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Assessment of the trophic status of four coastal lagoons and one estuarine delta, eastern Brazil

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Abstract Anthropogenic eutrophication of aquatic ecosystems continues to be one of the major environmental issues worldwide and also of Brazil. Over the last five decades, several approaches have been proposed to discern the trophic state and the natural and cultural processes involved in eutrophication, including the multi-parameter Assessment of Estuarine Trophic Status (ASSETS) index model. This study applies ASSETS to four Brazilian lagoons (Mundaú, Manguaba, Guarapina, and Piratininga) and one estuarine delta (Paraíba do Sul River), set along the eastern Brazilian coast. The model combines three indices based on the pressure–state–response (PSR) approach to rank the trophic status and forecast the potential eutrophication of a system, to which a final ASSETS grade is established. The lagoons were classified as being eutrophic and highly susceptible to eutrophication, due primarily to their longer residence times but also their high nutrient input index. ASSETS classified the estuary of the Paraíba do Sul river with a low to moderate trophic state (e.g., largely mesotrophic) and low susceptibility to eutrophication. Its nutrient input index was high, but the natural high dilution and flushing potential driven by river flow mitigated the susceptibility to eutrophication. Eutrophication forecasting provided more favorable trends for the Mundaú and Manguaba lagoons and the Paraíba do Sul estuary, in view of the larger investments in wastewater treatment and remediation plans. The final ASSETS ranking system established the lagoons of Mundaú as "moderate," Manguaba as "bad," Guarapina as "poor," and Piratininga as "bad," whereas the Paraíba do Sul River Estuary was "good."

Keywords Trophic state · Eutrophication · ASSETS model · Estuaries · Eastern Brazil

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Introduction

Over the last five decades, many fresh, estuarine, and coastal waters developed into the most fertilized environments of the world. Eutrophication, which refers to the enrichment of nutrients, organic matter, and the associated enhancement of primary production, has become a widespread water quality issue accelerated by the anthropogenic activities in the watersheds (Golterman and Oude 1991; Nixon 1995; Cloern 2001). For example, evaluation of historical changes in nutrient loading revealed that estuarine systems have experienced a six to 50 times increase in the nitrogen (N) load and an 18–180 times in the phosphorous (P) load as compared to pristine conditions (Conley 2000). Among some of the multiple drivers of eutrophication are agriculture and associated fertilizer usage, population growth with untreated effluent discharge, industrial development, and the increase of combustion of fossil fuels (Likens 1972; Boesch 2002). The development of excessive algal and/or harmful algal blooms (HABs), shifts from benthic to pelagic dominated productivity, loss of submerged aquatic vegetation (SAV), low dissolved oxygen (DO) (hypoxia and anoxia), alteration of foods webs, and loss of biodiversity are considered as some of the main multiple symptoms (Bricker et al. 1999; Anderson et al. 2002; Cloern 2001; Ferreira et al. 2005; Glibert et al. 2010).

Over time, many methods and conceptual approaches have been developed to assess the trophic state and eutrophication of aquatic water bodies, also in support for management purposes (Carlson 1977; Lambou et al. 1983; Vollenweider et al. 1992; Knoppers et al. 1991; Nixon 1995; Bricker et al. 1999; Conley 2000; Nobre et al. 2005; Scavia and Bricker 2006; Borja and Dauer 2008; Paerl 2009; Primpas and Karydis 2010; Devlin et al. 2011; Ferreira et al. 2011). In addition to the establishment of standard variables to monitor eutrophication, it has become necessary to adopt indices which combine quantitative and qualitative indicators for assessing the trophic conditions (Izzo et al. 1997). Selecting key indicators is required to adequately describe the trophic status of the environment. Such parameters must reflect a gradient of the levels of human-induced impacts, in which an increase in nutrient loads leads to a decrease of water quality (Ferreira et al. 2011).

Furthermore, a wide discussion has also emerged from the issue of nitrogen and phosphorous co-limitation in aquatic systems, which entails the necessity of certain site-specific modeling adaptations (Nixon 1995; Cloern 2001; Howarth and Marino 2006; Elser et al. 2007; Conley et al. 2009; Paerl 2009; Ferreira et al. 2011). Most of the earlier concepts developed for temperate systems adopted phosphorous as the limiting nutrient in freshwaters whereas nitrogen in estuarine and coastal waters. Observations in tropical coastal lagoons of the state of Rio de Janeiro (Brazil) indicated phosphorus limitation in short periods during the dry season (Knoppers et al. 1999). It must be borne in mind that tropical estuarine systems are generally subject to a continuous growth period, and seasonal variability is governed by changes in precipitation, temperature, and tidal exchange, in contrast to temperate systems prone to seasonal light limitation of growth.

This study applies the ASSETS model to five tropical coastal estuarine systems of the east coast of Brazil, all limited by nitrogen and characterized by different degrees of human impacts and residence times of water. ASSETS was developed by a group of specialists following the NOAA's Estuarine Eutrophication Survey (Bricker et al. 1999, 2003) and used to rank the eutrophication status of estuaries and coastal areas of USA. This methodology has been also applied for diverse European and Asiatic estuaries (Bricker et al. 1999, 2003; Ferreira et al. 2007; Xiao et al. 2007; Scavia and Bricker 2006; Whitall et al. 2007; Bricker et al. 2008) and lately also to two systems in southeast Brazil (Mizerkowki 2011). The experiences using the ASSETS methodology appear to be sufficiently robust to allow its application to a range of different types of coastal systems (Ferreira et al. 2007).

Materials and methods

The study areas

The geographical location, physiographic features, and population densities of the study areas are summarized in Table 1, and Fig. 1 depicts the systems themselves. Further details are described below.

