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ECOLOGICAL CHARACTERISTICS OF THE COASTAL LAKES IN SOUTHERN BRAZIL: A SYNTHESIS.

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Resumo - CARACTERÍSTICAS ECOLÓGICAS DAS LAGOAS COSTEIRAS DO RIO GRANDE DO SUL: UMA SÍNTESE.

Os critérios de avaliação das características ecológicas das lagoas costeiras do Sul do Brasil são decorrentes de seu funcionamento especial, resultante da sua morfologia e localização geográfica nas proximidades do mar. As lagoas costeiras do Rio Grande do Sul foram estudadas durante 8 anos, entre 1979 e 1986. A morfologia, transparência e as comunidades bentônicas foram estudadas em 48 lagoas e os parâmetros físicos e químicos em 39 destas. As propriedades ecológicas destes lagos rasos não estão em concordância com os sistemas convencionais de classificação de lagos. Pode-se distinguir cinco tipos limnológicos baseados em características morfológicas, óticas, físico-químicas e no estado trófico de 39 lagoas costeiras.

Abstract - ECOLOGICAL CHARACTERISTICS OF THE COASTAL LAKES IN SOUTHERN BRAZIL: A SYNTHESIS.

Criteria for the evaluation of the ecological characteristics of the southern Brasizilian coastal lakes derive from their special functions resulting from their morphology and their geographical location near the sea. The coastal lakes of Rio Grande do Sul were studied during 8 years, between 1979 and 1986. Lake morphology, transparency and benthonic communities were studied in 48 lakes and physico-chemical parameters were measured in 39 of these.

The ecological properties of these shallow lakes are not in agreement with the conventional lake classification systems. We may distinguish five limnological types based on morphological, optical, physico-chemical properties and trophic state.

Introduction

The southern Brazilian coastal plain is part of the Restinga, which extends more or less consinuously along the coast of Brazil, from the state of Rio Grande do Sul in the south to Maranhão in the northeast. The coastal plain of Rio Grande do Sul is geologically young. The dynamics of its formation involved Pleistocene and Holocene transgression and regression

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phases coupled with fluvial and aeolian erosion of the exposed parts of the shore during times of regression leading to the formation of ephemeral shallow lakes of different age, morphological structure and ecological characteristics. Their properties are not in agreement with conventional lake classification systems.

The coastal plain of Rio Grande do Sul shows a high density and diversity of aquatic ecosystems.. In this paper the morphological, physico-chemical, sedimentological, optical and trophic conditions of the coastal lakes of southern Brazil are described and discussed. Results and conclusions presented here are based on data collected during earlier studies conducted on these ecosystems and which have been presented elsewhere (SCHWARZBOLD & SCHÄFER, 1984, LANZER 1989, SCHÄFER, 1989).

Material and methods

The coastal lakes of Rio Grande do Sul were studied during a period of 8 years, between January 1979 and March 1986. Lake morphology transparency and benthonic communities were studied in 48 lakes and physico-chemical parameters were measured in 39 lakes of these. The Standard Methods (APHA, 1976) were used for chemical analysis of water and sediments (details in SCHÄFER, 1989). The ecological characterization of the coastal lakes is based on summer mean values (1980-1982) of chemical (nutrients, salinity), biological (chlorophyll-a) and physical (transparency, oxygen and temperature budget, RTR) data.

Area investigated

The coastal plain of Rio Grande is located between 29°12'S and 33°48'S and 49°40'E and 53°30'E and has a total extension of 37000km². Approximately 61% of this area is land, 39% is water surface. The two most extensive water bodies being the Lagoa dos Patos (9.280km²) and the Lagoa Mirim (3.520km²). The other lakes cover an area of about 1460km². The coastal plain is subdivided by the estuary of Lagoa dos Patos into two units, a northern and southern region. In the northern region the Lagoa dos Patos occupies a large area and the sequence of lakes along the atlantic coast appears similar to beads in a rosary (DELANEY, 1960). In the southern region there are samaller lakes in the swampy area of Taim and the large channel-like coastal lake of Lagoa Mangueira. These southern lakes that are close to the sea and the lakes in the northern part of the coastal plain are described here.

