leading to strong upwelling along the Portuguese west coast (Fiúza, 1983).

3. Methodology

MOHID (www.mohid.com), Portuguese acronym for *MOdelo HIDrodinâmico* [Hydrodynamic Model], is the numerical model applied on this work. This model has been largely applied in several studies for coastal and estuarine systems (Mateus & Neves, 2008; Vaz *et al.*, 2009; de Pablo *et al.,* 2013; Fossati & Piedra-Cueva, 2013; Otero-Díaz *et al.,* 2014; Sousa *et.al.*, 2014), having shown its ability to simulate complex systems and processes.

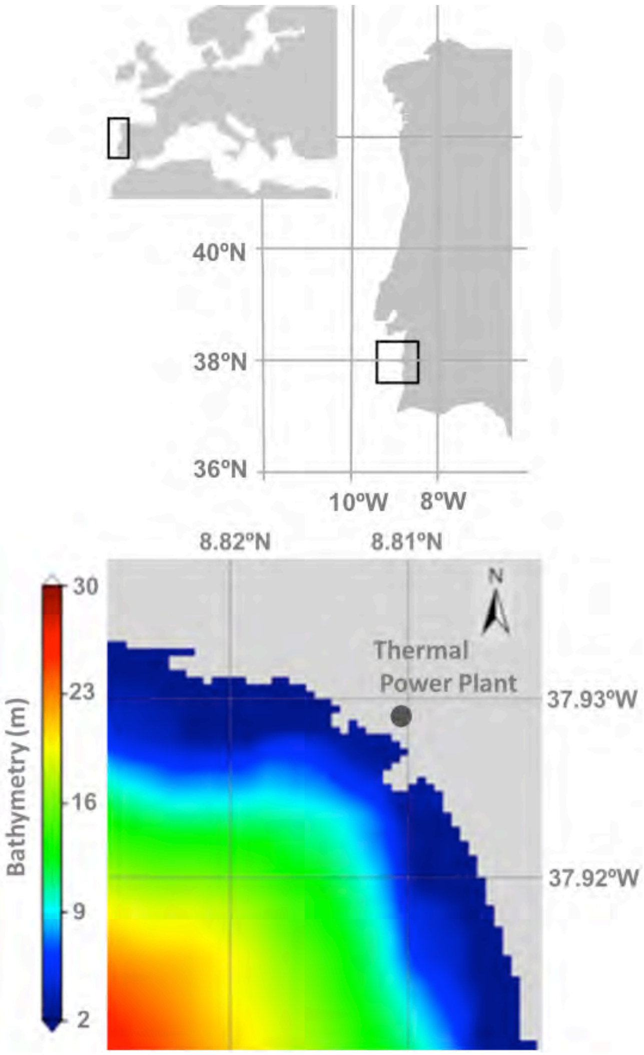

Figure 1 – (a) Location of the study area. (b) Bathymetric data around the around the Sines thermal power plant intake and outlet structures.

Figura 1 – (a) Localização da área de estudo. (b) Batimetria junto à zona de tomada e descarga de água de refrigeração da central termoelétrica de Sines.

MOHID water system solves the three-dimensional incompressible primitive equations, equilibrium, Boussinesq approximation and Reynolds approximation. The governing continuity equations are described in Supporting Information II.

For this work, the horizontal turbulent viscosity is set uniform in each domain. To handle vertical turbulent viscosity MOHID is coupled to the General Ocean Turbulence Model (GOTM, online at http://www. gotm.net), through which the k-ε model is parameterized according to Canuto *et al.* (2001).

The mass-balance equation for temporal and spatial variations of salinity and temperature is expressed in Supporting Information II. The density is solved with the UNESCO state equation as a function of salinity, temperature and pressure (Supporting Information II).

Regarding temporal discretization, MOHID uses semi-implicit algorithms to compute the processes that have higher stability requirements, like vertical advection and diffusion, and explicit methods for processes less constrained to the stability problems, like horizontal transport (Neves, 2013). A more detailed description of the numerical algorithms can be found in Martins *et al.* (2001).

In this study the numerical model was implemented with a downscaling methodology. Such method is useful to interpolate the boundary conditions of locally refined models from regional, less resolved, models (Ascione *et al.*, 2014). The model was configured using four nested domains as shown in Supporting Information III. The first level (A) has a spatial resolution of 6000 m, the second (B) and third (C) levels have 1200 m and 240 m, respectively, and the fourth (D) and most refined level is discretized using 48 meter cells. The geographic dataset used for the bathymetries was obtained from the European Marine Observation and Data Network (2014). All the domains were setup in 3D, where a z-level vertical discretization (Martins *et al.*, 2001) was adopted. This way it was possible to implement 7 sigma-type layers on the top for all domains, and a variable number of fixed layers below, according to its bathymetric topology.

The domain A works as an acquisition window, acquiring data from the PCOMS operational model (www.mohid.com/operational), which provides results for tide levels, velocity fields, density, temperature and salinity for the whole Portuguese coast, as described by MOHID water system solves the three-dimensional incompressible primitive equations, assuming Hydrostatic Mateus *et al.* (2012). Hence PCOMS provides horizontal open boundary conditions for regional models like the present one. Open boundary conditions are then applied through a Flow Relaxation Scheme (FRS) for temperature, salinity and velocities (Martinsen & Engedahl, 1987) whereas level is radiated through a condition provided by the Flather method (Flather, 1976), both described by Riflet (2010). At the vertical open boundary with the atmosphere the model is forced with atmospheric results, provided by Mesoscale Meteorological Model 5 operational model (MM5, online at http://meteo.ist.utl.pt/), for air temperature, wind intensity and direction, atmospheric pressure, solar radiation and cloud coverage. From this data, the model computes momentum and heat fluxes, allowing for a variable interaction between free surface and atmosphere.

The intake and discharge structures are accurately modelled on the domain D, as well as the nearby port of Sines. For the water intake, a constant flow of 40 m^3/s, is considered and modelled by a simple sink, whereas the effluent is modelled by a source term, injecting a 30 m^3/s local discharge at the downstream section of the open channels and two 5 m^3/s lateral linear discharges, simulating the crosswise flow percolating through the breakwaters. The intake and discharge of water are both made along the water column simulating the real conditions. It was also implemented a bypass function that prescribes a 10ºC rise in temperature of the discharged water temperature, relative to the intake. This continuous offset value was obtained by applying the heat equation to the turbine generators and cooling system.

4. Results and discussion

4.1. Model validation

The model setup used in this study was validated at two different domain levels. The regional solution of the model PCOMS, from where the horizontal open boundary conditions were downscaled, was validated with remote sensing data for sea surface temperature (SST) and *in situ* observations. This is a routine validation described by Mateus *et al.* (2012). The local higher-resolution model, where the thermal discharge was implemented, was validated with *in situ* observations for water level and sea surface temperature, recorded by a moored buoy located near the Sines port (Instituto Hidrográfico, 2014a, b).

Temperature data acquired during in situ monitoring campaigns, disclosed by the power plant executive board, was also used to validate the higher-resolution model application. These campaigns were conducted directly, by sampling the water column in the vicinity of the discharge and in a location displaced from the area of influence of the thermal plume. Remote sensing data was not used to validate the higher resolution model given the lack of resolution in the images.

Results for water level show a good fit with field data, with a Pearson correlation coefficient of 0.99 (Supporting Information IV). The root mean square error (RMSE), shows a relatively small difference (0.17ºC) between model predictions and field observations for SST, denoting a good fit between model outputs and data (Supporting Information IV).

Nonetheless, the model misses the high frequency fluctuations in the SST recorded by the buoy, as seen in Supporting Information IV. Apparently, the model tends to overestimate superficial temperature, as evidenced by the bias error (BE) (Supporting Information IV). The calculated temperature by the model is an average value for a 48 × 48 meters cell (1 meter deep), and not a single point matching the location of the buoy, which may explain this outcome. Moreover, the variability recorded by the buoy can be related with it is sensitivity to surface currents and wind, since the float sensor is located right below the water surface.

The model follows the trend of in-depth monitored temperature with significant accuracy. A Pearson correlation coefficient of 0.97 was obtained for both locations, suggesting that the model exhibits a positive variation relative to field data (See Supporting Information IV). The RMSE denotes some overestimation of temperature by the model (~ +1 ºC) in the vicinity of the outlet, and a slight underestimation of the temperature in the reference site (~ -0.4 ºC). The wider difference between modelled and observed data may be related to the assumption made for the discharge; the model relies on a constant yearly average value, ignoring possible variations on the power plant operation during the simulated period.

4.2. Thermal plume dynamics

Temperature affects almost every aspect of aquatic life. Hence, thermal effluents from power plants have the potential to cause significant perturbations to the coastal marine environment. There are now mounting evidences of the detrimental impact of thermal stress on the biota (e.g., Young & Gibson, 1973; Poornima *et al.,* 2006; Arieli *et al.,* 2011; Ingleton & McMinn, 2012; Jiang *et al.,* 2013), and its combined effect with the chloride used as an antifouling agent in power stations pipes (e.g., Holmes, 1970; Poornima *et al.*, 2005; Saravanan *et al.*, 2008; Chuang *et al.,* 2009).

Considering the harmful effects that the cooling water may have on the costal environment, it is important to understand the magnitude and range of its influence upon discharge. In this context, simulating velocity fields using coastal models is extremely useful to monitor and interpret the dispersion of the warmer plume (Wei *et al.,* 2013). Within this framework, we set up a three-dimensional hydrodynamic and temperature model to simulate the transport of the cooling water under two distinct wind conditions, August and October 2013 featuring dominant north and south winds, respectively, and compared them to the reference scenario.

Surface velocities are usually higher under north wind regimes than under south wind, as seen in Figures 2 and 3. The presence of the cooling water discharge induces an increase on surface velocity in the vicinity of the outlet, by approximately 0.1 m/s, in both the north (Figure 2b) and south (Figure 3b) wind scenarios. This is an expected outcome, since the wind pushes the warmer and less dense water discharged in the coastal area.

The effect of the thermal plume on the surface temperature field under north wind and south wind conditions is depicted in Figure 4 and Figure 5, respectively. Also, the anomaly in surface temperature induced by the presence of the plume is illustrated Figures 6 and 7.

A maximum temperature increase of approximately 10ºC is observed near the outlet, when compared to the baseline simulation (no thermal effluent). Under north wind conditions with an intensity about 5 m/s, there is

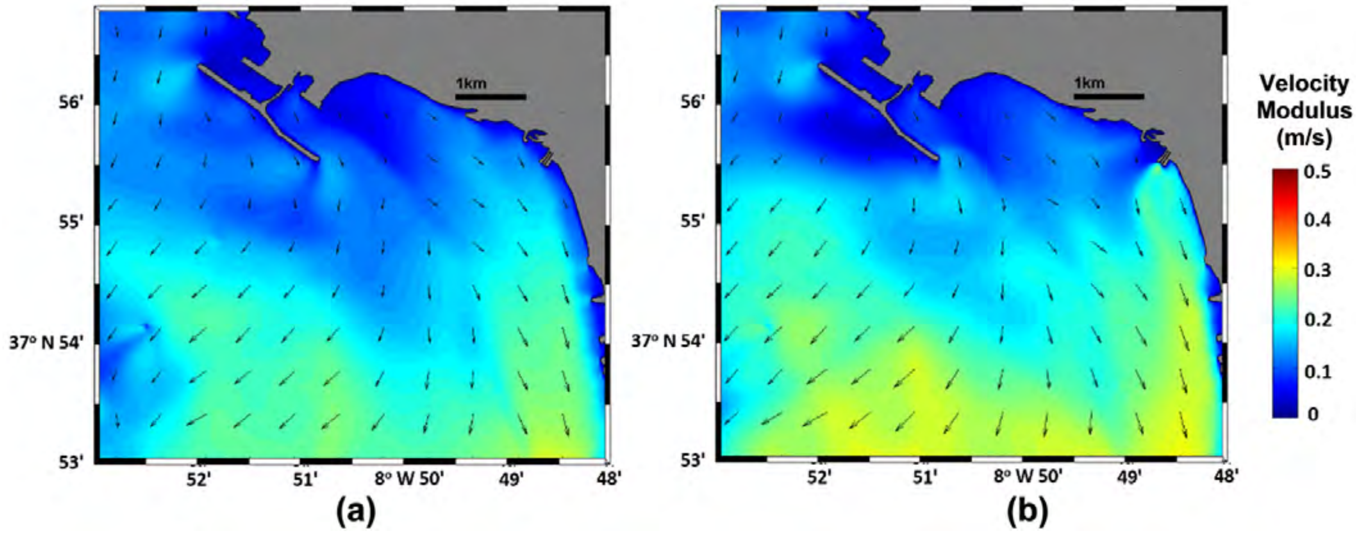

Figure 2 - Model results for the velocity modulus, without (a) and with (b) discharge, in north wind scenario.

Figura 2 - Resultados para o módulo da velocidade, sem (a) e com descarga (b), no cenário de vento norte.

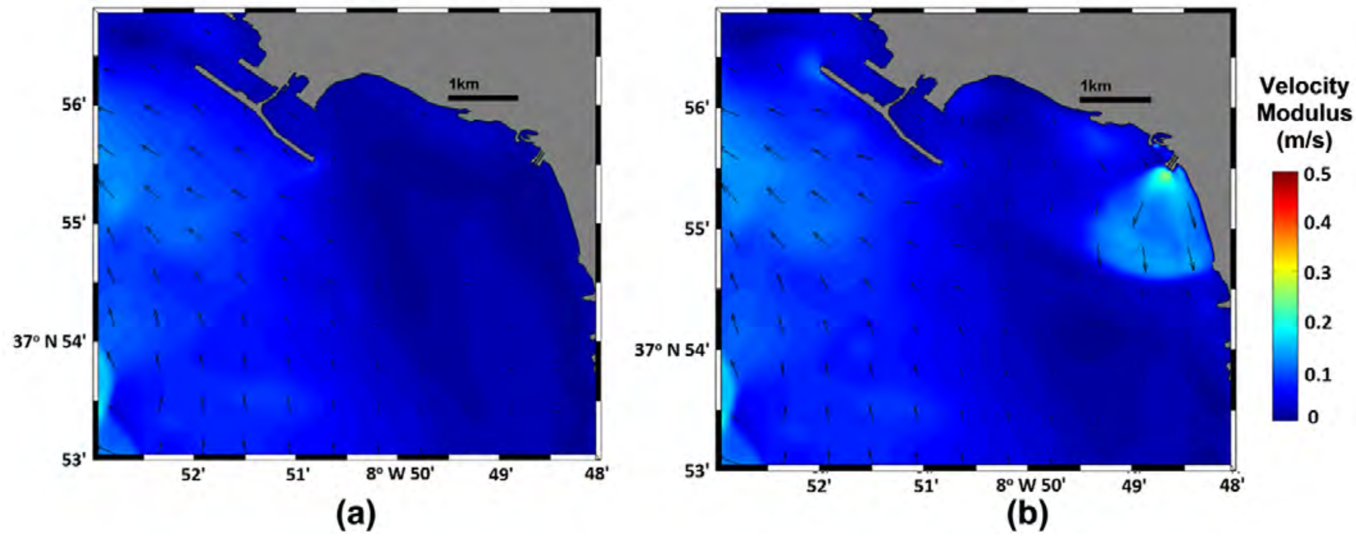

Figure 3 - Surface velocity, without (a) and with (b) discharge, in south wind scenario.