The Mundaú–Manguaba lagoon–estuarine system

Mundaú–Manguaba lagoon–estuarine system (MMELS) is located in the state of Alagoas at the northern premises of the eastern coast of Brazil (latitude 9°35′ and 9°46′S;

Table 1 Summary of physical characteristics and watershed population density for each estuary

Features		MUL	MAL	GL	PL	PSE
Location	Latitude S	9°35′[a]	9°46′[a]	22°56′[b]	22°56′[b]	21°37′[c]
	Longitude W	35°44′[a]	35°58′[a]	42°42′[b]	43°00′[b]	41°01′[c]
Surface area (km^2)		24[a]	43[a]	6.38[b]	2.9[b]	21.5[c]
Volume (10^6 m^3)		69.8[a]	97.7[a]	6.5[b]	2[b]	43.1
Average depth (m)		1.5[a]	2.1[a]	1[b]	0.7[b]	2[c]
Tidal range (m)		0.2[a]	0.03[a]	0.03[b]	0.04[b]	0.85[c]
Tidal prism (10^6 m^3)		17.3[a]	6.1[a]	0.38[b]	0,11[b]	18.3[c]
Average freshwater discharge (m^3 s^{-1})	Rainy	65.9[a]	57.2[a]	–	–	1,000[c]
	Dry	14.1[a]	15.9[a]	–	–	450[c]
	Annual	3[a]	28[a]	0.46[b]	0.1[b]	725[c]
Watershed population (×10^6 hab)		0.9[d]	0.3[d]	0.1[d]	0.2[d]	4.9[d]
Residence time (days)		16[a]	36[a]	14[b]	30[b]	0.75

MUL Mundaú lagoon, *MAL* Manguaba lagoon, *GL* Guarapina lagoon, *PL* Piratininga lagoon, *PSE* Paraíba do Sul estuary

[a] Oliveira and Kjerfve (1993)

[b] Knoppers et al. (1991)

[c] Sterza and Fernandes (2006)

[d] IBGE (2010)

longitude 34°44′ and 35°58′W). MMELS falls into the category of a choked estuarine–lagoon system, with long residence times of water, a large potential for material recycling and retention, and exhibits eutrophic conditions (EC). MMELS consists of three distinct compartments (Table 1), the larger Manguaba and the smaller Mundaú lagoons and a maze of narrow channels connected via a single 250-m-wide tidal inlet to the sea, which dissipates around 90 % of the tidal energy before reaching the lagoons. Residence times of water are longer in MAL than in MUL (Table 1). A distinct seasonal cycle is observed with a dry summer (November to March) and a wet winter (May to August) period and the climate is of Köppen Type As. Sugarcane waste effluents are transported by the rivers, and untreated urban sewage is introduced directly into MUL from the large City of Maceió and from several smaller cities into MAL. According to IBGE (2008), less than 10 % of the total urban sewage is treated (primary and secondary treatments). Crop burning activities have been affecting the entire lower drainage basin and also Maceió city (Oliveira and Kjerfve 1993).

Guarapina lagoon

The eastern Fluminense coastline between the cities of Niterói and Cabo Frio, state of Rio de Janeiro, Brazil harbors a series of choked lagoons. Guarapina lagoon (GL) (longitude 22°56′S, latitude 42°42′W) forms part of the Maricá lagoon system. The small watershed is bordered by a relative pristine mountainous ridge. The lagoon is fed by three rivulets with a combined freshwater discharge of 0.5 m^3 s^{-1}. The lagoon is used for fishing and recreation (Machado and Knoppers 1988) and still maintains its traditional land use of low-density cattle pastures and urban conglomeration at the seaward end of the lagoon and sand barriers (Bitton et al. 1999). The population growth according to the last census of IBGE (2010) was 5 % year^{-1} and the system harbors 3,525 households, of which only 31 have sewage treatment representing 8 % of the total population (IBGE 2008).

The Piratininga lagoon

Piratininga lagoon (PL) (latitude 22°56′S, longitude 43°00′W) is located near the city of Niterói, state of Rio de Janeiro, and represents a small internal lagoon cell of the Piratininga–Itaipu system (Table 1). The drainage basin is fed by the Jacaré and Arrozal streams and other undefined diffuse sources (Wasserman et al. 1999). PL has been under a gradual increase of cultural eutrophication due to the combined effect of low