For an understanding of the present geomorphological structure of coastal plains, the knowledge of its evolution is important. Studies of the Brazilian coast have shown that results of studies about coast evolution of the northern hemisphere need not be applicable for the southern hemisphere (FLEXOR et al., 1984), in particular with regard to Pleistocene transgressions and regressions (SUGUIO et al., 1984). Moreover, the lack of information about isostatic movements of the shield of Rio Grande do Sul or the Central Basin makes it difficult to reconstruct the evolution of the coast of southern Brazil (VILLWOCK, 1984). The different phases of the evolution of the coast of Southern Brazil are discribed by VILLWOCK (1984).

Climatologically the study area belongs to the southern region of Brazil, comprising the federal states of Paraná, Santa Catarina, and Rio Grande do Sul. This region is characterized by rather homogeneous climate (NIMER, 1979). The study area is located at the east cost of South

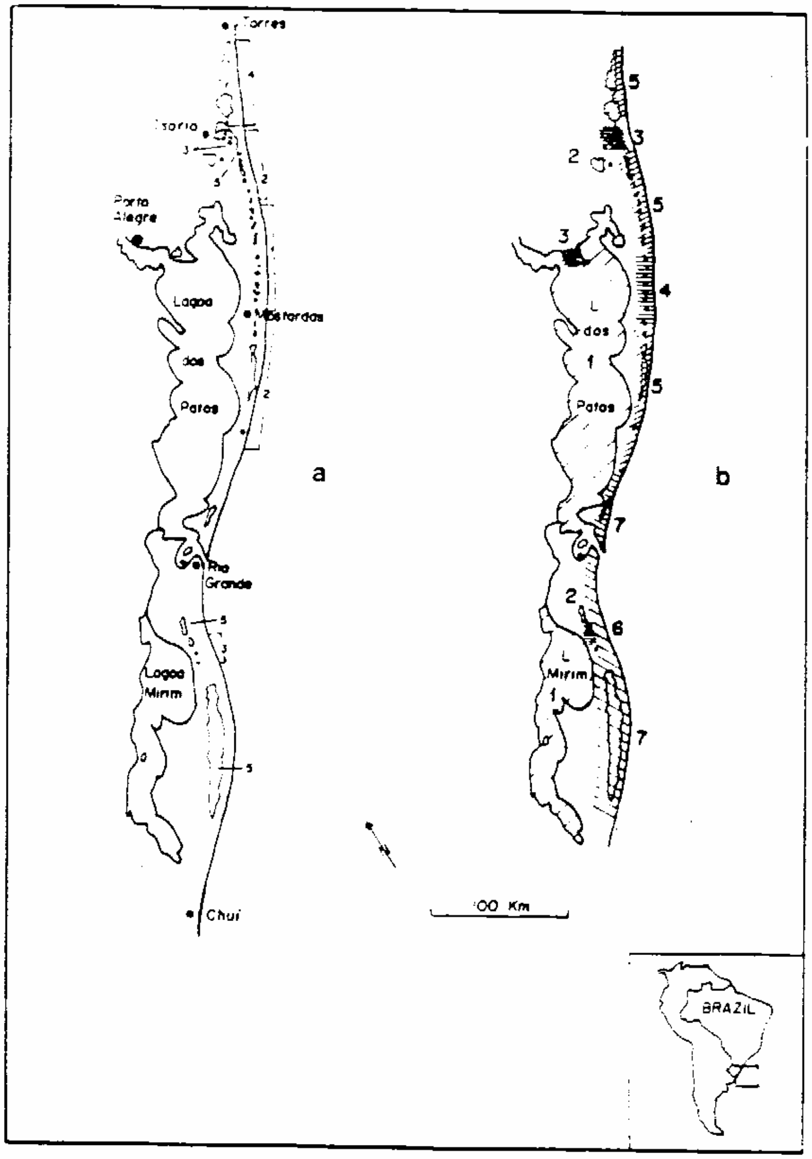

Fig. 1.: Evolution, age and ecological types of the coastal lakes of Rio Grande do Sul.
a) study area and geographical distribution of ecological lake types in the coastal plain of Rio Grande do Sul. See text for explanations.
b) evolution and age: 1=Riss Glacial origin (about 125,000 B.P.); 2=Würm Glacial isolation (14,000 B.P.); 3=Würm Glacial fluvial development of hollow moulds and lakes formation during the first phase of the Holocene Santos transgression (6500 B.P.); 4=Formation of the lakes in the Würm Glacial fluvial erosional channel in the course of the regression following the maximum Holocene transgression (5100 B.P.) concomitant with 5; 5=Formation of the near-shore chain of lakes after the maximum Holocene transgression (5100 B.P.); 6=Beginning of the isolation of Lagoa Mangueira (3600 B.P.); 7=Isolation of the swamp area during the last Holocene transgression (2600 B.P.).

America and has a southeastern exposition (Fig. 1a). The latter fact explains the strong influence of subtropical marine warm air masses which cause the high precipitation rates. Of lesser importance are the mountain ranges in the west, the Serra Geral, and the Shield of Rio Grande do Sul. Orographical factors are important in the northern part only. The greater part of the study area has mediterranean climate, with precipitation maxima during months with short day lengths.

Predominance of northeasterly winds during the whole year characterizes the northern part of the coastal plain of Rio Grande do Sul. Only the southern part is, mainly during winter, exposed to cold southern and southeastern winds. The location of the study area near the sea results in a permanent importance of wind.

Ecological characteristics of the coastal lakes

Origin, Morphology and Developmental Trends