Figura 3 - Velocidade superficial, sem (a) e com descarga (b), no cenário de vento sul.

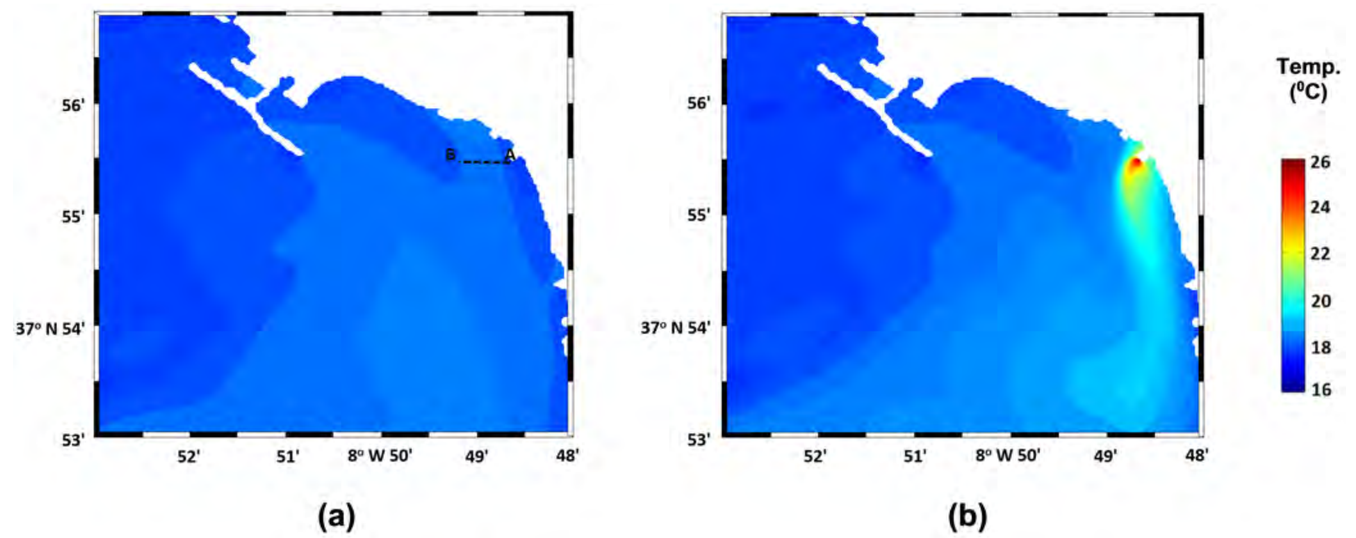

Figure 4 - Model results for superficial temperature, without (a) and with (b) discharge, in north wind scenario.

Figura 4 - Resultados para a temperatura à superfície, sem (a) e com descarga (b), no cenário de vento norte.

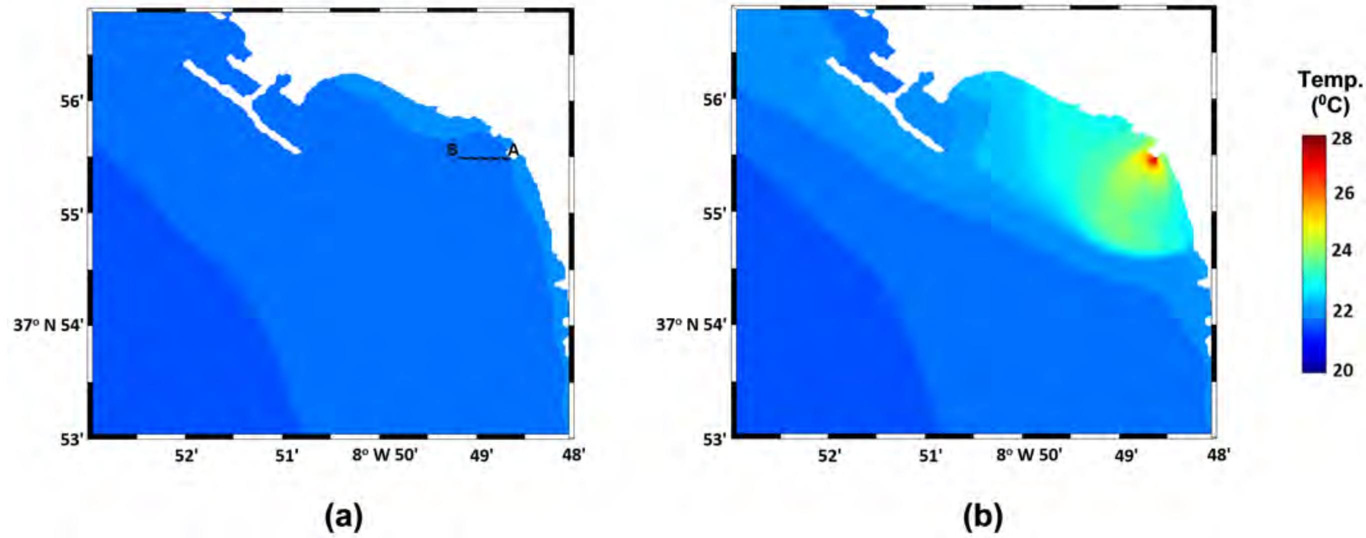

Figure 5 - Model results for surface temperature, without (a) and with (b) discharge, in south wind scenario.
Figura 5 - Resultados para a temperatura à superfície, sem (a) e com descarga (b), no cenário de vento sul.

an increase of temperature ranging from 2 to 10°C (Figure 6), relatively to the reference scenario, and the effect on surface temperature is noticed up to a maximum distance of approximately 2 km from the outlet. In south wind scenario, with wind intensity about 4 m/s, a thermal plume is also noticeable at surface (Figure 7). There is an increase of temperature varying between 2 and 10ºC (Figure 7) in a maximum distance around 2 km from the outlet, as in the north wind scenario.

These values are generally comparable to values found by other studies for both the temperate anomaly (Lardicci *et al.,* 1999; Chuang *et al.*, 2009; Arieli *et al.*, 2011; Madden *et al.,* 2013) and extent of influence (Arieli *et al.* 2011). While in the north wind scenario the plume extends longer along the coast, under the south wind scenario the plume extends and impacts a wider area around the outlet.

Tide also plays a significant role on the dispersion of the thermal plume. As observed in Figure 6 and 7, the extent of the plume is higher in ebb or low-tide conditions. Inversely, the plume is more compressed and closer to the coast in flood and high-tide conditions. Results suggest that ebb conditions facilitate the dispersions of the thermal effluent, while flood keeps the warmer waters closer to the outlet.

In both scenarios the thermal plume develops along the direction of the dominant wind incidence. When the south wind is dominant the thermal plume is pushed northward, and finds the coastline, a physical barrier that confines the plume, as seen in Figure 6. In these conditions the thermal plume develops toward the water intake, and the process can be further aggravated during flood and high-tide conditions. This means that a feedback process may occur, by which the water used in the cooling process is continuously drawn at increasing temperatures and, consequently, so is the discharged effluent.

Therefore south wind conditions are the less favorable for the thermal power plant efficiency, although this regime occurs with low probability for this area. This is particularly relevant since the availability of cooling water for steam condensation is a major criterion in the location of power plants.

The release of a warmer mass of water at the coast line, and associated increase in the surface temperature field leads to the vertical thermal stratification. This effect could be reduced with a discharge system that induces mixing like a multiport diffuser system (Kim & Cho, 2006). In this case the vertical thermal stratification is shown in Figures 8 and 9 (corresponding to the line represented in Figures 4a and 5a), for north and south winds, respectively. In the reference scenario a well-mixed water column is visible, with colder waters flowing upward, as opposed to the simulations featuring the effluent, where an increase in temperature is visible over the whole water column in the vicinity of the outlet. North wind conditions induces greater initial mix in the effluent discharge, when compared to the south wind scenario. This can be explained by higher wind intensity (north wind) that promotes a stronger mixing of the water column situation, and by the associated upwelling that brings colder and deeper water to the surface.

The thermal signature is stronger at the surface because of the lower density of the warmer that leads to higher buoyancy, and becomes less evident with increasing distance from the shore. Similar observations have been reported for thermal effluents (Arieli *et al.*, 2011), but in this particular situation the intense hydrodynamic regime of the coastal area prevents the enhancemtn of

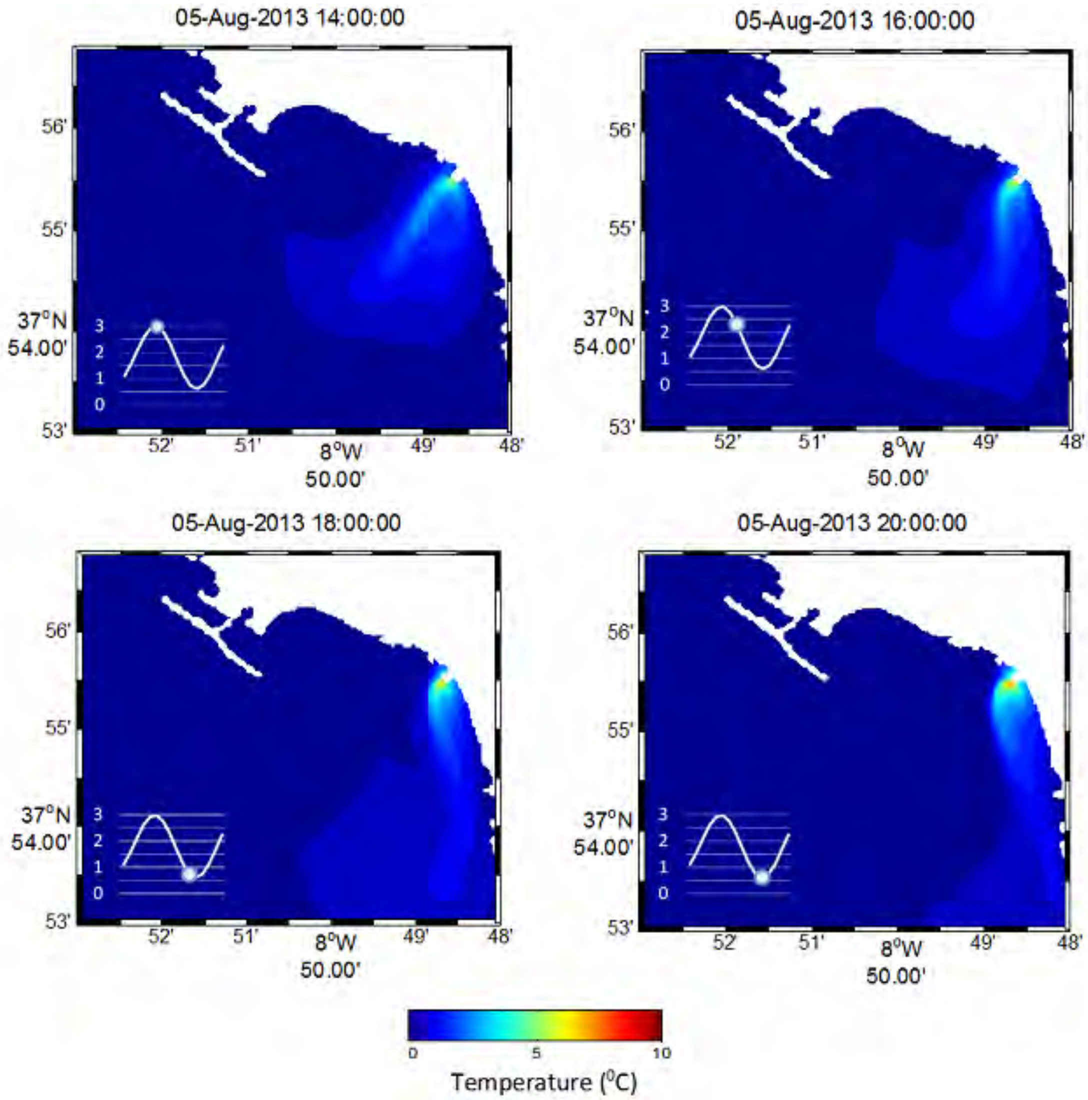

Figure 6 - Sea surface temperature anomaly induced by the presence of the cooling water discharge in the coastal area, in north wind scenario.

Figura 6 - Efeito da descarga térmica na temperatura superficial do oceano, caso do vento norte.

strong and persistent thermal stratification similar to the one observed in lakes (Eloranta, 1983; Kirillin *et al.*, 2013).

4.3. The choice of model

Reported works display different approaches to simulate the effect of thermal plumes on the receiving waters: simple models to account for thermal stratification of the water column (Kirillin *et al.,* 2013), mixed approaches using physical and numerical models (El-Ghorab, 2013), schematic studies using 2D (You-liang *et al.,* 2011) or 3D numerical models (You-liang & Jing, 2011), and Lagrangian coherent structures (Wei *et al.,* 2013).

The Sines power plant is similar to other energy production units with water pumped into the power plant to cool the turbines and then channeled back into the sea, lake or river via an open canal (Klein & Lichter, 2006; Ingleton & McMinn, 2012; Kirillin *et al.,* 2013). In such setting the water discharged at the outlet is similar distinct physical properties (temperature) from the to a discharge from a small river or tributary, having receiving water body. The model of choice in this study (MOHID) has been extenseivelly used to simulate coastal systems with comparable discharges (Vaz *et al.*, 2005, 2007, 2008, 2009a, 2009b, 2014), and our results show that it adequatly models the physical control of wind and tide on the dispersion of the thermal effluent in the coastal area.

