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HYDROLOGICAL REGIMES IN LAGOA DE GUARAPINA, A SHALLOW BRAZILIAN COASTAL LAGOON

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RESUMO - REGIMES HIDROLÓGICOS NA LAGOA DE GUARAPINA, UMA LAGOA COSTEIRA BRASILEIRA RASA

A Lagoa de Guarapina situa-se a 40 km a leste da cidade do Rio de Janeiro, Brasil, e caracteriza-se por uma área de 6,38 km², uma profundidade média de 1 m, e um acesso restrito ao mar através de um canal. O canal controla, de modo significativo, a troca de água entre o mar e a lagoa, caracterizando-a como um sistema lagunar do tipo "sufocado". O nível, a troca e a salinidade da água variam nitidamente em função do ciclo hidrológico. O nível de água pode atingir oscilações de até 0,5 m em função de variações metereológicas tendo apresentado nos últimos três anos um acréscimo médio de 0,45 m. Noventa e quatro porcento da amplitude de maré astronômica e filtrada ao longo do estreito canal de maré, resultando em amplitudes dentro da lagoa inferiores a 0,03 m. A entrada de água marinha de 33‰ ocorre principalmente durante marés de sizigia e tempestades que promovem elevações do nível de água oceânica. Por outro lado, durante épocas de

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quadraturas e níveis elevados de água da lagoa, o sistema permanece em condições de vazante com salinidades estáveis por períodos de até 2 a 3 semanas. A salinidade média da Lagoa de Guarapina decresceu drasticamente durante os últimos três anos, variando entre 15-20‰ entre 1985-1986, 10-15‰ em 1987 e 5-10‰ em 1988. O tempo de renovação médio das massas de água na Lagoa de Guarapina em relação a descarga de água doce foi estimado em 1,5 meses, embora esteja sujeito a significativas variações relativas em função da descargas.

ABSTRACT - HYDROLOGICAL REGIMES IN LAGOA DE GUARAPINA, A SHALLOW BRAZILIAN COASTAL LAGOON

Lagoa de Guarapina is a 6.38 km² shallow choked coastal lagoon 40 km east of Rio de Janeiro, Brazil. Water level, water exchange, and salinity vary in response to the hydrological cycle. Water level oscillates 0.5 m at subtidal frequencies as a result of weather events and has increased by an average of 0.45 m in the past three years. Ninety-four percent of the astronomical tidal amplitude is filtered within the long and narrow entrance channel, resulting in less than 0.03 m lagoon tidal range. The tide advects 33 ppt waters into the lagoon during spring tides and storms. Otherwise, the salinity remains constant for periods of 2-3 weeks, while the lagoon experiences outflow. The salinity has decreased during the past three years from 15-20 ppt in 1985-1986, 10-15 ppt in 1987, to 5-10 ppt in 1988. The lagoon turnover time associated with freshwater runoff averages 1.5 months but varies according to runoff.

INTRODUCTION

Coastal lagoons are common landforms that make up

13% of all coastal environments on a worldwide basis (BARNES, 1980). They are particularly common along coasts with wide and flat coastal plains and continental shelves (EMERY, 1967) which have experienced submergence during Holocene sea level rise (NICHOLS & ALLEN, 1981). They have formed behind coastal barriers in marginal depressions and are ephemeral landforms because of sediment infilling and continued eustatic change in sea level (KJERFVE & MAGILL, 1988). Coastal lagoons are inland marine areas, most often oriented parallel to the coast, separated from the ocean by a barrier, and connected to the ocean by inlets (PHLEGER, 1969), at least on an intermittent basis (MOORE & SLINN, 1984; KJERFVE, 1986a; KJERFVE & MAGILL, 1988). In general, coastal lagoons are delicately balanced systems as a result of development, population growth, and runoff from human, industrial, and agricultural sources. Planning and implementation of coastal management strategies are now high priority issues in many countries, including Brazil.

Choked coastal lagoons are one of three geomorphic lagoon types (KJERFVE, 1986a). Choked lagoons are characterized by (1) a single long and narrow channel between lagoon and ocean, open at least intermittently; (2) restricted water exchange with the coastal ocean; (3) long hydrodynamic turnover time; (4) water depth on the order of 1 m; (5) highly variable salinity responding to local climate and hydrological cycles; (6) strong dynamic filtering of tidal effects in the entrance channel; (7) coastal tides with a microtidal range less than 1 m; (8) circulation and mixing driven by wind forcing; (9) location along coastlines with high wave energy and associated littoral drift; and (10) susceptibility to eutrophication, pollution, and sediment infilling as a result of limited water exchange with the ocean and local land-use practices. Choked coastal lagoons are particularly common in Australia, Brazil, and South Africa. Our purpose is to describe the salient physical characteristics of Lagoa de

Guarapina, a small choked Brazilian coastal lagoon, and to identify its dominant hydrological regimes.

