Estuarine, Coastal and Shelf Science (1996) **42,** 701–725

Hydrology and Salt Balance in a Large, Hypersaline Coastal Lagoon: Lagoa de Araruama, Brazil

Björn Kjerfve[a,b], C. A. F. Schettini[b,c], Bastiaan Knoppers[b], Guilherme Lessa[d] and H. O. Ferreira[b]

[a]*Belle W. Baruch Institute for Marine Biology and Coastal Research, Marine Science Program, and Department of Geological Sciences, University of South Carolina, Columbia, SC 29208, U.S.A.,* [b]*Departamento de Geoquímica, Universidade Federal Fluminense, CEP-24.020-007 Niterói, RJ, Brazil,* [c]*Curso de Oceanografia, UNIVALI, CEP-88.301-970, Itajaí, SC, Brazil, and* [d]*Centro Estudos do Mar, Universidade Federal do Paraná, CEP-83.255-000 Pontal do Sul, PR, Brazil*

Received 11 March 1994 and in revised form 20 March 1995

Keywords: coastal lagoon; salinity; water balance; hypersaline; evaporation; rainfall; evapotranspiration; advection; runoff ratio; salt balance; salt production; flushing time

Lagoa de Araruama in the state of Rio de Janeiro, Brazil, is a hypersaline coastal lagoon as a result of semi-arid climate conditions, a small drainage basin and a choked entrance channel. The lagoon has been continuously hypersaline for at least 4·5 centuries, but the mean salinity has varied substantially. It has recently decreased from 57 to 52 as indicated by density (salinity) measurements between 1965 and 1990.

Analysis of more than 20 years of salinity time series data, in addition to monthly lagoon cruises to measure the spatial salinity distribution, indicate that the lagoon salinity largely fluctuates in response to the difference between evaporation and precipitation. The major factor explaining the long-term trend of decreasing salinity in the lagoon is the constant pumping of 1 $m^3 s^{-1}$ of freshwater to the communities surrounding the lagoon from an adjacent watershed, and subsequent discharge of this water into Lagoa de Araruama. The net salt budget is primarily a balance between the advective import of salt from the coastal ocean and eddy diffusive export of salt to the ocean, although the extensive mining of salt from the lagoon during past decades is also a small but significant contribution to the salt budget. The flushing half-life is proposed as a useful time scale of water exchange, is calculated based on a combination of hydrological and tidal processes, and is excellent for comparison of lagoons and assessing water quality changes. The flushing half-life measures 83·5 days for Lagoa de Araruama, considerably longer than for most other coastal lagoons. The proposed dredging of a second ocean channel to Lagoa de Araruama is probably not a good idea. It is likely to accelerate the decrease of lagoon salinity and somewhat improve the lagoon water exchange. At the same time, this will eliminate the apparent buffering capacity provided by the hypersaline environment, and thus may potentially cause water quality problems.

0272–7714/96/060701+25 $18.00/0 © 1996 Academic Press Limited

Introduction

Hypersaline coastal lagoons occur permanently in semi-arid and arid coastal regions in the Middle East (Al-Ramadhan, 1988), Australia (Noye, 1973) and Mexico (Phleger & Ewing, 1962; Postma, 1965), and seasonally in other areas, e.g. Texas (U.S.A.) (Copeland, 1967) and México (Mandelli, 1981). Moore and Slinn (1984) gave an interesting account of the hydrology of the sometimes hypersaline 175 km^2 Caimanero-Huizache system on the west coast of México, where the salinity varies from 23 in the wet season to 84 in the dry season. Previously, permanently hypersaline lagoons, e.g. the Khowr Al-Zubair in Iraq (Al-Ramadhan, 1988) and the Laguna Madre in Texas (Smith, 1988) have, in recent years, been altered into an estuarine and a partially hypersaline system, respectively, by deepening of existing channels and construction of new channels to adjacent water bodies. Most permanently hypersaline lagoons are comparatively small.

Laguna Ojo de Liebre on the Pacific coast of Baja California, Mexico, measures approximately 610 km^2 with 240 km^2 of adjacent salt flats, and may be the largest hypersaline coastal lagoon in the world. The seaward third of this lagoon experiences salinities below 38, but the salinity increases to 52 at the head of the system (Phleger & Ewing, 1962; Postma, 1965). Lagoa de Araruama is the largest hypersaline coastal lagoon in Brazil, measuring 210 km^2 in addition to 65 km^2 of adjacent salt-producing ponds. The mean salinity of 52 is a result of semi-arid climatic conditions, a very small drainage basin, and energetic coastal ocean waves that maintain the bordering sand barrier and inhibit the lagoon-to-ocean channel from expanding. The objectives of this paper are to estimate the order of magnitude of the processes that maintain the salt balance in Lagoa de Araruama, examine the extent to which the salinity has changed in the lagoon during the past decades, and to discuss some ecological consequences.

Coastal lagoons occupy 13% of coastal areas worldwide, and are often impacted by both natural and anthropogenic influences (Mee, 1978; Sikora & Kjerfve, 1985). Depending on local climatic conditions, lagoons exhibit salinities which range from completely fresh to hypersaline (Kjerfve, 1986; Kjerfve & Magill, 1989; Knoppers *et al.*, 1991). This is particularly true for the type of coastal lagoon that is referred to as *choked* (Kjerfve, 1986; Kjerfve *et al.*, 1990), where the lagoon is connected to the coastal ocean, at least intermittently, via a single channel, and the tidal variability is largely filtered out during propagation of the tidal wave into the lagoon (Keulegan, 1967; Kjerfve & Knoppers, 1991). Such lagoons and the ecosystem they represent generally exist in a precarious balance. In the case of hypersaline systems, the water turnover time is comparatively long, which in turn leads to deteriorating water quality in response to even modest pollution loading. Choked coastal lagoons are by no means in steady state, but are continuously being transformed by climatic variability, hydrological modifications, dredging to change channel width or depth, siltation, anthropogenic loading, and other factors. How variable climatic conditions, global climatic change, and urbanization and development affect lagoons and adjacent ecosystems has received scant attention.

The study area: Lagoa de Araruama

The 100-km long, east–west stretching Fluminense coast (Figure 1) from Rio de Janeiro to Cabo Frio, Brazil, is characterized by a series of choked coastal lagoons (Oliveira, 1974; Lacerda *et al.*, 1984; Kjerfve *et al.*, 1990; Knoppers *et al.*, 1991). The easternmost of these is Lagoa de Araruama (Figures 1 & 2), located at latitude 22°50′–22°57′S and

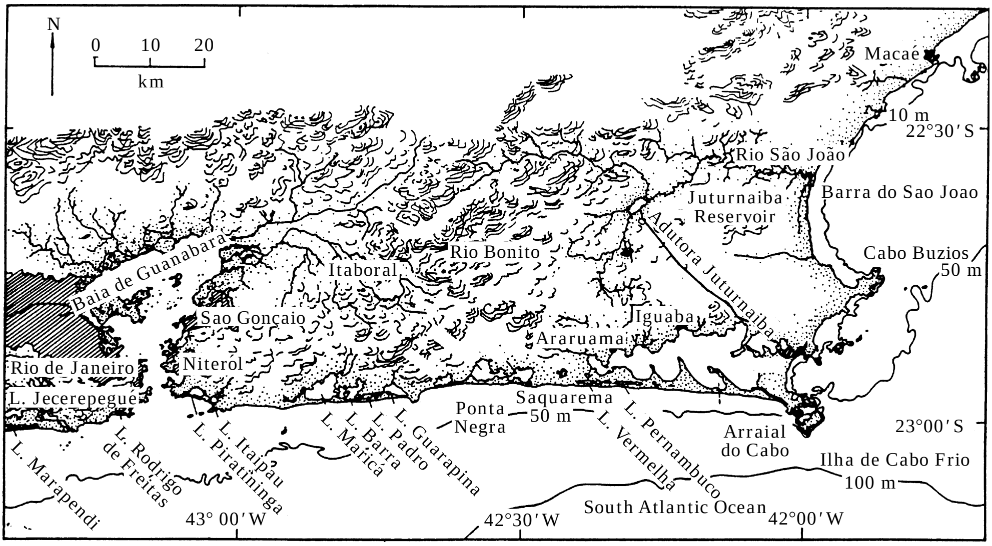

Figure 1. The Fluminense coast of the state of Rio de Janeiro, Brazil, showing the location of the 11 largest lagoons and also the location of the Juturnaiba water supply duct.

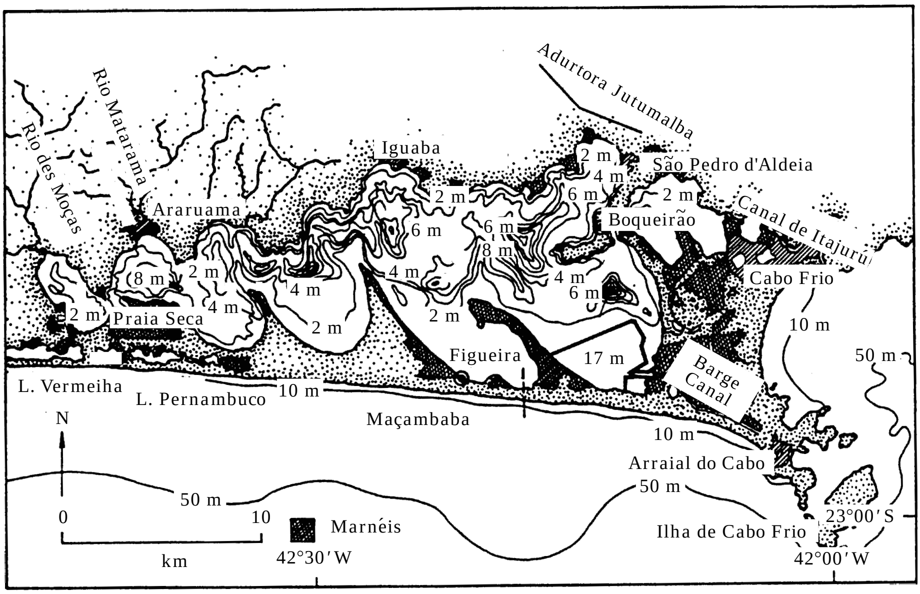

Figure 2. Bathymetry of Lagoa de Araruama, main river input to the lagoon, and also showing the approximate location (– – –) of a proposed second dredged channel to the coastal ocean east of Figueira.

longitude 42°00′–42°30′W. As a result of a semi-arid climate and a negative water balance, Lagoa de Araruama is permanently hypersaline (André *et al.*, 1981; INPH-Portobras, 1987, 1988) with a mean salinity of 52, and is also characterized by carbonate sedimentation. In spite of being one of the largest permanently hypersaline coastal lagoons in the world, Lagoa de Araruama measures only 2% of the size of the world's largest lagoon, the almost fresh Lagoa dos Patos in southern Brazil (Kjerfve, 1986).

Lagoa de Araruama and the entrance channel occupy an area of 210 km^2. The lagoon has a mean depth of 3 m, a maximum depth of 17 m, is 40 km long, has a maximum width of 13 km, a perimeter of 331 km (measured from a map of scale 1:50 000), and a water volume of 0·618 km^3. The lagoon proper consists of seven more or less elliptical cells of varying size (Figure 2), separated by extensive cuspate sand spits and submerged shallows. The lagoon is connected to the ocean via a single 14-km long channel, Canal de Itajurú, which includes two additional extremely shallow lagoon cells, and a narrow channel, which is 4 m deep close to the ocean entrance. A number of small streams intermittently flow into the lagoon from the north. Of these, Rio das Moças and Rio Matarama in the westernmost portion of the lagoon are the only notable runoff sources, covering more than 50% of the entire lagoon watershed.

