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Urbanization Impact on Subtropical Estuaries: a Comparative Study of Water Properties in Urban Areas and in Protected Areas

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ABSTRACT

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The creation of protected mangrove areas has allowed retaining, at least locally, the increasing urbanization in coastal areas. The physical, chemical and biological spatial dynamics of the aquatic system draining into the Bay of Santa Catarina Island, Southern Brazil, was evaluated to verify the effects of urbanization. A hierarchical design with various spatial scales of samples within urban and non-urban (control) estuaries was used. As control areas, three estuaries situated within protected mangrove areas were chosen. Three other estuaries with environmentally similar features to those of the control ones, except for being located within urban sites, were chosen as anthropogenically-impacted areas. The concentrations of dissolved nutrients, suspended particulate matter and phytoplanktonic biomass were found to be between three to six times greater in urban estuaries than in non-urban ones. The nutrients average concentrations in the non-urban estuaries were 13 ± 3.4 µM for ammonia, 0.5 ± 0.2 µM for nitrite, 6.2 ± 7.5 µM for nitrate, 0.67 ± 0.29 µM for phosphate, and 39.8 ± 19.9 µM for silicate; and in the urban estuaries, they were 72.5 ± 39 µM for ammonia, 3.2 ± 1.8 µM for nitrite, 14 ± 13.4 µM for nitrate, 3.32 ± 3.43 µM for phosphate, and 31.5 ± 21.3 µM for silicate. In urban estuaries, the dissolved inorganic nitrogen was generally three times greater than in non-urban ones, and although the differences in dissolved organic nitrogen and phosphorus concentrations were not as high between them, the variations were the greatest. Similarly, chlorophyll-*a* and phaeophytin-*a* presented a higher concentration in urban estuaries (31.1 and 46.4 $\mu g.L^{-1}$) than in non-urban ones (15.8 and 26.2 $\mu g.L^{-1}$), hence the average ratio Chlo*a*:Phaeo*a* was twice as much in non-urban estuaries. The maintenance of the current mangrove areas, as well as a more efficient control of the domestic and industrial discharges and other activities occurring around the protected areas is suggested as a necessary strategy to maintain the water quality in the Bay of Santa Catarina Island.

ADDITIONAL INDEX WORDS: *Eutrophication, spatial variation, inorganic nutrients.*

INTRODUCTION

In the first decade of the 21st century it has been estimated that half of the world's population will be living in urban areas (BARBIÉRI, 1999). As developed countries are already highly urbanized, urbanization growth is nowadays occurring in developing countries. In Brazil, the recent increase in the number of contamination episodes recorded all along the coastal region (almost 7500 km) has been found to be related, directly or indirectly, to the effects of urbanization (DIEGUES, 1999; BRAGA *et al.*, 2000; LEÃO and DOMINGUEZ, 2002).

Urban growth in coastal cities causes evident alterations in the quality of marine environments, affecting animals and plants. The increase concentration of inorganic nutrients and dissolved organic matter to concentrations above natural levels are the most serious and common form of perturbation affecting coastal marine systems (GESAMP, 2001). Eutrophication, particularly, is a process able to lead a whole aquatic system to collapse. Some of its typical symptoms are increase turbidity, excessive growth of opportunistic plankton species, oxygen depletion and extensive mortality of benthic organisms. Typically, these events tend to occur in shallow areas, where sediments are fine and the water column stratified, such as estuaries (GRAY *et al.*, 2002; DE JONGE *et al.*, 2002).

Due to retain the organic matter and dissolved inorganic nutrients coming directly from the terrestrial environment or through sewage, estuarine systems play a fundamental role in the biogeochemical cycling. The maintenance of the ecological properties of estuaries depends on the balance between their capacity to dilute the pollutants and the type and magnitude of the discharge in the system.

Presently, the challenge for coastal cities lies in the need for simultaneous management of the rapid urban growth and the sustainable protection of the environment. In order to reduce these impacts, various strategies at regional and global levels have been suggested and encouraged. In this context, the creation of protected areas has been invocated to salvaguard the gene pool and biological variability in the ecosystems. However, in spite of the great importance of protected areas, especially for aquatic units, many questions about their implementation, such as minimum area needed, on the one hand, and cultural, social and political conflicts, on the other, remain unanswered. Hence, are protected areas, in actual fact, able to sustain the biological diversity and the essential ecological processes of aquatic environments? Is environmental quality guaranteed by the implementation of aquatic protected areas or does it depend on the human activities carried out in the surroundings?