Area Description

Numerous choked coastal lagoons dot the Fluminense coastline, between the localities of Rio de Janeiro and Cabo Frio (Fig. 1). Lagoa de Guarapina (Fig. 2) is located 40 km east of the City of Rio de Janeiro at 22°56' S and 42°42' W. It is the most seaward lagoon in a system of four interconnected, shallow lagoons separated from the ocean by a 25 km long, narrow beach ridge plain (restinga). Whereas Guarapina is only 6.5 km², the water-covered area of the entire lagoon system occupies 35 km² and receives runoff from a 350 km² drainage basin. The other lagoons that form the interconnected system are, from east to west, Padre, Barra, and Maricá, for which morphometric characteristics are shown in Tab. 1.

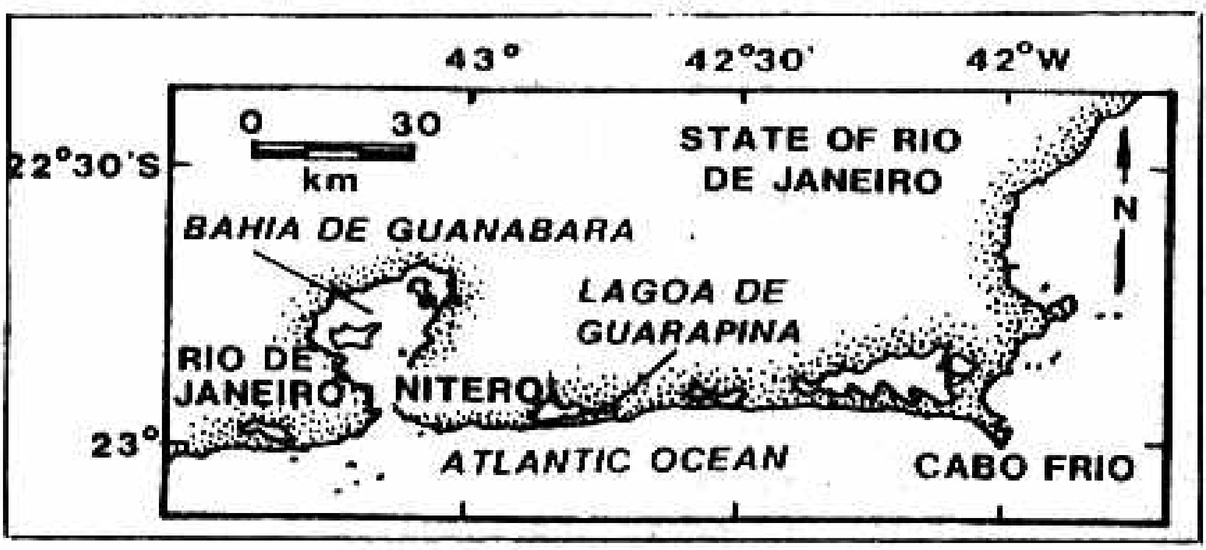

Figure 1 - Map of the Fluminense lagoon region.

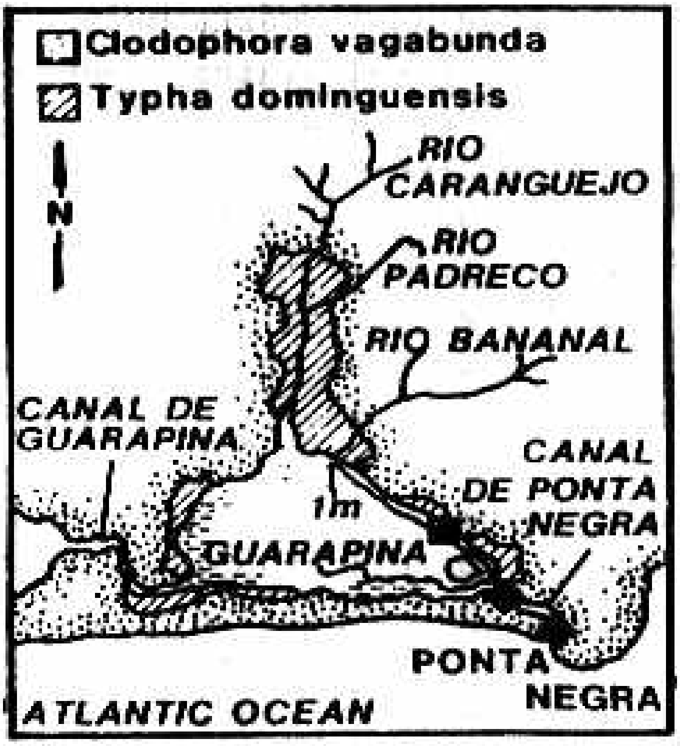

Figure 2 - Map of Lagoa de Guarapina, indicating the location of the two S4 instruments ( ) and the site of the Superintendência Estadual de Rios e Lagoas (SERLA) water level gauge ( ).