Similar modeling approaches have been used to simulate the dispersion of thermal plumes (Kolluru et al. 2003, Bedri *et al.*, 2013), while other rely on models that solve the near field dilution, such as CORMIX (Roberts & Tian, 2004). However, these models were mainly developed for effluent discharges via submarine outfalls, frequently with multiport diffuser. Since this is

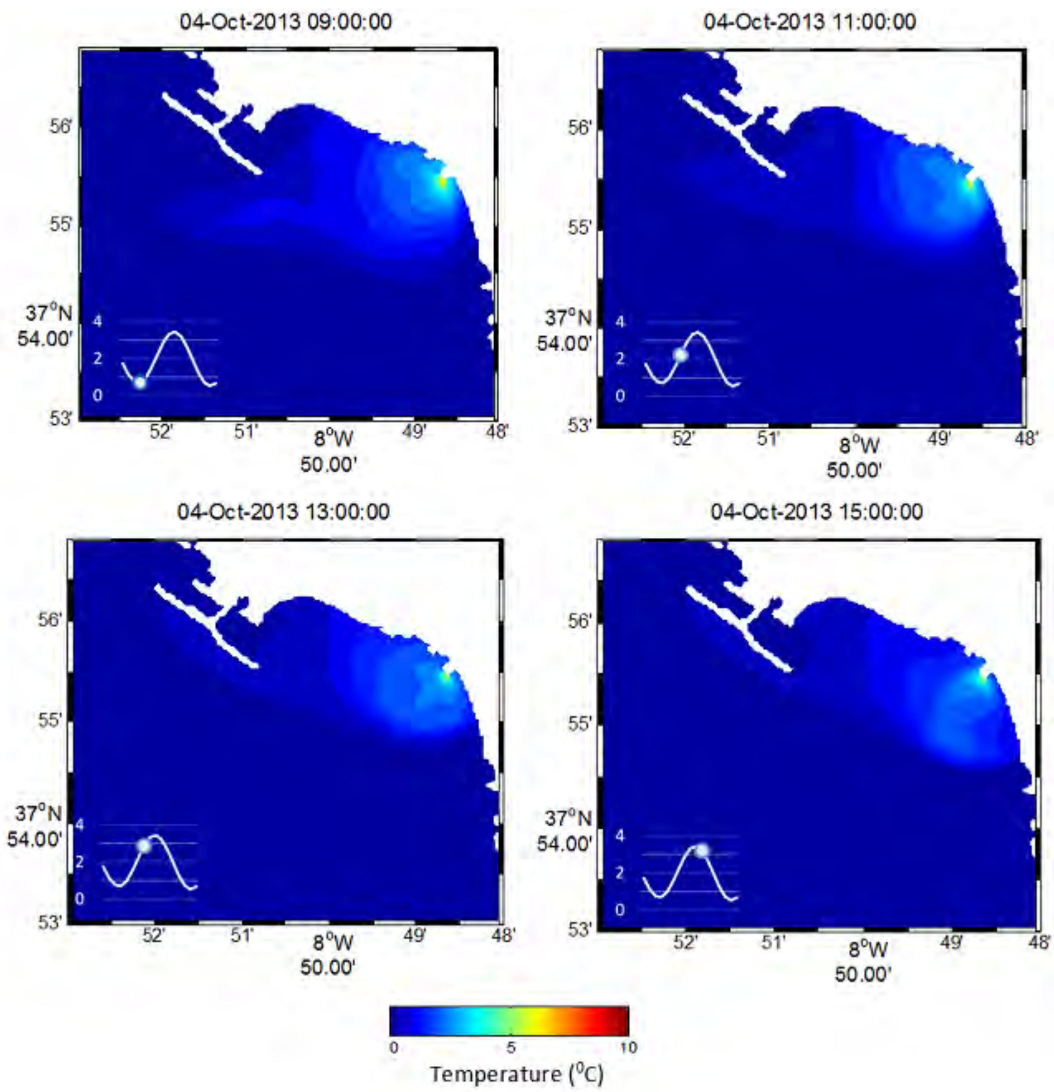

Figure 7 - Sea surface temperature anomaly induced by the presence of the cooling water discharge in the coastal area, in south wind scenario.

Figura 7 - Efeito da descarga térmica na temperatura superficial do oceano, caso do vento sul.

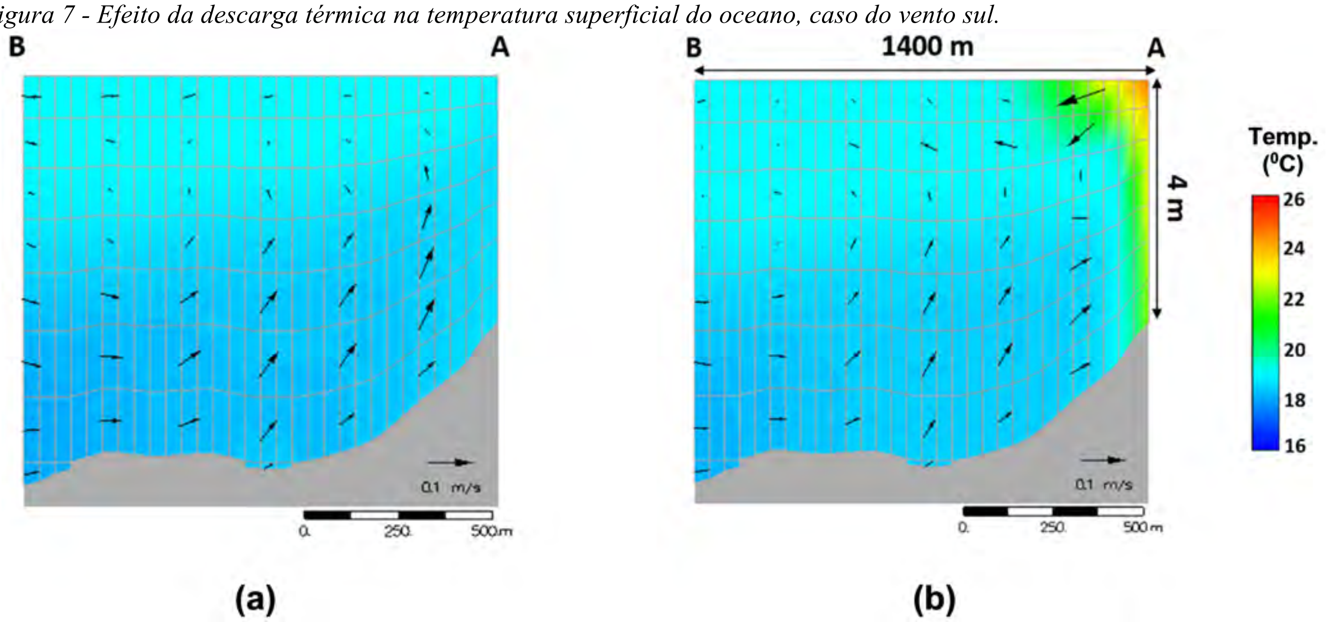

Figure 8 - Results for temperature profile, without (a) and with (b) discharge, in north wind scenario.

Figura 8 - Resultados para o perfil de temperaturas, sem (a) e com descarga (b), no cenário de vento norte.

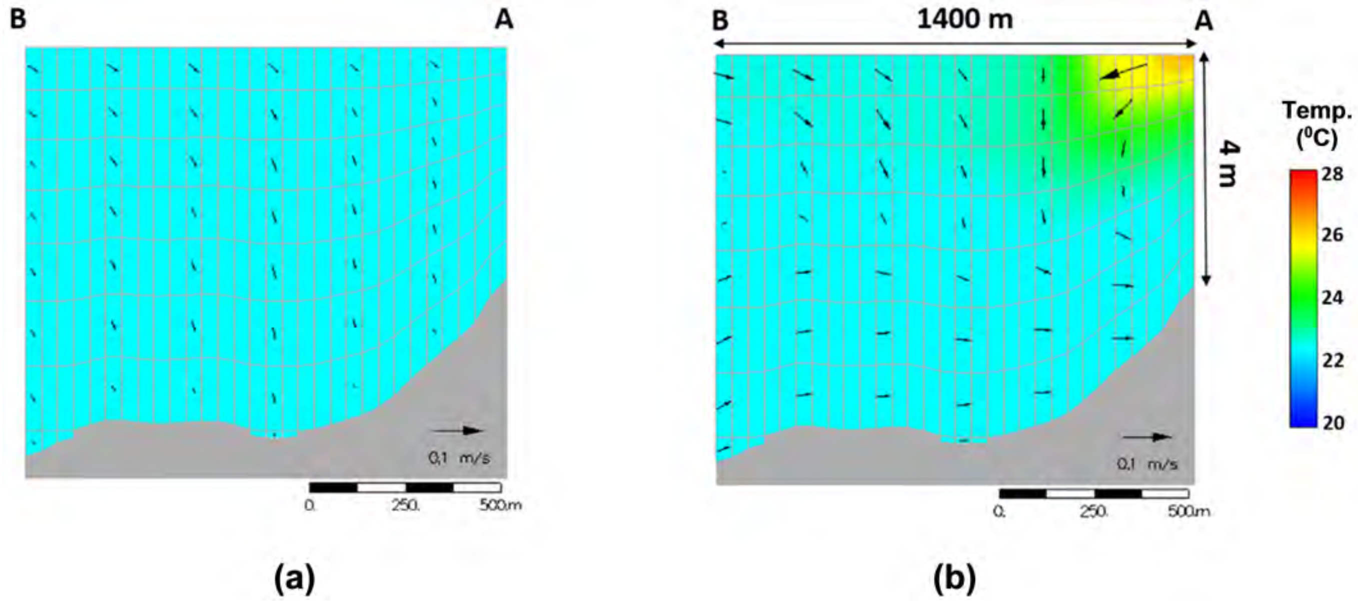

Figure 9 - Model for temperature profile, without (a) and with (b) discharge, in south wind scenario simulations.

Figura 9 - Resultados para o perfil de temperaturas, sem (a) e com descarga (b), no cenário de vento sul.

not the case with the thermal effluent at Sines, addressing the near field dilution would not necessarily lead to better results. Also, while performing optimally for simple discharges into large basins, in complex ambient environments such as at Sines, CORMIX has been proved to overestimate the dilution, resulting in smaller and cooler modeled plumes than the measured plumes (Schreiner *et al.,* 2002, Roberts & Tian, 2004).

5. Concluding remarks

Numerical models are essential to assess the potential impact of thermal effluents from power plants on the physical and ecological dynamics of natural systems. As the construction of a new generation of coastal power stations in European countries demands robust standards for thermal discharges to transitional and coastal waters (Wither *et al.,* 2012), the dependency on numerical modeling will increase. Similarly to other studies (e.g., Bedri *et al.,* 2013; Shawky *et al.,* 2013) the present work is of particular relevance for the coastal zone management of the Sines area, by contributing to a better understanding of the thermal effluent impact on coastal dynamics.

Model results allowed for a good representation of the thermal effluent effects on coastal circulation and thermal structure. The main effect of the discharge of the cooling water is the formation of a thermal plume and consequent vertical temperature stratification. Model simulations show that wind direction and tide play a significant role on the dispersion of the plume and, consequently, of the surface temperature anomaly induced by the thermal discharge. A well-mixed and elongated plume is observed under north wind dominance, as opposed to a constrained wider plume during south wind conditions.

The worst case scenario, regarding the thermal plume extents, is the south condition. This scenario possibly carries major efficiency losses for the operation of the power plant, since the water at the intake is continuously warming

Appendix

Supporting Information associated with this article is available online at http://www.aprh.pt/rgci/pdf/rgci-577_Salgueiro_Supporting-Information.pdf

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Use of geoindicators in vulnerability mapping for the coastal erosion of a sandy beach*

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ABSTRACT

Pititinga beach, located in the municipality of Rio do Fogo on the eastern coast of Rio Grande do Norte, Brazil, lives with the conflict between the actions of the sea and human occupation, giving rise to a striking landscape featuring the damaged waterfront homes of the Pititinga fishing community, which have been destroyed by the action of the sea. Thus, the coastal erosion of Pititinga beach was analysed according to the natural and human conditions and their mutual relations. The methodological procedure used a Digital Elevation Model (DEM) and a geoindicators coastal erosion map, which took account of shoreline parameters, the frontal and transgressive dunes, vegetation, and anthropogenic structures. An area was delimited for the generation of the DEM and to collect information for the production of the geoindicators map. The crossing of the DEM with the geoindicators map resulted in an erosion vulnerability map. The data and information obtained were integrated and stored in a Geographic Information System (GIS). The results show different behaviours in three sections along the shoreline studied, in accordance with the characteristics of each. When frontal and transgressive dunes occur, the vulnerabilities are medium and low, respectively, and when these are absent, as in the village of Pititinga, vulnerability is predominantly very high.

Keywords: Coastal erosion, Geoindicators, Coastal vulnerability, Geographical Information Systems (GIS).

RESUMO

Uso de geoindicadores no mapeamento da vulnerabilidade à erosão costeira de uma praia arenosa

A praia de Pititinga situada no município de Rio do Fogo, litoral Oriental do Rio Grande do Norte, Brasil, convive com o conflito entre a ação do mar e as ocupações humanas fixadas no local, resultando em uma paisagem impactante em que a comunidade de pescadores de Pititinga apresenta casas à beira-mar degradadas e destruídas pela ação do mar. Deste modo, a erosão costeira da praia de Pititinga foi analisada a partir de condicionantes naturais e humanos e suas relações mútuas. O procedimento metodológico utilizou um Modelo Digital de Elevação (MDE) e um Mapa de Geoindicadores de Erosão Costeira, o qual levou em conta parâmetros praiais (mais específicos da linha de praia), das dunes frontais e interiores, Vegetation e estruturas antrópicas. Foi delimitada uma área para a geração do MDE e para o levantamento de informações para a produção do mapa de Geoindicadores. O cruzamento do MDE com o Mapa de Geoindicadores resultou num Mapa de Vulnerabilidade à Erosão. Os dados e informações obtidos foram integrados e armazenados em um ambiente de Sistema de Informações

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Geográficas (SIG). Os resultados alcançados mostram comportamentos distintos em três trechos ao longo da linha de costa estudada, de acordo com as características de cada um. Quando ocorrem dunes frontais e transgressivas as vulnerabilidades são Medium e Low, respectivamente, e quando da ausência destas, como ocorre na vila de Pititinga (dotada de estruturas de engenharia), a vulnerabilidade apresentou-se predominantemente muito alta.

Palavras-chave: *Erosão costeira, Geoindicadores, Vulnerabilidade costeira, Sistema de Informações Geográficas (SIG).*

1. Introduction

The village of Pititinga is a beach community in the state of Rio Grande do Norte, whose traditional inhabitants are fishermen and their families. This community has incipient tourism with rudimentary infrastructure (a few low-quality hotels, boarding houses, restaurants, and commerce in general). With relatively little accommodation, the summer vacation season is not as thriving as that of other beaches in the same state.

The community is marked by the action of coastal erosion, which gives rise to a visual impact on the location, given that many residences have been totally destroyed and others are substantially threatened, all of which creates a serious social problem. For this reason, studies on the understanding of coastal erosion are of great relevance.

On the east coast of Rio Grande do Norte state, more specifically on the stretch between the municipalities of Natal and Touros, research and studies have been conducted which focused on the understanding of the coastal dynamics, notable examples being the works of Nunes (1987), Vital (2003), Vital (2006), Nogueira *et al.* (2006), Amaral (2008), Carneiro (2011), and Lima & Amaral (2013). However, there is still a lot to be done in order to underpin the elaboration of a rational policy for land use and occupation in the region.

It is possible to verify evidence of coastal erosive processes along the entire coast of the state of Rio Grande do Norte. The beaches are eroded when they lose more sediment than they receive from several sources. As the volume of beach material diminishes, the beach level is lowered and its width reduced (Bird, 2008). Coastal erosion is commonly an effect of a negative sedimentary balance. The reduction of the amount of sediments on the coast tends to cause the retreat of the shoreline in the direction of the continent, a process that signals a state of erosion.