Morphometric studies of the south Brazilian coastal lakes were undertaken by the first time by DELANEY (1960) and later by SCHWARZBOLD (1982) and SCHWARZBOLD & SCHÄFER (1984). SCHÄFER (1989) used morfological data of 48 lakes to (1) develop a framework for ecological interpretations, and (2) get an insight into the evolution of the lakes in the study area, particularly for the coastline east of the Lagoa dos Patos. According to their surface area and maximum depth the coastal lakes in southern Brazil may be subdivided into four groups:

1) large lakes of medium maximum depth
:ry small to medium large, shallow lakes
, ery small to medium large, deep lakes
4) large and deep channel-like lakes

Lake surface: very small:<1km^2; medium:10-60km^2; small:1-10km^2; large:>60km^2
Maximum depth:shallow:<3m; medium:3-7.4m; deep:7.5-11m

The geographic distribution of morphological lake type in the south Brazilian coast underscores the interrelation between structure and evolution of the coastal lakes (fig. 1b). The lake morphology depends largely on formation processes of the coastal plain of Rio Grande do Sul, which are described above. Lake depths rise from 4m in the northern part to 11m in the central part of the coastal plain (lake 4 in Fig. 1b) and decrease in direction to Lagoa Mirim in the southern part. This series may be a result of fluvial processes of erosion during the Würm Glacial regression. The maximum depth resulting from postglacial transgression and regression processes is 7.5m (=depth of Lagoa Mangueira, the largest lake formed by sedimentation of beach ridges; type 7 in Fig. 1b). The present shapes of the lake basins result from segmentation and the lake origin (marin or fluvial). One typical morphological phenomenon, the asymmetry of the lake basins,warrants further discussion. While the larger lakes in the north of the littoral and all smaller swanpy lakes show a regular shape (pan-shaped; lake type 3, 5 and 6 in Fig. 1b), the shape of the deep smaller lakes is asymmetric with regard to the main wind direction (lake type 4 in Fig. 1b). This irregular relief of the lake banks is caused by shifting dunes on the eastern sides of the lakes and by alluvial deposition processes on the western sides. Moreover, the western to southwestern banks are older parts of the lake basin which had been slowly filled during transgression phases of the early periods of the postglacial. These parts have a lower inclination than the more recent banks which are shaped by shifting dunes. The extreme asymmetry of the deep lakes in the central section of the littoral is therefore mainly caused by aeolian processes of erosion and accumulation. The eastern banks of the deep asymmetric lakes are constantly shifting by the blow-in drift sands. This almost totally prevents the establishment of bank vegetation. Along the shallow western banks more or less well developed communities of macrophytes may occur, depending on trophic parameters and on bank development.

