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Impact of the Icaraí Sewage Outfall in Guanabara Bay, Brazil

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ABSTRACT

The present study aimed to evaluate the water quality of the Icaraí Sewage Outfall (ISEO) area. Sampling was conducted during winter and summer, and water samples were analyzed for dissolved oxygen, pH, temperature, salinity, dissolved inorganic nutrients (DIN), seston, particulate organic matter (POM), and pigments. Results showed that the water chemistry of the area suffers temporal and spatial variation. Great variability was also seen in the C:N:P ratios of POM (August, 112:30:1; December, 59:11:1) and in the DIN concentrations. Chlorophyll-a and ammonium concentrations (4.5 $\mu g\ L^{-1}$ - 71.2 $\mu g\ L^{-1}$, and 0.20 μM - 52,6 μM, respectively) characterized the ISEO area as eutrophic. The dispersal of the material was not effective under certain oceanographic conditions.

Key words: eutrophication, sewage outfall, water pollution, nutrients, Guanabara Bay

INTRODUCTION

Guanabara Bay, located on the southeastern coast of Brazil and surrounded by one of the country's largest urban agglomerations (7.3 million inhabitants) has suffered serious damage due to intensive pollutant discharge during the last three decades. The bay has two harbors, 16 oil terminals and 6,000 factories, receives about 480 tons day^{-1} of BOD input (Coelho and Fonseca, 1977; SEMA, 1998), and the high concentration of these organic wastes is responsible for the partial, or total, degradation of certain areas. Severe eutrophication has rendered the water inadequate for recreational use and caused a 90% fisheries decline (Carreira et al., 2002; Rebello et al., 1988).

During the early 80's, the State Environmental Agency (FEEMA, 1979) drew up a plan for improving water quality, but in spite of it, water quality has become critical, especially in the inner/upper areas of the bay. More recently, in the 90's, both the Federal and the State Governments began to tackle the improvement of the bay's environment by means of the Guanabara Bay Restoration Program (FEEMA, 1990; JICA, 1994). This program gave priority to basic sanitation, and comprised the construction and/or amplification of several sewage treatment stations and sewage marine outfalls.

The successful marine outfalls have been reported in the literature (Koop and Hutchings, 1996), and alternatives has been subject to criticism in several countries, since some of these plants have

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contributed to degradation of water bodies, mainly in areas with restricted circulation. In the latter cases, the most common effects are organic matter deposition in the outfall area, foul-smelling and foul-looking marine shores, and spreading of wastes and pathogens to adjacent beaches (Officer and Ryther, 1977; Grace, 1978; Carreira and Maia, 1990; Wagener, 1998). Therefore, continuous monitoring studies are needed to overlook the outfall performance (Grace, 1978; Phillip and Pritchard, 1996; Rendel and Pritchard, 1996).

In view of a dearth of information on the potential changes due to the Icaraí Marine Sewage Outfall (ISEO), this paper aimed to make a first evaluation of its performance by analyzing water quality in the area. An evaluation of the fertilization potential of the sewage outfall was also made.

MATERIAL AND METHODS

Study Area and Sampling

The Icaraí Sewage Outfall (ISEO) is located on the southeastern coastline of Brazil, at 22^o 55’ 04’’ S and 43^o 08’ 35’’ W, in the Jurujuba Inlet, which is part of Guanabara Bay (Fig. 1). The bay, with an area of 384 km², a water volume of 1.87 x 10^9 m^3 and a medium depth of 5.7 m, is characterized by extreme eutrophication of its inner waters (Ribeiro, 1996). However, half-life of water turn-over ($T_{50\%}$) is relatively short, 11.4 days (Kjerfve et al., 1997), exemplified by the good water quality of the deep central channel which connects the bay to the ocean, and where the ISEO discharge point is located (Fig. 1). This channel, which runs on a north-south direction, is approximately 20 km long and 3 km wide, and 15 - 20 m deep (SEMA, 1998). Predominance of sandy sediment at the bottom of this sector reflects the high hydrodynamism of the area (Baptista Neto and Silva, 1996). The tide regime in Guanabara Bay is predominantly semidiurnal, with medium range of 0.3 m at neap tide and 1.1 m at spring tide (Kjerfve et al., 1997). The currents which occur in the ISEO discharge area are mainly influenced by the tides and are in the order of 1.5 m/s (JICA, 1994). The climate is characterized by a dry season in winter and a rainy one in summer. Total annual rainfall varies from 1,000 mm to 2,000 mm. Meteorological cycles are driven mainly by cold fronts coming in from the South, which occur frequently in winter. In good weather E and NE trade winds predominate (JICA, 1994).

