Hydrobiologia **440**: 307-315, 2000.

Nutrification impacts on coral reefs from northern Bahia, Brazil

O. S. Costa Jr.[1,2], Z. M. A. N. Leão[2], M. Nimmo[1] & M. J. Attrill[1]

[1] *Plymouth Environmental Research Centre, University of Plymouth,*
Drake Circus, Plymouth, Devon, PL4 8AA, United Kingdom. Tel: +44 1752 232951
E-mail: O.Costa@plymouth.ac.uk

[2] *Coastal Studies Laboratory, Geoscience Institute, Federal University of Bahia, Brazil*

Key words: coral reef, eutrophication, nutrients, groundwater contamination, Brazil

Abstract

Coral reefs extend for 20 km along the north coast of the state of Bahia, Brazil. Over the last 15 years, this region has experienced an acceleration of generally unplanned urbanisation, with the irregular and indiscriminate use of septic tanks in urban centres contaminating the groundwater. This infiltration of nutrients and pathogens is facilitated by both the soil permeability and an accented hydraulic head, which eventually leads to the percolation of nutrient-rich groundwater seaward to the reefs. The groundwater nutrient concentrations (nitrate, nitrite, ammonia, phosphate and silicate) from Guarajuba beach (a highly urbanised area) are over 10 times higher than groundwater from Papa Gente beach, an area of low human occupation. The pH values of the groundwater samples also indicate the predominance of reducing conditions in Guarajuba, due to the high availability of organic matter and consequent bacterial activity. Additionally, faecal coliform data indicate domestic wastewater as the source of groundwater contamination. High densities of macroalgae and heterotrophic organisms on the impacted reefs as well as higher concentrations of nutrients evoke the effects of eutrophication on this coral reef ecosystem. These data suggest that the high availability of nutrients is affecting the trophic structure in the study area, especially in Guarajuba, with the increased turf and macroalgae growth reducing light penetration to the coral colonies, competing with them for space and inhibiting the settlement of new coral larvae.

Introduction

In marine systems the eutrophication process is dependent on a complex set of interactions. The accumulation of organic matter (derived from primary production) will only occur if nutrient supply to the system exceeds the losses such as deep layer sedimentation, denitrification and the export of zooplankton and detritus to adjacent waters. In coral reefs, despite the extremely high gross productivity at low levels of nutrient supply, the concentration of particulate material in the water column is low and biological activity is concentrated in the benthos (D'Elia & Wiebe, 1990). However, with continuous nutrient-enrichment of coastal waters, eutrophication constitutes an increasing threat to the health and biodiversity of coral reefs, either directly (calcification rates – Marubini & Davies, 1996, Marubini & Atkinson, 1999) or by enhancing secondary stresses on corals, such as phytoplankton blooms, sedimentation increase, epiphytic algal growth, coral diseases, light limitation, elevated water temperatures and coral bleaching (Bell, 1992). In coastal coral reefs, eutrophication has primarily anthropogenic causes resulting directly from population growth and development (Hallock *et al.*, 1993). In particular, the last 2 decades has seen an enhanced research effort to assess the significance of nutrient enriched groundwater inputs to coastal coral reefs, such as those reported in Guam (Marsh, 1977), Australia (Johannes, 1980), Hawaii (Bienfang, 1980), Jamaica (D´Elia *et al.*, 1981), Barbados (Lewis, 1985), Bermuda (Jickells *et al.*, 1989), and Florida (Lapointe *et al.*, 1990; Shinn *et al.*, 1994; Szmant & Forrester, 1996).

Brazil has the only coral reefs in the south-western Atlantic Ocean and the coast of Bahia State is the most extensive and richest area. Although a large number of impacts has been documented on Brazilian reefs (Belém *et al.*, 1986;

Leão, 1996; Leão & Ginsburg, 1997; Leão *et al.*, 1997), there is no information regarding the role of eutrophication and no published literature addressing the problem of nutrient enrichment in these coral reef systems. In the north coast of Bahia (Fig. 1) the coastal coral reefs occur along a small strip of discontinuous carbonate build-ups. In the last 15 years this region has experienced an accelerated urbanisation process, with the construction of roads and the rapid expansion of small villages, especially in Guarajuba area, leading to an increase in the number of residents and tourists. This comparatively unplanned human occupation was not accompanied by the implantation of an adequate sewage treatment system, thus stimulating the irregular and indiscriminate use of septic tanks in the urban core. The construction of a sewage collection system only began in the spring of 1997.

In this study, we examine the contamination of groundwater and its pathway, and attempt to assess the relationship between the contaminated groundwater seepage and the eutrophication of the coastal coral reefs. To produce evidence of such contamination, we analysed the inorganic nutrient (nitrate, nitrite, ammonia, phosphate and silicate) concentration and pathogen content (*E. coli*) of samples taken from coastal lakes, groundwater and coral reefs during both rainy and dry seasons. A quantitative assessment of the benthic macrofauna and macroflora in the reef flat was also performed. In order to evaluate the anthropogenic influence on the eutrophication process, the study was conducted on two Bahian coastal coral reef systems with different levels of human occupation (urbanised and underdeveloped).

Study area

Situated in the northern portion of the Brazilian State of Bahia (38°03'W and 12°38'S), the coral reefs extend for 20 km along the coastline, between the beaches of Abaí and Papa Gente (see Fig. 1). These reef systems are located on the narrowest part of the Eastern Brazilian Shelf (15km average width) in a transition from siliciclastic to carbonatic sediments (Leão *et al.*, 1988). In this area, two transects were established perpendicular to the coastline (Fig. 1): transect 1 is located at Guarajuba beach, an urbanised village; transect 2 is located at Papa Gente beach, an area of low population density.