Table 1 - Dimensions of the lagoon system.

Lagoa	Volume (10^6 m^3)	Surface Area (km^2)	Basin Area (km^2)
Guarapina	6.5	6.5	70
Padre	1.4	2.7	10
Barra	12.6	9.0	55
Maricá	23.9	17.1	215
Total	44.4	35.3	350

The drainage basin consists of cattle pastures, sugar cane fields, and agricultural plots. The northern part is characterized by steep relief with a maximum altitude of 879 m in the adjacent Serra de Mato Grosso, but with more than half of the total drainage basin less than 25 m above mean sea level (msl). The low-lying area adjacent to the lagoon is covered by dense growth of the freshwater reed, *Typha dominguensis*. The lagoons are commercially important because of rich fisheries of mullet (*Mugil* spp.), crab (*Callinectes* spp.), and shrimp (*Penaeus* spp.). The city of Maricá with 30,000 inhabitants is the major population center, otherwise the drainage basin is sparsely populated.

The barrier system exhibits both regressive and transgressive sediment sequences associated with relative sea level changes during the Quarternary (DIAS & SILVA, 1984). The coastal ocean is characterized by energetic swell conditions and ample sand supply in dunes, sand barriers, and deposits on the adjacent 100 km wide continental shelf. The littoral transport system is extremely active with a history of rapidly closing ocean entrance channels (LAMEGO, 1945). A natural connection between Lagoa Maricá and the ocean closed up several decades ago.

The man made channel leadling into Guarapina, just west of the Ponta Negra headland, is less than 1 m deep, 30 m wide, and 1.4 km long. It is presently the only connection between the lagoon system and the ocean. It was constructed in 1945 (LAMEGO, 1945) and dredged several times thereafter to allow the navigation of fishing canoes into the lagoons. Several attempts have been made to construct ocean entrance channels to Lagoa de Barra, but have failed within weeks of completion because of rapid sand deposition in the channels and reconstruction of the beach ridge barrier by wave and wind processes.

The climate is tropical, relatively dry, and can be classified as Awa according to the KÖPPEN (1900) classification. The annual rainfall over the drainage basin varies from 1.1 m at Maricá to 1.7 m in the Serra de Mato Grosso at the top of the drainage divide. Near Lagoa de Guarapina, minimum rainfall occurs in July (58 mm) and maximum in December (250 mm), but there are substantial differences between adjacent stations as result of elevation differences and the strong climatic gradient from Rio de Janeiro to Cabo Frio. The annual evaporation rate at nearby Iguaba measures 1.4 m (BARBIÈRE, 1984). Mean air temperature is 23.5°C with mean seasonal values varying from 19 to 27°C, and extreme annual values varying from 10 to 40°C.

Field Sampling

The hydrological field program in Lagoa de Guarapina consisted of: (1) biweekly sampling over an annual cycle; (2) daily sampling during a two-week period within the annual cycle; (3) hourly sampling during two 24-hour periods; (4) continuous time series measurements for a two-month period; and (5) complementary water level and meteorological data for the times of hydrological sampling. The biweekly sampling over the annual cycle was carried out from 20 June 1985-20 July 1986 as a component of a multidisciplinary field program, consisting of 24 sampling dates. These data were complemented with daily field sampling during 14 days, 4-19 August 1985, and hourly sampling during two 24 hour periods, 9-10 and 14-15 August 1985. A separate study of the physical dynamics of Lagoa de Guarapina was conducted on 18 May-24 July 1988. We have selected a 10-day time series, 22 May-1 June 1988, and a 5-day record, 16-22 June 1988, for interpretation. Manual water level measurements were made daily when the lagoon sampling occurred. Concurrent meteorological data for all sampling periods were obtained irom the permanent meteorological stations at Flamengo (Rio de Janeiro), at Maricá, and Iguaba.

Sampling during the annual cycle was conducted from seven stations between the tidal entrance channel and the freshwater source. Measurements of salinity and temperature were made at 0.5 m intervals from surface to bottom (and at 0.1 m intervals where sharp vertical gradients occurred). For the most part, there were no significant differences in temperature and salinity between the surface and the bottom in the lagoon, suggesting a homogeneous water mass. Vertical gradients only occurred near the entrance channel and the river mouths.

The lack of tidal variability in Lagoa de Guarapina eliminated the need for measurements over complete tidal cycles without aliasing of the data (KJERFVE, 1986b). Thus, biweekly sampling over the annual cycle and the daily measurements for the 14-day period were made as single transects between 1100 and 1400 local time. Transect measurements were also made hourly during the two intensive diurnal cycles to verify the lack of tidal variability.

As a separate investigation of the physical dynamics of Lagoa de Guarapina, time series measurements of current velocity, water elevation, conductivity (for calculation of salinity), and temperature were made simultaneously at both ends of the tidal entrance channel. InterOcean S4 electromagnetic current meters were mounted 0.5 m above the channel bottom at each location. The instruments were programmed to sample at a rate of 2 Hz for 2 min every 10 min and to calculate and to store internally 2-min averaged values.