The ISEO has a diameter of 1.0 m, its diffuser has 248 m long, and it is built in high density polyethylene. It receives sewage which has undergone secondary treatment from 234,000 inhabitants, corresponding to 52% of the Niterói County network total. Mean diffuser outflow is about 952 L s^{-1}, and the effluent still contains pathogenic organisms and nutrients. Coliform concentration is estimated to be 3 x 10^7 counts/ 100 ml (Multiservice Engenharia, 1995).

In the present study water samples were collected in the area of the ISEO diffuser, situated near the entrance of Guanabara Bay, and in the coastal region of the city of Niterói, close to the following beaches: Adão e Eva, Charitas, São Francisco, Icaraí and Boa Viagem. The ISEO area was the subject of two sampling trips (winter and summer, respectively), while sampling of the coastal area was performed only in summer (Fig. 1).

The first sampling took place in winter (August 1999), comprising high and low tides, characterized by tide range in the order of 1.20 m. Surface water samples were collected at 12 sites (1 to 12) radiating out from the outfall diffuser (Fig. 1). The total area covered was approximately 2 km^2. The first 7 sites (1 to 7) corresponded to the period of the flood tide, while the other 5 sites (8 to 12) corresponded to the ebb tide.

In the second trip (December 1999), surface water samples from the ISEO area were also taken during high and low tides, but the range was only 0.4 m. The first station (13), situated near the diffuser, corresponded to the end of the flood tide, whereas the following stations, 14 to 27, to the ebb tide. Stations 19 to 22, as well as 27 corresponded to the coastal region (Adão and Eva, Charitas, Icaraí, Boa Viagem and Icaraí beaches, respectively). Sampling in the region of the outfall diffuser was carried out on surface and depth (10 m).

Sampling Procedures and Anlytical Methods

Water samples were collected using 2 L VanDorn bottles. Immediately after collection, subsamples were taken to measure pH and dissolved O_2 analysis (Winkler Titration). Temperature, salinity and pH were obtained *in situ*. The first two parameters were measured using an Electronic Switch Gear, type MC5 probe, London.