The lagoon watershed is exceptionally small, measures only 350 km^2, and consists of salt-producing ponds (*marnéis*), urban development, animal pastures, sugar cane fields, and forested slopes with relief up to 600 m. Seaward of the lagoon, the coast is characterized by two beach-parallel barrier ridge systems (*restingas*) separated by a low-lying wetland area containing a series of smaller lagoons (Martin & Suguio, 1989). The barrier lagoon systems developed as a result of relative sea-level fluctuations, trapping local runoff and thus moulding the Fluminense lagoons (Muehe & Corrêa, 1989). Recent sediment cores, radio-chronology and sedimentological observations (Ireland, 1987; Turcq *et al.*, in press) indicate that Lagoa de Araruama and the internal beach ridge system formed during the Pleistocene, before 123 000 years B.P., subsequent to which a sea-level drop promoted progradation of the coastline and isolation of what today is Lagoa de Araruama. The lagoon was again submerged during a Holocene transgression 7000 to 5000 years B.P., when the seaward barrier system and the smaller lagoons between the barriers began to form. The *restingas* and the low-lying wetland swales form a unique and fragile ecosystem rich in flora and fauna (Lacerda *et al.*, 1984), which is 4 km wide in places.

The sand or silty sand sediment bottom in portions of the eastern part of the lagoon is abundant with deposits of shells of the bivalve *Anomalocardia brasiliensis*. The mollusc shells measure 2–4 cm in length on average and are deposited in the top centimetres of sediments. They are dredged from the lagoon bottom and used for commercial production of sodium carbonate in what may be the largest industry in the lagoon area. Because the bivalves occur and reproduce in coastal environments with salinities ranging from brackish to euhaline (Araújo & Maciel, 1979; Barroso, 1987), they cannot be used to assess Holocene salinity variations in the lagoon. Because of hypersaline conditions, fishing is of secondary importance in the lagoon and is limited to artisinal shrimp and mullet fishing in or near Canal de Itajurú (Barrosso, 1989).

The current population in the lagoon drainage basin measures 200 000, but varies seasonally and during weekends. The lagoon region is a major recreation area for the city of Rio de Janeiro (Barbiére, 1981; FEEMA, 1988). Significant tourism expansion and development have been slated for the lagoon borders during the coming decades with a potential 10-fold population increase. Implementation of the development plan is likely to result in irreversible change and damage to the lagoon and adjacent ecosystems. Freshwater resources are scarce in the lagoon region as a result of the semi-arid conditions and the population density. This led to construction of the Juturnaiba duct (*adutora*) in 1977, and pumping of water from the Juturnaiba Reservoir in the São João drainage basin to the north (Figure 1).

Salt extraction from Lagoa de Araruama

Salt is extracted commercially along the borders of Lagoa de Araruama from 65 km^2 of shallow diked evaporation ponds (*salinas* or *marnéis*). The lagoon has, in recent decades, contributed 10% of Brazil's gross salt production, but the lagoon salt production is currently declining. Since the First World War, the lagoon salt production has varied from 70 000 to 322 000 tons year^{-1} (Barbosa, 1973; Lamego, 1974; Barbiére, 1975), but central production data have apparently not been collected during the last decade. Nowadays, most of the salt production in Brazil takes place in Rio Grande do Norte (Barbiére, 1975), where the salt quality is better and the production cost is lower.

The Portuguese navigator, Gabriel Soares de Sousa, sailed to Cabo Frio in 1587 (de Sousa, 1971) and explored the Brazilian coast, including Lagoa de Araruama. He noted high salinities compared to the ocean and observed Indians who scooped large white salt crystals by hand from the lagoon margins (de Sousa, 1971; Hutter, 1988). A lucrative salt commerce soon developed in salinas around the lagoon, taking advantage of natural evaporation (Alcoforado & Quinan, 1925; Saint-Hilaire, 1974). To ensure continued export of expensive salt to its colony, the Crown of Portugal forbade extraction of salt in Brazil from 1631 to 1801 (Lamego, 1974). This, however, did little to stop illegal salt commerce and smuggling (Ellis, 1969).

Subsequent to the salt extraction ban, salt was again produced commercially in Lagoa de Araruama in 1820 by Luiz Lindenberg, who induced evaporation by boiling, but experienced only a marginal success rate. Large-scale commercial salt mining was only realized in Lagoa de Araruama in 1870, and flourished after the First World War. Léger Palmer re-introduced an ancient Indian method on a commercial scale, using wind-induced hydraulic gradients to move lagoon water systematically into evaporation ponds with successively saltier water–salt mixtures (Pinto & Ribeiro, 1930). This salt production technique is still practised today, although wind mills are used to pump the water from one pond to the next.

The main conclusion to be drawn from this historical description is that Lagoa de Araruama has probably been continuously hypersaline at least since the Portuguese colonization in the 16th century. Geological records indicate that the lagoon has been at least intermittently hypersaline throughout the Holocene. Based on readily available data from 1961 to 1977, salt production from Lagoa de Araruama amounted to an average of 12% of the total salt production in Brazil. However, the rate of production varied substantially from year to year, at least in part an indication of variations in lagoon salinity. The mean salt production from Lagoa de Araruama was 195 000 tons year^{-1} with a range from 100 000 to 294 000 tons year^{-1} during the period of data (Barbiére, 1975). However, since at least the mid 1980s, salt production from Lagoa de Araruama has declined substantially due to socio-economic changes in the region and increasing land prices as a result of a shift towards recreation and tourism (Barbiére, 1981).

The study

The data used in this investigation consist of: (1) nine, approximately monthly, oceanographic cruises on Lagoa de Araruama with collection of near-surface and near-bottom water quality data from 14 stations (Figure 3) in April 1991–March 1992; (2) monthly hydrometer lagoon water density and water temperature measurements by Companhia Nacional de Alcalis (CNA) near Arraial do Cabo (CNA_1; Figure 3) in

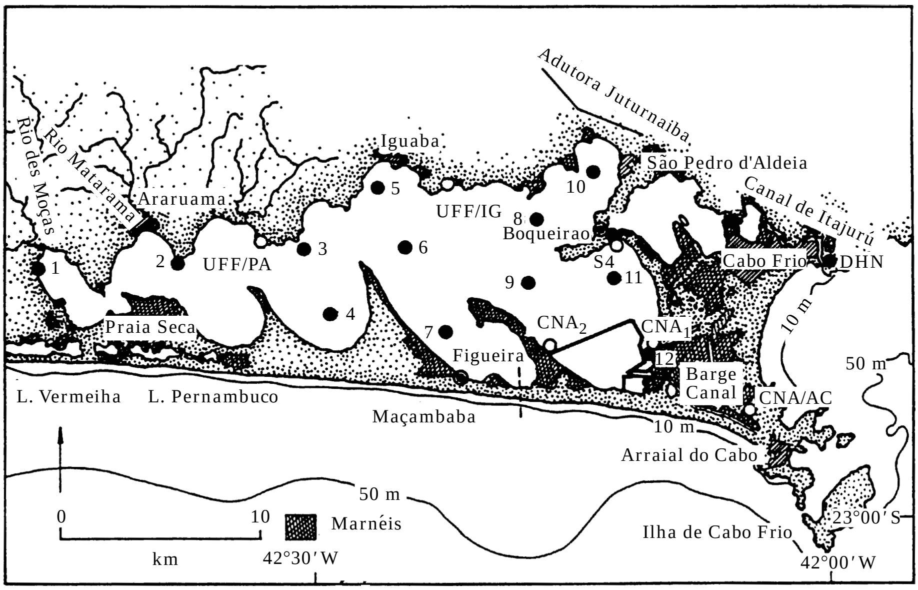

Figure 3. Lagoa de Araruama, showing the 14 lagoon-wide 1991–92 salinity sampling stations ●; the multi-year salinity (density) measurement locations by Companhia Nacional de Alcalis (CNA_2) near Arraial do Cabo, and by Universidade Federal Fluminense west of Iguaba Grande (UFF/IG) and at Ponta de Antunes (UFF/PA); the present study's daily salinity (density) and water-level measurement location (CNA_1); the meteorological stations at CNA (CNA/AC) near Arraial do Cabo and UFF (UFF/IG) west of Iguaba Grande; the location of the S4 instrument in January–February 1992 near Boqueirão; and the DHN tide measurement location at the entrance to Canal de Itajurú in Cabo Frio.

1965–91; (3) twice daily lagoon water density and temperature measurements by CNA at another site near Arraial do Cabo (CNA_2; Figure 3) in August 1990–February 1992; (4) once daily lagoon hydrometer water density and water temperature measurements at the Universidade Federal Fluminense Campus em Extensão near Iguaba Grande (UFF/IG; Figure 3) in September 1976–October 1980; (5) once daily lagoon hydrometer water density and temperature measurements by UFF personnel at Ponta dos Antunes (UFF/PA; Figure 3) in March 1977–January 1979; (6) daily or more frequent meteorological measurements by CNA at Arraial do Cabo (CNA/AC; Figure 3) 1965–85, and at the Universidade Federal Fluminense Campus em Extensão near Iguaba Grande (UFF/IG: Figure 3) in 1970–91; (7) field installation of one InterOcean S4 electromagnetic current meter at the lagoon entrance to Canal de Itajurú near Boqueirão (S4; Figure 3) in January–February 1992; (8) cross-calibration of salinity measurements with different types of instruments; and (9) an assortment of supporting data, including DHN hourly water level measurements, for more than 1 year at the entrance to Canal de Itajurú (DHN; Figure 3).

Salinity determination

Determination of salinity in hypersaline environments is not trivial. The ionic composition of the salt may not correspond to the Law of Constant Ratios, and the equation of state and conductivity-to-salinity conversions only extend to 42 (for the temperature range −1–30 °C) (Fofonoff & Millard, 1983). The standard silver nitrate precipitation method (Strickland & Parsons, 1972; Grasshoff *et al.*, 1983) is not applicable for hypersaline samples. Since the salinity consistently exceeds 50, and the temperature at times exceeds 30 °C, the determination of salinity in Lagoa de Araruama required special consideration.

During the 9-day sampling cruises on the lagoon in 1991–92, 1-l water samples were collected from each of the 14 stations, consisting of a single near-surface sample when the water depth was less than 1 m, and surface and bottom samples when the water depth was greater than 1 m. The surface sample at Stations 3, 6 and 8 were replicated with collection of three separate water samples. Salinity and temperature were determined immediately in the field using a refractometer and a mercury thermometer, respectively. Upon return to the laboratory in Niterói, the salinity was redetermined more accurately and precisely. A 20 ml aliquot was taken from each sample bottle, mixed with 60 ml of distilled water, and the sample and distilled water masses were determined with an Ainsworth precision scale. The resulting mixture had a suitably low salinity to permit the use of a standard bench-top conductivity meter. A Radiometer Copenhagen CDM83 Conductivity Meter with a platinum type cell was used, which is a microprocessor-controlled high-precision laboratory instrument. The cell was calibrated during each sampling occasion using standard seawater at approximately 25 °C. Most importantly, the samples had to attain the temperature of the standard seawater before measurements could proceed. The conductivity ratio was then determined for the mixture of sample and distilled water, and salinities were calculated (Fofonoff & Millard, 1983) to a precision of ±0·01. The actual lagoon salinities were finally calculated by multiplication with the ratio of mass of the sample-distilled water mixture to the mass of the sample. All salinities determined by the bench-top measurements on the refractometer determinations were regressed, thus obtaining a high coefficient of determination, $r^2=0{\cdot}98$. In a number of instances, conductivity meter readings were not available, so the in-field refractometer readings had to be adjusted slightly, using the regression relationship, to be consistent with bench-top conductivity determinations for the other samples when both types of measurements were available.