It is important to highlight that Pititinga beach presents the configuration of a beach with a bay in the form of a "zeta", called a *zeta curve bay* (Halligan, 1906), *half-heart shaped bay* (Silvester, 1960), or *headland bay* (Yasso, 1965), which when plotted, expresses the portion of the curve which is most closely linked to a promontory and a rectilinear portion or a gentler curvature separated from this promontory. In the case of Pititinga beach, Coconho Point performs the role of the promontory. Amaral´s work (2000) with regard to Rio Grande do Norte stands out; it studies the shoreline of the eastern coast of this state, observing the existence and functioning of the zeta curve bays there.

Coastal erosion can be analysed according to the susceptibility that a portion of the coast presents in the light of its physical and ecological characteristics and, especially, in the light of the tension between the hydrodynamic beach processes and the anthropogenic constructions along the coast. It is relevant to observe that if this tension promotes a negative sediment balance, the vulnerability of the coastal systems will be accentuated (Komar, 1983).

The term *vulnerability* assumes different meanings according to its use in the most distinct scientific fields. In Geography, the Geosciences, and the Environmental Sciences, Tagliani´s (2003) understanding of the term can be adopted, by which environmental vulnerability means the greater or lesser susceptibility of an environment to the potential impact provoked by any kind of anthropogenic use. The term *susceptibility* alludes to the tendency (denoting passivity) to undergo impressions, changes, or deformations or to acquire different qualities from those already possessed. Corroborating this, the "United Nations International Strategy for Disaster Reduction" - UNISDR - (2009) defines vulnerability, considering the characteristics and the circumstances of a community, system, or good that makes it susceptible to the negative effects of the hazard in question.

Cutter (2011) explains that vulnerability is the potential for loss. Santos and Caldeyro (2007), on the other hand, express a more geographical definition by taking into consideration that vulnerability corresponds to an intrinsic condition belonging to each fraction of the land, which in interaction with the type and magnitude of the event we induce, results in an amount of adverse effects.

In this article, the physical as well as the human and geographical factors were considered, encompassing *vulnerability to coastal erosion* as a term that highlights the importance of the existing conflict between the sea and the settlements established along the shoreline. In this way, it is not a formulation that considers exclusively aspects of a natural order. On the contrary, human actions are included, taking into consideration the nature and arrangement of settlements.

To carry out the analysis, geoindicators were employed, which act as an instrument for the assessment of the state of ecosystems exposed to human activity. Geoindicators are, according to Berger & Iams (1996), measurements (magnitudes, frequencies, rates, and tendencies) of geological processes and phenomena that occur in or near to the earth´s surface and are subject to changes and which are significant for the understanding of environmental alterations over a period of a hundred years or less.

The choice of using geoindicators to evaluate coastal erosion was especially due to the possibility of obtaining quick answers for the assessment of coastal risks (Bush *et al.*, 1999). Geoindicators are qualitative instruments with scientific validity for the rapid identification of potential risk which also allow the quick generation of mitigation and management plans. The same authors explain that geoindicators are viable, low-cost alternatives, because they do not require the use of high technologies for historical analysis techniques and for environmental monitoring, which are often expensive and, when applied to the mapping of hazards and risk evaluation, normally occur on a regional scale, depending on incomplete global databases (Bush *et al.*, 1999).

Given that scenario, this article produces information on Pititinga beach, observing characteristics of the physical environment and of the engineering structures with the aim of mapping, evaluating, and characterizing the degree of vulnerability to coastal erosion using geoindicators. For this, in the study, we (a) considered data and information of the hydrodynamics of this shoreline; (b) studied the parameters related to the geology, geomorphology, and vegetation; (c) observed the impacts on the engineering structures (constructions like houses, access points, and structures for containing the erosion process; and (d) mapped and zoned the areas vulnerable to erosion on the coast with the aid of geoindicators.

2. Material and methods

2.1. Location of the studied area

The study area is located on the east coast of the state of Rio Grande do Norte, more precisely in the municipality of Rio do Fogo – between the Ponta do Coconho, on the border of the municipality of Maxaranguape, to the south, and the lower course of the River Punaú to the north. It corresponds with Pititinga beach and the emerged adjacent coastal zone, in the east, bordering the BR-101 highway. It is around 50 km to the north of the city of Natal, the state´s capital, located at the UTM coordinates 234231.383 and 243588.683 mE and 9409181.617 and 9400886.067 mN (*Datum* WGS84) in the 25 M zone (Figure 1).

2.2. Geological and oceanographic characterization

For Nogueira (2008), the Cenozoic units that make up the Potiguar Basin are represented by the Barreiras Formation, Supra-Barreiras Rocks, Beachrocks, Deposits of Fixed and Mobile Dunes, Recent Beach Deposits, and Alluvial Deposits.

Nunes (1987), on considering lithological units of the eastern coast of Rio Grande do Norte situated to the north of Natal, subdivides the Cenozoic sediments into two groups: the Barreiras Group and the Recent Sediments, which encompass the Sub-Recent Beach Deposits, Recent Beach Deposits, Dune Deposits, and Alluvial Deposits. In this same study area, in geological mapping, Barreto *et al*. (2004) identify marine terrace deposits, active dunes (barchan, barcanoid crest, and parabolic), inactive dunes with clear morphology, inactive dunes with tenuous morphology, sand sheets, alluvial deposits, and pre-quaternary geology. More specifically on the Pititinga coast, Lima (2010) identifies the following geological units: sand sheets, alluvial deposits, lacustrine deposits, beach sediment deposits, aeolian deposits of fixed dunes, and aeolian deposits of mobile dunes.

On the east coast of the state in question, data on waves originating from long-duration direct measurements are not known. However, it is possible to find wave, current, and tide data in isolated studies that have been carried out on this coast. Thus, Souza (2004) explains that there are waves 0.2 to 1.5m high in the breaker zone and coastal currents of around 0.1 to 0.8 m/s, predominantly in the south–north direction.

In relation to the tides, records of tides on the coast of Natal show a maximum level varying from 2.85 to 2.95 m, an average level of 1.4m, and a registered minimum level between –0.05 and –0.25m. This characterizes the local tide as a meso-tide type with semi-diurnal regime and periodicity of around 12 h 42 min (Cunha, 2004).

2.3. Methodological aspects

This study is grounded in the interpretation of remote sensing data products, field visits to diagnose the beach situation according to the geoindicators, and the elaboration of a coastal erosion vulnerability map.

The materials used in the laboratory as well as in the field were: 1) digitalized orthophotos, rectified and georeferenced (resolution of 2 m), of PRODETUR produced in 2006; 2) planialtimetric charts of PRODETUR/NE (2006) with contour lines at an equidistance of 5 m; 3) ArcGIS 9.3 software; 4) Microsoft Office 2007 Excel spreadsheet; 5) Bush *et al.*´s (1999), Coburn´s (2001), and Rudorff´s (2005) geoindicator coastal erosion check-list; 6) a digital camera; and 7) mapping GPS and topographical equipment.

2.3.1. Production of the coastal erosion geoindicators map

For the evaluation of the vulnerability of Pititinga beach to coastal erosion, the method proposed by Rudorff

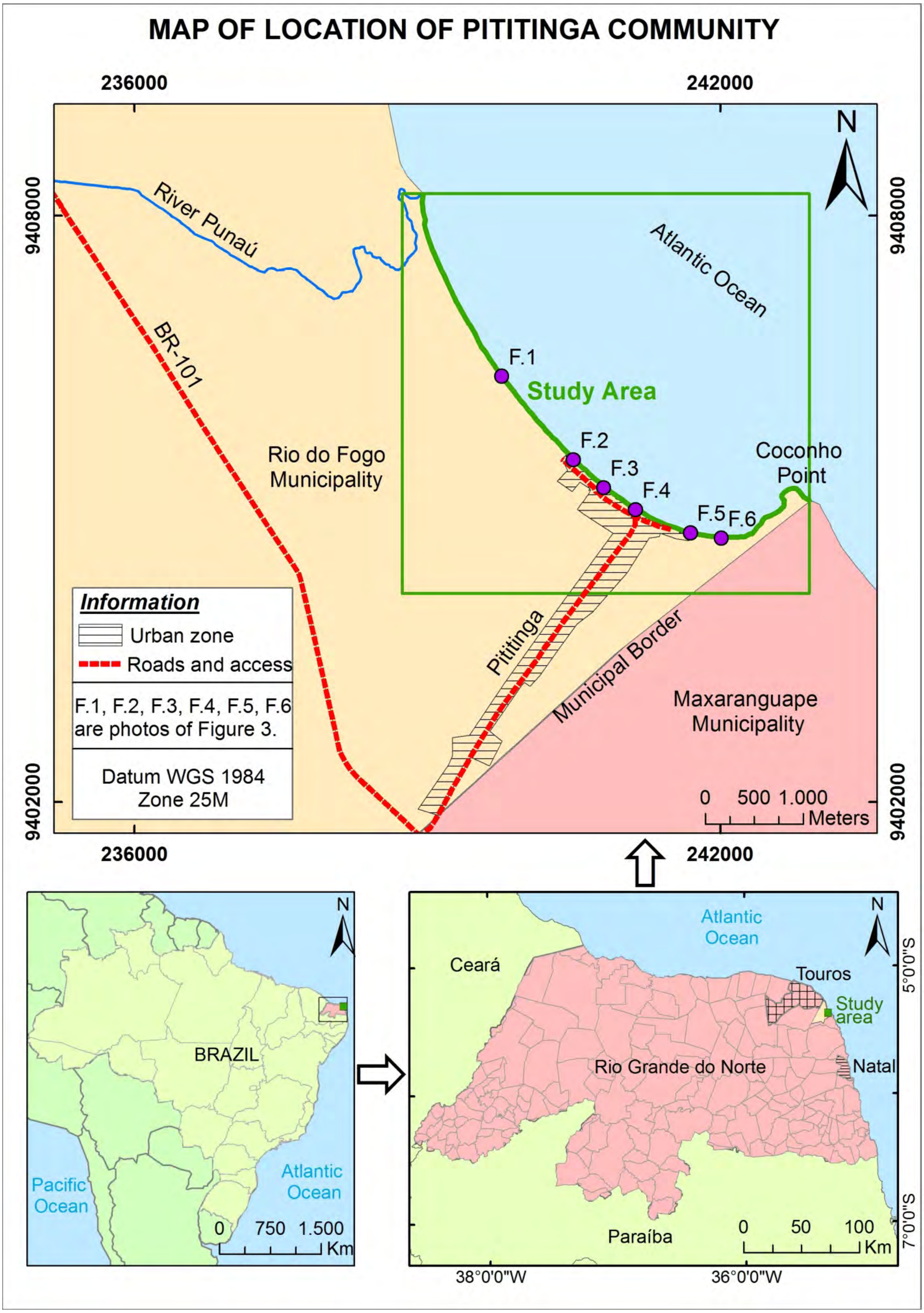

Figure 1 – Map of the study area. Points F.1, F.2, F.3, F.4, F.5, and F.6 refer to the photographs at Supporting Information.

Figura 1 – Mapa de localização da área de estudo. Os pontos F.1, F.2, F.3, F.4, F.5, e F.6, referem-se às fotografias incluídas na "Supporting Information".

(2005) was applied, using geoindicators for its evaluation. In that work, an index was elaborated by means of Multicriteria Evaluation, which is based on two types of indicators: geoindicators obtained by field checking and the fuzzy Digital Elevation Model (DEM).

The geoindicators were selected based on the works of Bush *et al.* (1999), Coburn (2001) and Rudorff (2005) and adapted for the geo-environmental framework of Pititinga beach. The geoindicators take into consideration two coastal environments along the beach profile: the shoreline and the transgressive dunes. In the first environment the following geoindicators were observed: 1) erosion rate; 2) height, type, and condition of the foredune; 3) wave energy; 4) foredune or backshore vegetation; 5) average width of the dry beach; and 6) engineering structures. In the case of the transgressive dunes, their condition (absence, scarp, or fragmented, high and well developed) was observed.

The matrix of the geoindicators contains the categories and weights of each category; the geoindicator and respective weights; normalized scoring; the attributes of each geoindicator; and the weights of each attribute and scoring. The weights of the categories and of the geoindicators were determined based on the weights attributed by Coburn (2001), although adapted to the characteristics of Pititinga beach (See Supporting Information SI.I and SI.II).

The normalized scoring is the result of the multiplication of the geoindicator´s weight by the weight of its category. The scoring was a result of the product of the normalized scoring and the weight of the attribute, and the total score was given by the sum of the scores of the geoindicators. The sum of the maximum scores of each geoindicator corresponds to a maximum score of 10.0.

Rudorff (2005) divided the indexes of susceptibility into five classes: very high susceptibility ($8 < \text{weight} \leq 10$), high susceptibility ($6 < \text{weight} \leq 8$), moderate susceptibility ($4 < \text{weight} \leq 6$), low susceptibility ($2 < \text{weight} \leq 4$), and very low susceptibility ($\text{weight} \leq 2$).

Two field trips were conducted to diagnose the coast according to geoindicators. The first was on 15 November 2009 and the second, for new observations and rectifications, was on 18 April 2010. A GPS with positional accuracy estimated at around 7m was used for mapping, along with topographical equipment, a fieldwork check-list, and a map with the collection points previously defined along the studied beach at 150 m intervals. This was the fixed distance that best represented each modification of the beach environment, taking as reference the foredunes, residences, and transgressive coastal dunes.

The values of the geoindicators observed were inserted into a Microsoft Office 2007 Excel spreadsheet to carry out the calculations of the vulnerability indexes. Following that, the geoindicator data were input into the ArcGIS 9.3 software for visualization and spatial correction (transformation of the data from the spreadsheet into shapefiles) with the orthophotos and for the attribution of their respective indexes. The interpolation of the collected points with regular distribution along the beach generated a regular continuous grid with the values of the indexes along the shoreline.

For the interpolation of the geoindicators, the method of Inverse Distance Weighting (IDW) was adopted, which, according to Longley *et al.* (2005), is the interpolation method most commonly used in GIS. The IDW is a deterministic method for local effects in which each point of the surface is estimated only from the interpolation of closer samples; that is, the sampled points of locations next to the node to be estimated receive greater weight than the points sampled from more distant locations (Landim, 2000; Camargo *et al.*, 2004). It is presupposed, then, that the merely local effects prevail, no other statistical hypothesis on spatial variability being made. Thus, a non-sampled point has the value of a "z" attribute as the expression of an average of the points that occur in the surroundings of the non-visited point and weighted according to the distances (Burrough & McDonnell, 1998).

The geoindicators – the average width of the dry beach and wave energy – were measured directly on the beach under study over twelve months (from May 2009 to April 2010) from the construction and analysis of transversal topographical profiles for the beach and the measurement of wave height, according to the methodology presented by Muehe (2005).

The geoindicator "rate of erosion" was determined from a check-list adapted from Bush *et al.* (1999). From this, the states of erosion of the beach were classified into categories from severe erosion to long-term stability (accretion).