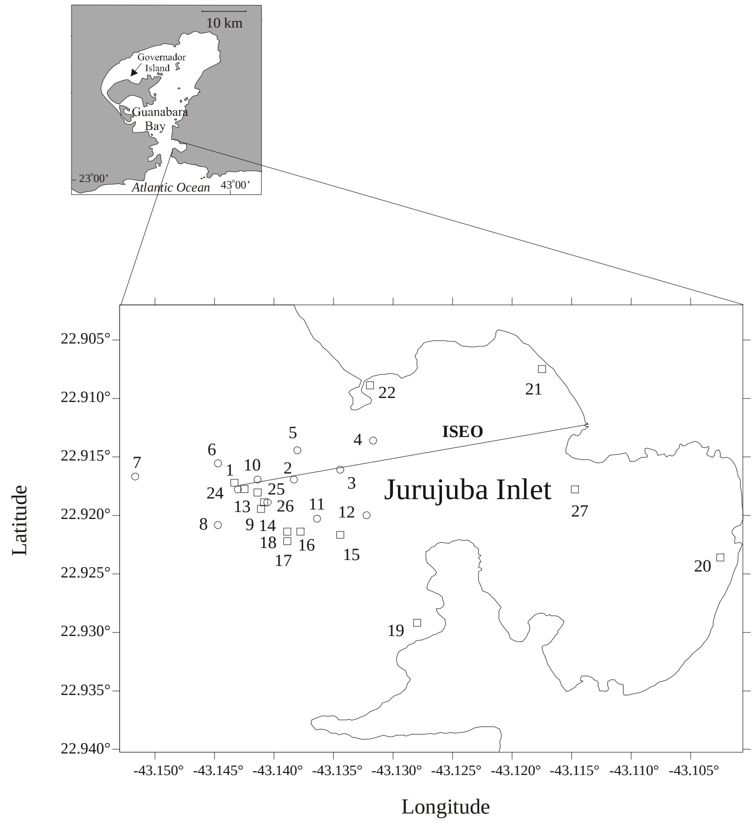

Figure 1 - Map of the study area, showing sampling sites in the outfall area during winter (1 to 12) and summer (13 to 18, and 23 to 26), and in the coastal area (19,20,21,22).

Subsamples of water from the bottles were filtered through a precombusted GF/C Whattman membrane to separate the dissolved and particulate fractions, and stored on ice for transportation. Dissolved oxygen, pigments, dissolved inorganic nutrients (ammonium, nitrite, nitrate, phosphate and silicate) and particulate organic matter (POC, PON and POP) were analyzed following Grasshoff et al. (1983) and Strickland and Parsons (1972).

RESULTS AND DISCUSSION

Physico-chemical Parameters

In addition to high salinity values, winter samples were characterized by lower pH, dissolved oxygen, chlorophyll-*a* and phaeophytin values. During summer, the opposite situation was observed (Table1).

Table 1 - Summary of temperature, salinity (S), pH, dissolved oxygen (DO), and pigments near the Icaraí Sewage Outfall (ISEO) and in coastal areas (CA) of Guanabara Bay.

Location (sampling period)	n	Temperature (oC)	S	pH	DO (mg L^{-1})	Chlorophyll-a (μg L^{-1})	Phaeophytin (μg L^{-1})
ISEO (aug/99)	12	23.4 21.6 - 24.0	34.0 33.7 - 34.2	8.18 8.09 - 8.24	6.9 6.4 - 7.2	9.0 4.5 - 17.9	1.8 0.2 - 4.2
ISEO diffuser (aug/99)	1 (surface) 1 (10m depth)	21.6 20.6	33.7 34.7	8.09 8.12	6.8 -	12.5 -	2.0 -
ISEO (dec/99)	10	23.6 23.5 - 24.0	28.1 23.0 - 30.0	8.74 8.66 - 8.81	11.8 10,9 - 13.4	43.1 29.5 - 71.2	20.6 1.0 - 40.6
ISEO diffuser (dec/99)	1 (surface) 1 (10m depth)	23.5 23.0	29.0 29.0	8.75 8.61	11.0 6.7	39.7 38.5	21.2 22.7
CA (dec/99)	5	24.1 22.5 - 25.0	31.2 30.0 - 32.0	8.73 8.58 - 8.83	11.6 10.7 - 12.6	37.5 31.5 - 43.2	11.0 2.3 - 19.5

Table 2 - Summary of chemical composition of dissolved and particulate matter parameters measured at Icaraí Sewage Outfall (ISEO) and coastal areas (CA) of Guanabara Bay. (PM - particulate matter; POC - particulate organic carbon; PON - particulate organic nitrogen; POP - particulate organic phosphorus; particulate C:N:P ratio; $N\text{-}NO_2^-$ - nitrite; $N\text{-}NH_4^+$ - ammonium; $P\text{-}PO_4^{3-}$ - ortophosphate; $Si\text{-}Si(OH)_4$ - silicate).