The long-term salinity time series data that were analysed were collected by salt pond operators (*marineiros*) at fixed locations near the border of the lagoon. The measurements included in the present analysis were collected in the open lagoon rather than in the salinas. These long-term salinity determinations were actually density determinations, using a hydrometer and augmented with a temperature reading. The units of measure are degrees Baumé (Bé° @ 25 °C), which is related to density, ρ (kg m^{-3}) according to:

$$\rho=\left[\frac{145}{145-\text{Bé}}\right]10^3 \tag{1}$$

CRC (1979). Bé = 0 for distilled water at 4 °C. Extensive cross-calibrations were made of several tens of water samples, comparing refractometer readings, bench-top conductivity determinations, and hydrometer readings expressed as Bé @ 25 °C. The small influence on density of the seasonal temperature fluctuation (22–29 °C) in the lagoon was ignored, and a regression relationship was derived:

$$s=11{\cdot}0\ \text{Bé}-2{\cdot}9 \tag{2}$$

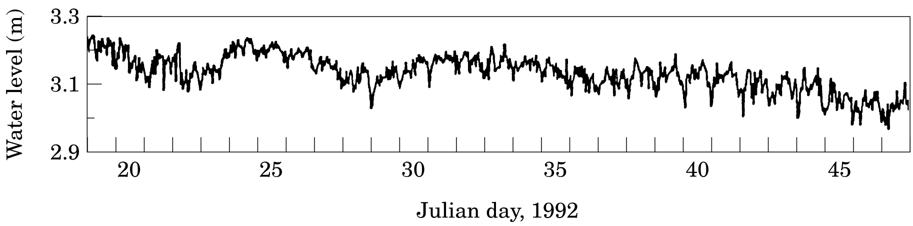

Figure 4. Water-level time series measured by the InterOcean S4 electromagnetic current meter at Boqueirão (Station 14) January–February 1992. The water level had to be adjusted for the first 24 h by 28 cm because the bottom stand overturned.

where *S* is salinity and Bé is the density (Bé @ 25 °C). Standard error of the salinity estimates were 0·3 for the density range 3·0–10·0 Bé.

Variations in tidal water level

Since lagoon salinity measurements have been collected daily, monthly, and on a variety of other time scales, the risk of aliasing of the data is a potential danger. This is particularly hazardous when sampling is performed on a daily basis or another low-frequency time scale in systems which experience variations on tidal frequencies.

Lagoa de Araruama connects to the ocean via Canal de Itajurú (Figure 3). From time to time, DHN (Diretoria de Hidrografia e Navegação) makes tidal measurements at Cabo Frio, where the semi-diurnal tidal range is 1·05 m on average with a spring tidal range of 1·30 m and a neap tidal range of 0·80 m (Lessa, 1989, 1990). However, the channel acts as a filter (cf. Kjerfve & Knoppers, 1991). At a distance of 5·4 km from the ocean, the tidal range is 0·12 m. After 8·3 km from the ocean, the tidal range is 0·12 m, and after 14 km from the ocean, the tidal range is negligible according to Lessa (1989). Thus, Canal de Itajurú chokes the tide as it enters Lagoa de Araruama, and the $3{\cdot}71 \times 10^7$ m^3 tidal prism is largely confined to the canal (Lessa, 1989).

To assess water level and current variability, an internally recording InterOcean S4 electromagnetic current meter was installed at Boqueirão (Number 13; Figure 3) 0·75 m above the bottom, using a weighted bottom stand in 3·6 m water depth. The current measurements were rendered useless after the first day, because a fisherman's net overturned the stand. The water-level measurements (Figure 4), however, were easily corrected for this 1 day. To permit standard harmonic tidal analysis, measurements were taken for 29 days, 19 January–17 February 1992. The S4 was programmed to calculate a 2-min average based on 0·5 s samples, repeated every 6 min. Harmonic analysis (Franco, 1988) indicated that the variability of tidal water level was small, and the overall root mean squared (rms) water-level variability measured only 6 cm where the lagoon and Canal de Itajurú join. Of the diurnal astronomical constituent tides, only K_1 was significant with a 2·2 cm amplitude (Table 1). Whereas the semi-diurnal tide was removed during propagation through Canal de Itajurú, the diurnal K_1 component tide was only diminished to 44% as compared to Cabo Frio and took 3·0 h to travel the length of the canal (Table 1). The 2·2 cm amplitude S_2 component tide was also significant but was probably totally radiational and due to lagoon wind forcing, probably the land–sea breeze cycle. Overall, the water-level variability at Boqueirão was small with numerous non-coherent high-frequency fluctuations, but it was not negligible as suggested by Lessa (1989).

TABLE 1. Amplitude and phase (°G) of the main tidal harmonic constants for Cabo Frio (CB) seaward of Canal de Itajurú (1989 data from DHN, Diretoria de Hidrografia e Navegação); and for Boqueirão (Boq) from the 29-day S4 installation at Station 14 in 1992, calculated according to Franco (1988)

Component tide	CB (cm)	CB (°G)	Boq (cm)	Boq (°G)	Period (h)
Mm Monthly lunar	5·7	308			661·309
O_1 Principal lunar diurnal	2·7	075			25·891
K_1 Luni–solar diurnal	5·0	147	2·2	192	23·934
N_2 Larger lunar elliptic	4·7	089			12·658
M_2 Principal lunar semi-diurnal	32·6	079			12·421
L_2 Smaller lunar elliptic	2·2	092			12·192
S_2 Principal solar semi-diurnal	17·2	088	2·2	011	12·000
M_4 Main M_2 shallow-water effect	1·9	025			6·210

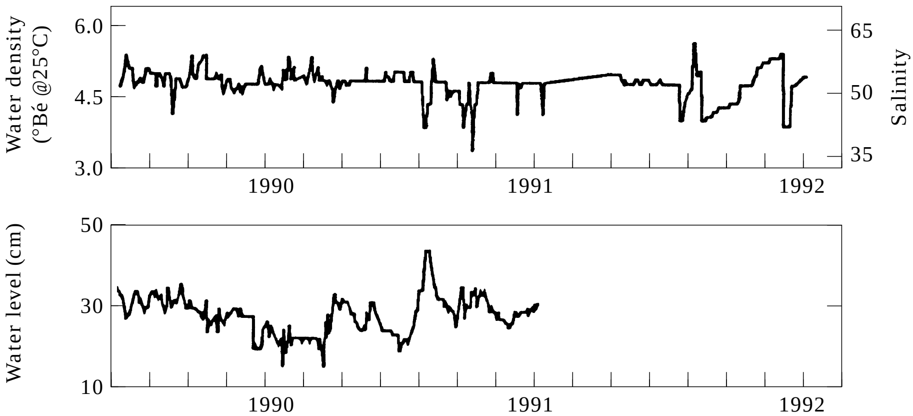

Figure 5. Daily salinity (density and water level measurements at CNA_1, 1990–92, encompassing 416 and 268 daily measurements, respectively. Approximately 2 months of salinity data were not collected in January–February 1991 and were interpolated as a straight line.

Since tidal and meteorological water-level fluctuations at most times are small in the lagoon, associated tidal and other water parcel excursions are also small. Thus, the risk of aliasing lagoon data by daily measurements is minimal. This is further amplified by the water-level measurements made daily at Station 12 (CNA_1) 1990–91 (Figure 5). The 268 daily water-level measurements yielded a standard deviation of 14·0 cm, mostly due to fluctuations on time scales of weeks–months.

Climatic and meteorological characteristics

The Fluminense coast exhibits a strong climatic gradient with arid conditions towards the east. Classification of the climate (Köppen, 1900) at Arraial do Cabo and the extreme eastern part of Lagoa de Araruama yields Bsh, semi-arid warm climate. However, most of the lagoon is a mixture between Bsh and Aw, tropical climate with rainy summers and dry winters (Barbiére, 1984). Comparison of time series of annual means of air temperature, precipitation, evaporation and relative humidity in 1965–91, at Arraial do Cabo (CNA/AC; Figure 6) and Universidade Federal Fluminense Campus

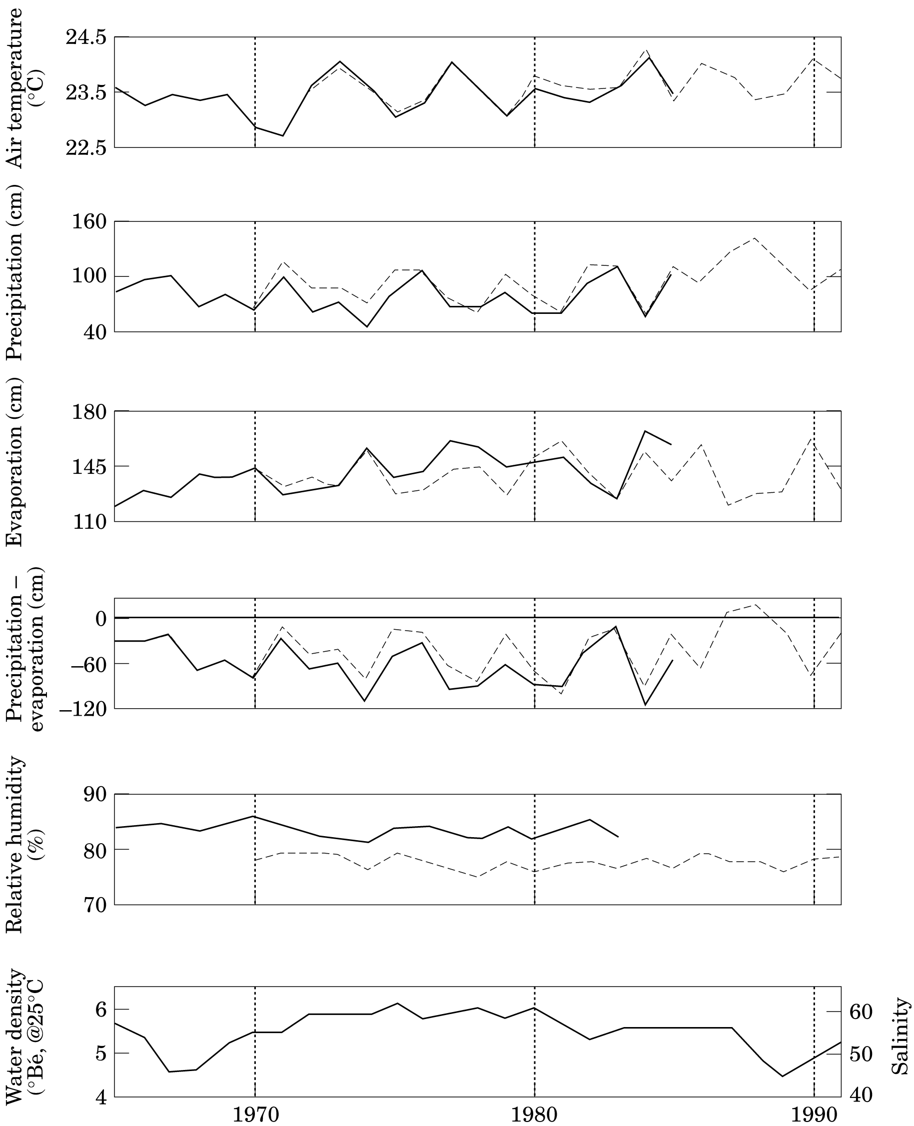

Figure 6. Comparison of time series measurements, 1965–91, of annual means of meteorological parameters (air temperature, precipitation, evaporation, the difference between precipitation and evaporation, and relative humidity) at CNA/AC (——) and UFF/IG (– – –), and annual salinity calculated from the hydrometer measurements at CNA_2.