2.3.2. Production of the Digital Elevation Model

Topography is understood as an important indicator of vulnerability to coastal erosion, given that a point situated on a high topography will certainly have fewer chances of suffering impact from the sea and will therefore be less vulnerable to hazard. On the other hand, the present relief is the result of a set of surface modelling processes, thereby being a beacon of dynamic interactions which have occurred.

This criterion was integrated into the vulnerability assessment by means of the theory of fuzzy sets, with the use of a fuzzy pertinence function in which the borders and edges between classes are undefined. In this way, fuzzy set theory fits for cases in which the limits of classes are not, or cannot be, well- defined. To generate the DEM, a PRODETUR/NE (2006) planialtimetric chart was used with contour lines at 5 m equidistant intervals. The contours and their elevations were transformed into points, from which they were interpolated by Ordinary Kriging, generating a DEM continuous surface (fuzzy logic).

The kriging method or geostatistics uses spatial dependence between neighbouring samples, which are revealed in the semivariogram, with the aim of estimating values at any position in the field; it generates unbiased estimates with minimum variance, and in this way it consists of an optimum estimator (Carvalho & Assad, 2005). According to Vieira (2000), the kriging is capable of generating better estimates in terms of interpolation, given that it is based on two basic premises: nonbias of the estimator and minimum variance of the estimates. Ordinary kriging is considered to be the best unbiased linear estimator. It is a linear estimator that can estimate an unknown value by linear combination of the weights of the values observed in the neighbouring samples; as well as being unbiased, it allows the global mean of errors, that is, the mean of differences between the estimated values and the observed values, to be null (Barros Filho, 2007).

With the application of fuzzy logic to the DEM, it was possible to obtain the fuzzy DEM. The criterion adopted is that altitudes with values close to 0 m have maximum susceptibilities, close to 10, and the greatest altitudes tend to have minimum susceptibilities, close to 0 (See Supporting Information SI.III).

2.3.3. Production of the coastal erosion vulnerability map for Pititinga

In order to characterize the vulnerability to coastal erosion, two raster planes, crossed by map algebra, were used: (a) the interpolated geoindicators and (b) the fuzzy DEM. For the crossing, each plane received a differentiated weight in accordance with Rudorff (2005): a weight of 0.8 was attributed to the interpolated geoindicators and a weight of 0.2 was attributed to the fuzzy DEM, resulting in the following function:

$$\text{Susceptibility} = (\text{geoindicators} \times 0.8) + (\text{fuzzy\_ DEM} \times 0.2) \quad (3)$$

The attribution of these weights follows the argument of Robin (2002), who, after consulting several specialists, concluded that topography has an order of importance of 0.22 in relation to other geoindicators, resulting in the weight of 0.2.

Susceptibility was classified by dividing it into five classes, as in the previous case for the geoindicators: very high susceptibility ($8 < \text{weight} \leq 10$), high susceptibility ($6 < \text{weight} \leq 8$), moderate susceptibility ($4 < \text{weight} \leq 6$), low susceptibility ($2 < \text{weight} \leq 4$), and very low susceptibility ($\text{weight} < 2$).

The coastal erosion vulnerability map was elaborated on an original scale of 1:25,000. This scale allowed the whole study area to be encompassed.

3. Results and discussion

Other authors have studied coastal erosion vulnerability in nearby and similar coastal regions. Among these authors, Silva *et al.* (2013) and Mallmann and Araújo (2007) can be highlighted. Silva *et al.* (2013) assessed the coastal erosion vulnerability of the coast of Recife and Jaboatão dos Guararapes in Pernambuco. Using remote sensor data, they divided the study area into sectors. Fuzzy Modelling was applied in each sector, considering as input variables the following conditioning factors of vulnerability: backshore morphological conditions, natural attributes, coastal processes, and anthropic processes. From the input variables, some simulations were established and from these, modelling with 114 rules that are part of the fuzzy inference process was used, and an output variable, the thematic classification of vulnerability to erosion as low, moderate, high, and very high, was established.

Mallmann and Araújo (2007) developed a Coastal Vulnerability Index (CVI) that is calculated from the sum of five Partial Vulnerability Indexes (PVI), which are related to coastal morphology, to the presence of natural attributes, to marine influence, to coastal processes, and to anthropic factors (degree of urbanization of the beachfront, type of constructions, sector of the beach where the first strip of constructions is located, presence of coastal protection structures, and rate of demographic growth). The work carried out statistical calculations of the mean, median, mode, standard deviation, and quartile (first, second, and third), from which the coastal segments are classified regarding the degree of vulnerability as low, medium, or high.

Although they are interesting and have consistent parameters, the cited studies were set aside in our study, given our understanding that their methods present statistical analyses that are more complex and costly, which makes them more lengthy. Differently, the method proposed here exhibits simplicity in the collection and analysis of primary data, making it quicker, more practical, and cheaper, without the need for costly equipment, and it is therefore very useful to researchers who study coastal areas with scarce availability of secondary data.

Treating particularly the vulnerability of Pititinga beach to coastal erosion and based on the list of geoindicators obtained from field data, a cartographic product was generated that allows the visualization of zones of greater vulnerability and lower vulnerability to provoked erosion, mainly by the action of the sea.

Added to the interpolation of the geoindicators is another product, the DEM. The algebraic operation of these maps provides the supporting information to classify erosion by degree of vulnerability. The DEM assumes importance because altitude becomes a relevant factor to verify erosion for one simple reason: the higher the topographic compartments (natural) that interact with the beach, the greater will be the difficulty of erosion of the stretch of beach contained in this situation. The inverse also occurs: when the coast is low, without relevant topographic compartments, there is greater possibility of erosion. Therefore, the DEM acts by strengthening or softening the effects of erosion when added to the geoindicators.

Geoindicators supply information on the characteristics of geological, geomorphological, vegetation, and engineering structures, making it possible to obtain a framework of characteristics that reveal the zones that are more or less vulnerable to erosion. Thirty-five points along Pititinga beach were collected at approximately 150 m intervals between each point (Figure 2). It is possible to verify on this map that more to the north (between 21 and 35 points), the vulnerability to predominant erosion is "medium", since it corresponds to an area dominated by foredunes that are relatively continual, from low proportions (generally lower than 2 m) and unoccupied but with ephemeral ground vegetation (of grasses distributed in a more or less regular way along the foredune – in some stretches there is no grass or just withered grass), characteristics that together produce, in this stretch, a picture of vulnerability to intermediate erosion (See Supporting Information photo F.1).

For the area between points 19 and 20, erosion remains intermediate, since even though there are buildings on this stretch, they are few and are protected by foredunes covered by herbaceous vegetation (See Supporting Information photo F.2). Between points 10 and 19 there is a zone of high and very high vulnerability. In this stretch, vulnerability increases due to the lack of a foredune and due to the dense occurrence of habitats with trees (coconut) which are fallen or about to fall, denoting a real zone of more intense erosion that is easily observable on a quick tour of the beach (Supporting Information photo F.3 and F.4). In this portion, there is the most severe and intense erosion of the beach under study, with some habitats on the seafront being extremely deteriorated or destroyed by the sea and the presence of some structures for protection from the sea, which themselves have also become desolate. The habitations, along with the non-existence of a foredune in this location, are the main factors that dictate the change in the degree of the beach´s vulnerability.

In the stretch of beach extending from points 1 to 10, a decrease in vulnerability was noted with a short stretch of medium vulnerability (represented by the colour yellow) and a bigger stretch of low vulnerability (in light green), within which another stretch of very low vulnerability is found (dark green). All of this stretch is marked by the absence of land occupation and by the presence of coastal dunes, with the sea reaching its windward slope. These dunes migrated from Maracajaú beach, a neighbouring beach to the south of Pititinga (considering the easterly direction of the coast of Rio Grande do Norte) (Supporting Information photos F.5 and F.6). However, around point 6 the medium vulnerability (in yellow) arises from the absence of coastal dunes; that is, between points 7 and 10 there are coastal dunes that interact with the sea; they are discontinuous at point 6 but arise again at point 5 and extend until point 1. Between points 3 and 5, the beach is wider, which contributes to the decrease in vulnerability of this stretch.

These differentiated characteristics allowed the zoning of the beach that characterized it in a way that is compatible with what is observable and probably compatible with what can be gauged in research of a more quantitative kind, such as surveys of transversal profiles.

The DEM was obtained from the interpolation of 1,199 points by the ordinary kriging method (Gaussian) (Figure 3). However, interpolations were also conducted using the Natural Neighbour method, for its characteristic of not generating information in areas lacking in data. Some mapped areas do not match the real ground surface, producing fewer subdivisions (classes) than the kriging classification. This method considers the number of points necessary to calculate a local mean and integrates the spatial characteristics of the sample points (size, orientation, and distribution form), permitting the creation of gentler surfaces that generate information in which there are no points or fewer samples (Landim, 2000).

The DEM map contributes to the analysis of erosion vulnerability exclusively as a function of altitude. It should be emphasized that the DEM is not the final map of vulnerability to erosion, but it is a parameter that allows its analysis. Thus, the lower the altitude, the greater the vulnerability. It is possible to note that the nearer the sea, the greater will be the vulnerability, which decreases as the distance from the sea increases in the direction of the interior of the continent due to the increase in the altitude.

It was noted that the southern sector is the one that presents the highest altitudes close to the shoreline: altitudes are around 15 m. Along the most central beach sector, the shoreline presents low altitudes, close to zero, gently increasing in the direction of the interior and reaching an altitude of around 5 m at a distance between 120 and 150 m. The most northerly sector is marked by foredunes and deflation surfaces with altitudes between 5 and 7.4 m, which vary gently from the coast to the continent, resulting in a greater density of

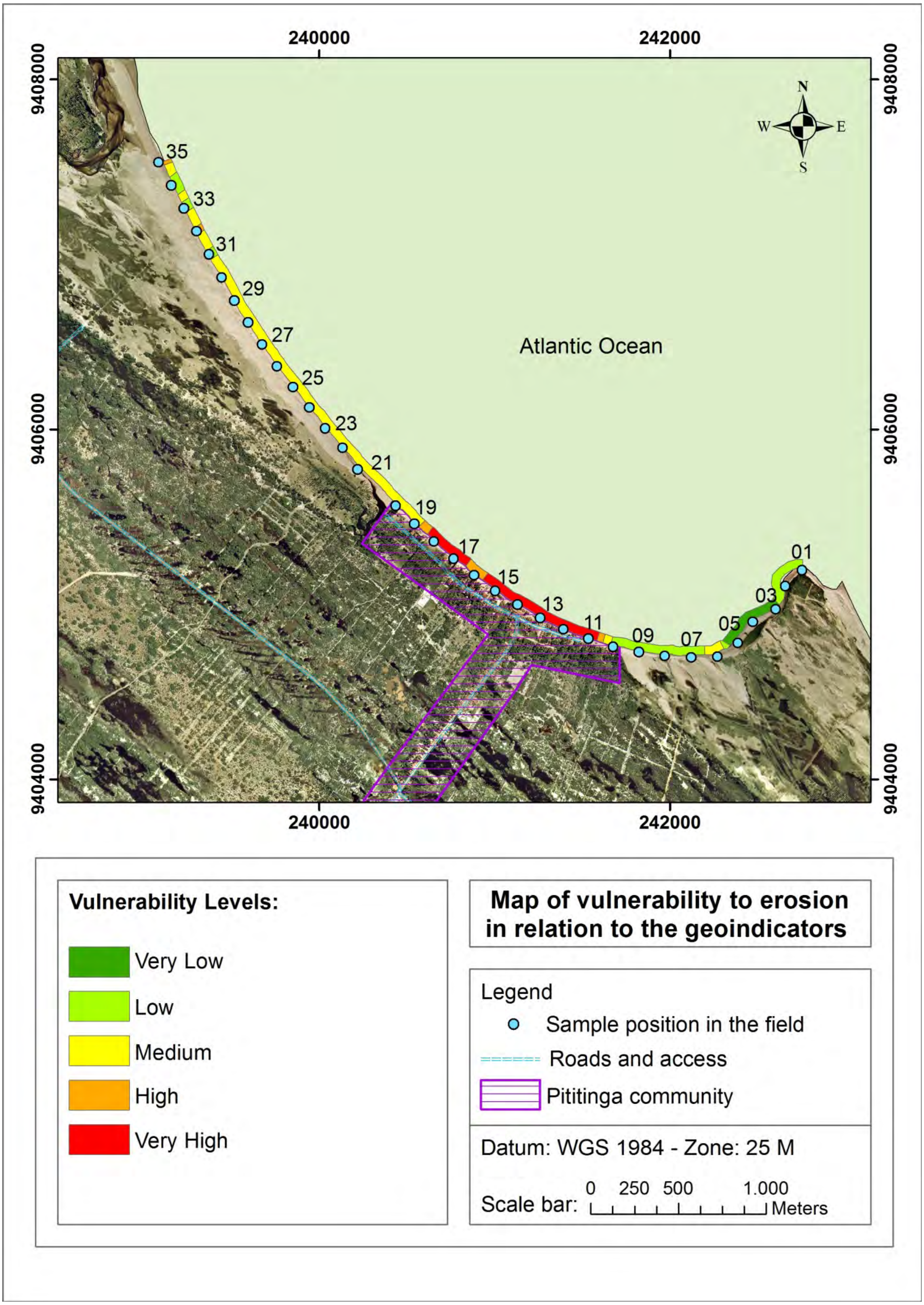

Figure 2 – Erosion geoindicator map of Pititinga beach.

Figura 2 – Mapa dos Geoindicadores de Erosion da praia de Pititinga.

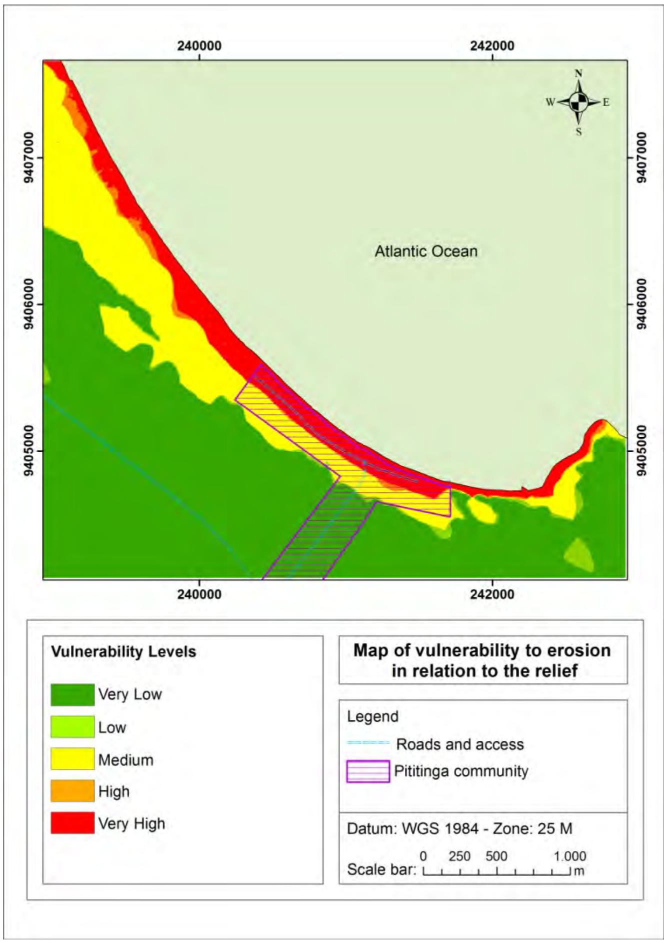

Figure 3 – Digital Elevation Model correlated with the vulnerability associated with the kind of relief.