The coastal belt along the State of Bahia has a tropical humid climate, with an elevated average temperature (25ºC) and a high rainfall (1800mm/year). The rainy season occurs between April to July, producing 53% of the annual rainfall, whilst the dry season extends from September to December (Rao *et al.*, 1993). Dominant E winds occur in January and September, NE winds are frequent from October to December and from February to March and stronger SE winds can occur during storms (April to August; DHN, 1993). The tides (from the port of Salvador city, 50km distant from study site), ranged between 2.8m (maximum high) to -0.2m (minimum low) (DHN, 1997).

The coastal plain in the study area is characterised by two generations of sand barriers, formed by quaternary sea level fluctuations (Martin *et al.*, 1979). They run parallel to the coastline, generally in a NE-SW direction. Between the two generations of sand barriers occurs a shallow, sediment filled lake. Adjacent to the beaches occur emergent reefs, also parallel to the coastline, whose dimensions vary from 50m to 2km long and 20m to 500m wide. Depth of water around these reefs does not exceed 10m (Leão, 1996). Typical reef lagoons do not exist and the back reef zone usually slopes downward to the quartz-sand beaches. However, the reef tops have a horizontal flat, which remain exposed during low tides. On these exposed surfaces, large dead coral heads (that have been truncated by erosion) alternate with small pools and meandering channels where small heads of living corals survive along with a variety of soft algae. A few kilometres off the coast shallow bank reefs occur, with irregular shapes and dimensions. Depth here varies from 5 to 20m (Nolasco & Leão, 1986).

Materials and methods

The comparative nutrient study between the two sites was based on the determination of nitrogen compounds (nitrate, nitrite and ammonia), phosphate (orthophosphate) and silicate (reactive silica) concentrations. Salinity, temperature, pH and faecal coliform organisms, which were used as tracers of groundwater percolation, were also measured. Water and groundwater sampling were undertaken during May and June (rainy season) and November and December (dry season) 1997.

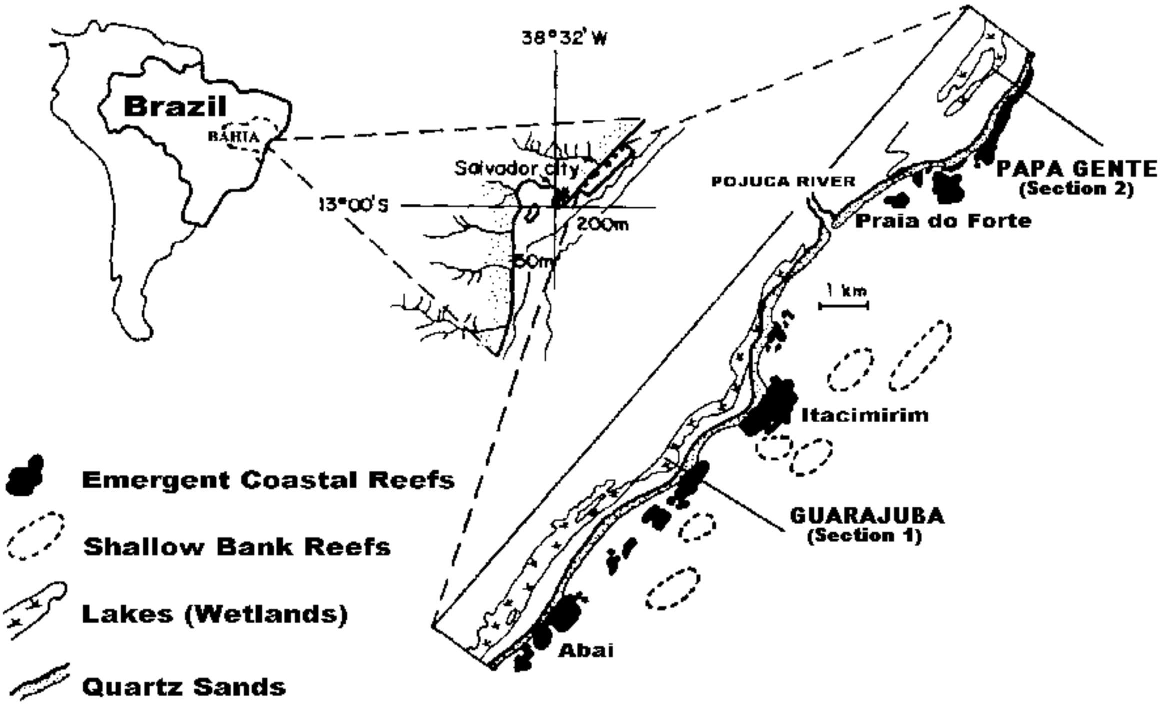

Figure 1. Study area. The Guarajuba reefs are in a dense urbanised region; the Papa Gente reefs are in a underdeveloped region (modified from Leão et al., 1997)

Seven wells were core-drilled (maximum depth 2.34m) into the external sandy barrier, four at Papa Gente and three at Guarajuba, to determine the groundwater level and to collect water samples. These wells were fitted with PVC casings (30cm diameter) and the samples, collected in glass and polyethylene bottles, were filtered through a GF/C filter and frozen until analysis. For the nutrient analysis a total of 33 samples were taken from Guarajuba and 37 from Papa Gente, both in the internal lakes, groundwater and coral reefs. For the faecal coliform counting a total of 13 samples were taken from Guarajuba and 12 from Papa Gente.