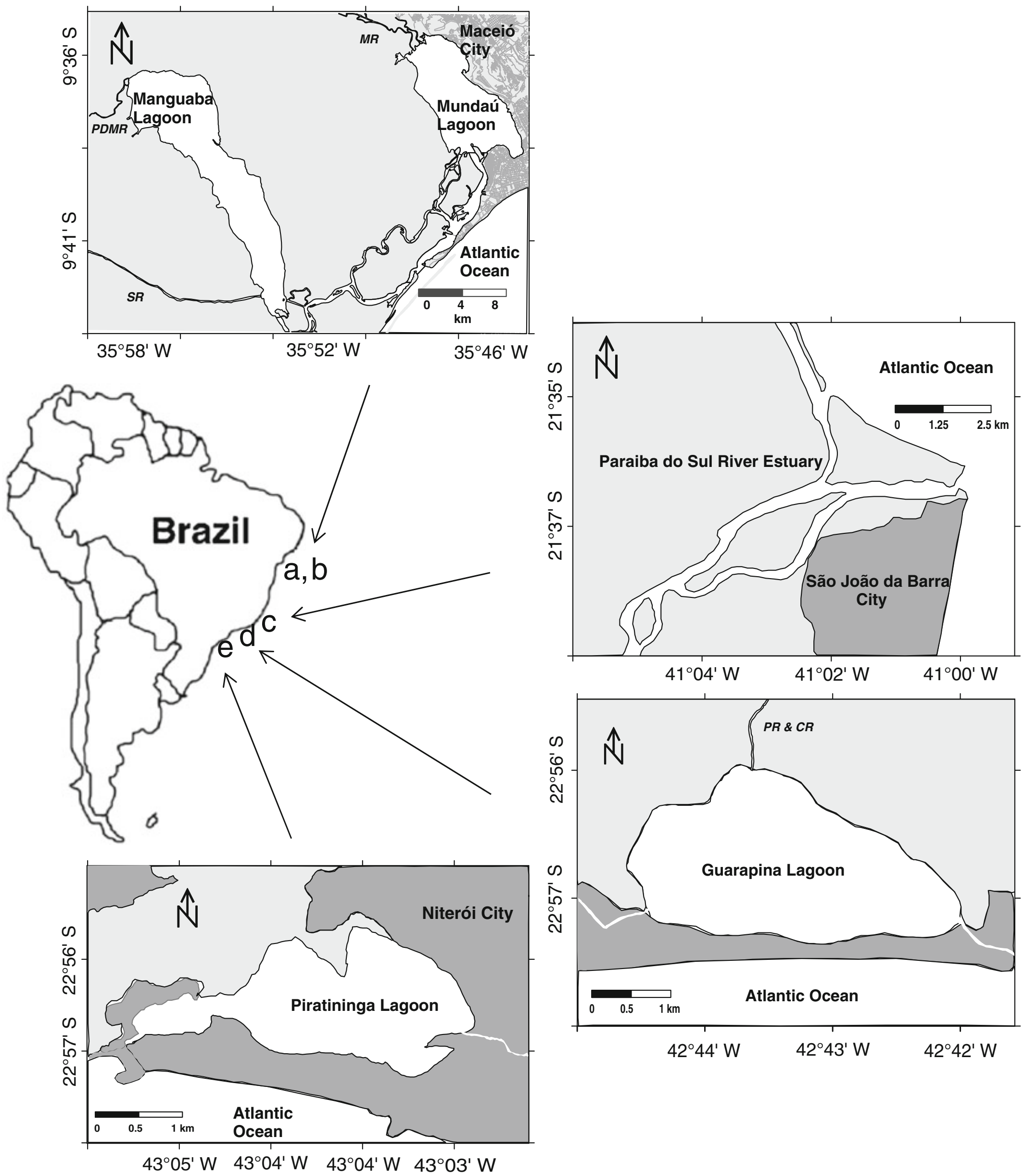

Fig. 1 Map location of the systems analyzed. *a*, *b* Mundaú and Manguaba lagoons; *c* Paraíba do Sul River Estuary; *d* Guarapina lagoon; *e* Piratininga lagoon

tidal flushing and uncontrolled domestic sewage discharge (Knoppers et al. 1991, 1999). The benthic macroalgae *Chara* sp. began to proliferate in the 1960s and occupies more than 60 % of the lagoon's area (Carneiro et al. 1994). The demographic expansion rate has been 11 % year^{-1} (Bitton et al. 1999; IBGE 2010), and the wastewater treatment attends less than 9 % of the households (IBGE 2008).

The Paraíba do Sul estuary

The Paraíba do Sul estuary (PSE) is located at the northern premises of the state of Rio de Janeiro (latitude 21°37′S, longitude 41°01′W) and is composed of a main river channel and a minor secondary channel. The latter harbors a mangrove forest of approximately 8 km^2 (Sterza and Fernandes 2006). The coast is characterized by high wave energy regime and microtides (Table 1). The summer season (November to January) is humid and the winter season (July to August) dry, with a climate of Köppen type A_w. The river is an example of highly impacted system. It drains one of the most populated and industrialized regions of Brazil, receiving nutrient loads from upstream sources along its river course. The Paraíba do Sul River fulfills a wide range of economic services to the inhabitants of the states of São Paulo, Minas Gerais, and Rio de Janeiro, Brazil. It receives industrial, agricultural, and domestic effluents; provides potable water for most of the cities located along its course; generates energy from hydroelectrical dams; and maintains a substantial local fishery in its coastal waters. The percentage of the population with access to sewage collection varies along the course of the Paraíba do Sul River. The effluent treatment covers 10.2 % of the population in the state of São Paulo while only 1.2 % in the state of Minas Gerais and 2 % in the state of Rio de Janeiro (ANA 2006a).

Sampling strategies

Sampling in all systems covered the estuarine mixing zone between the fresh and marine end members. In each of the compartments of MMELS, 07 sampling campaigns were performed covering the wet and dry seasons between 2006 and 2008. MUL was covered by 16 stations set along longitudinal transects, MAL by 20 stations, and the tidal channels by 10 stations per campaign. Additional water samples were taken at the critical effluent point sources (B. Knoppers, personal communication). The lagoon proper of GL was sampled at bi-weekly intervals at three sampling stations over an annual cycle, with three additional stations set in the rivulets and one off the lagoon's mouth (Knoppers et al. 1999). The lagoon proper of PL was sampled along a transect with seven stations at monthly intervals during an annual cycle, including also its two main rivulets (Carneiro et al. 1994; Knoppers et al. 1999). The estuarine gradient of PSE was sampled at monthly intervals at five stations in accordance to the unimodal seasonal pattern of river flow (Sterza and Fernandes 2006). Additional samples were collected at Campos City 30 km upstream (e.g., the freshwater end-member) and also in its coastal waters (i.e., marine end-member). More information on the physical and biogeochemical features and sampling strategies of the GL and PL systems are encountered in Knoppers and Kjerfve (1999) and Knoppers et al. (1999) and for PSE in Carvalho and Torres (2002), Sterza and Fernandes (2006), and Jennerjahn et al. (2010). Information on the overall physical setting and water quality of MMELS is restricted to Oliveira and Kjerfve (1993), and the present data used for the ASSETS model have as yet been unpublished.

All systems were assessed by a congruent set of physical and chemical parameters and were measured as follows: Temperature, salinity, pH, and dissolved oxygen were measured in situ with either WTW-50 (Germany) or YSI 6600 (USA) multi-probes; dissolved inorganic nitrogen (ammonia, nitrite, and nitrate) and phosphate (orthophosphate) were quantified as in Grasshof et al. (1983) and chlorophyll-*a* (Chl-*a*) as in Strickland and Parsons (1972). Whatman GF/F filters were used for the chlorophyll-*a* analyses and the filtrate for the nutrient analyses. All water samples were kept in the dark and on ice during transport to the respective laboratories, and nutrient samples and chlorophyll-*a* filters kept at −18 °C in a freezer prior to analyses.

Information on the distribution and biomass of macroalgae, frequency, and species composition of phytoplankton blooms, including HABs when present, was obtained for MMELS from Melo-Magalhães et al. (2008), for GL as in Knoppers et al. (1999), and for PL from Carneiro et al. (1994). Macroalgae have only been reported for PL and harmful algal blooms have been scant.