Figura 3 – Modelo Digital de Elevação correlacionado com a vulnerabilidade associada ao tipo de relevo.

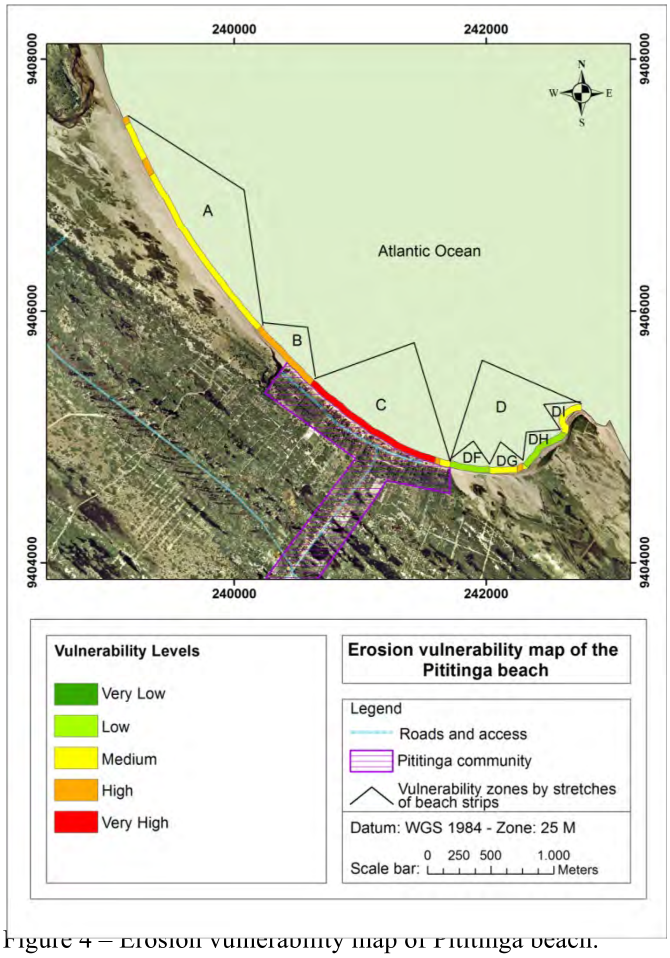

Figure 4 – Erosion vulnerability map of Pititinga beach.

Figura 4 – Mapa de vulnerabilidade à erosão da praia de Pititinga

the colour yellow (intermediate altitudes) in an east–westerly direction. Such foredunes are always reached by the sea in the spring tides.

With the crossing of these two maps it was possible to generate a map of vulnerability to coastal erosion at Pititinga (Figure 4). Because a typically low coast is being referred to, the DEM, as a whole, reinforced the erosive characteristics revealed by the geoindicators, and with this, there was an increase in the general vulnerability of the beach and consequently, the reduction of less susceptible stretches, which can be observed on the map in Figure 4.

In the extreme north portion of Figure 4, in stretch A, there is a strip of beach that alternates between medium and high vulnerability, with predominance of the former. This area has already been exposed and is marked by the presence of foredunes, in the northwest–southeasterly (NW–SE) direction. In relation to the geoindicator map, the portions of low vulnerability ceased to appear, and the areas of medium vulnerability increased their size a little more.

According to Rebêlo & Brito (2004), the foredunes generally occur in the most indented part of the beach on a strip of sand that allows the embedding of vegetation, because it is far from the reach of the sea´s action, even during winter storms, and thus from the cycles of erosion and accretion that modify the beach´s profile. In the case of Pititinga, these dunes are in daily contact with the sea´s action as a function of the high tides, especially the spring tides. Thus, most of them are escarped (Figure 4), which is evidence of the erosion process in these stretches; however, at the same time there is a return to the beach of the sediments that were transported by the wind in the direction of the coast, which permits the formation of such dunes.

Still in the portion corresponding to stretch (A), there is a predominance of other characteristics that are evidence of the erosive process, such as the narrow beach (< 11 m), the presence of grassy vegetation on the foredunes (in a relatively continuous form, dried out at some points and absent on the escarped dune faces), and the lack of engineering structures.

Stretch (B) is marked by high vulnerability, since on this stretch the foredunes are smaller and exert less protection against corrosive action, as well as being further from the shoreline, which makes the topography (represented on the DEM) cause an increase in vulnerability in relation to the geoindicator map in this stretch. Near the transition stretch between strips (A), (B), and (C), there are some houses protected by foredunes smaller than 2m high (Supporting Information photo F.2).

In the most central portion of the studied area (Figure 4), in stretch (C), vulnerability is very high. The stretch of very high vulnerability (shown in the colour red) is that in which the sea acts directly on the habitations (constructions), being the most vulnerable area of the whole span under analysis. In this stretch, the beach exhibits severe erosion, there are no foredunes, vegetation is absent or fallen (coconut trees), the medium width of the dry beach is less than 11m or zero, there are holiday homes and local residents´ homes, some of which are very deteriorated and abandoned, and there are engineering structures aimed at containing the erosive action of the sea (Supporting Information photo F.4). At the end of stretch C, the colour gradually changes until it meets stretch (D).

In the southeast portion of Figure 4, in stretch (D) the domiciles cease and there is a zone marked by the presence of transgressive dunes, which originate in Maracajaú beach (more to the south) and have migrated through the continent (over the point of Coconho) through the influence of trade winds from the SE, reaching Pititinga beach in such a way that its leeward slope interacts with the sea (Figure 5). There is, in this stretch, a beach–dune interaction that is a little different from that which occurs with the foredunes in the stretch discussed above.

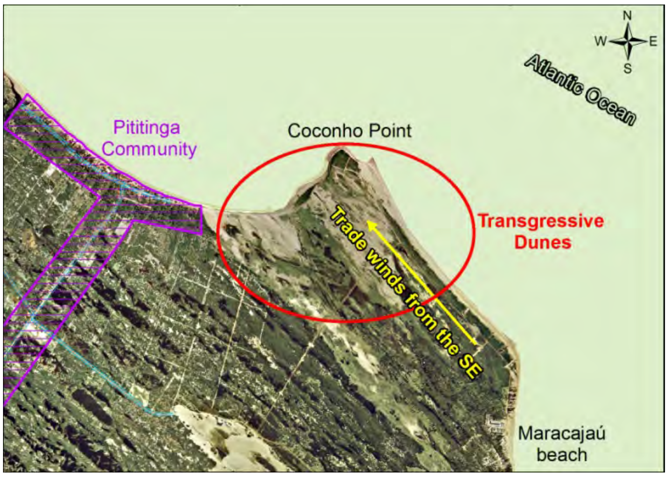

Figure 5 – Illustration of the advance of transgressive dunes towards Pititinga beach.

Figura 5 – Ilustração do avanço das dunas transgressivas em direção à praia de Pititinga.

Here the dunes are transgressive (Supporting Information photos F.5 and F.6), and currently there are restrictions regarding their sustenance by sediments originating from Maxaranguape beach (currently, sediment track located windward is substantially covered with vegetation which hinders the transport of sediments). However, this dune field is still influenced by SE winds and consequently carries sediments to the sea; furthermore, these dunes are affected by the waves, which can cause more or less evident escarpments due to the dune dynamics and the oscillation of the tides.

In this way, they protect the beach and the continent from the erosive action of the waves and supply sediments to the beach, as do the foredunes. For this reason, in this study, they were studied from the same perspective as the foredunes, and so despite their distinct geneses, they play a similar role to geoindicators or coastal erosion. In the whole portion of the stretch (D), there are neither engineering structures nor housing.

According to the theory of the bays in zeta formation, the stretch D is the sector that suffers the greatest amount of erosion. In a zeta-form bay just after the Coconho Point, a vortex occurs which is caused by the interaction of the displacement of the longitudinal current (in this case, in a south–north direction) with a promontory or a tip. This vortex tends to generate greater erosion in this portion of the bay than in the portion further north, which is straighter (or less curved).

However, in stretch D, transgressive dunes occur that mitigate the erosive process through the exchange of sediments with the beach (by wind transport, which throws sediments into the sea, and removes sediments from the dune during contact of the sea with the dune in the high tide of syzygy), as well as by the imposition of the feature (a screen that protects the advance of the sea on the continent) (Figures 4 and 5).

Still regarding the effects of the vortex just downstream from Coconho Point (considering the direction of the longitudinal current), the portion of Pititinga beach occupied by anthropic structures suffers from erosion (Figure 5 – stretch C). The lack of a local screen – natural or anthropic – leaves the community more exposed to the coastal dynamics.

The strip of beach codified as DF is marked by the presence of the abovementioned dunes with the windward slope well developed. The stretch DG exhibits these less developed dunes and is situated between two deflation zones, which added with the effect of the DEM created a medium and high vulnerability zone. In the DH stretch, the dunes have vegetation and are lower (although they are still high); however there is an increase in the average width of the dry beach (greater than 18 m; this is the portion where this characteristic assumes greater width in the whole span of the study) and the beginning of the protection by beachrocks (which are not visible in the image used for this work, because they are covered by the seawaters). In the DI stretch, the dunes continue to have vegetation and are relatively lower, while the beachrocks are more developed the closer they get to Coconho Point and stand out because they reduce the energy of the waves that reach the present beach (Figure 5).

4. Conclusions

It is in the community of Pititinga that there exists the greatest concern regarding erosive processes. This is a reality that has existed for quite a while there, worrying the inhabitants and holidaymakers who have homes on the seafront.

In the studied area, medium and high vulnerability predominates. This is verified especially by the escarpment of the foredunes and by the destruction of buildings and engineering structures in the urban part of Pititinga on the coast.

Among the main consequences of erosion on Pititinga beach are: a) the reduction of the beach´s width; b) the disappearance or reduction of the backshore; c) the elevation in the frequency and magnitude of coastal inundations, caused by undertow (meteorological tides) or by very high spring tides; d) the loss of properties and goods along the shoreline; e) the destruction of artificial structures parallel and transversal to the shoreline; f) the loss in value of the coastal landscape, which consequently has a negative effect on the potential for tourism in the community and region.

In this context, it will be interesting to consider the preservation of the foredunes and the transgressive ones (in contact with the beach) as a feature or element of the reduction of vulnerability to coastal erosion on the beach in question. The foredunes protect the coastal zone, preventing the waves from reaching land beyond the backshore and avoiding the retrogradation of the shoreline.

The portion of the coast that has habitations should be reconstructed in such a way that measures and structures are adopted to avoid or minimize future problems arising from local coastal erosion. However, any solution in this sense, be it with the use of artificial structures or with the replacement of the beach, should be carefully studied so that the problem does not worsen with the adoption of inadequate measures.

Such recuperation should consider the conservation of the natural landscape of the beach so that it is possible to take advantage of its touristic potential. Tourism endeavours should be conducted by and for the community since in this way local customs and habits will be preserved.

The adoption of larger recesses in relation to the shoreline is a measure to be considered in urban planning.

This beach requires more studies on erosion, mainly regarding temporal analysis, taking into consideration that the testimonials of inhabitants of this region reveal that the sea has risen and has already been causing erosion and destruction for more than a decade.

The method employed also allowed a reasonable zoning of the beach regarding its vulnerability to erosion. However, there remains the need to define new parameters to refine the analysis by geoindicators. In the case of the Rio do Fogo coast and adjacent municipalities, it is noted that several beaches exhibit their destructive power attributed not only to the force of the waves but mainly to the wave and sea interaction. It is important to emphasize that Pititinga beach has a meso-tidal regime and it is noticed that during periods of full and new moons, the wave energy varies significantly between low and high tide. One way of considering the tide would be to attribute distinct weights to micro-tidal (lower weight), meso-tidal (intermediate weight), and macro-tidal (greatest weight) beaches.

It would also be interesting to consider data related to cliffs on the list of geoindicators. A comparison between studies previously conducted in the study area and the present study is unviable, since scientific studies have not been carried out previously at this beach with the aim of quantifying and assessing erosion. However, some studies conducted in nearby areas present similar results and can be integrated in an effort to unify methods.

Appendix

Supporting Information associated with this article is available online at http://www.aprh.pt/rgci/pdf/rgci-502:Lima_Supporting-Information.pdf

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Water quality along the Alagoas State Coast, Northeast Brazil: advocacy for the coastal management

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Abstract

Poorly planned urban development and the associated lack of sanitation infrastructure are the main causes of ecosystem alteration and contamination of Alagoas coastal zone. As these ecosystems are significantly linked with human use, such as recreation and tourism, the impacts on human health cannot be obviated. The present study evaluates the water quality of the Alagoas coastal zone analyzing five years of monitoring data obtained from the state Environment Office. Results suggest a worsening of the water quality between the years 2007-2011. Low levels of sanitation, especially sewage collection and treatment, the lack of an effective land planning, environmental development of agribusiness activities and low perceptions of sustainability appear to be the main factors impacting the water quality of the Alagoas state coast. On the other hand, investment in sanitation has boosted investor confidence and driven development, to the extent that sanitation infrastructure capacities have been exceeded and raises potential water quality issues.

Keywords: Sanitation infrastructure, domestic sewage, tourism impact, land planning, pollution.

Resumo

A qualidade da água ao longo do Estado Alagoas Coast, Nordeste do Brasil: a defesa da gestão costeira

A contaminação da zona costeira resultante do desenvolvimento urbano mal planejado é uma das principais causas da alteração dos ecossistemas, com efeitos sobre a saúde humana. O presente estudo estabelece um diagnóstico da zona costeira de alagoas, avaliando cinco anos de dados de monitoramento obtidos da secretaria de meio ambiente local. Os resultados sugerem a piora ao longo dos anos (2007-2011). Baixos níveis de saneamento, especialmente coleta e tratamento de esgoto, a falta de um planejamento urbano efetivo, o desenvolvimento das atividades do setor agrícola parecem ser os principais fatores impactantes da qualidade das águas da costa do estado de Alagoas. Por outro lado, em Barra de São Miguel, os investimentos em saneamento melhoraram as condições ambientais, incrementando ainda mais o turismo e a expansão urbana,o que sobrecarrega a própria infraestrutura sanitária existente.

Keywords: Infra-estrutura de saneamento, esgotos domésticos, impacto do turismo, ordenamento de território, poluição

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1. Introduction

Coastal environments contain some of the marine world's most important ecosystems and represent significant resources for human industry and recreation. The biological richness of coastal ecosystems is widely recognized, and makes them attractive areas for the establishment and development of human communities worldwide: Approximately 60% of whom are found in coastal areas (Constanza *et al.,* 1997). Currently, 24.6% of Brazil's population lives in coastal counties, accounting for 4.1% of the total area of the country (IBGE, 2011a).