In the smaller lakes in the northern part of the study area, which are further away from the sea, shifting dunes have no impact on bank formation (lake type 3 in Fig. 1b). Increase in sedimentation and water plant biomass lead to silting-up, partially accelerated by human impact. As a result these lakes have symmetric shapes, characterized by a more or less well pronounced segmentation of the water bodies. The shape of the basins of the swampy lakes in the south is also only a result of silting-up (lake type 6 in Fig. 1b). Because of changing wind directions in summer and winter there is no uniform shifting of dunes and hence sand accumulation only rarely affects bank shape.

The lakes with medium maximum depth are intermediate in shape-type. They are influenced by shifting dunes, but they silt up more quickly than deep lakes because they are shallower. Their basins are only a little asymmetric related to the main wind direction (northeast). The western banks show more or less large belts of silting-up, the northeastern banks are very steep because of the dunes. As a consequence these lakes show a tendency to fragment.

The long chain of lakes close to the sea, between the Lagoa dos Patos and the Atlantic, is a result from such recent segmentation processes. The natural "aging" of these lakes can only partly be explained by biological factors. Material which is easily eroded and transported away by the wind has lead to the greater parts of the areas close to the sea being covered by blown-in sand and shifting dunes. Starting from an originally channel-like type of lake (at about 6500 B.P.) different types of lakes have developed which presently show a tendency to becoming isolated swampy lakes. As a result of biological and mineralogical processes the water bodies of the lakes become constantly smaller finally leading to isolated lakes rich in biomass. This particularly applies for the coastal lakes in the north of the coastal plain which are further away from the sea. Their low depth promotes the formation of isolated lakes by the accumulation of nutrients and the increase of biomass of macrophytes (SCHÄFER et al., 1985).

Temperature and Oxygen Budgets

Coastal lakes are characterized by their shallow water bodies and their exposure to seawinds since they lack orographical barriers. This action of wind results in high dynamics of horizontal and vertical water circulations which are also affected by the Coriolis force (SCHWARZBOLD, 1982). Temperature and oxygen budgets play a crucial role in understanding these dynamics. Stabilities of water bodies can be expressed by their Relative Thermal Resistance (RTR), after VALLENTYNE (1957). The deeper lakes of the central littoral of Rio Grande do Sul, in which stratification should be expected because of their morphological structure, have low RTR values indicating high mobility of the water bodies in these lakes. In the shallow swampy lakes, however, stable stratification may be recorded due to the mechanical resistance of the submersed vegetation to water movement and due to differential filtering of light at various depths. The RTR values obtained are comparable to discontinuity layers as found in the deep lakes of the temperate zone. Daily and seasonal differences in RTR values occur mainly in coastal lakes with opaque water. Lakes with transparent water have constant conditions throughout the year (SCHÄFER, 1989). Seasonal temperature conditions in the study area determine the temperature budgets of the coastal lakes. They are not covered with ice during winter, but have low temperatures (14°), during summer temperatures are about 26°.

The oxygen budget depends on lake morphology and prevailing plant communities. Two extreme types may be distinguished, i.e. large, mostly opaque, medium-deep coastal lakes with little aquatic vegetation and little, shallow swampy lakes with dense stands of aquatic plants. In the first group of lakes oxygen concentrations are almost exclusively determined by solution processes, in the second group oxygen concentration is largely dependent on biological production and consumption.