The ASSETS model

The ASSETS model was developed for the US National Estuarine Eutrophication Assessment (Bricker et al. 1999) and adopts the conceptual pressure–state–response (PSR) approach. ASSETS works with quantitative and semi-quantitative components, using field data, models, and expert knowledge to provide PSR indicators (Bricker et al. 2003). The three indices (pressure–state–response) are briefly described below; for a full description, see Bricker et al. (1999, 2003) and Ferreira et al. (2007).

Pressure—influencing factors

Influencing factors (IF) help to establish a link between a system's natural susceptibility to eutrophication as a function of the dilution and flushing potential and the specific nutrient nitrogen loading (N) (Bricker et al. 2008). Physical and hydrologic data are used separately to define the dilution and flushing potential (i.e., rates) which are combined to give a susceptibility rating. For example, the dilution potential is characterized by the degree of mixing of the water column (i.e., homogeneous or stratified) and the freshwater or saline volume fraction of the estuary. The flushing potential considers the combined effect of the tidal range and the ratio between the freshwater inflow and the estuaries' volume. The final classification of susceptibility is a combination of the "dilution and flushing potentials," as shown in the matrix of Table 2 from Bricker et al. (1999). The matrix exemplifies that higher dilution and flushing rates lead to lower retention times for nutrients (i.e., low susceptibility), and the opposite situation can lead to enhanced eutrophication (i.e., high susceptibility).

The N loading susceptibility model, initially developed for estuaries with regular river flow (Bricker et al. 2003), has been further adapted for other estuarine–coastal systems (Ferreira et al. 2007). The model defines the variation of nitrogen mass as DIN in the estuary as a ratio between the anthropogenic load and the total mass of nutrient loading considering also the freshwater input and the nutrient discharged by advection and exchange with the ocean.

Considering the hypothetic situation that there is no human input, the background levels can be described as (Ferreira et al. 2007):

$$M_b = \left(\varepsilon\, T_{\mathrm{p}}\, M_{\mathrm{sea}}\right)\left(\varepsilon\, T_{\mathrm{p}} + Q\, T\right)^{-1}$$

where ε is the fraction of water leaving the bay at ebb tides does not return in the flood (proxy for re-entrainment), T_{p} is the tidal prism (in cubic meters), M_{sea} is the N concentration offshore (in kilograms per cubic meter), Q is the freshwater input (in cubic meters per second), and T is the tidal period (seconds).

Under the assumption that there is no oceanic input of N, the anthropogenic influence (M_{h}) is considered as the N load from the rivers (M_{in} in kilograms per cubic meter) and the effluent discharge (M_{ef} in kilograms per second) as follows:

$$M_{\mathrm{h}} = \left(T\left[QM_{\mathrm{in}} + M_{\mathrm{ef}}\right]\right)\left(Q\, T + \varepsilon\, T_{\mathrm{p}}\right)^{-1}$$

The nutrient input, regarded as a human influence (HI), is henceforth defined by:

$$\text{Nutrient input} = M_{\mathrm{h}}\left(M_{\mathrm{h}} + M_{\mathrm{b}}\right)^{-1}$$

Nutrient input scores are framed into three classes as low (0–0.4), moderate (0.4–0.8), and high (0.8–1). The susceptibility rating is combined in a matrix with a rating for nitrogen loads to determine the final influencing factor rating.

State—eutrophic conditions

The EC is a rating based on five indicators or symptoms that are determined according to the salinity zones—freshwater (S=0–0.5), mixing (0.5–25), and seawater (>25 psu). Ratings for the primary symptoms Chl-*a* and macroalgae are averaged for each salinity zone. The secondary symptoms used are DO, changes in the coverage of SAV, and the occurrence of nuisance and/or harmful algal blooms (HABs) (Devlin et al. 2011). Bricker et al. (2003) presented detailed information on the logical decision process for the determination of the level of expression and respective scores of the primary and secondary symptoms. EC is then calculated by aggregating primary and secondary symptoms, using a combination matrix (Bricker et al. 2003).

Where possible, ASSETS employs data rather than "expert knowledge," for instance by using statistical criteria for determination of the status for Chl-*a* (90th percentile) and for DO (10th percentile) of average

Table 2 Matrix for the determination of the estuarine susceptibility to eutrophication

		Dilution potential		
		High	Moderate	Low
Flushing potential	High	Low susceptibility	Low susceptibility	Moderate susceptibility
	Moderate	Low susceptibility	Moderate susceptibility	High susceptibility
	Low	Moderate susceptibility	High susceptibility	High susceptibility

Source: Bricker et al. (1999)

annual data values. The application of the percentile-based approach is illustrated for Chl-a (Fig. 2) and for DO (Fig. 3) with data from the Mundaú lagoon as an example. The percentile value approach is being used within the European Water Framework Directive (WFD; see Ferreira et al. 2011) for evaluating the ecological and chemical status for all European water bodies until 2015 (Beliaeff and Pelletier 2011).

Response—future outlook

An analysis of the future outlook (FO) is performed to determine whether the present conditions of nutrient pressure in an estuary will worsen, improve, or remain similar at a medium time scale (e.g., over the next two decades). The assessment of expected changes in nutrient pressure is based on a variety of drivers, including demographic trends, wastewater treatment, and remediation plans, together with expected changes in agricultural practices and watershed uses, and finally complemented by expert knowledge. The susceptibility component is combined with a projection of the future outlook. The foreseeable evolution is graded into five classes from better to worse (Bricker et al. 2003; Nobre et al. 2005; Xiao et al. 2007).

Synthesis—the overall ASSETS grade

The final stage of the ASSETS determination synthesizes the three scores of PSR to provide an overall description of the system status in terms of eutrophication. The combination of the PSR results in a matrix of combinations leads to the classification of the aquatic system into five categories: high (better), good, moderate, poor, or bad (worse). These categories are color-coded following the convention of the WFD and provide a scale for setting reference conditions for different types of transitional waters with regard to eutrophication (Bricker et al. 2003).