As part of a wider study that evaluates the growing effects of urban centers in coastal environments, this study investigated the physical, chemical and biological spatial dynamics of aquatic systems of urban and non-urban estuaries in the Bay of Santa Catarina Island, southern Brazil. The sampling was carried out in locations where control areas were situated within protected areas, hence potentially pollution-free, and also in similar areas, but adjacent to urban centers, thus potentially impacted.

METHODS

The hydrodynamics of the Bay of Santa Catarina Island is controlled by the micro-tidal force, with average amplitudes of 0.83 m for spring tides, and 0.15 m for neap tides (CRUZ, 1998). Whereas the predominant winds are north/north-eastern,

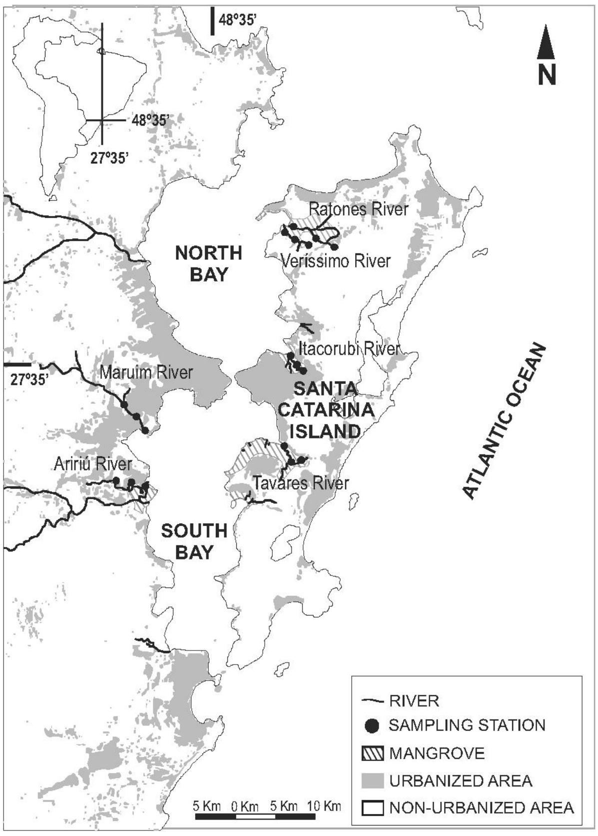

Figure 1. The Bay of Santa Catarina Island, southern Brazil.

the south/south-eastern ones are of greater intensity. The latter ones being responsible for the formation of derive waves, causing some water turbulence in the interior of the bay. Several estuaries that occur all along the almost 80 km long coast and drain their waters into the bay are originally colonized by mangroves and salt-marshes (Figure 1). The mangroves which are composed mainly by *Rhizophora mangle*, *Avicennia schaueriana* and *Laguncularia racemosa* species, are at their limit of the geographic distribution in the southern Atlantic coast of South America. Salt marshes, on the other hand, are composed of large mono-specific banks of *Spartina alterniflora* species. The largest two remaining areas of mangroves and salt marshes in the region are the Carijós Ecological Station, with the Ratones and Veríssimo estuaries as their principal water receptors, and the Pirajubaé Marine Sustainable Reserve, drained by the Tavares Estuary. In this investigation, these areas were considered as pristine and were used as controls for the urbanized estuaries.

According to the local authorities, although not quantified, the principal effects of urbanization are caused by the disposal of domestic, industrial, and hospital residuals, agricultural run-off, and soil erosion (SANTA CATARINA, 1997). Over 600.000 people inhabit the drainage basin of the Bay of Santa Catarina Island, figure which over the warm months of the year, tends to triplicate with the tourist arrival. The agricultural work in the region is based on the horticultural farming, principally tomatoes that use in average 188 kg/farm/year of agro-chemicals, usually belonging to the carbamates and organophosphates chemical groups. Thus, the Itacorubi, Ariríú and Maruim estuaries are located in the middle of urban centers, and were chosen to analyze their water quality as potentially polluted estuaries (Figure 1).