em Extensão near Iguaba Grande (UFF/IG; Figure 6), yielded less than excellent correlations, $r^2 = 0{\cdot}92$ for air temperature, $r^2 = 0{\cdot}69$ for precipitation, $r^2 = 0{\cdot}44$ for evaporation, $r^2 = 0{\cdot}64$ for the difference between precipitation and evaporation, and $r^2 = 0{\cdot}15$ for relative humidity. Mean differences between the two meteorological stations indicate that precipitation is somewhat higher, evaporation somewhat lower, and relative humidity substantially lower at UFF/IG (Figure 6). Whereas the annual mean data indicate that only 1987 and 1988 were years with a positive difference between precipitation and evaporation (Figure 6), the monthly mean difference series (Figure 7)

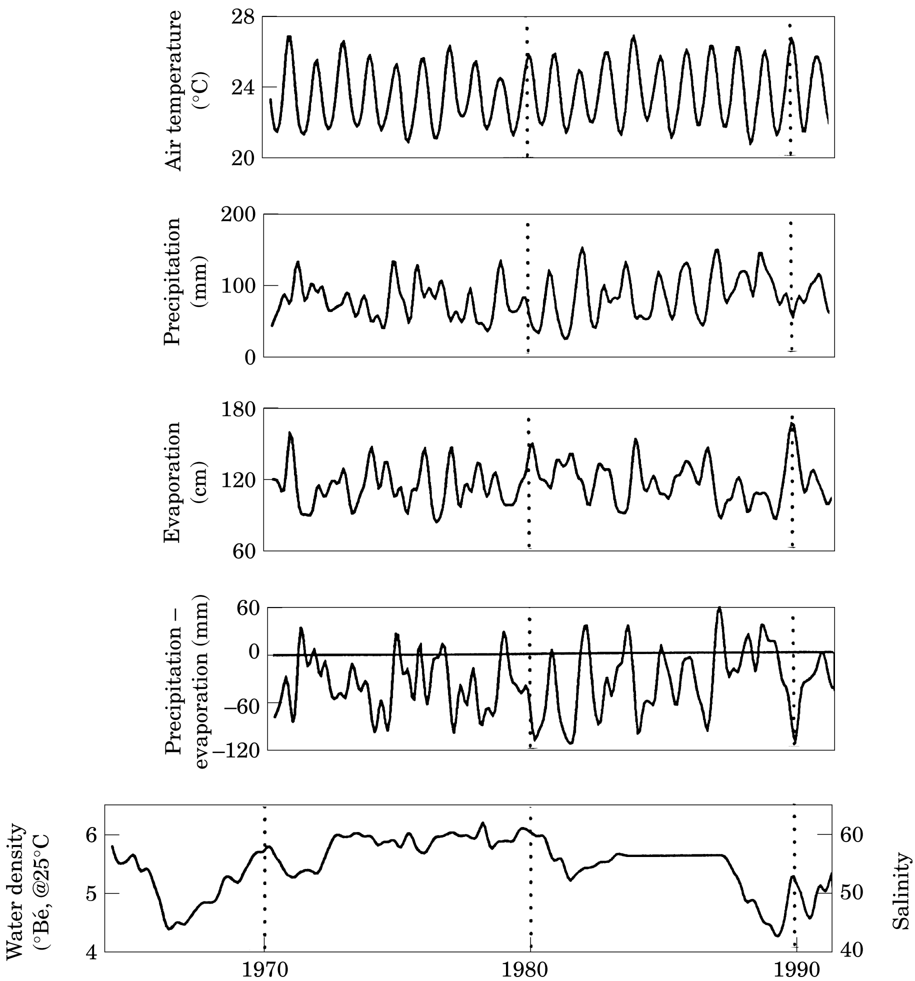

Figure 7. Time series, 1965–91, of mean monthly precipitation, mean monthly evaporation, mean monthly difference between precipitation and evaporation at CNA/AC, and monthly salinity at CNA_2.

clearly shows that many periods with a positive difference have occurred in the past two decades, especially during the beginning of the austral summer (Figure 7).

Since most of the lagoon is more typical of the UFF/IG location, the authors consider the UFF/IG data more characteristic of Lagoa de Araruama as a whole as compared to the CNA/AC data from Arraial do Cabo. At Arraial do Cabo, the semi-arid climate is closely linked to the occurrence of intense cold-water upwelling offshore from Ilha de Cabo Frio, which in turn helps to explain the negative regional water balance and occurrence of hypersaline lagoons (Turcq *et al.*, in press).

Lagoa de Araruama experiences strong north-easterly winds year-round (Figure 8), which have an average speed of 5·2 m s^{-1} but frequently 10 m s^{-1} as measured at UFF/IG in 1980–89. These north-easterly winds are particularly energetic from September to April, when the anticyclonic synoptic flow is augmented by a well-developed daytime sea breeze. The north-easterly winds produce intense coastal upwelling along the coasts of the states of Espírito Santo and Rio de Janeiro, especially

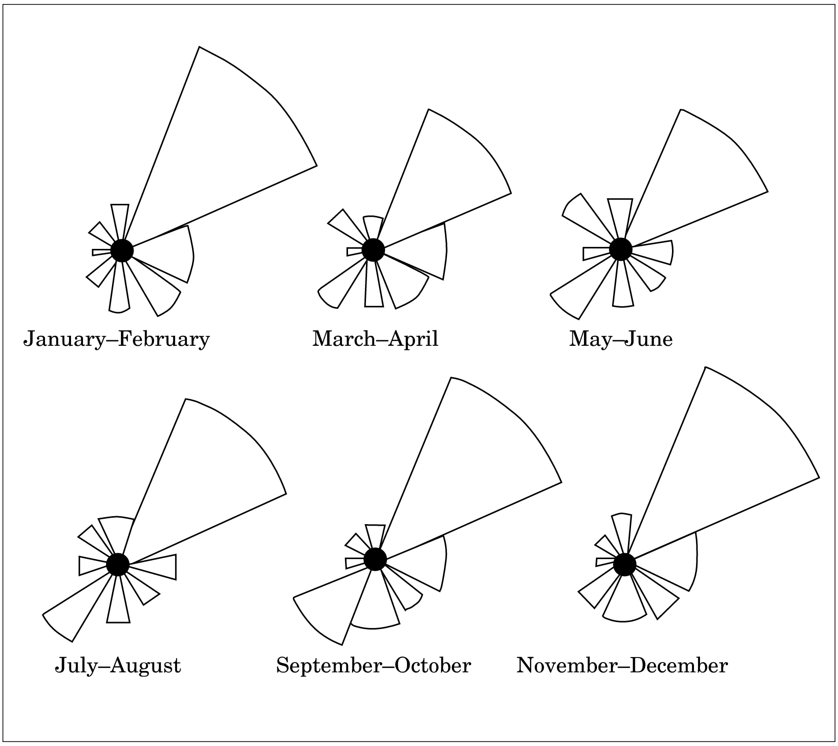

Figure 8. Bimonthly wind roses for Lagoa de Araruama based on data from Universidade Federal Fluminense Campus em Extensão near Iguaba Grande (UFF/IG) meteorological station, 1980–89.

southward of major coastal capes. Cold surface waters, often 13–15 °C, appear south of Ilha de Cabo Frio as the Brazil current veers further from the coast, allowing South Atlantic central waters to ascend onto the shelf and upwell close to the coast (Martin & Flexor, 1992). The Cabo Frio upwelling is positively correlated with El Niño events along the coasts of Ecuador and Peru. During El Niño years, a north-westward flowing tropospheric tropical jet stream, is pushed to the south, crossing southern Brazil and acting to block or partially block the northward propagation of polar fronts from reaching the Fluminense coast (Martin & Flexor, 1992). Consequently, north-easterly winds continue to blow strongly for most of the year and enhance and prolong upwelling, especially during intense El Niño years such as 1983 (Martin & Flexor, 1992).

North-easterly winds blow 38% of the time and are the primary forcing of Lagoa de Araruama during the entire year (Figure 8). They produce wind-driven currents, low-frequency lagoon-water-level fluctuations, setup–setdown, and choppy waves with heights sometimes exceeding 1 m. During the austral winter months, June–August, sharp polar frontal systems propagate northward at 500 km day^{-1} from the South Atlantic and give rise to intense, short-duration south-westerly and southerly lagoon winds subsequent to the arrival of the front. A recent satellite study indicated that an average of 13 cold fronts arrive at the Fluminense coast annually, with 6 days between consecutive fronts (Stech & Lorenzzetti, 1992). Although winds from the south-west (11% frequency) and south (9% frequency) only average 3·3 and 3·8 m s^{-1}, respectively, peak winds from these sectors occasionally exceed 25 m s^{-1}. Mean wind speeds

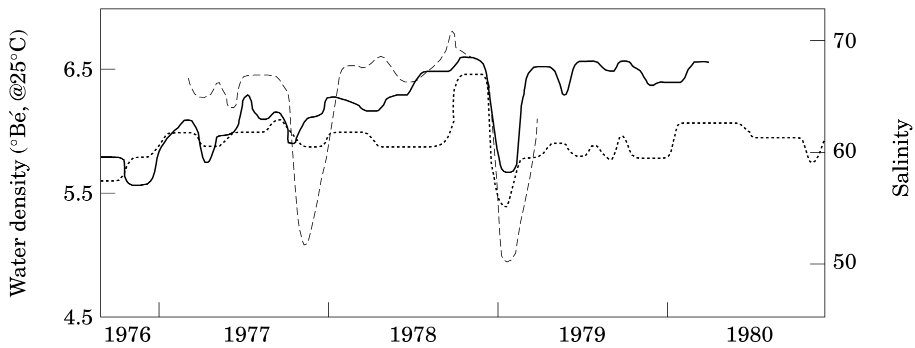

Figure 9. Comparison of mean monthly salinity (density) time series measurements, 1976–80, at three locations in Lagoa de Araruama: at Arraial do Cabo (CNA_2; (· · · ·), at Iguaba Grande (UFF/IG; ——), and at Ponta dos Antunes (UFF/PA; – – –).

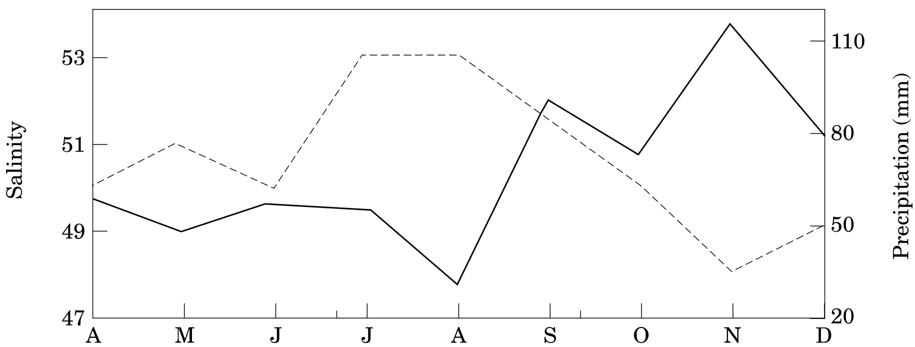

Figure 10. Time series of the salinity in Lagoa de Araruama, calculated as the mean of the pooled measurements at the 14 stations during the 1991–92 lagoon-wide cruises, compared to the cumulative precipitation (mm $month^{-1}$) measured at UFF/IG for each cruise date. – – –, salinity; ——, precipitation.

at UFF/IG, 1980–89, measured 3·8 m s^{-1} from the north for 5% of the time, 4·3 m s^{-1} from the east for 9% of the time, 3·8 m s^{-1} from the south-east for 9% of the time, 1·7 m s^{-1} from the west for 2% of the time, and 2·3 m s^{-1} from the north-west for 6% of the time. Eleven percent of the time, the winds are calm.