Inorganic nutrient concentrations were determined according the methods described in Grasshoff (1983). The light absorption was measured in a spectrophotometer (Varian, model DMS80). The detection limits of these methods in our experiment were found to be 0.03μM for PO_4^{3-}, 1μM for SiO_2, 0.01μM for NO_3^- and 0.05μM for NH_3. The efficiency of nitrate reduction in the cadmium column was regularly validated to be over 95%. All nutrient values were corrected by using analytical blanks.

Salinity was determined using a Sper Scientific refractometer and temperature with a mercury thermometer. To measure pH the Oakton pH Tester-1 kit (model 35624-00) was used. Faecal coliform count was determined using the membrane filtration technique (APHA, 1992).

The ecological assessment (determination of percent cover of macroalgae and heterotrophs) was performed on the flat for each studied reef utilising a PVC 1m² quadrat with a grid of 10x10cm subdivisions (each of it corresponding to 1% of the total area) formed using nylon strands. Data were obtained from a total of 66 haphazard quadrats in Guarajuba (30 in the rainy season and 36 in the dry season) and 64 in Papa Gente (28 in the rainy season and 36 in the dry season) distributed throughout the whole reef flat. For each quadrat, the area covered by each studied category was recorded: sponges, Zoanthidea, corals (stony corals as well as hydrocorals and soft corals) and algae (macroalgae and turfs). We also recorded the percent of bare and/or sand covered areas. According Foster *et al.* (1991) these percent cover estimates could be used as measures of abundance.

The topographic level of the coastal sand barrier in the two transects at Guarajuba and Papa Gente beaches was also measured in order to estimate the hydraulic head between sea and lake levels, as well the amount of groundwater that reaches the coastal reefs.

Table 1. Mean values of all variables measured at both studied sites: (a) rainy season (n=18) and (b) dry season (n=18)

PAPA GENTE						VARIABLES	GUARAJUBA				
Lake	**Well 1**	**Well 2**	**Well 3**	**Well 4**	**Reef**		**Lake**	**Well 1**	**Well 2**	**Well 3**	**Reef**
a) Rainy season											
0.0	0.0	0.0	0.0	0.6	34.0	**Salinity (PSU)**	0.0	0.0	0.0	0.8	33.3
30.2	27.7	27.3	27.0	27.0	26.0	**Temperature (°C)**	29.8	26.8	25.8	27.9	28.6
5.7	6.7	7.0	7.5	7.4	8.9	**PH**	4.7	5.0	5.2	4.4	8.1
0.47	0.25	0.32	0.25	0.17	0.09	**Nitrite (µM)**	0.22	1.30	1.49	1.42	0.16
6.54	5.14	5.47	5.94	2.16	1.68	**Nitrate (µM)**	4.38	8.47	16.07	21.20	8.03
13.98	11.24	11.70	10.65	8.73	3.59	**Ammonia (µM)**	2.73	64.14	76.25	24.75	4.81
3.06	2.02	1.52	1.67	1.98	0.18	**Phosphate (µM)**	0.25	7.86	7.27	7.59	1.42
35.82	17.48	14.41	12.36	11.67	8.22	**Silicate (µM)**	48.64	104.08	126.47	91.57	11.21
b) Dry season											
0.0	0.0	0.0	0.1	0.8	35.0	**Salinity (PSU)**	0.0	0.0	0.0	1.2	33.7
28.5	28.0	26.5	27.0	26.0	27.5	**Temperature (°C)**	29.5	27.7	26.8	26.2	28.7
5.5	4.6	5.0	6.2	7.0	8.3	**PH**	4.9	4.3	3.9	4.0	8.1
< 2	< 2	-	-	-	-	***E. coli* (col./100mL)**	< 2	6	8	4	-
0.25	0.18	0.20	0.15	0.13	0.05	**Nitrite (µM)**	0.24	0.53	0.62	0.59	0.34
2.83	2.65	2.32	1.88	1.27	0.41	**Nitrate (µM)**	2.57	46.20	65.67	42.14	5.75
3.87	3.30	2.67	2.54	1.86	0.86	**Ammonia (µM)**	5.62	74.22	88.82	81.23	10.69
2.53	2.07	1.72	0.86	0.44	0.13	**Phosphate (µM)**	0.59	6.59	4.95	4.78	0.35
122.48	105.04	96.80	64.86	43.40	14.43	**Silicate (µM)**	203.54	197.77	203.38	201.30	25.86

Results

The topographic profiles for both transects (Guarajuba and Papa Gente) are shown in Figure 2. These profiles refer to the external sandy barrier, located between the lake and the reef, where the groundwater sampling occurred. The Papa Gente transect extended for 840m, bounded by the lake margin and the reef slope. The vertical distance between the lake water level and mean sea level is 5.02m (see Fig. 2a) but can reach 5.90m at low tides, generating a groundwater flux of approximately 45 litres.m^{-2}.day^{-1} towards the coastal reefs. The Guarajuba transect has an extension of 605m and a vertical drop of 2.06m between the lake and sea level (see Fig. 2b) which can reach 3.5m in lower tides. In this case, the flow rate of groundwater to the reefs is approximately 20 litres.m^{-2}.day^{-1}.