To evaluate the physical, chemical and biological variables of the aquatic compartment, a hierarchical sampling design was used. Two groups of estuaries were selected, those localized within urban areas and those within protected areas. Each of these groups was composed of three estuaries. In each estuary, three different sites along its length were sampled: at the mouth of the estuary, at the limit of the tidal influence and in the intermediate region between those two.

Using a bottle of the type "Van-Dorn", water from near the bottom of the estuaries was sampled for a period of a week in April 2002. Similarly, using a portable pH meter (Hach, mod. 50205, 0.01 precision), water temperature and pH were measured in the field. For the dissolved oxygen analysis, samples were collected and processed according to WINKLER (GRASSHOFF *et al.*, 1983). Likewise, salinity was measured using the conductivity method (TDS Hach mod. 44600). To assess the amount of suspended matter and phytoplanktonic pigments present, water samples were filtered (GF-52C SCHLEICHER and SCHUELL). The filtered solution was then used to analyze the dissolved inorganic nutrients. The concentration of ammonia, phosphate and silicate were measured by using spectrophotometry and the colorimetric method (GRASSHOLFF *et al.*, 1983). Nitrite and nitrate were analyzed using the Auto-Analyzer II system Bran-Luebbe (TRÉGUER and LE CORRE, 1976). The dissolved organic phosphorus (DOP) and nitrogen (DON) were determined by the photo-oxidation technique (ARMSTRONG *et al.*, 1966). Dissolved inorganic nitrogen (DIN) was calculated by the sum of nitrate, nitrite and ammonia concentrations. Chlorophyll-*a* and phaeophytin-*a* were determined by spectrophotometry.

To analyze the data distribution pattern, the multi-dimensional scaling ordination (n-MDS) was used, taking the Euclidian distance index as descriptors. The significance of the difference between urban and non-urban areas was evaluated through an analysis of similarity (ANOSIM), a permutation test.

RESULTS

The physical, chemical and biological variables from the bottom water of urban and non-urban estuaries are summarized in Table 1. In average, pH and temperature were rather similar between sites and estuaries. Salinity values, conversely, showed greater variations in urban estuaries than in non-urban ones, varying from 0.1 to 35.6 and from 1 to 20.6, respectively. Although the dissolved oxygen showed similar averaged values, the more extreme values were found in urban estuaries, varying from 0,00 to 5,20 $ml.L^{-1}$, while in non-urban ones the variation was from 1,02 to 3,20 $ml.L^{-1}$.

Silicate concentration were found to be high in both urban (2.6 to 82.7 µM) and non-urban areas (7.4 to 73.8 µM), the highest concentrations being found in the Veríssimo and

Table 1. *Summary of the physical, chemical and biological variables of water in urban and non-urban estuaries of the Bay of Santa Catarina Island, southern Brazil. O_2 in $ml.L^{-1}$, Nutrients in µM, Seston in $mg.L^{-1}$, Chla and pheoa in $\mu g.L^{-1}$.*

	Urban (n = 27)		Non-urban (n = 27)	
Variable	Average (±Sd)	Range	Average (±Sd)	Range
Salinity	13.8 (13.5)	0.1-35.6	6.4 (6.2)	1.0-20.6
pH	7.0 (0.4)	6.5-7.7	7.0 (0.2)	6.7-7.3
T °C	24.1 (0.9)	22.8-26.0	24.8 (1.2)	23.3-26.7
O_2	2.28 (1.76)	0.00-5.21	2.20 (0.79)	1.02-3.20
$SI(OH)_4$	31.5 (21.3)	2.6-82.7	39.8 (19.9)	7.4-73.8
PO_4	3.32 (3.43)	0.39-12.45	0.67 (0.29)	0.22-1.20
POD	4.5 (1.6)	0.0-5.9	5.1 (0.2)	4.4-5.6
%POD:PTD	64 (27)	0-93	88 (5)	80-96
NH_4	72.5 (39.0)	17.0-161.3	13.0 (3.4)	8.5-23.0
NO_3	14.0 (13.4)	1.3-48.8	6.2 (7.5)	0.5-27.2
NO_2	3.2 (1.8)	0.8-7.3	0.5 (0.4)	0.1-1.8
NOD	75.8 (58.8)	12.7-214.0	24.1 (9.4)	1.7-46.3
%NOD:NTD	44 (21)	9.9-77	55 (14)	6.8-73.9
%NID:NTD	89 (45)	19-180	19 (9.8)	10-43
%NH_4:NID	82 (11)	5.8-94	74 (18)	36-95
%NO_3:NID	14 (11)	2.3-37	23 (19)	4.5-63
N:P	66 (82)	8-336	30 (9)	15-52
Seston	26.8 (7.9)	13.4-46.8	31.4 (20.8)	5.7-62.8
Chl*a*	31.1 (38.3)	0.0-122.8	15.8 (19.4)	0.0-69.4
Pheo*a*	46.4 (48.5)	0.0-176.2	26.2 (31.9)	0.0-108.9
Chl*a*:Pheo*a*	2.5 (4.0)	0.1-14.2	4.9 (7.3)	0.1-20.0