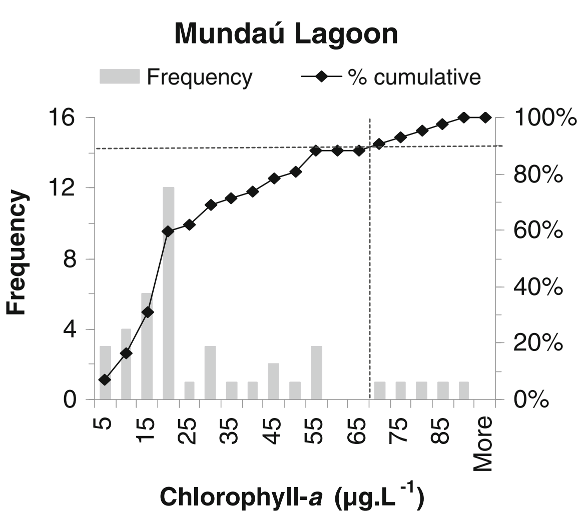

Fig. 2 Percentile 90 value for chlorophyll-*a* (*dashed lines* intersection) in the mixing zone of the Mundaú lagoon

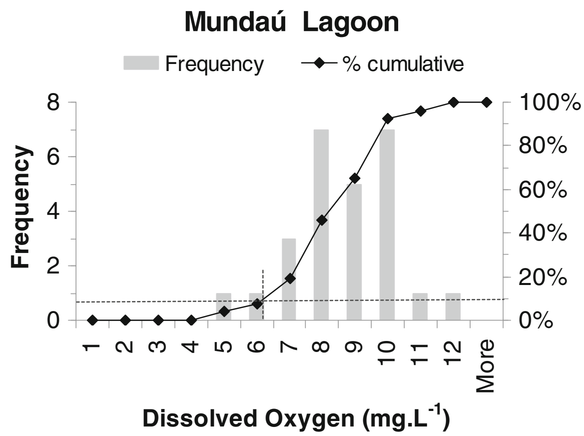

Fig. 3 Percentile 10 value for dissolved oxygen (*dashed lines* intersection) in the mixing zone of the Mundaú lagoon

Results

Salinity zones

The salinity zones of the study areas are shown in Table 3. The calculations were carried out by averaging values for an annual cycle. MUL and MAL are dominated by a freshwater zone at its upper to central areas, while the mixing pattern was observed from their central to lower regions. MAL is governed by a higher freshwater fraction than MUL, but the seawater percentage is small for both. GL showed a predominance of mixed waters, with the freshwater zone restricted to an insignificant small portion of the rivulets mouth. The PL area was classified presenting about 83.5 % of mixed waters and 16.5 % of seawater. PSE being a typical deltaic estuary presented a more evenly distributed estuarine gradient and distinct seasonal shifts between dry–wet seasonal patterns (Sterza and Fernandes 2006), with one period of more pronounced intrusion of seawater (dry period) and the other (rainy period) more dominated by

Table 3 Average percentage area of the salinity zones for the estuarine systems

Salinity zone classification	MUL	MAL	GL	PL	PSE		
					Annual	Dry	Rainy
Freshwater (0–0.5)	28	41	0	0	46.1	16.0	75.0
Mixing (0.5–25)	70	54.4	100	83.5	33.2	50.0	18.8
Seawater (>25)	2	4.6	0	16.5	20.7	33.3	6.3

freshwater. Over an annual cycle, PSE was divided into around 46 % of freshwater, 33 % of mixing, and 21 % of seawater zones.

Susceptibility

Under annual average conditions of the volume of estuarine waters and the tidal range, the results yielded a low dilution and flushing potential for the lagoons and a moderate dilution and high flushing potential for the river estuary. Hence, the estuarine susceptibility is classified as high for the lagoons and moderate to low for the Paraiba do Sul River estuary (Table 4).

Nutrient input

The results of the model calculations for the nutrient inputs for the five systems are presented in Table 5. The concentrations of DIN in rivers (M_{in}) were higher in PL with 28.5 μM (3.2×10^{-3} kg m^{-3}) and in PSE with 22.1 μM (3.1×10^{-4} kg m^{-3}). Offshore surface concentrations were 3.1 μM (4.4×10^{-5} kg m^{-3}) for the Mundaú–Manguaba system, 2.5 μM (3.5×10^{-5} kg m^{-3}) for GL and PL, and 13.5 μM (1.9×10^{-4} kg m^{-3}) for PSE (Jennerjahn et al. 2010).

The anthropogenic input to the systems derived from effluent discharge (M_{ef}) was estimated by adopting the average N release per capita considered as 9.04 g N day^{-1} (FEEMA 1987; Meybeck and Helmer 1989; Meybeck et al. 1989). The watershed of the PSE is the one that receives the highest input of nutrients followed by MUL, MAL, PL, and GL. The calculation of the PSE anthropogenic input by per capita release (17,308 TN year^{-1}) is corroborated by other river flux studies along the eastern Brazil coast, with an estimate of 18,672 TN year^{-1} in 1998 (unpublished data) and 19,200 TN year^{-1} in 2010 (C. Gonçalves, personal communication).

For the Mundaú–Manguaba lagoon system, the contribution of effluents related to the sugar cane practices was estimated, yielding fluxes of around 2.4×10^{-2} and 1.6×10^{-2} N kg s^{-1} for MUL and MAL, respectively, with 21,700 ha of the cultivated area being in the MAL and 29,480 ha in the MUL watersheds. The emission factors adopted in this study were taken from Lacerda et al. (2008). The calculated background concentrations were higher in MAL and PL. The calculated anthropogenic influence (M_h) varied in according to the estuaries, with high values in MUL and PL, while the final nutrient input was determined for all systems.

Influencing factors—pressure

Susceptibility and nutrient inputs are combined to determine the IF. Higher susceptibility combined with high nutrient input results in a high score for IF, whereas the opposite holds for better conditions (low score). The classification of IF was high for all lagoons, whereas for PSE the classification was moderate to low.