Water Chemistry and Salinity

The content and composition of salts dissolved in a lake depend on climatic and edaphic conditions in the catchment area. According to GIBBS (1970) the main factors influencing the water chemistry are precipitation, dominant geological layers, and processes of evaporation and crystallization. Worldwide studies in different coastal areas demonstrate that the distance between the stagnant water bodies and the sea largely determines the chemical composition of the water (YOSHIMURA 1936, TIMMS 1986). The composition of ions is characterized by the domination of sodium and chloride. This is also the case in the coastal lakes of Rio Grande do Sul, where is a significant correlation between the chloride concentration of lake water and the distance of the lakes to the Atlantic Ocean:

...d on YOSHIMURA (1936):	after TIMMS (1986):
Cl^-=47.97-11.07D	Cl^-=29.9-3.09D
r=-0.82; p<0.01; n=9	r=-0.67; p<0.05; n=9

south Brazilian coastal lakes:

Cl^-=68,05-3,09D

r=-0,53; p<0,01; n=37

Cl^-=chloride (mg/1); D=distance to the sea (km)

The relatively low percentage of the variance in chloride content in the coastal lakes of Rio Grande do Sul which is explained (28%) by the distance to the sea, results from regional differences, as for instance the exposition of the coast line to the main wind direction.

Contrary to most other coast lines in the world most of the lakes of the study area freshwater lakes often with drinking water quality (during summer conductivity varies between 45 and 610 µS/cm, average: 190 µS/cm). One essential factor for this is the freshwater lens of the Lagoa dos ...and the Lagoa Mirim. Freshwater sources are the Jacuí River and, to a smaller extent, the ...a tributaries. The freshwater lens together with the balanced precipitation regime prevents salification of the ground water and of the water of the lakes.

Sediment

The inorganic content of sediments in coastal lakes consists of a mixture of sands wich are from marine of fluvial terraces or from shifting dunes or flying sands and associated with siltymuddy autochthonous recent or fossil lake deposits. The processes of sedimentation in the coastal lakes of Rio Grande do Sul are to a large extent dependent on the morphology of the lake basins and the processes of sedimentation and erosion upon the lake bottom.

The importance of lake morphology for the grain size distribution of the sediment is best illustrated in the deep asymmetric coastal lakes with a relatively extensive Area of Accumulation (after HAKANSON, 1982). The structure of the sediment in large, shallow coastal lakes with pronounced hydrodynamics and a small area of accumulation at the lake bottom is irregular and does not correlate with water depth. Another criterion by which to evaluate sedimentological conditions is lake evolution. The banks of the deep coastal lakes of the central part of the littoral are mainly composed of dune sands with a fraction of fine sand of over 90%; in the deeper water layers still finer fractions are accumulated. There is no general correlation between the maximum depth of a lake and its content of metals, nutrients and organic particles of the sediment. Especially in coastal lakes with a large area of sediment accumulation sediment composition differs between parts of the lakes. No general statements can be made with regard to a classification of the coastal lakes based on sediments. However, acid humus with an organic C content of over 50% and a C/N ratio of over 10 may be expected in swamp lakes and in the deeper coastal lakes where the bank is swampy. A distinction between the sediment types of Dy and Gyttia (after HANSEN 1959) could not be made of the study area.

Optic Characteristics

Following KIRK (1983) the coastal lakes of Rio Grande do Sul belong to the optic type T(=turbidity), where suspended matter determines light absorption. Despite the influence of seawinds on the deep and transparent lakes of the central littoral no suspended load is present. Therefore they belong to type W (water absorbance). During summer 52% of the lakes examined have a transparency of 0.55 to 1.5m and 81% a transparency of 0.3 to 2.0m. The deep, transparent lakes of type W (SD > 3.8m) are represented with 8% (type 1, Fig. 1a). The highest Secchi depth measured was 6.8m in the Lagoa Moleques, with a maximum depth of 11m and a surface area of 1.06km^2. Especially these lakes of the central part of the littoral and the small, shallow lakes in the north near the city of Osório which are not influenced by shifting dunes and the Serra tributaries have an euphotic water body.