Mean values for physico-chemical variables in both seasons are presented in Table 1. The seasonal and spatial differences were evaluated statistically using a 2-way ANOVA. Water temperatures in lake and groundwater samples were influenced mainly by changes in the insolation and rainfall between the wet and dry seasons, not varying between the two studied sites (Tables 2a and 2b). In the reef area, however, the action of waves and currents led to extremely variable temperature behaviour, not only between seasons but also between sites (Table 2c). Salinity of groundwater was consistently less than 2 PSU (Table 1) and appeared to be independent of tidal action. In the lakes all the samples were equal to 0 PSU, therefore indicating a unidirectional flow of groundwater migrating seaward to the reefs. Conversely, the salinity in the reef area is highly influenced by a combination of tides and groundwater percolation, as the lowest values were found during low tides when the flux of low salinity groundwater is intensified. This pattern was consistent for both study sites and in the two seasons (Table 2c). The pH, however, responded differently and significant differences were recorded, not only between the two sites (ρ=0.000003) but also between seasons (Table 2c). Lake and groundwater samples in Guarajuba presented lower pH values than Papa Gente in all seasons (Table 1).

Table 2. Results of anova for all investigations. (a) lake (wetlands) ; (b) groundwater (wells); (c) reef pools

	Sites **Guarajuba & PapaGente**		**Seasons** **(Dry & Rainy)**		**Interaction** **(site & season)**	
Variable	**F (1,32)**	**p**	**F (1,32)**	**p**	**F (1,32)**	**p**
(a)						
Salinity		All	**samples**	= 0 PSU		
Temperature	0.7033	0.4079	8.0572	***0.0078***	4.2616	***0.0472***
pH	21.9298	***<0.0001***	3.4312	0.0732	1.5079	0.2284
NO_3	247.708	***<0.0001***	1292.513	***<0.0001***	154.3320	***<0.0001***
NO_2	321.1496	***<0.0001***	181.6774	***<0.0001***	273.6422	***<0.0001***
NH_4	8081.11	***<0.0001***	4681.00	***<0.0001***	15145.71	***<0.0001***
PO_4	2293.389	***<0.0001***	3.8360	***<0.0001***	76.7920	***<0.0001***
SiO_2	4541.71	***<0.0001***	30070.32	***<0.0001***	2399.18	***<0.0001***
(b)						
Salinity	2.4828	0.1249	2.4828	0.1249	0.2759	0.6031
Temperature	3.7448	0.0619	21.8248	***<0.0001***	1.2414	0.2735
pH	314.1617	***<0.0001***	5.4512	0.2599	0.0097	0.9220
NO_3	9954.407	***<0.0001***	1114.513	***<0.0001***	1322.028	***<0.0001***
NO_2	6567.875	***<0.0001***	1726.464	***<0.0001***	1401.201	***<0.0001***
NH_4	570477.3	***<0.0001***	154277.1	***<0.0001***	251611.8	***<0.0001***
PO_4	7258.291	***<0.0001***	1389.548	***<0.0001***	117.760	***<0.0001***
SiO_2	43045.39	***<0.0001***	15231.04	***<0.0001***	4631.10	***<0.0001***
(c)						
Salinity	3.6333	0.0657	1.5973	0.2154	0.4125	0.5253
Temperature	36.0594	***<0.0001***	6.1346	***0.0187***	5.1211	***0.0306***
pH	31.6098	***<0.0001***	8.8049	***0.0057***	7.9024	***0.0084***
NO_3	3782.730	***<0.0001***	346.949	***<0.0001***	28.305	***<0.0001***
NO_2	211.3174	***<0.0001***	107.8150	***<0.0001***	250.1053	***<0.0001***
NH_4	41502.50	***<0.0001***	3363.48	***<0.0001***	25201.72	***<0.0001***
PO_4	4867.098	***<0.0001***	2841.483	***<0.0001***	2365.204	***<0.0001***
SiO_2	430.3752	***<0.0001***	900.9483	***<0.0001***	147.3870	***<0.0001***

Faecal coliform counts were performed to provide additional indications of anthropogenic contamination of the groundwater, rather than the occurrence of pathogens *per se*. Sampling was undertaken only in the dry season, when the number of tourists is greater due to the vacation period. These results are also shown in Table 1 and suggest that groundwater in Guarajuba has been contaminated by the outflow of septic tanks.

The mean nutrient concentrations between the two sites were distinctly different (Tables 1 and 2), despite their proximity and similar geologic and geomorphologic conditions, with the populated site (Guarajuba) containing nutrients at levels many times higher than the underdeveloped site (Papa Gente). Besides differences from one site to another, the nutrients also behaved distinctly between seasons (Tables 2a-c), reflecting the role of rainfall in nutrient dilution and transport.

The silicate concentrations varied between 5-17μM at Papa-Gente and 17-104μM at Guarajuba (Table 1), and the concentrations of ammonia in Guarajuba groundwater were about 10 times higher than Papa Gente, particularly in the dry season. High concentrations of dissolved phosphorus were also found in Guarajuba wells; the mean concentration of phosphorus for all groundwater samples at this site was about 3 times higher than the Papa-Gente site (see Table 1). The nitrate concentrations also followed the pattern of the other nutrients, with the highest levels observed in Guarajuba, mainly in dry season.

Table 3. Comparative nitrate and phosphate values for coastal reefs under land-based nutrient fluxes, including the studied reefs of Guarajuba and Papa Gente.