Location (sampling period)	n	PM (mg L^{-1})	C-POC (µg L^{-1})	N-PON (µg L^{-1})	P-POP (µg L^{-1})	C:N:P (atoms)	$N\text{-}NO_2^-$ (µM)	$N\text{-}NH_4^+$ (µM)	$P\text{-}PO_4^{3-}$ (µM)	$Si\text{-}SiOH_4$ (µM)
ISEO (aug/99)	12	14.7 12.4 - 21.1	428 317 - 683	143 105 - 252	12.4 4.7 - 41.4	112:30:01	0.99 0.58 - 1.99	11.1 2.8 - 52.6	0.91 0.70 - 1.86	11.4 7.6 - 21.4
ISEO diffuser (aug/99)	1 (surface) 1 (10m depth)	17.5 15.8	563 383	252 137	41.4 11.8	35:13:01 84:26:01	1.99 1.47	52.6 15.2	1.86 1.15	21.4 16.1
ISEO (dec/99)	10	63.5 49.1 - 80.2	1984 807 - 4376	440 150 - 654	89.2 25.8 - 135.2	59:11:01	0.09 0.04 - 0.19	1.1 0.2 - 2.4	0.20 0.01 - 0.35	1.2 0.7 - 1.6
ISEO diffuser (dec/99)	1 (surface) 1 (10m depth)	65.8 69.8	1540 1925	502 349	86.3 64.1	46:13:01 77:12:01	0.14 0.19	1,8 0.6	0.32 0.32	1.1 1.6
CA (dec/99)	5	66.3 57.5 - 78.8	2310 1553 - 3106	501 390 - 623	94.2 81.5 - 106.5	63:12:01	0.11 0.04 - 0.20	1.9 0.02 - 4.2	0.21 0.08 - 0.48	0.8 0.5 - 1.2

The concentrations of suspended particulate matter (PM) oscillated from 12.4 to 80.2 mg L^{-1} in the two periods, and also exhibited a well marked temporal variation. Summer averages were about 4 times greater than winter ones. This pattern was seen in all organic components of particulate matter (POC, PON and POP), indicating the presence of phytoplankton blooms during this period (Table 2). In addition, differently from the winter situation, during summer, positive significant correlations between chlorophyll-*a* X POC ($r = 0.65$; $p < 0.05$) and negative ones between chlorophyll-*a* x dissolved NH_4 ($r = -0.62$; $p < 0.05$) and PO_4 ($r = -0.74$; $p < 0.01$) were observed, indicating that a significant fraction of particulate organic matter (POM) was in effect incorporated by the phytoplankton. On the other hand, the other POM components (PON and POP) showed significant positive correlations ($r = 0.71$; $p < 0.01$) between themselves in the two periods, thus indicating a probable common origin, *i.e*., the ISEO.

Based on the Redfield ratio established for plankton (106:16:1) (Redfield et al., 1963), the average C:N:P ratio found for winter, 112:30:1, indicated an excess of nitrogen in the environment, which was surely related to the aloctonous contribution of nitrogenated compounds. The summer average C:N:P ratios, 62:12:01 and 59:11:1 (coastal areas and ISEO, respectively), were evidence of a carbon deficit.

C:N:P ratios showed great variability in aquatic environments and these variations were more frequent in impacted areas. In some of these areas, water N:P ratios oscillated from 0.1 to 200 (Day Jr. et al., 1989; Parsons et al., 1984). In the case of Guanabara Bay, the reported phytoplankton N:P ratios fluctuated between 11 and 17:1 (JICA, 1994), values that deviated ~ 13:1 from the average N:P ratio calculated in the winter sampling. Thus, a nitrogen excess in winter was pronounced as compared to summer, these results still provided indication of a nitrogen excess in the ISEO area, making the outfall's contribution evident.