This impact of population concentration and the development of various economic activities on coastal ecosystems are remarkable due to the poor environmental and territorial planning and the lack of infrastructure, especially sanitation. In addition to its resident population, its tropical climate and beautiful landscapes makes Brazil's coast attractive for tourism. According to the Ministry of Tourism, in 2012, Brazil received 5.67 million international tourists arrivals, - mostly from South America (2.63 million), Europe (1.62 million) and U.S. (0.59 million) (MT, 2013). However, domestic tourism is significant in Brazil, and has been driven by rising real incomes and a growing middle class. In 2012, domestic landings totaled 85.47 million, as opposed to 43.1 million in 2005 (MT, 2013), suggesting a phenomenal growth in the industry. This situation has generated great pressure on coastal ecosystems resulting in a decrease in water quality and biodiversity, loss of critical habitats, and an overall decrease in the health and quality of life of local inhabitants (MMA, 2005). The impact of population concentration, a growing tourism sector and the development of various economic activities on Brazil's coastal ecosystems are occurring within a milieu of poor environmental and territorial planning for infrastructure, especially sanitation.

Water quality is a major environmental health indicator, reflecting the interference of human activities both in the coastal zone and in the adjacent catchments. Expressed as bathing (in the present study), it refers to the quality of water for the purpose of primary contact recreation, i.e. direct and prolonged contact with water, with high probability of ingestion, as in activities of swimming, diving and some other water sports (MMA, 2005).

The bathing measures adopt microorganisms commonly present in stool, as an indicator of the level of contamination by sewage. The presence of pathogenic organisms is not assessed directly due to the large number and variety of these individuals (Noble *et al.,* 2003), associated with varying densities, sources and levels of risk that they present, which technically and financially impracticable for a systematic environmental monitoring. However, the improper bathing condition class indicates a high likelihood of pathogens, and therefore risks to public health. Brazilian law establishes standards for bathing for three groups of organisms: fecal coliforms, Escherichia coli and Enterococci (MMA, 2001).

Thus, this paper analyzes the beach bathing conditions in the state of Alagoas, northeastern Brazil, between 2007 and 2011, using an annual rate of bathing from the standards set by law (MMA, 2004).

2. Studied area

The study was carried out on the coast of Alagoas, which stretches for about 230 km (8º 55′ S – 36º 10′ W and 10º 30′ S – 36º 23′ W respectively) (Figure 1), and is composed mainly of coral and sandstone reefs, lagoons, rivers and mangrove ecosystems. Alagoas is one of the nine states of northeastern Brazil. It is subdivided into 102 municipalities and had a total population of 3,120,494 in 2010, 73.6% of which living in urban areas (IBGE, 2011b; IBGE,2011c). Maceió is the capital, with 933,000 inhabitants (30% of total State population), and is home to 40.6% of its urban population.

According to Brazilian law, the coastal zone is divided into two tracks: the sea, which corresponds to the territorial sea (12 nautical miles from the baseline of the coast), and the land, which is the band formed by areas of the continent suffering direct influence of coastal phenomena (MMA, 2004). In Alagoas, 23 municipalities met one of eight legal criteria that classify them as members of the land strip (IBGE, 2011a).

The main factors of potential negative impact on the quality of coastal waters of Alagoas are: cattle and cultivation of sugar-cane associated with deforestation, and lack of territorial-environmental planning and environmental sanitation infrastructure associated with the tourism (IBGE, 2011a).

The sugar cane production area is concentrated in the municipalities near the coast, having corresponding, in 2011, 29.9 million tons in a planted area of 435,000 hectares (IBGE, 2011a). The supply chain is related to the 25 sugar cane mills currently installed in the area (UDOP, 2012). This cultivation is mainly responsible for the strong deforestation in the Atlantic Forest region (Verdade *et al.,* 2012). With regard to environmental sanitation, only 26.6% of the population of coastal counties have sewage collection network for general or rain, while 65.8% use septic tanks (16.6% and 49.2% rudimentary septic) (IBGE, 2011b). Even in areas of collection, most of the sewage does not undergo treatment.

3. Material and methods

The main effect of the impacts on the water quality caused by the increasing human settlements near the coastal areas is the presence of pathogenic microorgan-

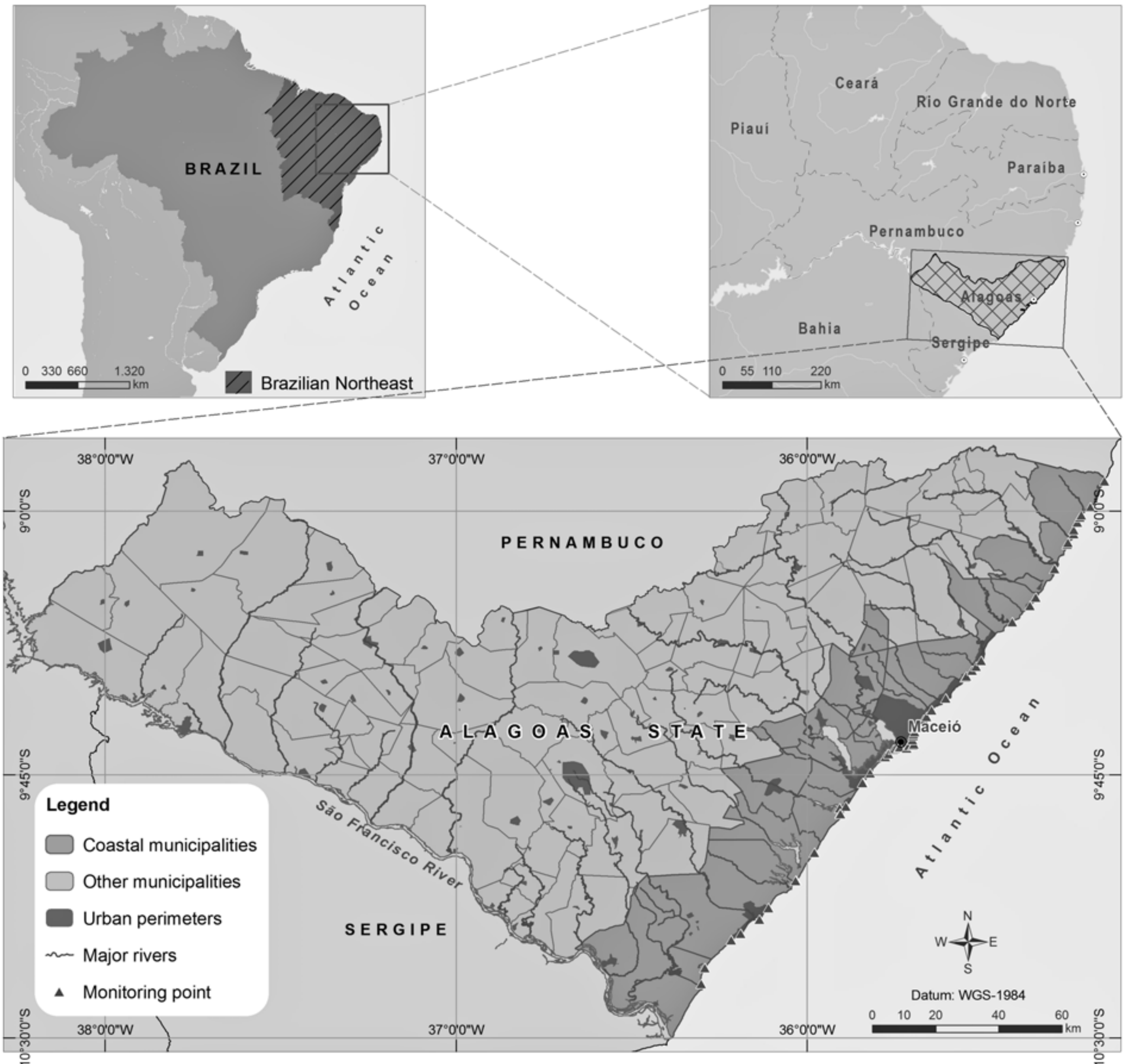

Figure 1- Study Área

Figura 1- Área de estudo

isms (Ramaiah, 2002) in coastal waters. Presence of fecal coliform bacteria, especially E. coli (Guan *et al.,* 2002), has shown strong correlation to swimming associated illnesses (Uzoigwe *et al.,* 2007). As fecal contamination and higher incidence of pathogens are reported in literature (Fujioka, 2002; Wilkes *et al.,* 2009), it is essential for collating the abundance of certain known human pathogenic bacteria along with the enumeration of coliforms. Based on this information, the coastal water quality in the Alagoas State was evaluated using thermotolerant coliform (fecal) as indicator, in 53 stations (Figure 2) monitored weekly by the Environmental Institute of the State of Alagoas. The data for the analysis captured a period of five years (February 2007 to December 2011).

The methodology of sampling and analysis was based on the 20th Edition of Standard Methods for the Examination of Water and Wastewater (APHA-AWWA-WPCF, 1999).

In the present study, a total of 250 reports were analyzed with more than 11,000 tested samples (IMA/AL, 2012). The results were digitized and integrated into a database and geographical information systems. Each sample was rated weekly for bathing according to the limits established by the Brazilian legislation, which is based on the last five consecutive weeks sampled (MMA, 2005) (Table 1). Based on this classification, the annual rate of bathing for each monitoring station using the index developed by CETESB (2012) (Table 2) were calculated.

Systematic monitoring of water quality data allows for the identification of trends that can be used in the coastal planning and management, as well as to improve monitoring effectiveness in the environmental change. In this study, seasonal effect was evaluated by both, the evolution of the annual rate of bathing (IAB) and the statistical test of Mann-Kendall. In the latter case, two annual average concentrations of fecal coli-

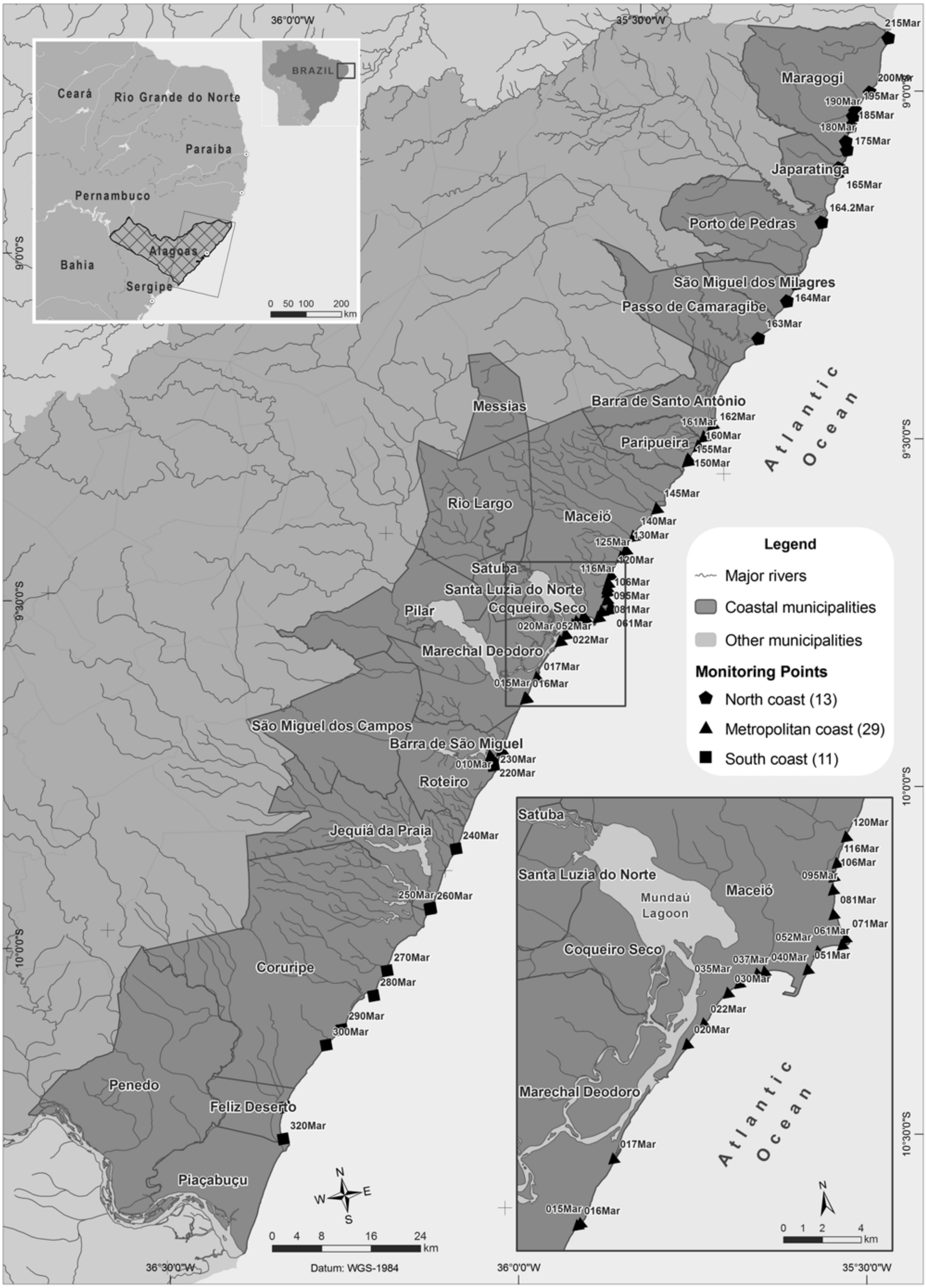

Figure 2- Sampling Stations.

Figura 2- Estações de Coleta.

Table 1 – Criteria for bathing classification according to Brazilian legislation.

Tabela 1 - Critérios para classificação da balneabilidade de acordo com a legislação brasileira.

CATEGORY		Fecal Coliforms (NMP/100 mL)
SUITABLE	Excellent	≤ 250 in at least 80% of the time or more
	Very good	≤ 500 in 80% of the time or more
	Satisfactory	≤ 1.000 in 80% of the time or more
UNSUITABLE		> 1.000 in 20% of the time or more
		> 2.500 measurement

Accordingly to MMA (2004).

Table 2 – Criteria for calculating the annual index of bathing (IAB)

Tabela 2 – Critério para o cálculo do índice anual de balneabilidade

CLASS (BI)	Bathing index
EXCELLENT	Beaches classified as EXCELLENT in 100% of the time
GOOD	Beaches classified as PROPER 100% of the time, except when EXCELLENT
REGULAR	Beaches classified as UNSUITABLE 25% of the time
BAD	Beaches classified as UNSUITABLE between 25% and 50% of the time
VERY BAD	Beaches classified as UNSUITABLE between 50% and 75% of the time
CRITICAL	Beaches classified as UNSUITABLE in over 75% of the time

Modified from CETESB(2012).

forms at each station were seasonally tested, subdivided in the rainy (March to September) and dry season (January-February and October-December) using Water Quality Analyzer 2.1.2.4. (Water Quality Analyser, 2011)

It is important to highlight, for the presentation and discussion of the results, that the Alagoas coastline were subdivided into three compartments (IMA/AL, 2012): north coast, metropolitan coast (or central) and south coast. This subdivision was proposed by Muehe (2006) based on geological and geomorphological macro context and limitations of the major watersheds.