Water Level Variations and Tidal Choking

The coastal tide at Ponta Negra is a mixed semidiurnal microtide with a mean range of 0.6 m and a form number, $F = (K_1+O_1)/(M_2+S_2)$, equal to 0.40 (DEFANT, 1960). The tidal range, duration and timing varies substantially from one tidal cycle to the next because of the need to include many harmonic constituents to explain the sea level variability (Tab. 2). The tide along the Fluminense coastline is in phase with high and low waters alternately occurring within ±30 min at Cabo Frio, Ponta Negra, and Rio de Janeiro. The annual sea level oscillation (Sa) has a range of 0.05 m, with highest water occurring in mid January as a result of steric changes in the coastal water mass.

In contrast, Lagoa de Guarapina is characterized by lack of tidal variability. The 1.4 km entrance channel with a mean depth of 0.8 m and cross-sectional area of 25 m^2 acts as a dynamic filter to water elevation changes at tidal frequencies. Ninety-four percent of the tidal water level oscillation at the seaward end of the entrance channel is filtered out at the interior end of the channel (Fig. 3, 4). The channel thus acts to choke the tide with the ratio of lagoonward tidal amplitude to seaward tidal amplitude measuring 0.06. The tidal range within the lagoon is less than 0.03 m, justifying sampling in the lagoon proper without regard to tidal phase. Measurements within the channel, however, depend on tidal phase.

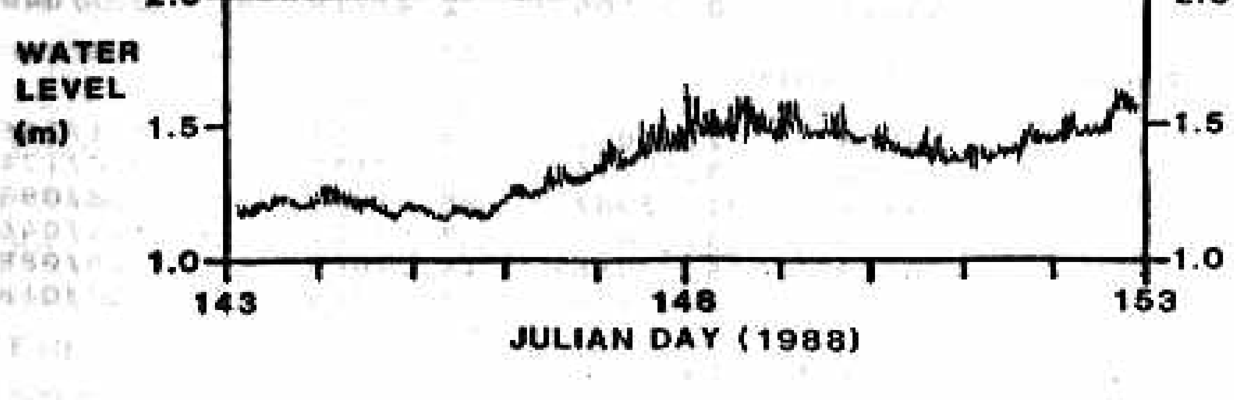

Figure 3 - Water level (m) time series at the lagoonward end of the entrance channel for 10 days, 0000 22 May - 0000 1 June 1988. Time is in GMT (Greenwich Mean Time or Geomagnetic Time), and each time division represents 24 hours.

Table 2 - Amplitude and local phase of the principal tidal constituents at three locations along the Fluminense coastline. Porto de Cabo Frio (22° 58.3'S and 42° 00.9'W) constants are based on a 32-day tidal record, 2 Feb-5 Mar 1971. Ponta Negra (22° 58.2'S and 42° 41.6'W) constants are based on a 32-day tidal record, 20 Nov-21 Dec 1964. Porto de Rio de Janeiro (22° 53.8'S and 43° 09.9'W) constants are based on a 365-day record, 1 Jan-31 Dec 1965. All constituents with an amplitude greater than 2 cm at Ponta Negra have been includede. The table is based on data from Ministério da Marinha, Diretoria de Hidrografia e Navegação [DHN]. A discussion of the harmonic constants is given in DEFANT (1960).