Coral reef sites (references)	Nitrate (μM)	Phosphate (μM)
Tumon Bay, Guam (Marsh, 1977)	**4.14 – 8.04**	**0.14 – 0.55**
Guarajuba, Brazil (this work)	**2.26 – 12.07**	**0.12 – 1.62**
Jakarta Bay, Indonesia (Tomascik *et al.*, 1993)	**2.71**	**1.36**
Pago Bay, Guam (Marsh, 1977)	**0.22 – 3.31**	**0.15 – 0.23**
Papa Gente, Brazil (this work)	**0.34 – 2.57**	**0.09 – 0.32**
Barbados (Tomascik & Sander, 1985, 1987a, 1987b)	**0.32 – 0.71**	**0.06 – 0.11**
Florida Keys: Inshore (Szmant & Forrester, 1996)	**0.46 – 1.07**	**0.01 – 0.17**
Florida Keys: Offshore (Szmant & Forrester, 1996)	**0.16 – 0.32**	**0.01 – 0.11**
Bahamas (Ferrer & Szmant, 1988)	**0.29**	**0.08**
Eniwetok, Ilhas Marshall (Webb *et al.*, 1975; Pilson & Betzer, 1973)	**0.10 – 0.30**	**0.16 – 0.18**

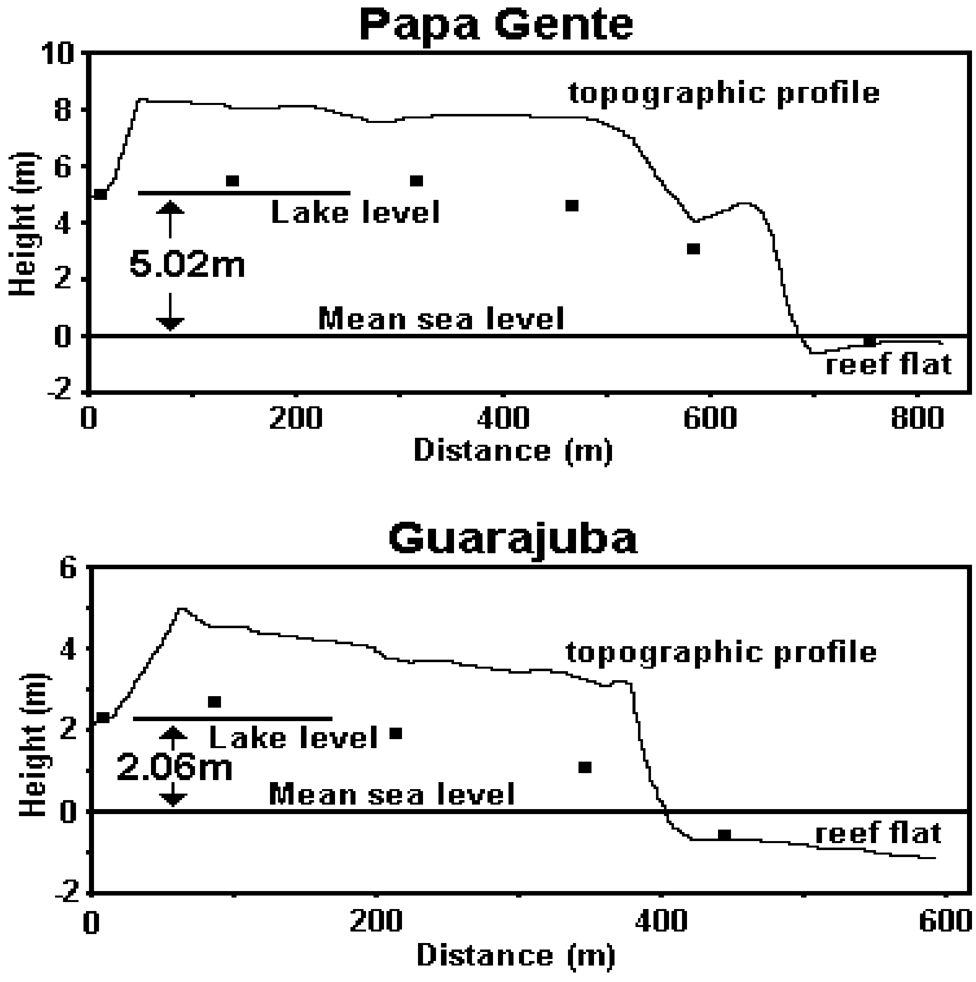

Figure 2. Topographic profiles of the sandy barrier in both study sites showing the hydraulic head between lake and sea levels. The squares indicate groundwater sampling points.