The usefulness of the parameter "transparency" for a limnological classification depends on the factors affecting this variable. These may be plankton density or mineral content of suspended matter, in the shallow near coastal water. Furthermore, as many of the lakes are connected with swampy areas humic matter may also be important. In such cases an unequivocal relation between trophic status and transparency, as required for an evaluation of standing waters is not given (HENNING, 1986). Regression analysis with data of the lakes studied, have shown that chlorophyll-a contents play a minor role for explaining the transparency compared to the suspensive load:

$SD(m)=2.88SL^{-0.514}(mg/l)$

$r=-0.96$; $p<0.0001$; $n=21$

$SD(m)=2.43\ Chlo\text{-}a^{-0.53}(mg/m^3)$

$r=-0.65$; $p<0.0001$; $n=39$

SD=Secchi depth; SL=suspensive load; Chlo-a=cholophyll-a

Factors Determining Trophic State

For the evaluation of the trophic status of standing waters HENNING (1986) has shown particularly useful parameters are transparency, chlorophyll-a content, and concentration of phosphorus. The application of loading models in the coastal lakes of Rio Grande do Sul is not feasible because no hydrogeological and detailed meteorological data are available to calculate turnover rates for the lake water. Because of difficulties in reaching the lakes during the rainy season, only during summer water was sampled on a regular basis from all lakes. As a consequence, only the Trophic-State-Index (after CARLSON 1977) and the concept of limiting algal growth (FORSBERG & RYDING, 1980) seem applicable as they are based on mean values of transparency, nutrient contents, and chlorophyll-a contents during summer.

For a characterization of the trophic status the relation between lake morphology and the contents of nutrients and chlorophyll-a should be know. SAKAMOTO (1966) first described the empirical relation between primary production, chlorophyll content and average depth and nutrient concentration. The expected concentrations of phosphorus and chlorophyll-a after SAKAMOTO (1966) were significantly higher than the values from the lakes studied:

after SAKAMOTO (1966):

P-tot $(mg/m^3)=64.56z_{med}^{-0.49}(m)$

Chlo-a $(mg/m^3)=248z_{med}^{-1.55}(m)$

south brazilian coastal lakes:

P-tot $(mg/m^3)=19.05z_{med}^{-0.57}(m)$

$r=-0.44$; $p=0.005$; $n=39$.

Chlo-a $(mg/m^3)=8.99z_{med}^{-0.65}(m)$

$r=-0.33$; $p<0.04$; $n=39$.

The shallow lakes show the highest divergence. This particularly applies for chlorophyll-a contents which are, due to the water dynamics and opaqueness because of minerals, significantly lower than in the lakes examined by SAKAMOTO (1966). RITTER (1985) comes to similar conclusions because of the fact that in extremely shallow and phosphorus rich water bodies with high turnover rates to significant correlation between the parameters as given in SAKAMOTO (1966) exists.

The low contents of phosphorus in the water may be explained by processes of autochthonous nutrient precipitation. Even in the lakes of the central littoral with low phosphorus concentrations in the water body high concentrations are found in the sediment. Because of the good supply of the sediment surface with oxygen the prevailing redox potentials prevent resolution of the phosphorus in the sediment. Exceptions are several swamp lakes where, in parts with dense submerse vegetation, permanent anaerobic conditions may occur on the sediment surface.

In the "Trophic-State-Index (ISI)" (CARLSON, 1977) contents of phosphorus and chlorophyll a are related to transparency without distinguishing between the "classical" lake types. CARLSON (1977) assumes that the trophic status is a continuum which cannot adequately be used to describe the delimitation of lake types. The TSI concept has been subject to criticism, particularly because evaluation is possible only if algal biomass is the only factor relevant for light attenuation. The coastal lakes of Rio Grande do Sul cannot be ecologically characterized by the CARLSONTSI because of the strong influence of suspended minerals.