4. Results and discussion

The results suggest high levels of improper bathing on the beaches of Alagoas, especially in the northern and metropolitan compartments. Over the five years analyzed (2007-2011), 37.9% of the samples of the north coast and 33.7% of the samples from metropolitan coast, showed the classification of bathing over the legal limit allowed for primary contact recreation (Figure 3). In annual change, there is relative stability of average rates of improper between 2007 and 2010, and an increase in the last year - 2011.

The north coast showed an average annual improper between 33.1% and 46.6% of the weekly analyzed samples, in the 13 stations. The metropolitan coast showed averages of improper between 29.1% and 38.4% in its 29 stations, while the southern coast showed the best aggregate result, averaging between 0.5% and 7.7% of improper in 11 monitored stations. The lowest levels of improper occurred in 2010, in the middle compartments, which coincide with the year of less rain (precipitation less than 10-20% compared with the period of 2007-2011) (Figure 4).

In the capital, Maceió, with extensive coastlines and higher density of monitored station (19) (Figure 2), the annual average of improper class ranged from 38.0% (2009) and 51.5% (2011), and the average of the period 2007 to 2011, 44.6% of the stations. Several surveys have studied (Neto *et al,* 2002; Santos Filho *et al.,* 2007) the watersheds that supply the city and flow to its coastline and therefore likely to have a direct relationship with the quality of the coastal waters of the region. According to Santos Filho *et al.* (2007) Riacho do Silva catchment, for example, is fully inserted in the urban city of Maceió, is a system rich in water resources, native flora and fauna. Some authors carried out in the catchment show the environmental degradation resulting from the human activity (Santos Filho *et al.,* 2007). On the other hand, Silva Júnior (2009) pointed out to the disorderly occupation of watersheds such as catchment Riacho Reginaldo also in Maceió, as a cause of increased soil impermeability, which increased runoff dynamics, hence up the contribution of contaminants in the coastal zone. Some authors describe the Maceio region as a major industrial concentration where companies do not treat their effluents which goes directly to sinks similar to systems used in sewage lagoons region or to the accumulation of rainwater (Neto *et al.,* 2002).

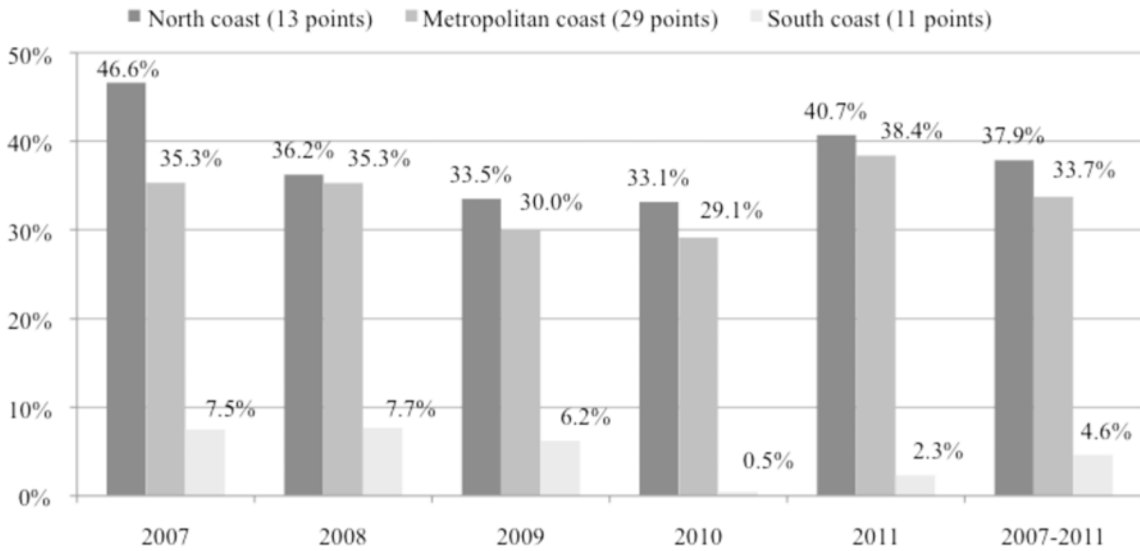

Figure 3 - Annual average (2007-2011) of improper bathing (%) per compartment.

Figura 3 - Média Anual (2007-2011) de balneabilidade imprópria (%) por compartimento.

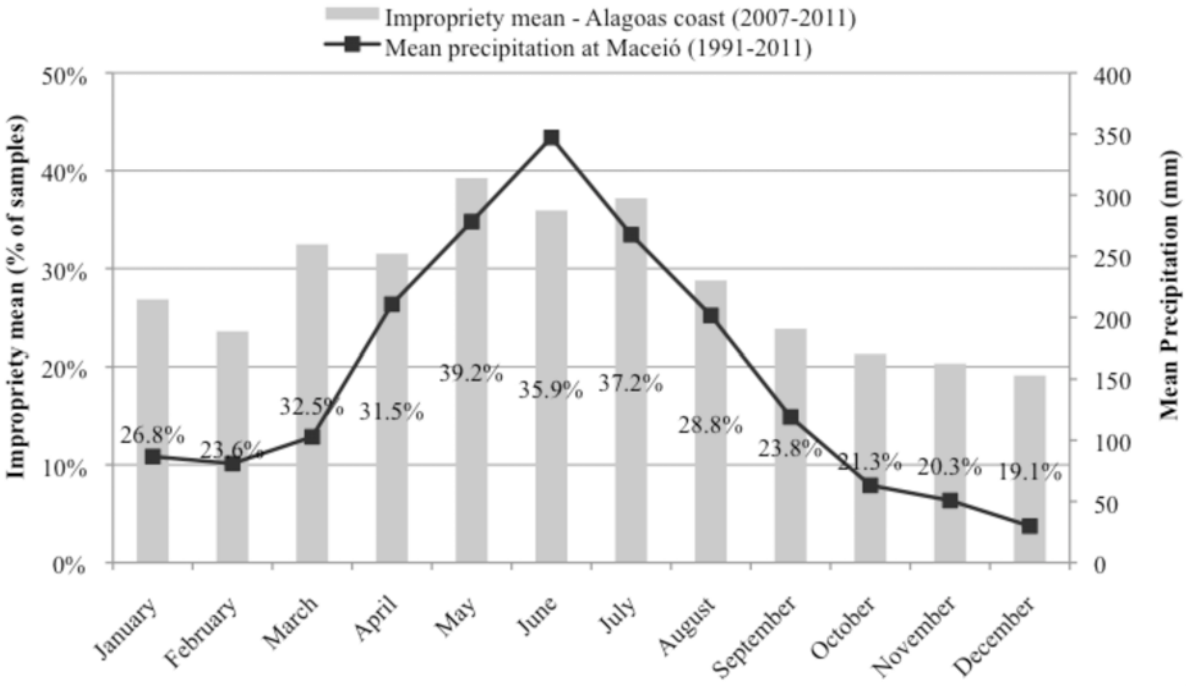

Figure 4 - Mean impropriety in the Alagoa´s littoral and mean precipitation in the Maceió.

Figura 4 – Média na balneabilidade imprópria no litoral de Alagoas e média da precipitação em Maceió.

The annual ranking of each monitoring stations in the state of Alagoas is presented in Supporting Infomation, as well as the outcome of the seasonal differences.

The north coast, between the stations of Japaratinga Beach (165Mar) and Maragogi Beach (215Mar) the situation is especially worrying due to the high incidence of impropriety, ranging from regular and bad/critical, being critical or poor in five years in three stations (Figure 2). In south-central coast of Maceió, in the 14 stations between the Pontal da Barra (020Mar) and Jacarecica Beach (Sea 120) the situation is even more serious, with many bad stations, bad or critical and five stations always bad or critical in the period of 2007 to 2011 (>50% of improper, reaching 100% of impropriety (Figure 2 and Supporting Information). Melo-Magalhães *et al.* (2009) studied the phyto-plankton communities of Mundaú Mangaba coastal lagoons, responsible for the continental runoff to the nearest stations of the Pontal da Barra. The results obtained in Mundaú and Manguaba lagoons characterized the two lagoons as strongly impacted environments. The area is also known for frequently cyanobacterial blooms resulting from the domestic input originated in the vicinity of the lagoons (Porfirio *et al.*, 1999; Oliveira & Kjerve, 1993) beyond the supply of tailings from the sugar cane production (Oliveira and Kjerve, 1993).

In general, there is relative stability in the classification of the stations between 2007 and 2011. Small track variations can be considered normal due to the conditions of sample collection. For example, the occurrence of rain in the last 24 hours. However, abrupt changes in the midst of a large set of samples suggest effective situations of improvement or worsening of water quality.

Among the areas with improved Bathing Index (IAB), it is noteworthy the south coast, with generally positive trend, reaching at most stations classes of good or excellent in 2011, which means 100% of the water property in the analyzed weeks. The station on the Coruripe Pontal (280Mar) showed the most significant improvement, starting with poor condition in 2007, becoming regular in 2008 and 2009 and reaching a good class in the last two years analyzed.

Metropolitan coastline, Praia da Barra de São Miguel (010Mar) also improved, going from regular status in three consecutive years (2007-2009) to good in 2010 and 2011, (100% of bathing conditions in the accordance with the Brazilian law – see Figure 2 and Supporting Information). The significant improvement is linked to the progress of sanitation in Barra de São Miguel (7,574 inhabitants) (IMA/AL, 2012), with a focus on remediation of Niquim River, which input into the ocean and was the main destination of sewage and garbage from residents.

The example of Barra de Sao Miguel highlights the benefits of investing in sanitation. The improvement of environmental conditions has driven even more tourism and housing developments in the city (MT, 2013), which also put pressure on the sanitation infrastructure. However, the consolidation of urban laws and parameters of spatial planning through the Master Plan approved in 2008 has provided a framework for the planned occupation (IMA/AL, 2012). The demographic and occupational characteristics, as well as the sources of environmental degradation, are very similar to the Barra de São Miguel in several coastal counties of Alagoas, which points to the actual possibility of improving the quality of water in these regions (IMA/AL, 2012).

In relation to the northern metropolitan coastline, the beaches of Paripueira and Barra de Santo Antônio (155Mar the 162Mar) showed trend of worsening annual ranking, since the beaches did not show 100% of bathing in the last three years. The same occurs with the station 164Mar in São Miguel dos Milagres. It is important to highlight that these stations cited worsened even in years in which the average quality of the compartment was good.

These three municipalities, with significant points of worsening water quality, present demographic and socioeconomic profile similar to Barra de Sao Miguel – with a population ranging between 7,000 and 15,000 inhabitants (IMA/AL, 2012), which reaches three times this size in the high tourism season periods, accompanied by rapid expansion of the occupation (MMA, 2005). However, in these areas there are no necessary investments in the environmental sanitation and urban planning. Barra de Santo Antônio, as an example, experienced a "boom" of sprawl, including the invasion of the land and many areas by low income population derived from more distant counties, resulted by the opening of the bridge that connects the mainland to the island of Crôa, in 2010. It should be noted that none of the three municipalities have municipal master plan approved till the present moment (IMA/AL, 2012).

Trend data through the annual bathing classifying suggests being very effective when rapid changes occur - as in points highlighted above. However, it does not appear to be sensitive, to changes that do not result in change of class (eg the increase of coliforms without leaving regular class, or its decrease without leaving the class bad). On the other hand, areas with better water quality index becomes very susceptible to occasional events (eg, at the stations that has always good bathing, a single isolated event, featuring over 1,000 coliforms NMP/100 mL, makes the beach improper in five consecutive weeks). In this sense, and also seeking to incorporate the seasonality of the phenomenon, the statistical trend (TE) emerges as an excellent analytical complement. In areas with significant changes in TE it showed the same trend based on the annual ranking, as in the case of reductions of coliforms in the south coast and increases between Paripueira and Barra de Santo Antônio (Table 1). In this second case, the TE also revealed worsening of water quality in neighboring stations (116Mar the 150Mar), especially in the dry season. Note that the entire region surrounding the station 116Mar is absorbing urban sprawl of Maceió and developing accelerated expansion of tourism and urbanization (MT, 2013).

The increasing concentrations of coliforms in the dry season suggest the worsening of the water quality in the northern and metropolitan coastal areas. This result indicates the intensification of point sources of domestic pollution in the period, which includes the festive periods, school holidays and summer, and that, based on the performance of tourism in recent years, implies a considerable increase of the floating population.

The southern coast, with low urbanization and weak tourism activities (IMA/AL, 2012), showed an improved water quality through data analysis, rating the results obtained based on the bathing index. Despite the positive results found in the present study, there is a lack of field sanitation (excessive accumulation of garbage and open sewage, for example) and poor spatial planning policy in the cities of the south coast, which slightly affects the quality of coastal waters due to small occupation and tourism.

The monthly basis and seasonal (rainy and dry seasons) data demonstrates the strong correlation between the concentration of fecal coliform in the rainiest months, indicating both the effect of diffuse pollution as well as the intensification of point sources of pollution (Figure 4).

The stations most affected by the rainy season were those with lower water quality and those near the river mouths and urban drainage. The positive correlation between fecal bacteria and precipitation is reported by several authors both in other parts of the world (such as Solo-Gabriele et al., 2000 and Alm et al., 2003) and in the northeastern Brazil (Medeiros, 2009; Morais and Silva,2012).

The results on the Alagoas coast also highlights to the increasing unsuitability in months of strong population growth due to tourism, especially in the months of January and July (MT, 2013). In a state where the rates of collection and sewage treatment are so low, even in the capital Maceió (IMA/AL, 2012), the pressure on the already fragile sanitation infrastructure seems to have a direct impact on the environmental quality of coastal waters. Figure 4 illustrates the improper monthly average of beaches monitored in five years, and the average monthly rainfall of a station located in Maceió.

5. Conclusions

The analysis of the environmental quality of the coast of Alagoas, focusing the coastal bathing, based on Brazilian law, at 53 monitoring stations, revealed a general trend of degradation of the water quality, although certain sections have shown improvement or variations close to stability.

Low levels of sanitation, especially sewage collection and treatment, the lack of an effective land planning and environmental development of agribusiness activities and low sustainability seems to be the main factors that negatively affect the quality of coastal waters of the state of Alagoas. According to coliforms content data, the growth in tourism and poor infrastructure, the pollutant loads to water bodies tributaries increased significantly, in recent years.

Appendix

Supporting Information associated with this article is available online at http://www.aprh.pt/rgci/pdf/rgci-562_Fontenelle_Supporting-Information.pdf

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