In both winter and summer situations, the concentrations of the parameters analyzed in the dissolved inorganic nutrients (DIN) behaved contrary to the respective patterns oberved in the particulate matter, *i.e.*, the highest dissolved nutrient concentrations were registered in August 1999 (winter) and the ammonium, nitrite, phosphate and silicate averages were at least 9 times higher than in the summer (Table 2). Aside from the high DIN values, high correlations ($r > 0.96$; $p < 0.001$) between these components were observed in winter, indicating availability of dissolved nutrients in that period, and a possible common origin for them. Likewise, low DIN concentrations, as opposed to the high POM and chlorophyll-*a* values in summer, corroborated the incorporation of nutrients by the phytoplankton in this period.

ISEO and Water Quality

In winter waters, the ISEO area was characterized by availability of inorganic nutrients dissolved and by the absence of autotrophic processes in the water column. Taking ammonium as an indicator of the ISEO effluents, the spatial distribution of its concentrations in the period constituted evidence of a gradient originating in the diffuser area

(Fig. 2). The others nutrients showed a similar pattern and this type of distribution was commonly observed in underwater sewage outfalls (the ISEO plume). Under these conditions, due to a density difference, the plume tended to ascend to the surface, where it be transported by the action of surface currents, waves and wind (Middleton et al., 1996). The depth of the plume location is mainly determined by other oceanographic parameters such as the thermohaline stratification of the water column (Middleton et al., 1996; Miller et al., 1996). In fact, vertical temperature and salinity distribution data obtained in the diffuser area during winter confirmed the absence of stratification in the water column in that period.

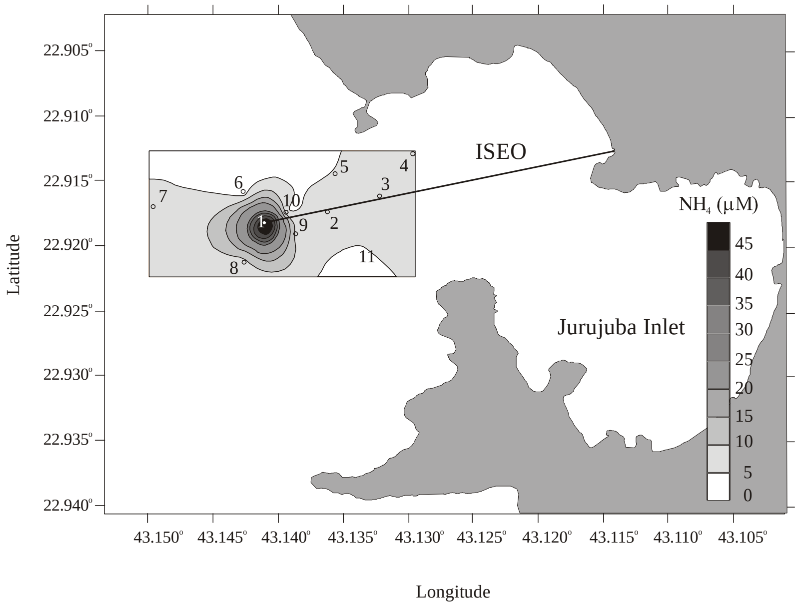

Figure 2 - Spatial distribution of ammonium (µM) for surface waters in the region of the ISEO during winter.