Lagoon rainfall measured 932 mm annually. Although the seasonal distribution of precipitation is relatively constant, November and December yielded the most rainfall and June–August the least (Table 2). Class A pan-evaporimeter measurements at UFF/IG indicate a mean annual evaporation rate of 1390 mm with peak rates during the austral summer months, when air temperatures are warmer and winds are stronger. Every month, with the exception of November, had a substantial net water deficit, which was most acute in February and August (Table 2).

Salinity distribution and variability

The approximately monthly lagoon-wide cruises between April 1991 and March 1992 yielded salinity, temperature and depth data from the 14 stations (Figure 3). Whereas data for most stations were measured from a research vessel, the data at Station 1 was collected by wading 100 m into the lagoon, at Station 2 from a dock, at Station 12 by

TABLE 2. Calculation of water balance components based on the monthly averages of 1970–91 meteorological data at Universidade Federal Fluminense Campus em Extensão near Iguaba Grande (UFF/IG; Figure 3)

Month	Temp (°C)	Rain (mm)	Evap (mm)	Diff (mm)	$\Delta f/r$ (−)	Q_R ($m^3 s^{-1}$)	Q_P–Q_E ($m^3 s^{-1}$)
January	26·2	92·0	133·4	− 41·4	0·12	1·1	− 4·3
February	26·8	62·2	139·5	− 77·3	0·04	0·3	− 8·8
March	26·1	81·8	130·9	− 49·1	0·09	0·8	− 5·0
April	24·5	92·3	105·7	− 13·4	0·14	1·4	− 1·4
May	22·7	81·3	95·6	− 14·3	0·13	1·1	− 1·5
June	21·4	50·3	93·1	− 42·8	0·05	0·3	− 4·5
July	21·0	50·2	106·2	− 56·0	0·05	0·3	− 5·8
August	21·4	41·1	117·0	− 75·9	0·02	0·1	− 7·8
September	21·6	67·3	116·7	− 49·4	0·10	0·7	− 5·2
October	22·8	84·3	115·0	− 30·7	0·14	1·3	− 3·2
November	24·0	113·6	109·5	4·1	0·21	2·6	0·4
December	25·4	115·1	119·3	− 4·2	0·19	2·3	− 0·4
Year	23·7	931·5	1381·9	− 450·4	0·11	1·0	− 4·0

Diff, difference between measured precipitation and evaporation; $\Delta f/r$, monthly runoff ratio; Q_R, monthly mean discharge from the drainage basin into Lagoa de Araruama, calculated for a drainage basin area of 285 km^2; Q_P–Q_E, water gain (+) or loss (−) from the 210-km^2 lagoon surface area plus the 65 km^2 of *marnéis* due to the difference between precipitation and evaporation.

wading 10 m into the lagoon, and at Station 14 from a bridge. A summary of the data are presented in Table 3.

The lagoon salinity was remarkably constant spatially (Figure 9) and during the different seasons (Figure 10) with a mean of 51·8 and an average standard deviation of only 1·2 in 1991–92 (Table 3). The stations that exhibited the largest temporal variability were the westernmost station (1) influenced by the discharge of Rio das Moças and the stations (13 & 14) in Canal de Itajurú, for which standard deviations varied between 2·5 and 4. The more shallow stations (4, 7 & 12) at the southern extremes of the lagoon cells exhibited intermediate salinity variability with standard deviations of 2–3, in response to greater local influence by rainfall and evaporation because of shallow depths and reduced water exchange.

Spatially, the lagoon water temperature was even more constant than the salinity. The average lagoon water temperature was 25·5 °C with an average temporal standard deviation over the year of 3·3 °C. Surface and bottom temperature differences were less than 0·5 °C throughout the lagoon. Only Canal de Itajurú (Station 14) exhibited significantly cooler mean water temperature than the lagoon by 2 °C, because of occasional intrusions of cold coastal waters with a significantly lower salinity than the waters in the lagoon (Table 3).

The long-term density (salinity) measurements in 1965–91 at CNA are shown in Figures 6 and 7, indicating substantial variability from year to year. The monthly variability (Figures 7 & 10) indicates minor fluctuations on this time scale, implying a very slow response of the lagoon to rainfall–runoff events. The most interesting feature of the time series is the substantial drop in the lagoon salinity approximately 1 year subsequent to the positive precipitation–evaporation difference in 1987 and 1988 (Figures 6 & 7). Although regression of salinity on time indicates a decreasing salinity trend of 0·15 $year^{-1}$ or 3·9 over the 26 years of data, this trend could possibly be a partial cycle of a long-term fluctuation related to climatic variability.

TABLE 3. Mean and root mean square salinities and temperatures from the 14 sampling locations, from near-surface and near-bottom, and the average recorded water depths, in Lagoa de Araruama, based on the nine sampling cruises, 16 April 1991–17 March 1992

Station	Depth (m)	$<S>$	S_{rms}	T_O (°C)	T_{rms} (°C)
1	0·6	46·4	3·1	25·8	3·6
2	0·8	51·9	1·4	25·4	3·6
3S		52·7	1·3	24·9	2·9
3B	8·1	53·1	1·7	24·7	2·7
4S		52·0	2·6	25·5	3·2
4B	3·7	52·2	2·7	25·0	3·2
5S		52·7	1·6	25·7	2·9
5B	3·5	53·0	1·2	25·5	3·1
6S		52·2	1·6	25·3	2·9
6B	5·8	52·7	1·2	24·9	2·4
7S		53·3	1·9	25·2	2·6
7B	2·4	53·3	1·8	25·0	2·3
8S		52·3	1·6	25·5	3·6
8B	6·5	52·1	2·0	25·2	3·3
9S		51·9	1·5	25·9	3·5
9B	6·1	51·9	1·2	25·6	3·4
10S		52·2	1·0	26·0	3·8
10B	3·9	52·0	1·1	25·7	3·5
11S		52·4	1·9	25·9	3·5
11B	5·8	52·2	1·8	25·7	3·4
12	0·4	53·7	2·4	25·6	4·6
13S		51·8	2·7	25·0	2·8
13B	3·1	52·4	2·6	25·0	2·9
14S		46·8	3·1	24·0	2·7
14B	2·1	47·4	4·2	23·0	0·7
Mean		51·8	1·2	25·2	3·3

rms, root mean square; S, near surface; B, near-bottom; S, salinity; T, temperature.

On a shorter time scale, the daily salinity (density) measurements in 1990–92 (Figure 5) at Station 12 indicate that the risk of salinity aliasing is minimal, even if measurements are made as infrequently as monthly. The mean salinity measured was 50·3 with a standard deviation of 3·0, based on 416 daily measurements. A paired *t*-test comparison between the daily salinities at Station 12 (CNA_1), collected on the days of the monthly lagoon cruises, and the mean lagoon salinities from the nine monthly cruises in 1991–92, yielded a statistically insignificant difference, although the mean lagoon salinity was more salty than that at Station 12 by 1·8. Thus, the long-term salinity time series, collected at either CNA_1 or CNA_2 are indeed representative of the lagoon salinity.

Lagoon water balance

To investigate the order of magnitude of the processes responsible for maintaining the hypersaline conditions in Lagoa de Araruama, the net water and salt balance terms in Lagoa de Araruama were analysed. The net water balance can be written:

$$\frac{dV}{dt} = Q_P + Q_E + Q_G + Q_R + Q_J + Q_C + Q_O \tag{3}$$

TABLE 4. Summary of steady state estimates of Lagoa de Araruama water flux and salt flux terms

Water balance ($m^3\ s^{-1}$)							
dV/dt^a =	Q_P	Q_E	Q_G [a]	Q_R	Q_J	Q_C	Q_O
0·0	+8·1	−12·1	0·0	+1·0	+0·7	+0·05	+2·25
Salt balance ($kg\ s^{-1}$)							
dS/dt =	S_M	S_C	S_A	S_D			
−3·0	−6·2	+1·8	−80·3	−78·9			

[a]Assumed equal to zero.
Estimates of the uncertainties of each of these terms are given in the text.
For abbreviations, see text.

The water fluxes are expressed in $m^3\ s^{-1}$ with the sign convention where water gain is positive and water loss is negative. The results of the water balance calculations are shown in Table 4.

The change in lagoon water storage is expressed by dV/dt, where V is lagoon volume (m^3), and the derivative is positive when the volume increases. Over the duration of the study, there are no indications that the mean water level changed. Thus, dV/dt was assumed to equal zero, but it was recognized that every 1-cm change in mean lagoon water level corresponds to a flux of $\pm 0{\cdot}09\ m^3\ s^{-1}$ when applied to the combined surface area of the lagoon (210 km^2) and the *marnéis* (65 km^2). Considering that many homes adjacent to the lagoon are built very near the lagoon margin and almost at mean lagoon level, and that a 10-cm mean water-level change from year to year would be excessive, the root mean square (rms) of the storage term is estimated to be less than $\pm 0{\cdot}9\ m^3\ s^{-1}$.

Q_P represents the precipitation flux onto the lagoon surface and the adjacent *marnéis*. The rainfall as measured at UFF/IG was used and assumed homogeneous for the lagoon. The Q_P term is calculated as the product of the rainfall rate and the lagoon surface area. The mean annual Q_P measured $+8{\cdot}1\ m^3\ s^{-1}$ with a rms corresponding to a flux variability of $\pm 1{\cdot}9\ m^3\ s^{-1}$ based on 26 years of annual data.

Q_E represents the evaporation flux from the lagoon surface and the adjacent *marnéis*, as measured at UFF/IG, and was assumed homogeneous for the lagoon. The evaporation rate was measured directly and when multiplied by the lagoon surface area yielded Q_E. The mean annual Q_E flux measured $-12{\cdot}1\ m^3\ s^{-1}$ with a rms corresponding to a flux variability of $\pm 1{\cdot}2\ m^3\ s^{-1}$ based on 26 years of annual data.

Q_G represents the groundwater flux into the lagoon. However, lacking information on local aquifer water levels, this flux was assumed to be zero in view of the semi-arid climate and the very low rainfall. Inclusion of real data would probably modify the water balance slightly.