Partial Tide	Frequency (°/hour)	Cabo Frio (cm/°K)	Ponta Negra (cm/°K)	Porto, RJ (cm/°K)
Low Frequency Constituents:				
Sa	0.0410686			2.7/021
Ssa	0.0821373			1.5/320
Mm	0.5443747	9.1/337	11.1/357	1.8/096
Msf	1.0158958	6.5/010	8.4/008	3.1/162
Mf	1.0980331			2.3/126
Diurnal Constituents:				
Q_1	13.398661	3.1/074	2.7/070	2.6/110
O_1	13.943036	10.8/089	10.5/106	9.2/104
P_1	14.958931	2.1/138	2.1/122	2.1/138
K_1	15.041069	6.5/138	6.4/122	6.2/144
J_1	15.585443	0.2/106	2.4/219	0.7/044
Semidiurnal Constituents:				
Mu_2	27.968208	2.2/092	4.6/151	1.1/156
N_2	28.439730	3.5/114	4.2/157	2.6/174
M_2	28.984104	31.4/082	28.6/075	31.8/093
L_2	29.528479	3.5/078	3.8/322	1.4/046
S_2	30.000000	16.0/086	14.2/063	17.9/088
K2	30.082137	4.4/086	3.9/063	5.7/018
High Frequency Constituents:				
M_4	57.968208	2.6/029	3.7/266	4.8/096
MS_4	58.984104	1.3/095	2.7/199	3.1/186

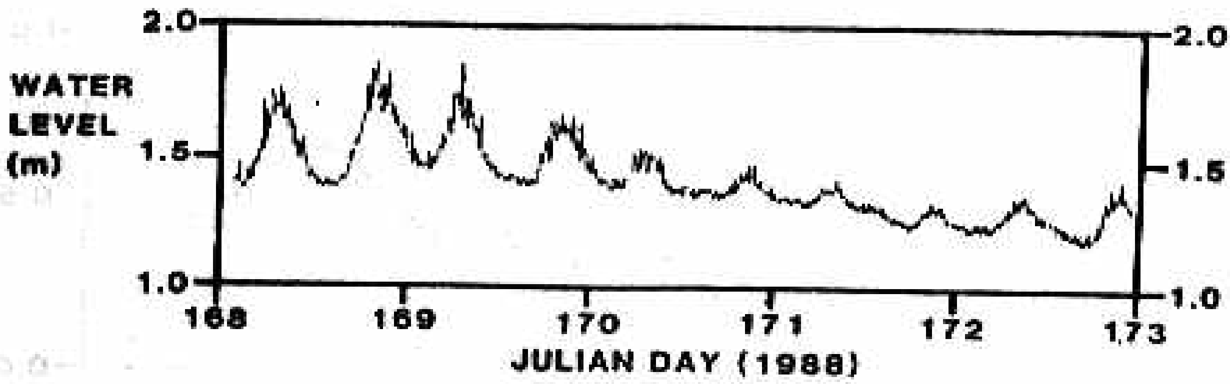

Figure 4 - Water level (m) time series at the seaward end of the entrance channel for 5 days, 0000 16 - 0000 21 June 1988. The fortnightly spring-neap tide cycle modulation of the tidal range is apparent. Time is in GMT, and each time division represents 12 hours.

Within the lagoon, the water level oscillates at subtidal frequencies in response to weather events (Fig. 3), runoff variation (Fig. 5), and the annual temperature cycle (steric change). When a winter front approaches and traverses the Fluminense coastline, the lagoon water level may increases 0.5 m during 2-3 days and fall equally rapidly as winds and runoff subside. This is illustrated for a frontal passage on 24-26 May 1988 (Fig. 3). The seasonal cycle of water level change is difficult to observe in our limited annual data set (Fig. 5), as most of the water level change during the 1985-1986 sampling was correlated with rainfall and runoff.

The mean water level in Lagoa de Guarapina has increased significantly from 1985-1988. The 1985 measurements yielded an average level of 0.38 (±0.05) m, the 1986 measurements 0.44 (±0.11) m, and the 1988 measurements 0.83 (±0.10) m as measured at the SERLA gauge (Fig. 2). The water level increase corresponds to a 50% increase in water volume as compared to the 1985 volume.

Although the water level inside the lagoon only oscillates at subtidal frequencies, the channel often