Ratones estuaries (Figure 2). Concentrations of DIP were 5 times greater in urban estuaries (0.39 a 12.45 µM) than in non-urban ones (0.22 a 1.20 µM). DOP, on the other hand, presented greater concentrations in non-urban areas (4.4 to 5.6 µM) than in urban ones (0.0 to 5.9 µM.). In relation to the total dissolved phosphorus (TDP), the percentage of DOP varied from 80 to 96 % in non-urban estuaries and from 0 to 93 % in urban ones.

Ammonia, nitrite and nitrate concentrations were 5, 2 and 6 fold in urban estuaries than in non-urban ones, respectively (Table 1 e Figure 2). DON concentrations, similarly, were 3 times as great in urban estuaries (75.8 ± 58.8 µM) than in non-urban ones (24.1 ± 9.4 µM). The principal constituent of the DIN was ammonia, varying from 58 to 94 % in urban areas and from 36 to 94 % in non-urban ones. While the DON in urban areas stood for the 45 ± 21 % of the total dissolved nitrogen (TDN), in non-urban ones (the DON) represented 55 ± 14 % (of the TDN).

Moreover, while in urban estuaries the N:P ratio varied from 8 to 336, with an average of 66 ± 82, in non-urban ones they varied from 15 to 52, with an average of 30 ± 9. Chlorophyll-*a* and phaeophytin-*a* concentrations were greater in urban areas than in the non-urban ones, varying from 0 to 122.8 $\mu g.L^{-1}$ and from 0 to 176.2 $\mu g.L^{-1}$ in urban ones, and from 31.1 to 46.4 $\mu g.L^{-1}$ and 15.8 to 26.2 $\mu g.L^{-1}$ in non-urban ones, respectively. Hence, the Chlorophyll-*a*:Phaeophytin-*a* ratio varied from 0.1 to 14.2 in urban areas, and from 0.1 to 20 in non-urban ones. The suspended matter content, conversely, varied more and showed greater concentrations in non-urban estuaries, with concentrations varying from 5.7 to 62.8 $mg.L^{-1}$, than in urban ones, varying from 13.4 to 46.8 $mg.L^{-1}$.

The differences in the physical, chemical and biological variables of the bottom water of urban and non-urban estuaries were evidenced by the multivariate analysis (stress = 0.16) and the similarity analysis confirmed it (ANOSIM, R = 0.502, p = 0.001, Figure 3). Due to the intrinsic variations of every estuary, the data in the graph was rather dispersed, independent of the sampled area.