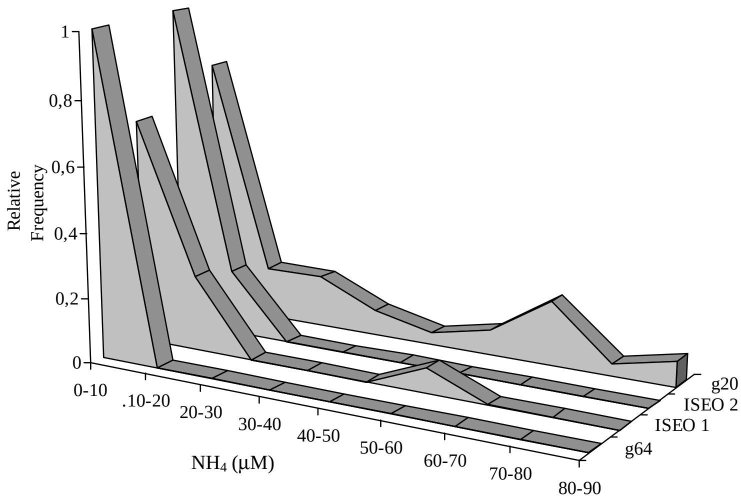

Figure 3 - Diagram showing the relative frequency of ammonium concentrations in the region of the ISEO (ISEO 1 - winter; ISEO 2 - summer) and in two sites monitored during 10 years by State Environmental Agency (FEEMA) prior to sewage outfall commission (g20 - Governador Island station located in inner, a highly degraded area of the bay; g64 - near the otufall).

In contrast to winter, summer was characterized by the incorporation of nutrients into the particulate organic matter, and by the predominance of photosynthetic processes. Nevertheless, these summer conditions be related to other factors than the outfall effluent. For example, during this period, high precipitation was observed determining a salinity decrease in surface waters. Moreover, Guanabara Bay receives SACW (South Atlantic Central Water) frequently also during the summer.

Kjerfve et al. (1997), analyzing temperature and salinity temporal series over a 10 year-period, have confirmed this pattern for Guanabara Bay. Thus, during summer sampling, sewage plume would be trapped under 10 m depth (Table 1) due to thermohaline stratification, which was verified by (Carreira, 1994; Maia, 1990) in another outfall off Rio de Janeiro State coast. Overall, the nutrient concentrations observed in summer (December 1999) were comparable to the data reported by FEEMA for station g64, collected near the outfall, but prior to its commission (Fig. 3). By contrast, some dissolved inorganic nutrient concentrations obtained in winter wereextremely high when compared to FEEMA's station g64, and just comparable to stations placed in inner, highly degraded regions, of Guanabara Bay (e.g. Station g20 in Governador Island) (Gonzalez et al., 2000) (Fig. 3). These data, therefore pointed to a modification in the water quality conditions in the ISEO area after the outfall was commissioned.

General Patterns of Water Chemistry

The variation of physico-chemical parameters recorded in the two samplings was analyzed by using principal component analysis (PCA) (James and McCulloch, 1990; Tabachnick and Fidell, 1989). The working matrix included 28 samples and 16 variables (temperature, salinity, pH, dissolved oxygen, chorophyll-*a*, phaeophytin, particulate matter, POC, PON, POP, C:N and N:P ratios, and dissolved inorganic nutrients). To improve the detection of non-linear relationships, all data were transformed into natural logarithms (Sokal and Rohlf, 1981). The first four principal components accounted for 96.4 % of total variance. The first (PC1) accounted for 75.0 % of total variance, with the second (PC2) contributing 10.4 % out of the total.