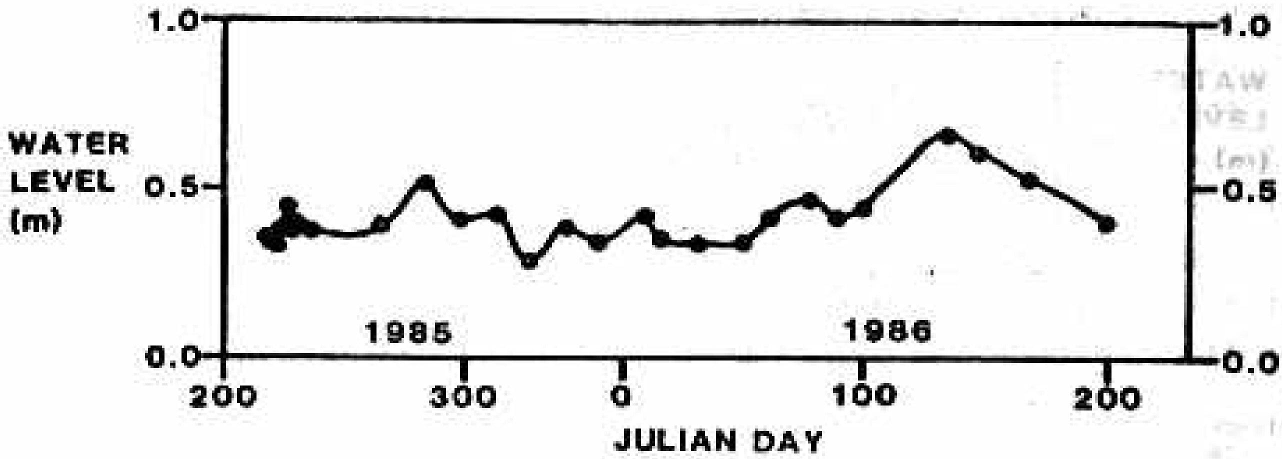

Figure 5 - Water level (m) data at the SERLA gauge on days of biweekly sampling during 1985-1986.

exhibits strong, reversing tidal currents (Fig. 6). During such flood tides, high salinity marine waters (30-34 ppt) are pumped into the lagoon. This occurs whenever the water level inside the lagoon drops below a threshold value for a sufficiently long time for the water surface pressure gradient to drive ocean water all the way into the lagoon. Because of the symmetrical shape of the salinity-time curve during a tidal cycle with reversing currents (Fig. 7), most

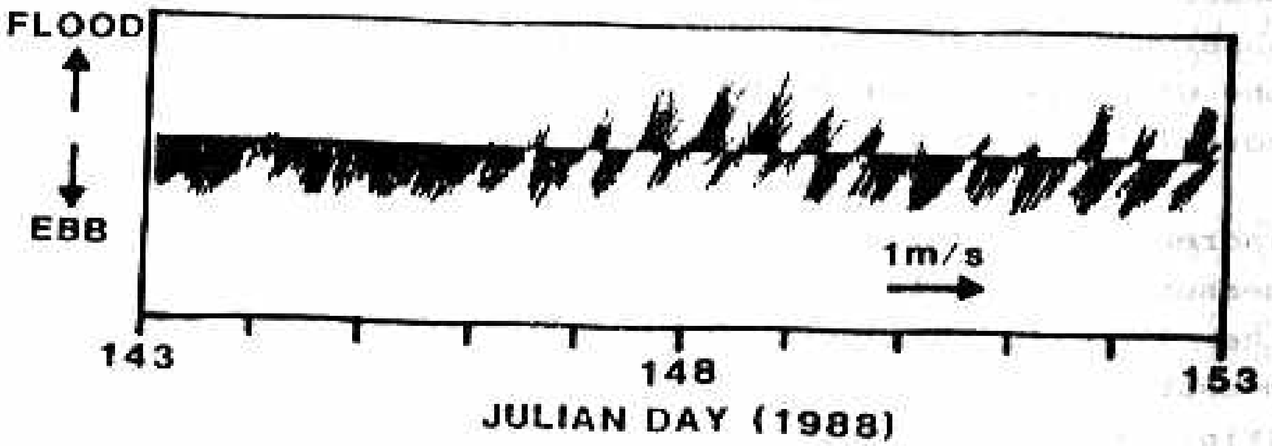

Figure 6 - Stick diagram of currents at the lagoonward end of the entrance channel for 10 days, 0000 22 May - 0000 1 June 1988. Maximum currents reached 0.8 m/s. North is towards the top of the diagram, and each horizontal division represents 0.5 m/s. Time is in GMT and each time division represents 24 hours.

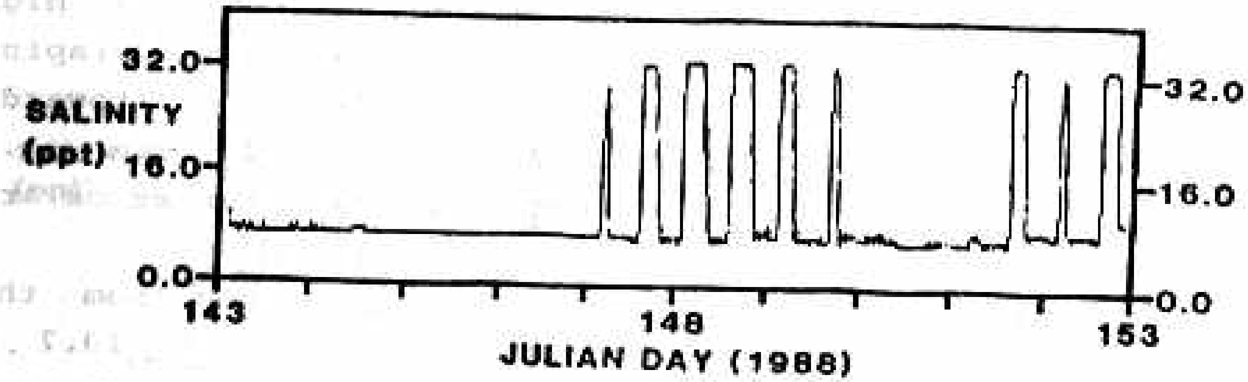

Figure 7 - Salinity (ppt) time series at the lagoonward end of the entrance channel for 10 days, 0000 22 May - 0000 1 June 1988. Time is in GMT and each time division represents 24 hours.

of the marine waters that enter the lagoon on a flood tide apparently exit the lagoon on the next ebb tide without mixing substantially with waters inside the lagoon. The entrance of marine waters into the lagoon on flood tides is a sudden event, characterized by a sharp salinity front with a 30 ppt difference in salinity on either side of the front.