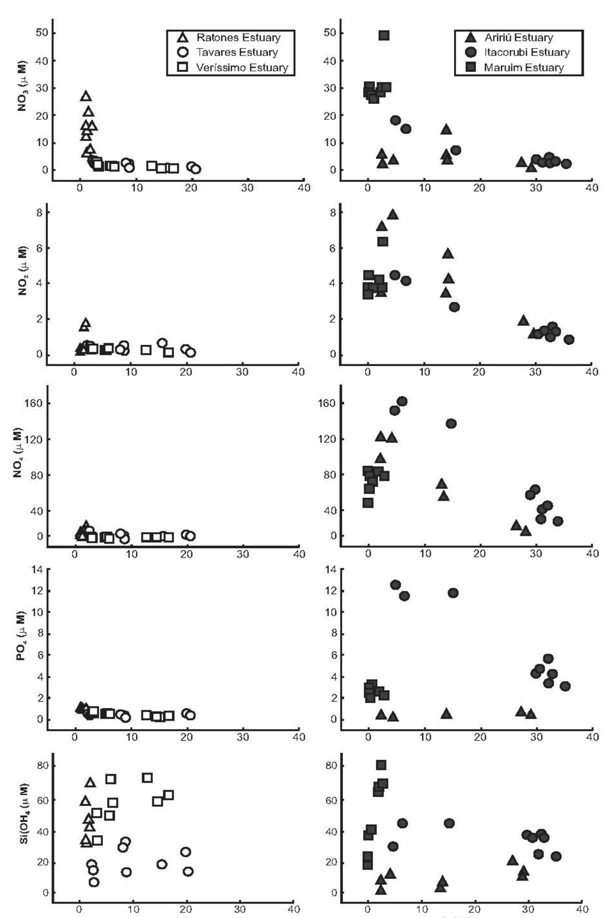

Figure 2. Nutrient concentrations versus salinity in non-urban (empty symbols) and urban (filled symbols) estuaries of the Santa Catarina Island Bay, southern Brazil.

DISCUSSIONS

The impact caused by human activities and presence have brought about a decline in mangrove and salt marsh swamp areas. The land reclamation and contamination of these water bodies are conspicuous and have been recorded all over the world (RIDGWAY and SHIMMIELD, 2002). This study was carried out in an area of high anthropogenic pressure and reduced industrial activity. The more evident effects are those related to the discharge of domestic sewage *in natura* directly from residences (when located at the mangrove margin) or the sewers (when coming from further up the estuary). The results showed the large overload of nitrogenous and phosphorous compounds released into the environment in urbanized estuaries. In the protected areas, on the other hand, these compounds exhibited values considered natural for pristine areas.

Values from dissolved nutrients exhibited in the water of several estuarine systems in the south and south-eastern Brazil are displayed in Table 2. In order to compare them with the data set of this study, the values between urban and non-urban areas, according to the authors' discussion, were examined and separated out. Until now, none of those studies had simultaneously evaluated the differences between urban and non-urban estuaries.

The dissolved inorganic nitrogenous and phosphorous compounds are important in the characterization and detection of problems related to eutrophication (CLOERN, 2001). Silicate, nitrite, nitrate, ammonia and phosphate concentrations reported in urbanized areas in this study were similar and sometimes even greater than those described in the Estuarine System of Santos, the Patos' Lagoon and the Bay of Guanabara (Table 2). These places in Brazil are assumed to be the most polluted estuarine systems situated in high population density areas, and where harbor and industrial activities are high. Independent of the urban-ring sizes in the surrounding area this result evidences that sewage discharge in water bodies can cause rather high nutrient values. In addition to that, it has to be said, particularly with reference to studies carried out by BRAGA *et al.* (2000), in the Estuary of Santos - state of São Paulo, by BAUMGARTEN *et al.* (1998), in the Patos' Lagoon - state of Rio Grande do Sul, and by KJERFVE *et al.* (1997), in the Bay of Guanabara - state of Rio de Janeiro, that their values were obtained directly from sewage entry points, hence being the sites with the highest concentrations of pollutants.

Silicate concentrations in the urbanized studied estuaries, gave evidence of terrestrial origin, varying according to localized sediment removal sites, either caused by dredging, straightening and widening of the banks, as in the Itacorubi Estuary, or caused by the presence of concrete walls directly above the water bodies, as at the Maruím Estuary mouth. Dissolved phosphate, on the other hand, exhibited particularly high concentrations in the Itacorubi Estuary, reaching concentrations as high as 50 times that of the others. These values can be resulting from processes, such as the assimilation and adsorption of it by suspended organic matter, and flocculation due to changes in salinity, inducing phosphate sedimentation, with lower concentrations at the mouth of the estuary. The concentrations of dissolved phosphate at the mouth of the Itacorubi Estuary, nonetheless, were still greater than any of the other five studied estuaries.