Table 4 Determination of the estuarine susceptibility according to the dilution and flushing potentials of the systems

	MUL	MAL	GL	PL	PSE
Volume (10^6 m^3)	69.8	97.7	6.5	2	43.1
Dilution volume[a]	1.10^{-2}	1.10^{-2}	1.10^{-1}	5.10^{-1}	2.10^{-2}
Dilution potential[a]	Low	Low	Low	Low	Low
Tide range[a]	Micro	Micro	Micro	Micro	Micro
Daily river input (10^6 m^3)	3	2.4	3.10^{-2}	7.10^{-3}	62.6
River input/estuary volume[a]	4×10^{-2}	2×10^{-2}	4×10^{-3}	3×10^{-3}	1.4
Export potential[a]	Moderate	Moderate	Low	Low	High
Estuarine susceptibility[a]	High	High	High	High	Moderate low

[a] The classification and calculation of this variables are well described in Bricker et al. (1999)

Table 5 Average DIN concentrations in rivers and offshore waters and estimated loads from anthropogenic effluents to systems and the respective nutrient input scores and classifications for each system

	MUL	MAL	GL	PL	PSE
M_{in} (kg m^{-3})	2.3×10^{-4}	1.6×10^{-4}	7.7×10^{-5}	3.2×10^{-3}	3.1×10^{-4}
M_{sea} (kg m^{-3})	4.4×10^{-5}	4.4×10^{-5}	3.5×10^{-5}	3.5×10^{-5}	1.9×10^{-4}
M_{ef} (kg s^{-1})	7.2×10^{-2}	2.6×10^{-2}	2.8×10^{-4}	1.6×10^{-3}	0.4×10^{-1}
M_b (kg m^{-3})	1.8×10^{-5}	4.1×10^{-6}	2.5×10^{-5}	7.4×10^{-6}	8.6×10^{-5}
M_h (kg m^{-3})	1.36×10^{-3}	9.9×10^{-4}	6.7×10^{-4}	1.5×10^{-2}	5.3×10^{-4}
$M_h/(M_b+M_h)$	0.99	1	0.88	1	0.86
Nutrient input	High	High	High	High	High

Eutrophic conditions—state

The eutrophic conditions of the systems are presented in Table 6. With the exception of PSE, all the systems presented high primary symptoms. In PL, the major problem is the large spatial coverage of macroalgae which attains more than 60 % of the surface area throughout the year (Knoppers et al. 1999), whereas the other systems were dominated by phytoplankton. Maximum Chl-*a* levels were indicative of hypereutrophic conditions (>60 μg Chl-*a* L^{-1}) for MUL, MAL, and GL, with a high spatial coverage (>50 %) and periodic frequency of occurrence (seasonal pattern) in the freshwater and mixing salinity zones. Moreover, the seawater domain of MUL and MAL was classified as medium eutrophic (>5≤20 μg Chl-*a* L^{-1}), also commonly regarded as mesotrophic (Vollenweider et al. 1992). For PSE, medium conditions were classified for the entire estuary and throughout the seasonal cycle based on Chl-*a* (>5≤20 μg Chl-*a* L^{-1}).

As for the primary symptoms, the classification was also variable for the secondary symptoms. No information was found for SAV, but low concentrations of DO and HABs have been documented. MUL did not exhibit values indicating biologically stressful conditions related to the dissolved oxygen content. PSE also was exempt of biological stress, except for the seawater zone (i.e., 4.3 mg L^{-1}). On the other hand, the 10th percentile value of GL was 3.38 mg L^{-1}, being prone to the category of biologically stressful conditions. In these three systems, the final classification for secondary symptoms was low. For PL and MAL, the secondary symptoms for eutrophic conditions are more critical. In PL, the DO value for the mixing zone was 2.5 mg L^{-1} (i.e., biological stress) and in seawater as low as 1.28 mg L^{-1} (i.e., hypoxia), with a high periodic frequency of occurrence. MAL exhibited the worst conditions with respect to the secondary symptoms due to frequent occurrence of HABs in the freshwater and mixing salinity zones. These HABs occur more during the dry period (Melo-Magalhães et al. 2008).

Table 6 Determination of eutrophic conditions (EC) by the combination of primary and secondary symptoms for the systems

Estuary	Primary symptoms	Secondary symptoms	EC
MUL	High	Low	Moderate
MAL	High	High	High
GL	High	Low	Moderate
PL	High	Moderate	Moderate high
PSE	Moderate	Low	Moderate low

Future outlook—response

The assessment of the expected future outlook incorporates both quantitative and qualitative information. It includes computations of the population growth trends obtained from the National Brazilian Census (Brazilian Institute of Geography and Statistics; IBGE 2010) multiplied by the per capita nitrogen load (e.g., 9.04 gN day^{-1}; FEEMA 1987; Meybeck and Helmer 1989; Meybeck et al. 1989), as well as the prognosis of planned remediation actions by local and/or federal authorities and the industries, with respect to wastewater treatment and fertilizer usage in agricultural practices and watershed uses, complemented by expert knowledge. The susceptibility component is combined within a matrix with the projections of the future outlook of the nutrient load scenarios (Bricker et al. 2003). Table 7 summarizes the future outlook for all the systems. The foreseeable development and associated socioeconomic and environmental actions are henceforth described for each system.

Table 7 Determination of future outlook by the combination of the susceptibility and future nutrient trend pressure for the systems

	MUL	MAL	GL	PL	PSE
Susceptibility	High	High	High	High	Low
Future nutrient pressures	Decrease	Decrease	Increase	Increase	Decrease
Future outlook	Improve low	Improve low	Worsen high	Worsen high	Improve high

The Mundaú–Manguaba estuarine–lagoon system ASSETS considered the future outlook for the MUL and MAL lagoons as apt for improvement but at a low level. MUL and MAL are, currently, being subject to management actions, particularly with respect to the impacts of the sugarcane and chlor-alkali industry effluents, environmental urban and rural sanitation, and protection of water and natural resources (ANA 2006b). The management plan is driven by the participation of several governmental committees, NGOs, and the public itself. The intention is to spend approximately of \$550 million with the action plan. IBGE (2010) data also estimated a maximum population growth rate of 5 % year^{-1}. As such, a decrease in nutrient inputs to these lagoons can be forecasted.