Water Balance, Salinity Trend, and Turnover Time

Fresh water reaches Lagoa de Guarapina via (1) three small streams, Caranguejo, Padreco, and Bananal; (2) Canal de Guarapina that connects Guarapina to the rest of the lagoon system (Fig. 2); and (3) direct rainfall.

During 1985-1986, the rivers Caranguejo, Padreco, and Bananal had mean discharges of 0.23, 0.06, and 0.06 m^3/s, respectively. The combined drainage area for the three streams measures 59 km^2, which is considerably less than the total area for the Guarapina system (Tab. 1). The runoff ratio, the surface runoff divided by total basin rainfall, measures only 0.16, using the 1985-1986 rainfall rate of 1.1/m. The runoff ratio is very low for a basin as small as the Guarapina basin and is the result of a high evapotranspiration rate. The flow in Canal de Guarapina between Padre and Guarapina averaged +0.57 m^3/s (towards Lagoa de Guarapina) during 1985-1986 but varied from -1.6 m^3/s to +4.0 m^3/s. The groundwater flow characteristics are not known.

Annual freshwater runoff into the lagoon from the local Guarapina drainage system is estimated to be 10.7×10^6 m^3, by adjusting for the 8% of the land area not gauged, and assuming that direct rainfall on the lagoon surface is balanced by evaporation (BARBIÈRE, 1984). Assuming a similar runoff ratio and similar basin rainfall and water surface evaporation rates for the remainder of the lagoon system, an estimated 42.3×10^6 m^3 of freshwater flows into Lagoa de Guarapina annually via Canal de Guarapina. It is now possible to calculate a turnover time for the freshwater in Lagoa de Guarapina as the ratio of lagoon water volume to annual freshwater input. This yields an average turnover time of 1.5 months for Lagoa de Guarapina, and implies an even longer turnover time for Padre, Barra, and Maricá. However, the turnover time varies considerably in response to weather events, and events rather than seasonal cycles act as controls on the hydrological behaviour of the lagoon. This is implied by the fact that the water level in the lagoon varies much more as a result of weather events than on a seasonal basis (cf. Fig. 3, 5). The estimate of turnover time would presumably be somewhat shorter if groundwater input could also be included.

Salinity variations in the lagoon are mainly low-frequency occurrences in response to runoff events rather than changes in tidal forcing. Laguna de Guarapina is becoming increasingly fresh every year. The salinity measurements in 1985-1986 indicate salinities in the range 15-25 ppt (Fig. 8). Salinity variations during 1987 were

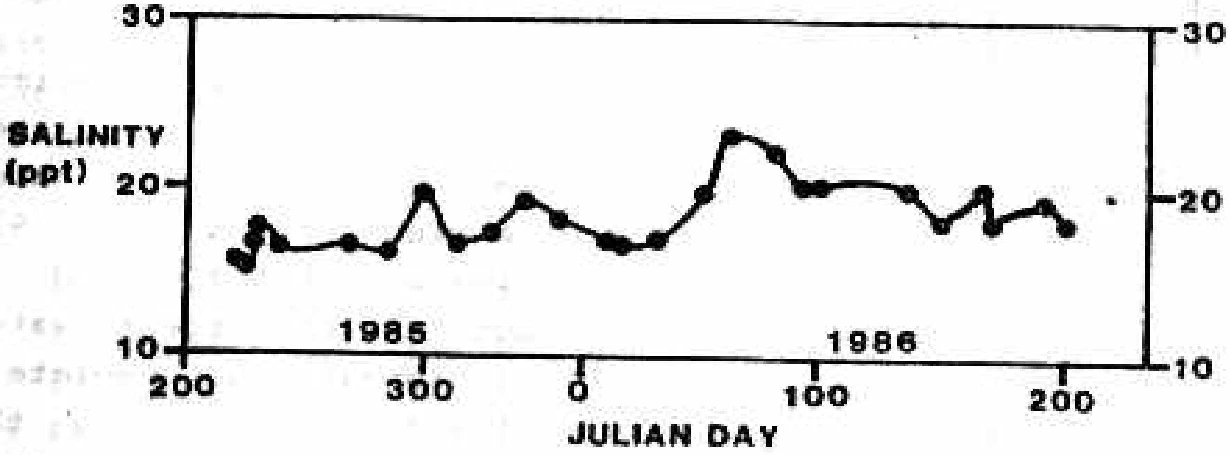

Figure 8 - Salinity (ppt) data from the middle of Lagoa Guarapina resulting from the biweekly sampling in 1985-1986. The data are surface readings but differ minimally from the bottom readings.