Q_R represents surface runoff from the 285 km^2 of the drainage basin not covered by *marnéis*. In the absence of stream gauging and the intermittent nature of the stream flow that enter Lagoa de Araruama, the runoff into the lagoon was estimated from an empirical model. The monthly runoff ratio, $\Delta f/r$, was expressed:

$$\frac{\Delta f}{r} = e\left(-\frac{e_o}{r}\right) \tag{4}$$

(Schreiber, 1904), where Δf is monthly runoff (mm), r is monthly rainfall (mm), and e_o is monthly potential evapotranspiration (mm), which was calculated as a function of air temperature, $T(K)$, according to:

$$e_o = 1{\cdot}0 * 10^9 \, \mathrm{e}\left(-\frac{4{\cdot}62 * 10^3}{T} \right) \quad (5)$$

(Sellers, 1965; Holland, 1978; Kjerfve, 1990). The mean monthly runoff, q_R, and the mean annual runoff, Q_R, into the lagoon were estimated based on UFF/IG average data from 1970–91 according to:

$$q_R = A_B \left(\frac{\Delta f}{r} \right) \frac{r}{2{\cdot}592 * 10^9} \quad (6)$$

(Kjerfve, 1990), where $A_B = 2{\cdot}85 \ 10^8 \ \mathrm{m}^2$ is the lagoon surface area not covered by *marnéis*, and the constant converts the monthly rainfall in mm to m s^{-1}. The mean annual surface runoff was calculated as the mean of the monthly values, and Q_R was found to be $+1{\cdot}0 \ \mathrm{m}^3 \ \mathrm{s}^{-1}$ with an estimated rms annual variability of $\pm 1{\cdot}0 \ \mathrm{m}^3 \ \mathrm{s}^{-1}$. The data and results are shown in Table 2. Although the above model is somewhat questionable for monthly data, the relative homogeneity of monthly rainfall and temperature data justified its use (Table 2).

Q_J represents the flux of water pumped from the Juturnaiba reservoir. Beginning in 1977, CEDAE (Companhia Estadual de Águas e Esgotos) started pumping freshwater from the adjacent Rio São João drainage basin via a 30-km long pipeline, *adutora* Juturnaiba (Figure 1), to supply freshwater to the communities surrounding Lagoa de Araruama. The pumping rate was initially $0{\cdot}4 \ \mathrm{m}^3 \ \mathrm{s}^{-1}$, increased to $0{\cdot}6 \ \mathrm{m}^3 \ \mathrm{s}^{-1}$ in 1982, $0{\cdot}8 \ \mathrm{m}^3 \ \mathrm{s}^{-1}$ in 1987, and has remained constant at $1{\cdot}1 \ \mathrm{m}^3 \ \mathrm{s}^{-1}$ since November 1990. Although no data exist as to the ultimate fate of this water, the authors estimated that 60–65% of the pumped water is eventually discharged into Lagoa de Araruama with a lag time of less than 1 month, whereas the remaining wastewater is discharged into the Saquarema lagoon system or directly into the ocean. Q_J measured zero prior to 1978, and reached $+0{\cdot}7 \ \mathrm{m}^3 \ \mathrm{s}^{-1}$ after 1991, whereafter the rms variability of this estimate is zero. The water flux to the lagoon from potable water carried by trucks to the region is negligibly small compared to other flux terms.

Q_C represents the flux of water that enters the lagoon through a dead-end barge canal with a lock operated by Alcalis near Station 12. To allow shell-dredge and supply barges to enter the inner-most area of the canal from the lagoon, the lock is filled by water pumped from the ocean near Praia Grande. The lock is 45 m long, 10 m wide, and is filled to increase the depth by 1·6 m, on average, six times a day since 1960. This corresponds to an average Q_C flux of $+0{\cdot}05 \ \mathrm{m}^3 \ \mathrm{s}^{-1}$ with an estimated annual rms variability of $\pm 0{\cdot}01 \ \mathrm{m}^3 \ \mathrm{s}^{-1}$.

Q_O represents the net water flux through Canal de Itajurú, which is the residual water exchange between the inflow of ocean water and outflow of lagoon waters on tidal, meteorological and longer time scales. Although oscillating flows in and out of the lagoon are far greater than the net water flux, reliable data to estimate the magnitude and variability of these shorter-term water fluxes do not exist. On the assumption that the mean lagoon water volume does not vary from one year to the next, Q_O was estimated as the difference in equation (3). The net annual ocean flux, Q_O, through Canal de

Itajurú, was calculated to be an inflow equal to $+2{\cdot}25$ m^3 s^{-1}, with an annual mean rms advective flux variability of $\pm 1{\cdot}2$ m^3 s^{-1}. Prior to construction and operation of the *adutora* Juturnaiba in 1977, the net ocean inflow would have been 31% greater than at present, according to these calculations.

Lagoon salt balance

The lagoon net salt balance was expressed as:

$$\frac{dS}{dt} = S_M + S_C + S_A + S_D \tag{7}$$

where the salt mass fluxes are expressed in kg s^{-1}, positive for import and negative for export, and the results are summarized in Table 4.

The change in lagoon salt storage is expressed by dS/dt, where S is the mass of salt in the lagoon, and the derivative is positive when the mass increases. It was assumed that the mass of salt in the lagoon had decreased steadily at a rate corresponding to the measured trend of 3·9 decline of salinity at CNA_2 over the past 26 years, but that the water volume had remained constant. This allowed calculation of ds/dt to equal $-3{\cdot}0$ kg s^{-1}, with an estimated annual rms variability of $\pm 2{\cdot}0$ kg s^{-1} based on the long-term salinity variability.

S_M represents salt mined from the *marnéis* along the lagoon margins. The annual S_M flux rate was calculated based on the linear regression of salt production on the difference between annual rainfall, P (m year^{-1}), and evaporation, E (m year^{-1}) at UFF/IG from:

$$S_M = -186{\cdot}2\ (P - E) + 108\,830 \tag{8}$$

which yielded a coefficient of variation, $r^2 = 0{\cdot}67$. This is less than perfect, but it does indicate the inverse relationship between salt production and the difference between precipitation and evaporation. However, $(P - E)$ was the best available predictor for the years of data. In extrapolating the salt production for the most recent decade, it is recognized that the calculated S_M fluxes overestimate the actual salt production, but this number will be used in the salt balance. The average salt production of 195 000 tons year^{-1} corresponded to an average export of salt from the lagoon of $-6{\cdot}2$ kg s^{-1} with an annual rms variability of $\pm 2{\cdot}5$ kg s^{-1} based on 13 years of salt production data.

S_C represents the salt flux into the lagoon from ocean water pumped into the barge canal lock at Alcalis. It was calculated from:

$$S_C = Q_C\, \rho \frac{s_o}{1000} \tag{9}$$

where ρ is the water density (kg m^{-3}) and S_o the average coastal ocean salinity of 35. This yielded an average S_C flux of $+1{\cdot}8$ kg s^{-1} subsequent to 1960, with a calculated annual rms variability of $\pm 0{\cdot}4$ kg s^{-1}.

S_A represents the net advective salt flux in Canal de Itajurú, which can be calculated as:

$$S_A = Q_O\,\rho\,\frac{s_o}{1000} \quad (10)$$

where s_o is the ocean salinity. The advective salt transport was calculated to be an influx equal to $+80{\cdot}3$ kg s^{-1} with an estimated annual rms variability of ± 40 kg s^{-1}, where the rms calculation is at best an order of magnitude estimate based on the calculated variability of Q_O and estimated variability of s_o.

S_D represents the net dispersive tidal (or eddy diffusive) flux in Canal de Itajurú and was estimated as the difference in equation (7). Tidal dispersion was found to yield a net export of salt of $-78{\cdot}9$ kg s^{-1}, with an estimated rms annual variability essentially equal to the rms variability for the advective salt import term, ± 40 kg s^{-1}. The dispersive flux can be expressed as:

$$S_D = -\frac{\rho A_C K_x}{\Delta x}\,\frac{s_{14} - s_o}{1000} \quad (11)$$

where s_{14} is the mean annual salinity measured at Station 14 in the Canal de Itajurú, closest to the ocean, based on measurements in 1991–92 (Table 3). K_x is an effective longitudinal tidal dispersion coefficient (m^2 s^{-1}). A_C was estimated at 400 m^2 for the cross-sectional area at Station 14, and Δx was estimated as 6300 m for the distance along Canal de Itajurú between Station 14 and the ocean entrance. Since the lagoon salinity is consistently greater than the ocean salinity, the dispersive flux represents a net flux of salt out of the lagoon. Equation (11) was used to calculate $K_x = 101$ m^2 s^{-1}, a reasonable value compared to values published for estuaries and coastal waters (Bowden, 1983), lending credence to the salt flux calculations.

Lagoon flushing time

One of the most critical measures for evaluation of lagoon water quality and the management of coastal lagoons is a time scale for water exchange, e.g. a flushing, turnover, or residence time (Zimmerman, 1981; Dronkers & Zimmerman, 1982; Merino *et al.*, 1990; Knoppers *et al.*, 1991). In estimating a steady state flushing rate for Lagoa de Araruama, the concept of flushing half-life ($T_{50\%}$ days) or the time that it takes to replace half of the lagoon water volume was adopted. It was assumed that complete mixing occurs rapidly compared to the flushing half-life, which is only a reasonable approximation when the turnover time is on the order of weeks. Assuming first order kinetics:

$$\frac{\mathrm{d}V}{\mathrm{d}t} = -\kappa V \quad (12)$$

(Pritchard, 1961), where V denotes the volume of water in the lagoon, t is time, and κ is a rate constant. Equation (12) was integrated from $t=0$ when the lagoon volume was V_o to a new time, $T_{50\%}$, when the total water volume is the same but only 50% of the original water molecules remain inside the lagoon, i.e. $V_{new}/V_o = 0{\cdot}50$. Thus:

$$T_{50\%} = 0{\cdot}69/\kappa \quad (13)$$

Flushing in coastal lagoons depends on the amount of water input (but not loss) to the lagoon because of runoff (Q_R), direct precipitation on the lagoon and *marnéis* surface areas (Q_P), water pumped into the lagoon (Q_J and Q_C), the canal ocean exchange (Q_O), and also the tidal flushing (Q_T). The authors chose to calculate the rate constant, κ, as the average fraction of lagoon water volume replaced each second by the sum of the water fluxes:

$$\kappa = \frac{[Q_R + Q_P + Q_J + Q_C + Q_O + |Q_T|]}{V} \tag{14}$$

This formulation is somewhat different than that of Knoppers *et al.* (1991). Whereas the Q_R, Q_P, Q_J, Q_C and Q_O terms represent net long-term water fluxes (Table 4), Q_T is an oscillating water flux on a tidal time scale, hence the need for the absolute value sign. The same volume or prism of water enters and leaves the lagoon during one tidal cycle.

Since tidal action in most coastal systems controls the flushing rate, Q_T is often many orders of magnitude larger than the net fluxes. In the case of Lagoa de Araruama, the tide is small although not negligible. Unfortunately, no reliable data exist to verify the tidal prism for the lagoon. Lessa's (1989) estimate of a tidal prism of $3{\cdot}71 \times 10^7$ m^3 would equal a tidal range of 0·18 m if the prism were distributed evenly across the lagoon, and is most certainly an inappropriate value to use. Based on the S4 water-level measurements at Station 13 and numerical model simulations, an average tidal range of 0·01 m for the lagoon and canal as a whole seems more reasonable.

The tidal prism represents 'new' tidal water entering the lagoon every flooding tide, and it was assumed that this water did not leave the lagoon during the previous ebb tide. This assumption is quite reasonable where littoral currents are strong. Since the Fluminense tide is semi-diurnal, the tidal exchange, Q_T, was expressed as the prism entering the lagoon system per tidal cycle, although in reality, this transport only occurs during half a tidal cycle. It was calculated that:

$$Q_T = \pm \frac{A_L \Delta h}{[44\,714]} \tag{15}$$

where Δh (m) is the mean tidal range, $A_L = 210$ km^2 is the lagoon surface area, and the constant (*s*) is the duration of the semi-diurnal tidal cycle. Q_T was calculated to equal ± 47 m^3 s^{-1}.