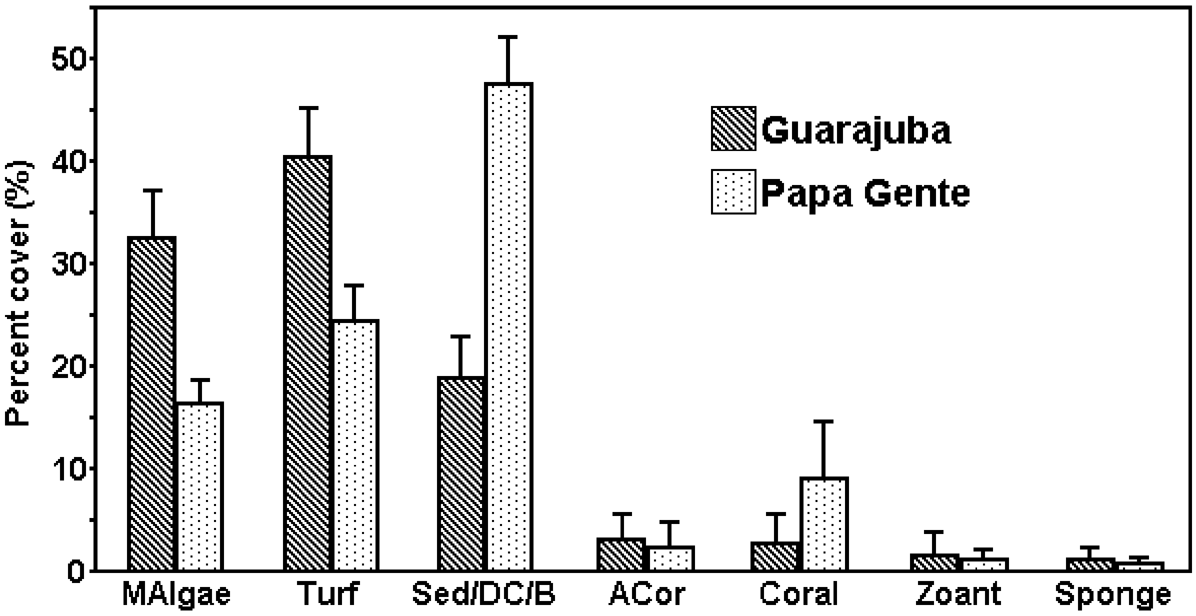

Figure 3. Reef flat percent cover of each major benthic community component in both studied sites. (Mal;gae = macroalga; Turf = turf alga; Sed/DC/B = sediment, dead coral and/or bare areas; Acor = coralline algae; Coral = living coral; Zoant = zoanthids; Sponge = sponges).

Results of the ecological assessment on the reef flats are presented in Figure 3. The algae (macro algae and turf algae) constitute the main component of the benthic community in the studied reef flats with 77% of total cover in Guarajuba and 41% in Papa Gente. Coral cover is extremely low varying from 2.31% in Guarajuba to 8.62% in Papa Gente. The other heterotrophs (sponges and zoanthids) contribute just over 1.2% of the total cover in Guarajuba but less than 0.5% in Papa Gente.

Discussion

Most of the bedrock underlying the study area is a highly porous sandstone and beach rock. The groundwater level is extremely shallow, as the drilling has shown (average value of 1.7m depth), and the contaminated wastewater in the septic tanks can easily flow through it. The pH values found in Guarajuba wells highlight the more reducing conditions of groundwater at this site, as a response to higher levels of organic matter. Similarly, faecal coliform counts, although low, do indicate that groundwater in Guarajuba has been contaminated by human waste. In addition, high concentrations of ammonia were found in groundwater, indicating contamination from septic tanks (Pitt *et al.,* 1975). Therefore, reducing conditions dominate this environment. However, differences in data obtained from the two seasons, and the lower levels of ammonia and higher nitrate found in the rainy season, may suggest that a recharge of the permeable aquifer by oxygenated rainfall infiltration can allow an increasing oxidation of ammonia to nitrate. Shinn *et al.* (1994) found similar patterns while studying percolation of human-waste contaminated groundwater in the Florida Keys.

Elevated concentrations of nitrate can be produced locally by groundwater discharge and surface runoff (Marsh, 1977) and therefore can also be used as an indicator of wastewater contamination. Again the average concentration values in the highly urbanised area were many times that of the undeveloped site, varying from 0.41-1.68μM in Papa Gente, and from 5.75-8.03μM in Guarajuba. The relatively low levels of intermediate nitrite, however, could be explained by the fact that ammonia oxidation (to nitrite) and nitrite oxidation (to nitrate) are closely coupled (Webb & Wiebe, 1975).

Silicate concentrations, along with salinity values, can be used as a marker of groundwater discharge (Montaggionni *et al.*, 1993). In the study area, the silicate values indicate that groundwater is likely to be producing a significant input of terrestrial nutrients onto the reef. Marsh (1977) reported that groundwater seepage to the fringing reef at Tumon Bay (Guam) occurred in the form of rills of brackish water (from a subterranean lens) which was observable at low tide. In our study area, a similar seepage occurred at both low and high tide due to the substantial drop between lake and sea water levels (see Fig. 2). Therefore, with a flow rate of at least 20 litres.m^{-2}.day^{-1}, the groundwater percolation in the study area is likely to constitute one of the main sources of nutrient-rich water to the coastal reefs, especially in Guarajuba.

This model of nutrient enrichment via groundwater seepage is a plausible mechanism that can explain the eutrophication occurring in coral reef systems on the northern coast of Bahia. The nutrient availability seems to be affecting the community structure and, in that condition, the fast-growing turf and macroalgae tend to colonise most of the open substrate, inhibiting the settlement of new coral larvae (Birkeland, 1977; Hallock *et al*., 1993). As the fishing pressure is the same for both studied sites (there is a fishing community covering the region, so no differential in predator removal) as well as the circulation pattern and geomorphology, the only factor that could explain the difference in the alga/coral cover between the two sites is the differential availability of nutrients. Additionally, the increases in density of bioeroders like sea urchins (e.g. *Echinometer lucunter, Eucidares* sp.) and sponges (e.g. *Anthosigmella varians, Spirastrella* sp.*, Cinachirella alboclade* and *Cliona* sp.) reflect the eutrophic conditions. These consequences are in agreement with previous work (Hallock & Schlager, 1986; Hallock, 1988; Montaggionni *et al*., 1993) in which excess of nutrients appears to be clearly deleterious to reef building biota and calcification rates. Table 3 presents a comparison between the data produced in this study with those reported in the literature for coastal reefs under the effect of land-based nutrient sources.

A further consequence of eutrophication is the reduction of water transparency as a product of nutrient increase, limiting the depth ranges of zooxanthelate corals, thereby reducing carbonate production. Thus, in eutrophic conditions, many fast-growing competitors are bioeroders that actively destroy the reef structure and, once the rates of carbonate production and bioerosion are similar, even modest increases in nutrient availability can shift a reef community from net production to net erosion (Ogden *et al*., 1973; Sammarco *et al*., 1974). This is probably the case in the northern bahian reefs, although more studies on bioerosion rates are required to support this affirmation.