At high concentrations, similarly, nitrogenous compounds also exhibited a dilution tendency along the estuaries. The water physical mixing processes, caused by seawater entrance in the system, remove and dilute compounds that are being discharged in the estuaries via small fluvial sewers, or directly from domestic residences. This phenomenon can be appreciated principally in Itacorubi and Aririú estuaries. Besides that, the high ammonia values can be additionally originating by the

Table 2. *Nutrient concentrations in urban and non-urban estuarine systems of southern and south-eastern Brazil. Referenced data are given as range data or mean; nd = not determinated.*

Location	NON-URBAN ESTUARIES					URBAN ESTUARIES				
	NO_3 µM	NO_2 µM	NH_4 µM	PO_4 µM	$SI(OH)_4$ µM	NO_3 µM	NO_2 µM	NH_4 µM	PO_4 µM	$SI(OH)_4$ µM
Santa Catarina Island Bay [1]	0.5-27	0-2	8.5-23	0.2-1	7-74	1-49	1-7	17-161	0.4-12	3-83
Conceição Lagoon [2,3,4,5]	0.4-4	0-0.3	1-2	0-7	1-39	0-3	0-0.5	0.5-11	0.0-5	2-77
Camboriú River [6]	-	-	-	-	-	0-6	0-2	2.4-66	0.13-3	15 -210
Babitonga Bay [7]	1-3	0.1-0.5	3-5	0-1	11-36	2.9	2.75	62.1	1.4	33
Paranaguá Bay [8,9]	0-3	0-1	0.4-22	0.2-1	11-99	0-13	0-1	0.6-13	0.3-4	20-362
Patos Lagoon [10,11,12,13]	10-79	0-1	0-14	0-2	0-400	1-101	0-3	0-924	0-44	1-256
Santos Bay [14,15]	0-19	0-4	1-23	0.5-3	10-50	0-120	0-15	0.8-95	0.2-24	1-160
Guanabara Bay [16]	-	-	-	-	-	1-7	0-3	2-124	0.3-12	nd

This study [1]	FONSECA *et al.* (2002) [5]	MACHADO *et al.* (1997) [9]	BAUMGARTEN *et al.* (1998) [13]
KNOPPERS *et al.* (1984) [2]	PEREIRA-FILHO *et al.* (2001) [6]	ALMEIDA *et al.* (1984) [10]	BRAGA *et al.* (2000) [14]
ODEBRECHT and CARUSO (1987) [3]	KUROSHIMA and BELLOTTO (1998) [7]	BAUMGARTEN *et al.* (1995) [11]	GIANESELLA *et al.* (2000) [15]
SOUZA-SIERRA *et al.* (1987) [4]	BRANDINI and THAMM (1994) [8]	SANTOS *et al.* (1997) [12]	KJERFVE *et al.* (1997) [16]

hydrolysis of urea (BRAGA *et al.*, 2000), especially considering the high amounts of DON present in these estuaries.

The DIN concentrations are directly related to the primary production and decomposition processes (GRAY *et al.*, 2002). Generally, the greater the nutrient concentration, the greater the production in the system and the higher is the chlorophyll-*a* concentrations. Nonetheless, a large organic matter contribution to the system can hinder nutrient regeneration and favor denitrification processes, resulting in oxygen depletion in Moreover, while in urban estuaries the N:P ratio varied from 8 to 336, with an average of 66 ± 82, in non-urban ones they varied from 15 to 52, with an average of 30 ± 9. Chlorophyll-*a* and phaeophytin-*a* concentrations were greater in urban areas than in the non-urban ones, varying from 0 to 122.8 µg.L^{-1} and from 0 to 176.2 µg.L^{-1} in urban ones, and from 31.1 to 46.4 µg.L^{-1} and 15.8 to 26.2 µg.L^{-1} in non-urban ones, respectively. Hence, the Chlorophyll-*a*:Phaeophytin-*a* ratio varied from 0.1 to 14.2 in urban areas, and from 0.1 to 20 in non-urban ones. The suspended matter content, conversely, varied more and showed greater concentrations in non-urban estuaries, with concentrations varying from 5.7 to 62.8 mg.L^{-1}, than in urban ones, varying from 13.4 to 46.8 mg.L^{-1}.