Based on the above numbers, κ was computed as $1{\cdot}0 \times 10^{-7}$ s^{-1} and $T_{50\%}$ flushing half-life was computed as 83·5 days for Lagoa de Araruama. If the actual tidal range is less than 1 cm, the flushing half-life will be longer and vice versa. Merino *et al.* (1990) calculated a residence time of 1·24 years for the 50-km^2, sometimes hypersaline Nitchupté lagoon system in México. However, they did not include tidal mixing in their calculations, and thus arrived at an extremely long residence time. Had the present authors proceeded similarly, the calculated residence time for Lagoa de Araruama would have been on the order of 6 years. A point to remember is that different methods of calculation yield results that can differ by orders of magnitude for the same lagoon. In comparing mixing or flushing time scales for lagoons, care should be exercised to compare only time scales that have been calculated in the same way. The flushing half-life calculations account for both the hydrologic and tidal dispersive processes and exchange time scales in a rational fashion. The authors believe that the flushing half-life is both a reasonable and easily understandable measure of flushing time suitable for ecological and water quality evaluation of coastal lagoons.

Discussion

Lagoa de Araruama is a large, continuously hypersaline coastal lagoon and has been hypersaline for at least 4·5 centuries. The present mean salinity is 51·8 (Table 3) and the temporal rms variation measures 1·2. The mean water temperature is 25·6 °C with a rms variation of 3·3 °C. Based on the approximately monthly cruises and sampling at 14 stations lagoon-wide, vertical density, salinity and temperature stratification were found to be negligible, and spatial variations were found to be very small (Table 3). Only near the mouth of Rio das Moças (Station 1) at the extreme western part of the lagoon and in Canal de Itajurú (Station 14) (Figure 3) are salinities, and sometimes temperatures, significantly different than for the body of the lagoon. However, measurements indicate that all of these stations are continuously hypersaline.

The excess of evaporation over precipitation is the dominant factor accounting for the hypersalinity of Lagoa de Araruama. Every month, except for November, experiences a water deficit, and the lagoon never has the opportunity to become estuarine in terms of salinity characteristics. Thus, evaporation and precipitation are the dominant terms in the water balance.

Other factors also contribute to the water balance but to a much lesser extent. These factors include river runoff, which is low on average and only occurs sporadically, constant pumping of freshwater from the Juturnaiba Reservoir for the past decade and a half, and the net water exchange through Canal de Itajurú.

Although the constant pumping of water from Juturnaiba occurs at a very low rate, 1 $m^3 s^{-1}$, it still plays a crucial role in the water balance by: (1) adding freshwater to the lagoon; and (2) diminishing the amount of net ocean water that enters the lagoon. Thus, it is an important contributing factor to the recent freshening of the lagoon. The salt balance is dominated by the advective transport of salt into the lagoon, and the dispersive transport of salt out of the lagoon through Canal de Itajurú as a result of oscillatory and short-term tidal and weather processes. These two terms are each more than one order of magnitude greater than the other fluxes in the salt balance. For example, salt mining in Lagoa de Araruama has a very small effect on the freshening of the lagoon, even in past decades when the rate of mining occurred at a significantly greater rate.

The implication of these results is that in the absence of pumping of water from the Juturnaiba Reservoir to the lagoon region, the net advective input of ocean water into the lagoon would have been 22% greater than the current rate, and the net advective input of ocean salt would likewise have been 22% greater. Adjustments in the dispersive transport of salt out of the lagoon and the net lagoon salt storage would presumably yield a salt balance for pre-*adutora* Juturnaiba conditions. Thus, the pumping of freshwater from the adjacent São João basin to the north, necessary to sustain the population of the lagoon region, does indeed contribute significantly to the freshening of the lagoon, measured to equal 0·15 $year^{-1}$, and may in fact represent the main reason for the freshening, since long-term changes have occurred in neither precipitation nor evaporation.

Lagoa de Araruama has a calculated flushing half-life of 83·5 days, when accounting for both hydrological and tidal dispersive processes. The flushing half-life model assumes both steady state conditions and complete mixing of the lagoon on a time scale that is short compared to the flushing half-life. However, both of these assumptions are usually violated in lagoons and estuaries, as coastal systems in general seldom achieve steady state and are almost always incompletely mixed. Thus, the calculated flushing half-life

Table 5. Measured and calculated hydrological characteristics of the nine largest coastal lagoons along the Fluminense coast between Niterói and Cabo Frio

Lagoon	A_L (km^2)	A_B (km^2)	h_o (m)	V (km^3)	Δh (cm)	P (m)	E (m)	$\Delta f/r$	S	$T_{50\%}$ (days)
Araruama[a]	275	285	2·9	0·618	1	0·9	1·4	0·11	52	84
Vermelha[b]	3	10	1	0·003	0	0·9	1·4	0·11	100	194
Fora	7	47	1·3	0·009	4	1·3	1·3	0·2	20	8
Urussanga	13	185	1·1	0·014	2	1·3	1·3	0·2	1	14
Jacone	4	29	1·	0·004	1	1·3	1·3	0·2	5	25
Guarapina	7	70	1·0	0·007	3	1·3	1·3	0·2	7	7
Padre	3	10	0·6	0·002	1	1·3	1·3	0·2	3	5
Barra	9	55	1·4	0·013	1	1·3	1·3	0·2	1	22
Maricá	17	215	1·4	0·024	1	1·3	1·3	0·2	0	30
Itaipu	2	23	1·2	0·002	30	1·4	1·3	0·2	30	1
Piratininga	3	22	0·9	0·002	2	1·4	1·3	0·2	3	13

[a]The 65-km^2 area of the *marnéis* has been shifted from A_B to A_L in the above table for the sake of the water balance calculations.
[b]A completely landlocked lagoon with probable salt seepage input from both Lagoa de Araruama and the ocean.
A_L, lagoon surface area; A_B, lagoon drainage area; h_o, mean lagoon water depth; V, lagoon water volume; Δ_h, mean lagoon tidal range, P, annual precipitation; E, annual evaporation, $\Delta f/r$, annual runoff ratio from the drainage basin; S, characteristic lagoon salinity; $T_{50\%}$, calculated flushing half-life.

should always be considered as a lower limit for water exchange or an ideal flushing time scale. The actual flushing half-life or exchange of 50% of the water in Lagoa de Araruama would in all probability require considerably longer than 83·5 days, although the authors' model is incapable of evaluating this. The real advantage of flushing half-life calculations is for comparative analyses of coastal lagoons, and also in making management decisions in lagoons where an estimate of a lagoon's flushing half-life as compared to other lagoons would be helpful in assessing and solving problems related to water quality and water renewal. The flushing half-life can be calculated, at least to a first approximation, for any lagoon system without a need for extensive data collection.

An ideal flushing half-life of 83·5 days for Lagoa de Araruama is indeed a very long time. This is best demonstrated by comparing Lagoa de Araruama to the 10 largest coastal lagoons along the Fluminense coast between Niterói and Cabo Frio (Figure 1). The data used in the present calculations and the resulting flushing half-lives for each lagoon are listed in Table 5. Lagoa de Vermelha, a small landlocked lagoon located between sand barriers immediately south of Lagoa de Araruama, has the longest flushing half-life of the systems with $T_{50\%} = 194$ days and a salinity of 100. However, comparisons to a landlocked system is hardly representative. Of the lagoons with an open connection to the ocean, usually via several other lagoons, Lagoa de Maricá has the longest flushing half-life (30 days) besides Lagoa de Araruama, and basically consists of freshwater. In contrast, Lagoa de Itaipu is a lagoon with strong tidal variations, almost oceanic salinity, and a flushing half-life of only 1 day. The flushing half-life of Lagoa de Araruama is indeed very long compared to the other lagoons along this coast. It needs to be said that salinity is not a good indicator of water renewal in lagoons, as is clear from the comparisons in Table 5, as both hypersaline and fresh lagoons can have long time scales of water exchange, depending on the local hydro-balance and degree or lack of tidal water exchange.

With the increasing human population in the lagoon region, and heavy anthropogenic loading of nutrients and untreated human waste into the lagoon, especially along the northern lagoon border, it is curious that water quality and health-related problems apparently are not, and have not been, a serious problem in Lagoa de Araruama. The hypersaline conditions of the lagoon seemingly function as a buffer, and eutrophic blooms and epidemic health outbreaks do not occur as they would be expected to in an estuarine or lagoon system with salinities less than in ocean water. This naturally leads to consideration and speculation about the proposed dredging of a second ocean channel near Figueira (Figures 2 & 3). The motivation for dredging a second channel is to improve water exchange, and thus improve lagoon water quality. A second channel would probably somewhat improve the water exchange of Lagoa de Araruama and lead to further reduction of salinity in the lagoon. This, in turn, would in all likelihood reduce the observed buffering capacity of the lagoon hypersalinity, and could lead to sudden and unprecedented ecological responses and water-quality-related health problems as a result of loading of nutrients and untreated waste into the lagoon, once the lagoon salinity is reduced sufficiently. It appears that dredging a second ocean channel would result in exactly the opposite effect, as compared to the argument in favour of dredging the channel. Thus, such a dredging project, even without considering economic costs and impacts to the fragile Maçambaba dune-ridge ecosystem, is ill-founded.

Acknowledgements

This work was funded by Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), National Science Foundation (NSF) grant INT 9001583, the National Geographic Society grant 3823–88, and Instituto Acqua through the PROLAGOS project. We thank José Luiz de Souza Dantas of Hotel Carapeba for providing the 15 m *Miss Juliana* for the monthly lagoon sampling cruises; Prof. Dr Gilberto T. M. Dias, Marcelo Corrêa Bernardes and Marcelo Travassos for help in the field during instrument recovery operations; Moacir Apolinário da Silva and José Carlos Sicoli Seoane for help in the field during the monthly cruises; Prof. Dr Jorge João Abrão for administrative support; Prof. Dr Raimundo Damaceno for use of his bench-top conductivity meter; and Profa. Mariz Bernadete Pinto dos Santos for assistance in the laboratory. Meteorological data were furnished by Instituto de Meteorologia (Sixth District, Rio de Janeiro) and Superintendência Estadual de Rios e Lagoas (SERLA). We appreciate the helpful comments by Dr H. Postma on an early draft of our manuscript. This is Contribution No. 1048 from the Belle W. Baruch Institute.

References

Alcoforado, P. G. & Quinan, F. J. 1925 *O sal Fluminense*. Graphica O Arauto, Cabo Frio, Rio de Janeiro, Brazil, 102 pp.

Al-Ramadhan, B. M. 1988 Residual fluxes of water in an estuarine lagoon. *Estuarine, Coastal and Shelf Science* **26,** 319–330.

André, D. L., Oliveira, M. C., Okuda, T., Horta, A. M. T. C., Soldan, A. L., Moreira, I. M. N. S., Rollemberg, M. C. E., Fonseca Heinzen, V. E. 1981 *Estudo Preliminar Sobre as Codições Hidroquímicas da Lagoa de Araruama—Rio de Janeiro*. Instituto de Pesquisas da Marinha, Ministério da Marinha, Brazil.