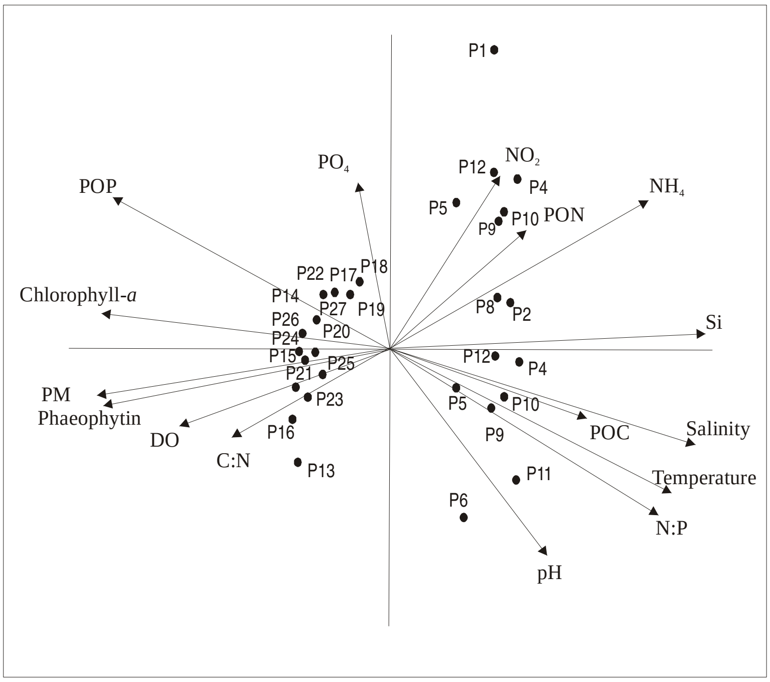

Figure 4 - Graphic representation of two first principal components from the PCA analysis performed at the matrix of physical chemical parameters containing all the samples taken in the region of the ISEO and in the coastal area (winter: p1 - p12, and summer: p13 - p25).

The principal gradient related to the first principal component showed a clear separation between the two sampling periods, *i.e.*, winter (positive values) and summer (negative values); this gradient was corroborated by the weighting of the variables on the axes (Fig. 4).
The second principal component did not generate interpretable gradients, but it did provide information relative to the difference between seasonal groupings (winter and summer). Data from the summer sampling displayed greater homogeneous conditions than the winter data, which was borne out by the greater grouping of stations on the left side of the diagram. Attention should be drawn to sample of site 1, collected in the diffuser area which, due to its position in the diagram, could be characterized as an outlier.
PON and N:P ratio (particulate matter), some components of the dissolved material (e.g. NH_4, NO_2) indicative of anthropic activities associated with sewage effluents, as well as temperature, pH and salinity, weighted positively on the first axis, which was probably related to the ISEO contribution during winter. On the other hand, the variables POP, PM, chlorophyll-*a*, phaeophytin and DO, indicators of autotrophic metabolic processes, weighted negatively on the same axis, a consequence of the higher summer concentrations of these parameters.

CONCLUSIONS

The physico-chemical conditions of the water column in the ISEO area were extremely heterogeneous and tended to display seasonality, which was determined by the different oceanographic and meteorological conditions during winter and summer;
Winter conditions, marked by the absence of stratification in the water column, resulted in surfacing of the plume, where it was then subjected to superficial current, wave and wind action. Under these conditions a concentration gradient of parameters indicative of effluents such as NH_4 from the area of the ISEO diffuser was observed. Summer conditions were characterized by an absence of the gradient, a pattern that was probably related to trapping of the plume under the surface, due to the penetration of SACW (South Atlantic Central Water) inside the Guanabara Bay.
The sum of the nitrogen, phosphorus and chlorophyll-*a* concentrations indicate an increase on the fertilization degree of the waters in the outfall region.
The ISEO plume distribution patterns indicated that its dispersion was not effective under certain oceanographic conditions.

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RESUMO

O presente estudo teve por objetivo avaliar a qualidade da água na área do Emissário de Esgoto de Icaraí (ISEO). A amostragem foi realizada durante o inverno e o verão, e as amostras de água foram analisada quanto ao oxigênio dissolvido, pH, temperatura, salinidade, nutrientes inorgânicos dissolvidos (NID), seston, matéria orgânica particulada (MOP) e pigmentos. Os resultados mostraram que a química da água apresenta variações temporal e espacial. Grande variabilidade foi também observada nas razões C:N:P do MOP (Agosto, 112:30:1; Dezembro, 59:11:1) e nas concentrações de NID. As concentrações de clorofila-*a* e amônia (4.5 $\mu g\ L^{-1}$ - 71.2 $\mu g\ L^{-1}$, e 0.20 μM - 52,6 μM, respectivamente) caracterizam a área do ISEO como eutrófica. A dispersão do material não é efetiva em certas condições oceanográficas.

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