In previous investigations undertaken in the reefs of northern Bahia, the implicit assumption has been that corals declined as a function of historical changes in sea level. However, even being true, this may be a too simplistic explanation, as the nutrification of reefs in this area is obvious and an eventual recovery will be limited by effects such as declining populations of reef building corals, increasing abundance of benthic algae, destabilised herbivore populations, increasing rates of bioerosion and reduction of calcification.

To further understand the process, future work should consider the evaluation of biotic pigments (chlorophyll and ATP) in the water around the reefs, since the biota, especially the benthic biota, play an important role in the uptake and retention of available nutrients (Laws & Redalje, 1979; Szmant-Froelich, 1983; Hallock *et al*., 1993; Szmant, 1997). In addition, the sediment evaluation (organic matter, carbon content, bacterial activity) should bring complementary information about the nutrification process, as the sediment constitute the major nutrient source for benthic producers in shallow water systems (Szmant & Forrester, 1996; Szmant, 1997).

Acknowledgements

The authors are grateful to Dr Vera Cancio, Rosane, Erika, Ana Paula and Audrey (Institute of Chemistry/UFBA) for their help with nutrient analysis**;** to Adriana, Miguel, Kelmo and Leda (Institute of Biology/UFBA) for help with algae, sponges and zoanthids identification**;** and to staff from Coastal Studies Laboratory/UFBA for incentive and support. This work was supported by grants from CAPES and CNPq (Brazilian Federal Government) and CADCT (Bahian State Government).

References

APHA, 1992. Standard methods for the examination of water and wastewater. APHA/AWWA/WEF, Washington, 949 pp.

BELEM, M. J. C.; C. ROHLFS; D. O. PIRES & C. B. CASTRO, 1986. S.O.S. corais. Ciência Hoje 5(26):34-42.

BELL, P. R. F., 1992. Eutrophication and coral reefs – some examples in the Great Barrier Reef lagoon. Water Research 26(5):553-568.

BIENFANG, P., 1980. Water quality characteristics of Honokohau harbour: A subtropical embayment affected by groundwater intrusion. Pacific Science 34:279-291.

BIRKELAND, C., 1977. The importance of rate of biomass accumulation in early successional stages of benthic communities to the survival of coral recruits. In proceedings of international coral reef symposium, 3, Miami, 1977, Florida, 1:15-21.

D'ELIA, C. F.; K. L. WEBB & J. W. PORTER, 1981. Nitrate-rich groundwater inputs to Discovery Bay, Jamaica: A significant source of N to local coral reefs? Bull. mar. Sci. 31(4):903-910.

D'ELIA, C. F. & W. J. WIEBE, 1990. Biogeochemical nutrient cycles in coral-reef ecosystems. In Z. Dubinsky (ed), Ecosystems of the world 25: Coral reefs, Elsevier Pub., Amsterdam, 49-74.

DHN, 1993. Atlas de Cartas Piloto. Marinha do Brasil, Diretoria de Hidrografia e Navegação, Rio de Janeiro, 24 pp.

DHN, 1997. Tábuas das Marés. Marinha do Brasil, Diretoria de Hidrografia e Navegação, Rio de Janeiro, 108 pp.

FERRER L. M. & A. M. SZMANT, 1988. Nutrient regeneration by the endolitic community in coral skeletons. In proceedings of international coral reef symposium, 6, Townsville, 1988, Australia, 3:1-4.

FOSTER, M.S.; C. HARROLD & D.D. HARDIN, 1991. Point vs. Photo quadrat estimates of the cover of sessile marine organisms. *J. Exp. Mar. Biol. Ecol.*, 146:193-203.

GRASSHOFF, K.; M. EHRHARDT & K. KREMLING, 1983. Methods of seawater analysis. Verlag Chemie, Germany, 419 pp.

HALLOCK, P., 1988. The role of nutrient availability in bioerosion: Consequences to carbonate buildups. Palaeogeography, Palaeoclimatology, Palaeoecology 63:275-291.

HALLOCK, P. & W. SCHLAGER, 1986. Nutrient excess and the demise of coral reefs and carbonate platforms. Palaios 1:389-398.

HALLOCK, P.; F. MULLER-KARGER & J. C. HALAS, 1993. Coral reef decline – anthropogenic nutrients and the degradation of Western Atlantic and Caribbean coral reefs. Research and Exploration 9(3):358-378.

JICKELS, T. D.; S. R. SMITH; S. BOYD & A. H. KNAP, 1989. Phosphorus limitation in the Bermuda inshore waters. Estuar. coast. shelf Sci. 28:121-132.

JOHANNES, R. E., 1980. The ecological significance of the submarine discharge of groundwater. Mar. Ecol. Prog. Ser. 3:365-373.

LAPOINTE, B. E.; J. D. O'CONNEL & G. S. GARRET, 1990. Nutrient couplings between on-site sewage disposal systems, groundwaters and nearshore surface waters of the Florida Keys. Biogeochemistry 10:289-307.

LAWS, E. A. & D. G. REDALJE, 1979. Effect of sewage enrichment on the phytoplankton population of a tropical estuary. Pacific Science 33:129-144.

LEÃO, Z. M. A. N., 1996. The coral reefs of Bahia: Morphology, distribution and the major environmental impacts. Ann. acad. bras. Ci. 68(3):439-452.

LEÃO, Z. M. A. N. & R. GINSBURG, 1997. Living reefs surrounded by siliciclastic sediments: The Abrolhos coastal reefs, Bahia, Brazil. In proceedings of international coral reef symposium, 8, Panama, 1996, Panama, 2:1767-1772.