Araújo, D. S. D. & Maciel, N. C. 1979 Os manguezais do recôncravo da Baía de Guanabara. *FEEMA* (*Fundação Estadual de Engenharia do Meio Ambiente*) *Série Técnica* 10/79, Rio de Janeiro, Brazil, 115 pp.
Barbiére, E. B. 1975 Ritmo climático e extração do sal em Cabo Frio. *Revista Brasiliera de Geografia* **37**(4), 23–109.
Barbiére, E. B. 1981 O fator climático nos sistemas territoriais de recreação. *Revista Brasileria Geográfica* **43,** 145–265.
Barbiére, E. B. 1984 Cabo Frio e Iguaba Grande, dois microclimas distintos a um curto intervalo espacial. In *Restingas, Origem, Estrutura, Processos* (Lacerda, L. D., Araujo, D. S. D., Cerqueira, R. & Turcq, B., eds). Universidad Federal Fluminense, Niterói, Rio de Janeiro, Brazil, pp. 3–14.
Barbosa, R. L. 1973 Perfil analítico do sal. *Ministérios de Minas e Energia, Boletim No.* 21, Rio de Janeiro, Brazil, 47 pp.
Barroso, L. V. 1987 Diagnóstico ambiental de Lagoa de Araruama, RJ. *Boletim FBCN (Fundação Brasileira para a Conservação da Natureza)* **22,** 30–65.
Barroso, L. V. 1989 Diagnóstico ambiental para pesca de águas interiores no Estado do Rio de Janeiro. Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis no Estado de Rio de Janeiro (IBAMA). Documento Assessoria de Cultura e Memoria da Pesca **4:** 1–177.
Bowden, K. F. 1983 *Physical Oceanography of Coastal Waters*. Halsted Press, New York, U.S.A., 302 pp.
Copeland, B. J. 1967 Environmental characteristics of hypersaline lagoons. *Publications of the Institute for Marine Science (University of Texas)* **12,** 207–218.
CRC (Chemical Rubber Company) 1979 *CRC Handbook of Chemistry and Physics*. 60th edition. CRC Press, Boca Raton, Florida, U.S.A., p. F-3.
Dronkers, J. & Zimmerman, J. T. F. 1982 Some principles of mixing in tidal lagoons. *Oceanologica Acta* **SP,** 107–117.
Ellis, M. 1969 O sal no Brasil colonial. *Revista do Arquivo Municipal* **178,** 137–178.
FEEMA *(Fundação Estadual de Engenharia do Meio Ambiente)* 1988 *Perfil Ambiental do Municípo de Araruama*, Rio de Janeiro, Brazil, 45 pp.
Fofonoff, N. P. & Millard Jr., R. C. 1983 Algorithms for calculation of fundamental properties of sea water. *UNESCO Technical Papers in Marine Science* **44,** 53 pp.
Franco, A. F. 1988 *Tides: Fundamentals, Analysis and Prediction*, Second edition. Fundação Cetro Tecnológico de Hidraúlica, São Paulo, Brazil, 249 pp.
Grasshoff, K., Ehrhardt, M. & Kremling, M. 1983 *Methods of Seawater Analysis*, Second edition. Verlag Chemie GmbH, Weinheim, 419 pp.
Holland, H. D. 1978 *The Chemistry of the Atmosphere and Oceans*. John Wiley & Sons, New York, U.S.A. 351 pp.
Hutter, L. M. 1988 Cabo Frio: Ponto de Referência para a Navegação no Atlântico Sul Desde o Século XVI. Centro de Estudos de História e Cartogarfia Antiga, Série Separatas 202, Instituto de Invetigação Cientifica Tropical, Lisboa, Brazil 24 pp.
INPH-Portobras. 1987 1a *Companha de Medicoes Hidraulico-Sedimentologicas na Lagoa de Araruama—RJ*. Campanha de Verão, Rio de Janeiro, Brazil 126 pp.
INPH-Portobras. 1988 2a *Campanha de Medicoes Hidraulico-Sedimentologicas na Lagoa de Araruama—RJ*. Campanha de Inverno, Rio de Janeiro, Brazil, 76 pp.
Ireland, S. 1987 The Holocene sedimentary history of the coastal lagoons of Rio de Janeiro state, Brazil. In *Sea-level Changes* (Tooley, M. J. & Shennan, I., eds). Basil Blackwell, London, U.K., pp. 26–66.
Keulegan, G. H. 1967 Tidal flow in entrances water-level fluctuations of Basins in Communication with seas. *Committee on Tidal Hydraulics, U.S. Army Corps of Engineers, Technical Bulletin* No. 14, 89 pp.
Kjerfve, B. 1986 Comparative oceanography of coastal lagoons. pp. 63–81. In *Estuarine Variability* (Wolfe D. A., ed.). Academic Press, New York, U.S.A., pp. 63–81. 509 pp.
Kjerfve, B. 1990 *Manual for investigation of hydrological processes in mangrove ecosystems*. UNESCO/UNDP Regional Mangrove Project RAS 79/002 and RAS/86/120, Occasional paper. New Delhi, India, 79 pp.
Kjerfve, B. & Magill, K. E. 1989 Geographic and hydrographic characteristics of shallow coastal lagoons. *Marine Geology* **88,** 187–199.
Kjerfve, B., Knoppers, B., Moreira, P. & Turcq, B. 1990 Hydrological regimes in Lagoa de Guarapina, a shallow Brazilian coastal lagoon. *Acta Linologica Brasiliensia* **III,** 931–949.
Kjerfve, B. & Knoppers, B. 1991 Tidal choking in a coastal lagoon. In *Tidal Hydrodynamics* (Parker, B., ed.). John Wiley & Sons, New York, U.S.A., pp. 169–179. 608 pp.
Knoppers, B, Kjerfve, B. & Carmouze, J. P. 1991 Trophic state and water turn-over time in six choked coastal lagoons in Brazil. *Biogeochemistry* **14,** 149–166.
Köppen, W. 1900 Versuch einer Klassifikation der Klimate, vorzugsweise nach ihren Beziehungen zur Pflanzenwelt. *Geographische Zeitschrift* **6,** 593–611, 657–679.
Lacerda, L. D., Araújo, D. S. D., Cerqueira, R. & Turcq, B. (eds) 1984 *Restingas*. Universidade Federal Fluminense Press, Niterói, Brazil, 475 pp.
Lamego, A. R., Jr. 1974 *O Homen e a Restinga*, Segunda Edição) Lidador, Rio de Janeiro, Brazil, 307 pp.

Lessa, G. C. 1989 Considerações sobre o comportamento hidráulico do canal de Itajurú—laguna de Araruama (RJ). In *Anais III Simp*. Geografia Fisica Aplicada, Nova Friburgo, pp. 334–347.

Lessa, G. C. 1990 Anomalias climáticas e seus reflexos no comportamento hidráulico do canal de de maré da Laguna de Araruama, RJ. In *Proceedings of II Simpósio de Ecossistemas Costeiros da Costa Sul-Sudeste Brasileira*, Vol. 2. Aguas de Lindóia, São Paulo, Academia Ciências São Paulo, pp. 63–72.

Mandelli, E. F. 1981 On the hydrography and chemistry of some coastal lagoons of the Pacific coast of Mexico. *UNESCO Technical Papers in Marine Science* **33,** 313–318.

Martin, L. & Suguio, K. 1989 Excursion route along the Brazilian coast between Santos (State of São Paulo) and Campus (north of State of Rio de Janeiro). International Symposium on Global Changes in South American during the Quaternary, São Paulo, Brazil, Special Publication No. 2. 136 pp.

Martin, L. & Flexor, J. M. 1992 Lagoon sediments of the Cabo Frio region as records of the variations of the local upwelling during the last 7,000 years. In *Paleoclimatic Changes and the Carbon Cycle* (Lacerda, L. D., Turcq, B., Knoppers, B. & Kjerfve, B., eds). Série Geoquímica Ambiental No 1, Socidade Brasileira de Geoquímica, Rio de Janeiro, Brazil, pp. 35–40.

Mee, L. D. 1978 Coastal lagoons. In *Chemical Oceanography*, Vol. 7 (Riley, J. & Skirrow, O. eds). Academic Press, New York, U.S.A., pp. 441–490.

Merino, M., Czitrom, S., Jordán, E., Martin, E., Thomé, P. & Moreno, O. 1990 Hydrology and rain flushing of the Nichupté lagoon system, Cancún, Mexico. *Estuarine, Coastal and Shelf Science* **30,** 223–237.

Moore, N. H. & Slinn, D. J. 1984 The physical hydrology of a lagoon system on the Pacific coast of Mexico. *Estuarine, Coastal and Shelf Science* **19,** 413–426.

Muehe, D. & Correa, C. H. T. 1989 The coastline between Rio de Janeiro and Cabo Frio. In *Coastlines of Brazil*. (Neves, C., ed.). American Society of Civil Engineers, New York, U.S.A., pp. 110–123.

Noye, B. J. 1973 *The Coorong–Past, Present and Future*. Department of Adult Education, The University of Adelaide, S. A., Australia, 47 pp.

Oliveira, von, L. P. H. 1974 Limnologische notizen über die Rio de Janeiro Lagunen. *Arkiv für Hydrobiologie* **2,** 732–763.

Phleger, F. B. & Ewing, G. C. 1962 Sedimentology and oceanography of coastal lagoons in Baja California, Mexico. *Bulletin of the Geological Society of America* **73,** 145–182.

Pinto, M. S. & Ribeiro, F. R. 1930 A industria do sal no estado do Rio. *Serviço Geológico e Mineralógico do Brasil* Boletim **52,** Rio de Janeiro, Brazil, 144 pp.

Postma, H. 1965 Water circulation and suspended matter in Baja California lagoons. *Netherlands Journal of Sea Research* **2,** 566–604.

Pritchard, D. W. 1961 Salt balance and exchange rate for Chincoteague Bay, *Chesapeake Science* **1,** 48–57.

Saint-Hilaire, A. 1974 *Viagem Pelo Distrito dos Diamantes e Litoral do Brasil*. Editoria Itatiaia, Belo Horrizonte, MG, 233 pp.

Schreiber, P. 1904 Ûber die Beziehungen zwischen dem Niederschlag und der Wasserfhrung der Flüsse in Mittleeuropa. *Meteorologische Zeitschrift* **21,** 441–452.

Sellers, W. D. 1965 *Physical Climatology*. The University of Chicago Press, Chicago, U.S.A., 272 p.

Sikora, W. B. & Kjerfve, B. 1985 Factors influencing the salinity of Lake Pontchartrain, Louisiana, a shallow coastal lagoon: analysis of a long-term data set. *Estuaries* **8,** 170–180.

Smith, N. P. 1988 The Laguna Madre of Texas: hydrography of a hypersaline lagoon. In *Hydrodynamics of Estuaries, Vol. II. Estuarine Case Studies*, (Kjerfve, B. ed.). CRC Press, Boca Raton, Florida, U.S.A., pp. 31–40.

Sousa, G. S. de. 1971 *Tratado Descreptivo do Brasil em 1587*, 4ª edição. Companhia Editora Nacional, Editora de São Paulo, São Paulo, Brazil, 389 pp.

Stech, J. L. & Lorenzzetti, J. A. 1992 The response of the South Brazil Bight to the passage of wintertime cold fronts. *Journal of Geophysical Research* **97,** 9507–9520.

Strickland, J. D. H. & Parsons, T. R. 1972 *A Practical Handbook of Sea Water Analysis. Bulletin of the Fisheries Research Board of Canada* **122,** 1–172.

Turcq, B., Martin, L., Flexor, J. M., Suguio, K., Pierre, C. & Tasayco-Ortega, L. Origin of the Quaternary coastal plain between Guaratiba and Cabo Frio, State of Rio de Janeiro, Brazil. In *The Fluminense Lagoons* (Bidone, E. & Knoppers, B., eds). Universidade Federal Fluminense Press, Niterói, Brazil, in press.

Zimmerman, J. T. F. 1981 The flushing of well-mixed tidal lagoons and its seasonal fluctuation. In *Coastal Lagoon Research, Present and Future*. UNESCO Technical Papers in Marine Science No. 33, Paris, pp. 15–26.