Another approach to characterize the nutrient budget and the primary production is on the basis of factors that limit phytoplankton growth. In the course of eutrophication the N:P ratio becomes smaller and nitrogen gradually becomes the limiting factor. Carbon limitation seems of relevance only when there is an oversupply with phosphorus and nitrogen (FORSBERG & RYDING, 1980). The coastal lakes of Rio Grande do Sul have very low alkalinity because of their carbonate-poor bottom. The relations between inorganic carbonate, nitrogen, and phosphorus cleary illustrate that inorganic nitrogen is never limiting. The coastal lakes may be subdivided into a prevailing phosphorus and carbonate limited group, respectively, by the limiting value C_{inorg}/P_{inorg} of 41:1.

The lakes in the swampy southern region of the coastal plain are, though having relatively high carbonate concentrations, predominantly carbon limited because of their high of phosphorus concentrations. Another extreme type are the medium-deep to deep lakes. They are predominantly phosphorous-limited because of low concentrations of this nutrient. Besides this subdivision regional high or low alkalinity is important. The lakes of the northern littoral are phosphorbus-limited because of their high content of carbonate compared to the other coastal lakes. As a consequence, no trophic sequence as deducible from N/P ratios, can be suggested from the C/P ratios. In the lakes studied limitation is a result of geological and historical processes which have affected water chemistry rather than an accumulation of nutrients from waste water.

Ecological types

With regard to their ecological characteristics, viz. morphology, oxygen and temperature budget, transparency, nutrient contents, and trophic state the coastal lakes of Rio Grande do Sul may be grouped (Fig. 1a).

pe 1: Lakes of the central littoral

Deep to relatively deep lakes, small to medium-large, mainly characterized by low nutrient contents, by their isolation and their temporary one-sided connection to the sea (water overflow during the winter). The transparent lakes of the optic type W which are free of suspended matter belong to this group. Except for one lake all are limited by phosphorus.

Type 2: Connected lakes in the northern and southern part, the area between the Lagoa dos Patos and the Atlantic, together with a few lakes of the off-coast lake district in the north of the littoral.

This heterogenous group comprises shallow to medium-deep lakes, intermediate in substance budget and optic characteristics between type 1 and type 3.

Type 3: Swamp lakes of the southern littoral and eutrophic lakes in the lake district of Osório in the north of the coastal plain.

Shallow eutrophic lakes, almost exclusively carbonate-limited because of their high or relatively high concentrations of phosphorus. The oxygen budget is mainly determined by biological production and consumption.

Type 4: Large, medium-deep lakes in the north of the littoral.

Lakes with low transparency caused by the high content of mineral suspended load resulting from the small accumulating surface of the sediment. The oxygen budget determined by interchange with the atmosphere.

Type 5: Lakes with special characteristics

These coastal lakes can be distinguished from the other types by their morphology and/or by their optical and physico-chemical characteristics (largely caused by lake origin).

The occurence of the ecological lake types in the coastal plain of Rio Grande do Sul is shown in Fig. 1a. The congruence of distribution between the origin and ecological type of the lakes studied is evident and underlines the importance of evolution processes of the coastal area on system characteristics of the coastal lakes in southern Brazil.

Table I - Ecological types of 39 coastal lakes of Rio Grande do Sul

[illegible] lake	type	coastal lake	type
[illegible]	4	21. Barro Velho	1
2. Qua[illegible]os	4	22. Moleques	1
3. Pinguela	4	23. Tarumã	1
4. Peixoto	2	24. Figueira	1
5. Caconde	3	25. Rebeca	1
6. Lessa	2	26. Cinza	1
7. Horácio	2	27. Papagaio	1
8. Inácio	2	28. Ponche	1
9. Veados	3	29. São Simão	1
10. Custódias	5	30. Fundo	2
11. Gentil	2	31. Pai João	2
12. Fortaleza	2	32. Veiana	2
13. Rondinha	2	33. Paurá	2
14. Cerquinha	2	34. Bojurú	2
15. Rincão d. Eguas	2	35. Caiubá	5
16. Cipó	2	36. Flores	3
17. Porteira	2	37. Nicola	3
[illegible]	1	38. Jacaré	3
[illegible]	1	39. Mangueira	5
...dão	1		

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