10-15 ppt, and during 1988, 5-10 ppt. These salinity observations are consistent with the concurrent increase in lagoon water level, implying that Laguna de Guarapina and the rest of the connected lagoons are changing their hydrological characteristics. This change is primarily the result of several wet years with increased runoff from 1985 until 1988. It is also possible, however, that Lagoa de Guarapina is becoming more choked because of entrance channel sedimentation, further limiting the water exchange between the lagoon system and the coastal ocean. This is likely in view of the dredging of the lower course of Rio Caranguejo (Fig. 2) during the study. Unfortunately, we do not have independent measurements to substantiate this speculation.

Temperature Variations

The Lagoa de Guarapina water mass undergoes (1) a seasonal temperature cycle, (2) random variations in temperature as a result of weather events, and (3) day and night temperature oscillations. All these temperature changes have the potential to affect directly biological processes and rates.

Seasonally, the temperature varies from a maximum of 32°C in January to a minimum of 18°C in July. The water temperature may drop as much as 6-8°C over a two to three days subsequent to the passage of a winter front (Fig. 9). The day-night temperature oscillation measures 3°C and is particularly pronounced during times of consistent water outflow from the lagoon, when tidal signals are completely absent in the temperature time series (Fig. 9). During tha passage of winter fronts, e.g. the storm on 24-26 May 1988 (Fig. 9), the water temperature may also vary tidally as a result of heat loss from the lagoon water surface and import of warmer high-salinity coastal waters into the lagoon during the flooding portion of the tide on cycles when the tide penetrates into the lagoon.

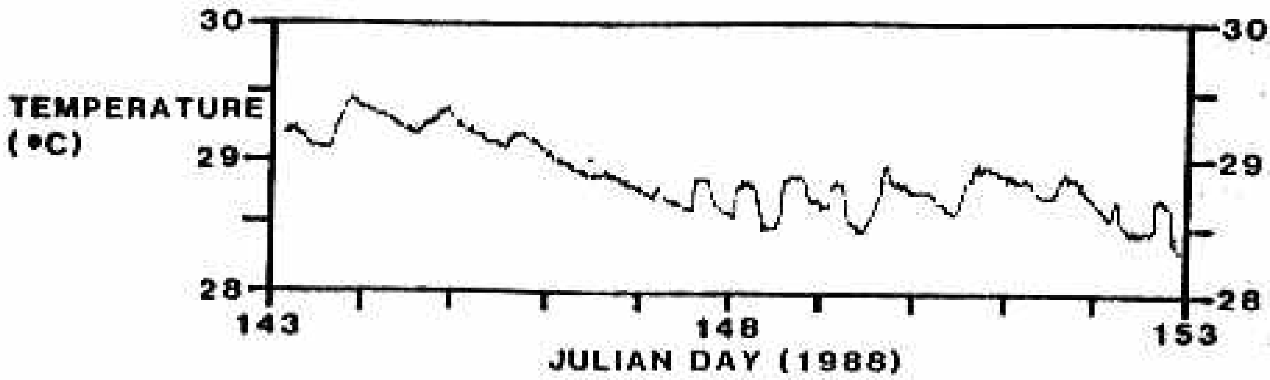

Figure 9 - Water temperature (°C) time series at the lagoonward end of the Lagoa de Guarapina entrance channel for 10 days, 0000 22 May - 0000 1 June 1988. Times in GMT and each time division represents 24 hours.

Hydrological Regimes

The physical measurements mad in Lagoa de Guarapina suggest that the lagoon hydrology is changing rapidly. Lagoa de Guarapina has become more of a freshwater environment than it used to be, with mean salinities having decreased from 17 to 6 ppt at the same time that the mean lagoon volume increased by 50%. At present, Lagoa de Guarapina experiences three distinct hydrological regimes:

(1) Periods of constant water outflow, persisting for one to three weeks, when the water level is high, substantial runoff occurs, the salinity is very low and decreases slowly at a linear rate, day-night temperature oscillations of 3^{o}C occur, and there is no tidal variability.

(2) Periods of strong tidal variability, usually associated with spring tides and high long-period ocean swells, lasting for approximately one week. Marine waters enter the lagoon on the flooding tide and exit the system on the ebbing tide. The sea level inside the lagoon usually changes rapidly during this period.

(3) Periods of quiescence, most common during neap tide periods with good weather, lasting for approximately one week, associated with steady salinity and water level, pronounced diurnal temperature oscillations, and week tidal forcing.

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