LEÃO, Z.M.A.N.; T.M.F. ARAÚJO & M.C. NOLASCO, 1988. The coral reefs off the coast of eastern Brazil. In proceedings of international coral reef symposium, 6, Townsville, 1988, Australia, 3:339-347.

LEÃO, Z. M. A. N.; R. K. P. KIKUCHI; M. P. MAIA & R. A. L. LAGO, 1997. A catastrophic coral cover decline since 3000 years B.P., Northern Bahia, Brazil. In proceedings of international coral reef symposium, 8, Panama, 1996, Panama, 1:583-588.

LEWIS, J. B., 1985. Groundwater discharge onto coral reefs, Barbados (West Indies). In proceedings of international coral reef congress, 5, Tahiti, 1985, French Polynesia, 6:477-481.

MARSH, J. A. Jr., 1977. Terrestrial inputs of nitrogen and phosphorus on fringing reefs of Guam. In proceedings of international coral reef symposium, 3, Miami, 1977, Florida, 1:331-336.

MARTIN, L.; J. M. FLEXOR; G. S. VILAS BOAS; A. C. S. P. BITTENCOURT & M. M. M. GUIMARÃES, 1979. Courbe de variations du niveau relatif de la mer au cours des 7000 dernières années sur un secteur homogène du littoral brésilien (Nord de Salvador - Bahia). In proceedings of international symposium on coastal evolution in the quaternary, São Paulo, 1978, Brazil, 264-274.

MARUBINI, F. & M. J. ATKINSON, 1999. Effects of lowered pH and elevated nitrate on coral calcification. Mar. Ecol. Prog. Ser. 188:117-121.

MARUBINI, F. & P. S. DAVIES, 1996. Nitrate increases zooxanthellae population density and reduces skeletogenesis in corals. Mar. Biol. 127:319-328.

MONTAGGIONI, L. F.; P. CUET & O. NAIM, 1993. Effect of nutrient excess on a modern fringing reef (Reunion Islands, Western Indian Ocean): Geological implications. In R. N. Ginsburg (compiler), proceedings of colloquium on global aspects of coral reefs: Health, hazards and history, RSMAS, University of Miami, Florida, 397-403.

NOLASCO, M. C. & Z. M. A. N. LEÃO, 1986. The carbonate buildups along the northern coast of the State of Bahia, Brazil. In: J. RABASSA (ed) Quaternary of South America and Antarctic Peninsula. A.A. Balkama Pub, Rotterdam, 4:159-190.

OGDEN, J. C.; R. A. BROWN & N. SALESKY, 1973. Grazing by the echinoid *Diadema antillarum* Philippi: Formation of halos around West Indian patch reefs. Science 182:715-717.

PILSON, M. E. Q. & S. B. BETZER, 1973. Phosphorus flux across a coral reef. Ecology 54:581-588.

PITT, W. A.; H. C. MATTRAW & H. KLEIN, 1975. Ground-water quality in selected areas serviced by septic tanks, Dade County, Florida. U.S.Geological Survey Open-File Report 75-607, 82 pp.

RAO, V. B.; M. LIMA & S. H. FRANCHITO, 1993. Seasonal and interannual variations of rainfall over Eastern Northeast Brazil. Journal of Climate 6:1754-1763.

SAMMARCO, P. W.; J. S. LEVINTON & J. C. OGDEN, 1974. Grazing and control of coral reef community structure by *Diadema antillarum* Philippi (Echinodermata: Echinoidea): A preliminary study. J. mar. Res. 32:47-53.

SHINN, E. A.; R. S. REESE & C. D. REICH, 1994. Fate and pathways of injection-well effluent in the Florida Keys. U.S.Geological Survey Open-File Report 94-276, 116 pp.

SZMANT-FROELICH, A., 1983. Functional aspects of nutrient cycling on coral reefs. In The ecology of deep and shallow coral reefs. NOAA Undersea Research Program, 1:133-139.

SZMANT, A. M. & A. FORRESTER, 1996. Water column and sediment nitrogen and phosphorus distribution patterns in the Florida Keys, USA. Coral Reefs 15:21-41.

SZMANT, A. M., 1997. Water quality characterization and the health of coral reefs. Internet WWW page at URL: http://www.epa.gov/OWOW/oceans/coral/szmant.html (accessed 19/11/1997)

TOMASCIK, T. & F. SANDER, 1985. Effects of eutrophication on reef-building corals. I – Growth rate of the building coral *Montastrea annularis*. Mar. Biol. 87:143-155.

TOMASCIK, T. & F. SANDER, 1987a. Effects of eutrophication on reef-building corals. II – Structure of scleractinian coral communities on fringing reefs, Barbados, West Indies. Mar. Biol. 94:53-75.

TOMASCIK, T. & F. SANDER, 1987b. Effects of eutrophication on reef-building corals. III – Reproduction of the reef-building coral *Porites porites*. Mar. Biol. 94:77-94.

TOMASCIK, T.; SUHARSONO & A. J. MAH, 1993. Case histories: A historical perspective of the natural and anthropogenic impacts in the Indonesian Archipelago with a focus on the Kepulauan Seribu, Java Sea. In R. N. Ginsburg (compiler), proceedings of colloquium on global aspects of coral reefs: Health, hazards and history, RSMAS, University of Miami, Florida, 304-310.

WEBB, K. L. & W. J. WIEBE, 1975. Nitrification on a coral reef. Can. J. Microbiol. 21:1427-1431.

WEBB, K. L.; K. W. DuPAUL; W. J. WIEBE; W. SOTTILLE & R. E. JOHANNES, 1975. Enewetak (Eniwetok) Attoll: Aspects of the nitrogen cycle on a coral reef. Limnol. Oceanogr. 20:198-210.