The Gaurapina and Piratininga lagoons According to the ASSETS outlook, GL and PL's future outlook will worsen at a high level. For GL and PL, no direct management actions have been established, apart from the construction of one local sewage treatment plant at PL, which has now been completed. Further uncontrolled housing construction and diffuse effluent discharge should deteriorate the ground water of both lagoons. These systems are also located close to Rio de Janeiro city, and they are being subject to a high population growth of about 10 % year^{-1} (IBGE 2010).

The Paraíba do Sul estuary As expected, the ASSETS outlook considered that PSE should improve at a high level. This is naturally brought about by the high dilution and flushing potential of the river and the estuary itself. A consortium implemented by the states of São Paulo, Minas Gerais, and Rio de Janeiro has been dealing with several remedial actions (ANA 2006a). The main objectives entail the reduction of pollutant loads, exploitation and rational use of water resources, urban drainage and flood control, coordinated action on water resources management and sustainable land use, and building tools of participative management by the local municipalities, considering also the impact from transboundary issues. The project was estimated at 251.6 millions of dollars for the lower river section and its estuary, and for the entire drainage basin, the investments reach \$1.5 billion.

The final overall ASSETS grade

The combined PSR index is presented in Table 8. PSE had the best indices, with a good final trophic status. MUL was classified with moderate eutrophic conditions, with a future outlook of low improvement and a moderate final classification. MAL and PL had the worst or highest eutrophic conditions for which a bad final ASSETS grade was discerned. GL presented moderate eutrophic conditions, but its future outlook is to worsen and the final ASSETS grade is poor.

Seasonality

The results obtained by the ASSETS model correspond to the average annual condition of the systems.

Table 8 Combination of the three PSR indices providing the final ASSETS for each system

	MUL	MAL	GL	PL	PSE
IF	High	High	High	High	Moderate low
EC	Moderate	High	Moderate	Moderate high	Moderate low
FO	Improve low	Improve low	Worsen high	Worsen high	Improve high
ASSETS	Moderate	Bad	Poor	Bad	Good

IF influencing factors, *EC* eutrophic conditions, *FO* future outlook, *ASSETS* Assessment of Estuarine Trophic Status

Table 9 Summary of the all indices of the ASSETS classification for the seasonal periods for MAL, MUL, and PSE

System	Period	Sus	N Inp	IF	P Symp	S Symp	EC	FO	ASSETS
MUL	Dry	H	H	H	H	L	M	IL	P
	Rainy	MH	H	H	H	L	M	IL	M
MAL	Dry	H	H	H	H	H	H	IL	B
	Rainy	MH	H	H	H	L	M	IL	M
PSE	Dry	M	H	MH	ML	L	ML	IH	M
	Rainy	L	H	ML	L	L	L	IH	H

Sus susceptibility, *NInp* nutrient input, *IF* influencing factors, *P Symp* primary symptoms, *S Symp* secondary symptoms, *EC* eutrophic conditions, *FO* future outlook

However, one should consider that seasonal shifts in the degree of eutrophication may occur in all systems due to the unimodal pattern of freshwater inflow and associated nutrients, as well as multiple land use practices, especially of agriculture. The ASSETS model was tested for the systems with the highest seasonal variability, the Mundaú–Manguaba lagoons and the Paraíba do Sul estuary. The data were treated as above but separated for the governing dry and wet periods. Table 9 summarizes all the PSR indices and also the final ASSETS grade.

PSE presented an improvement of the trophic status from the dry to the rainy period, whereas for MUL and MAL, no significant differences between the dry and wet seasons were discerned by ASSETS. The seasonal ASSETS classification in MUL and MAL were the same as obtained from the average annual data set, which was poor and bad, respectively. PSE, which received a good ASSETS grade based on the average annual data set, now received a moderate grade for the dry season and a high grade for the wet season. The differences in the seasonal expression of the trophic status in PSE are related to the marked unimodal seasonal pattern of river flow.

Discussion

The final ASSETS grade assigned to MUL was poor, to MAL as bad, to GL as poor, to PL as bad, and to PSE as good. However, the individual pressure–state–response indices differed between the systems not only due to differences in nutrient inputs and algal biomass but also due to the natural typology of the watersheds and the hydrological–geomorphological configuration of the systems.

The ASSETS methodology indicated that the lagoon systems addressed are naturally highly susceptible to eutrophication, as also indicated on a qualitative basis by studies from other lagoons of SE Brazil (Knoppers and Kjerfve 1999; Knoppers et al. 1999). All of the lagoons addressed fall into the category of choked lagoons with a high degree of enclosure from the sea and high residence times of water due to the efficient dissipation of tidal energy by more than 90 % in the tidal channels. This leads to efficient retention and also recycling of biogenic matter in the systems (Knoppers et al. 1999). All of these are naturally subject to eutrophication and the degree of differences in nutrient inputs versus residence times of water as dealt with the ASSETS model seems to have given acceptable results, when compared to earlier definitions of the trophic state (Knoppers et al. 1991, 1999).

On the other hand, the low susceptibility of PSE to eutrophication is a result both of its open access to the sea, tidal pumping, and the high freshwater flow leading to its high potential of dilution and flushing. During the wet season, the nutrients are rapidly flushed to the sea, diluted during plume dispersal, and primary production remains low within the estuary. Under these conditions, primary production may increase at the inner shelf after the gradual sedimentation of suspended particles (Balzer and Knoppers 1996). In contrast, during the dry season, the nutrients reside longer within the estuary, being more available to the biota and the primary production is favored.

The higher nutrient N inputs of PSE, MUL, and MAL were not only due to the much larger watersheds of these systems in comparison to those of GL and PL but also due to their multiple anthropogenic uses involving nitrogen. PSE, by far the largest system, receives nitrogen from intense urban and industrial point sources and agricultural uses (fertilizers) along its long river course. The smaller Mundaú–Manguaba lagoon system also receives relatively high nutrient N loads, but essential features distinguish both from each other.