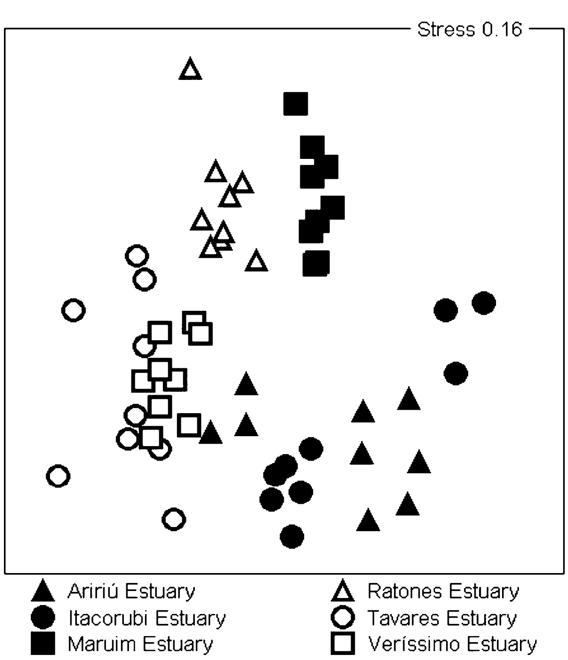

Figure 3. n-MDS of physical, chemical and biological variables of non-urban (empty symbols) and urban (filled symbols) estuaries of the Santa Catarina Island Bay, southern Brazil.

the water column (NIXON, 1981). In this investigation, this process was evidenced by the differences between the DIN compositions found in urban areas versus protected areas. In the former, the reductive nitrogenous form (ammonia) predominated in the DIN, whereas in the latter, although with still high values of DIN, there was an increase in the oxidative nitrogenous compounds (nitrate).

For phytoplanktonic production, the N:P average ratio in both types of estuaries systems, urban and non-urban, was found to be greater than the one proposed by Redfield (16:1). In non-urban estuaries, primary production in the inner waters were limited by phosphate, with salinity concentrations lower than 5 and high suspended organic matter content. At the mouth of the estuaries, conversely, where salinity concentration is at its highest, the limitation compounds were the nitrogenous ones. The discharge and maintenance of DIN in non-urban estuaries are greater than the DIP compounds, which must be being adsorbed by suspended solids (FONSECA *et al.*, 2002; KOCUM *et al.*, 2002). Besides that, the DIN dilution and assimilation along the estuaries can be the principal factor limiting its presence in the more saline waters. The average N:P ratio in urban areas was twice as high than in protected areas, this occurring without the variation of limiting nutrients along the salinity gradient. The phosphorus adsorption and the nitrogen diverse entry points along the estuaries continued to have a greater N:P ratio than 16, reaching extreme values of 336. These results are in accordance with the general tendency found in polluted and non-polluted coastal areas. The primary production is being limited by nitrogenous compounds in the non-impacted areas and by phosphorous compounds in the impacted ones (CLOERN, 2001; DE JONGE *et al.*, 2002).

The mangrove located in protected areas, however, are not totally free from the surrounding's urbanized dynamics. This was particularly evident in the Ratones and Veríssimo estuaries, both of which constitute the Carijós Ecological Station. Despite that, these estuaries exhibit high silicate values. With the purpose of draining the swamp areas, in the last decades the Ratones Estuary natural course was deviated through engineering works. Nowadays, a large and straight channel became the principal watercourse of the estuary. The change in water current caused by this man-made channel in both, the inlet and outlet, as well as the levelling of the ground in the surroundings can explain the sediment remobilization and maintenance of the silicate high concentrations. The Veríssimo Estuary, conversely, located in the same protected area and nearby the Ratones Estuary, has not suffered any change in its watercourse, hence is localized in the most preserved area of the unit. However, due to sand exploitation in the innermost region of it, near the Units limits could be causing the high silicate concentrations in this estuary. Besides that, the high nitrate concentrations in the Ratones Estuary was also very notorious, reaching values up to 30 times greater than the minimum one registered.

This work shows that water quality in urbanized estuaries around the Bay of Santa Catarina Island contained very high nitrogenous and phosphorous compounds values. The protected mangrove areas, on the other hand, by supporting the nutrients in normal levels, guaranteed water quality in the estuarine systems, even when located closed to urban centers. The maintenance of natural features in the aquatic system will depend to a large extend on the urbanization control carried out around these areas. Hence, the aquatic system responds and reflects to any activity carried out in the catchment. Due to this, mangrove size maintenance as well as the treatment of all foreign effluents are urgent measures that have to be implemented should these impacts are going to cease.

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