The MUL and MAL watersheds deliver N from diffuse urban sources and nutrient fluxes from sugarcane production. But MUL is drastically affected by the N input of one fourth of the total population of about one million of Maceió City; MAL only receives domestic effluents from a population of about 60,000. On the other hand, the average annual residence time of water of MUL is in the order of 2 weeks, while of MAL 6 weeks (Oliveira and Kjerfve 1993). It seems that higher flushing times of MUL as compared to MAL compensate for the higher nutrient inputs by dilution. ASSETS discerned a bad state for MAL and only a poor state for MUL, mainly due to differences between the systems secondary symptoms, which in MAL corresponds to the frequent occurrence of cyanobacterial blooms of *Anabaeana spiroides* and *Microcystis aeruginosa* in alternation with the diatoms *Cyclotella meneghiniana* and *Skeletonema* cf. *costatum*. The blooms and their chlorophyll *a* biomass values clearly induced eutrophic conditions and occasionally HABs (Melo-Magalhães et al. 2008).

The final ASSETS grade calculated to GL was equivalent to MUL, despite that nutrient loading to GL was smaller. However, both exhibited similar residence times of water (i.e., 2 weeks). GL is also characterized by a succession of phytoplankton species from *Cyanobacteria* in summer to a mixed population of diatoms and dinoflagellates in winter (Knoppers et al. 1999). But both systems differ considerably with respect to the area ratio between the watershed and lagoon surfaces, with GL also harboring a higher relief watershed with more preserved forests and MUL a larger but lower relief watershed with more human impacts. These differences did not affect the final ASSETS ranking.

In PL, low levels of DO are related to the massive proliferation of the macroalgae *Chara hornemannii*. Stagnation and light limitation of bottom waters within the algal banks lead to the degradation of organic matter produced at the top of the banks and henceforth to hypoxic or even anoxic conditions at the bottom. PL does not exhibit any direct riverine input of materials but is connected to another lagoon by a channel which has direct access to the sea (Carneiro et al. 1994). Urbanization in the entire area has induced eutrophication over time, but sewage treatment plants are only now being implemented.

The eutrophication symptoms varied within and across the system types. For instance, the phytoplankton species composition in transitional waters has been shown to be linked to the flushing time of waters (Bettencourt et al. 2003; Ferreira et al. 2005), including the lagoons from Rio de Janeiro (Knoppers et al. 1999). This can also be observed comparing the PSE and the GL systems. The watershed of PSE supplies 400 times more N than the watershed of GL, but the influencing factor of PSE is minor due to its high freshwater discharge and flushing potentials. For example, similar patterns are also found between San Francisco Bay and Chesapeake Bay, USA. The former receives a higher N and P loading than the latter, but San Francisco Bay has lower standing stocks of phytoplankton and little or no hypoxia as a result of its vigorous tidal mixing and light limitation caused by sediment resuspension (Boesch 2002). According to Sharp (2010), in the Delaware Estuary (USA), and probably many other urbanized estuaries, high nutrient inputs do not necessarily lead to adverse eutrophication responses that are controlled more by the aquatic ecology and physical dynamics, rather than anthropogenic inputs.

The definition of future outlook was variable between the systems because the watersheds of the Brazilian rivers and estuaries are managed by municipalities which do not commonly interact to cover the entire watershed under a single managing concept. Each committee of a determined sub-watershed is responsible for its management, but some are more articulated, organized, and established than others. The committees are responsible for the elaboration of the water resources plan of the areas. Committees which will in the future manage entire watersheds as a single functional unit are now being implemented for three of the systems (PSE, MUL, and MAL) (ANA 2006a, b).

The seasonal variability of system functioning is also an important feature to be considered for the application of the ASSETS model in tropical and subtropical estuaries and in management actions, as also evidenced by the exercise for PSE. The natural susceptibility was largely related to the seasonal variation of the residence times of water or as such the freshwater inflow controlled by precipitation. This directly affected the pressure component of the model. The eutrophic condition improves when freshwater flow is larger and nutrients bypass the system resulting in a lower uptake potential by primary producers. These conditions are especially evident in systems that have marked seasonal patterns, like in PSE. In the MUL and MAL, the river flow has different conditions between the seasons, but this difference is not sufficient to shift the ASSETS classification, indicating that in these lagoons, the eutrophication is persistent throughout the year due to, primarily, their longer residence times of water. In all, it seems that the hydrodynamic component of the ASSETS model, including the dilution and flushing potential, plays the major role in determining the degree of the trophic state rather than only the nutrient load itself.

Despite the fact that Brazil has a comprehensive and rigorous environmental legislation, Law enforcement is the caveat. Law 6938/1981 establishes the National Policy of the Environment, aimed to preserve, improve, and restore environmental quality. Law 9605/1998, known as Environmental Crimes Law, provides for criminal and administrative sanctions from harmful activities to the environment. The 357/2005 CONAMA Resolution provides for the classification and environmental guidelines for the framework of surface water bodies, as well as establishes the conditions and effluent discharge standards. However, laws and specific incentives dealing with the eutrophication problem (e.g., NEEA, WFD) for Brazilian water bodies have as yet to be implemented.

Conclusions

The differences established by ASSETS corroborated that the natural susceptibility in well-flushed systems was lower than in poor-flushed systems, such as the lagoons. As such, it becomes obvious that the typology and water residence times together with robust knowledge of the land uses and nutrient inputs of a system are the key factors for the understanding of the establishment of environmental status and its management.

Using the ASSETS, multi-parameter methodology to determine the trophic state of the addressed Brazilian systems highlighted the importance and utility of using systematic methods for coastal management. It was applied to rank eutrophication status of some Brazilian estuaries and provides one of the first works containing the status of eutrophication in Brazilian systems. Improvements to the ASSETS model are suggested in the pressure component, like insert aspects of nutrient co-limitation (N and P) for phytoplankton growth and add studies of ground water discharge. The evaluation exercise of the trophic status with ASSETS for PSE with distinct wet and dry seasons also yielded useful results and should be considered as a relevant factor in systems with great variations in climate and river run-off.

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