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Morphological characterization of eighteen lakes of the north and middle coast of Rio Grande do Sul, Brazil

Caracterização morfológica de dezoito lagoas do litoral norte e médio do Rio Grande do Sul, Brasil

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Abstract: Aims: The present study aimed at a morphological characterization of 18 lakes of the municipalities of Cidreira, Balneário Pinhal and Palmares do Sul, situated in the northern and middle coastal plain of Rio Grande do Sul, Brazil. **Methods:** The morphometric survey was conducted in the summer of 2011/2012, based on echo sounder coupled with GPS and the application of remote sensing and GIS procedures. The morphometric parameters used for the characterization were: surface area, perimeter, perimeter development, volume, relative fetch, maximum depth, average depth, relative depth, median depth of volume, length and width. The statistical interpretation included Test of Normality, Coefficient of Variation, Correlation and Regression Analysis, Cluster Analysis, Discriminant Analysis and Principal Component Analysis. **Results**: Eighteen lakes were described and five of them are presented by aerial photo and bathymetric map. They represent the proposed morphological lake types. The calculation of the coefficient of variation revealed larger amplitudes of parameters related to lake size than to depth. The application and interpretation of cluster analysis, confirmed by discriminant analysis, distinguished those lakes in five morphological groups, which differ mainly by size and subsequently by depth. The Principal Component Analysis identified the first component with positively charged variables of size and negatively charged relative depth, and a second component with positive charge of maximum and average depths. **Conclusions:** The low relative depths and the exposure to constant northeastern winds reduce the transparency of the lakes. Consequently, they are light limited by suspension of inorganic and organic matter. A property that limits the application of trophic state indices. The high dynamic of the water bodies produces an oxygenated sediment surface that facilitates the settlement by aerobic organisms all over the bottom area. The shallowness and the low median depths of volume are limiting factors for sustainable water supply management. The morphological characteristics of the coastal lakes make very difficult an accurate ecological assessment based on usual trophic state criterions and a sustainable water resource management using general guidelines.

Keywords: coastal lakes, morphology, coastal plain, Rio Grande do Sul, Brazil.

Resumo: Objetivos: O presente estudo teve como objetivo a caracterização morfológica de 18 lagoas costeiras dos municípios de Cidreira, Balneário Pinhal e Palmares do Sul, no Litoral Norte e Médio do Rio Grande do Sul, Brasil. **Métodos:** No verão de 2011 e 2012 foram realizados levantamentos batimétricos, orientados por GPS, com aplicação de sensoriamento remoto e SIG. Os parâmetros morfométricos utilizados para a caracterização foram: área, perímetro, desenvolvimento de perímetro, volume, fetch relativo, profundidade máxima, profundidade média, profundidade relativa, profundidade mediana do volume, largura e comprimento. A interpretação estatística incluiu teste de normalidade, coeficiente de variação, análise de correlação e regressão, análise de cluster, análise de discriminância e análise de componentes principais. **Resultados:** Dezoito lagoas foram morfologicamente descritas e cinco delas são apresentadas por meio de fotos aéreas e mapas batimétricos, representando os tipos morfológicos propostos. O cálculo do coeficiente de variação revelou uma maior amplitude de parâmetros relacionados ao

tamanho do que à profundidade das lagoas. A análise de cluster identificou cinco grupos morfológicos, confirmados pela análise de discriminância. A análise de componentes principais identificou o primeiro componente com carga positiva de variáveis de tamanho e com carga negativa da profundidade relativa e o segundo componente com carga positiva das profundidades máxima e média. **Conclusões:** As baixas profundidades relativas, combinadas com a exposição das lagoas a constantes ventos de nordeste, diminuem a transparência das lagoas. Consequentemente, elas são limitadas pela luz devido ao material orgânico e inorgânico em suspensão. Uma propriedade que dificulta a aplicação de índices de estado trófico. A alta dinâmica dos corpos de água gera uma superfície aeróbia do sedimento que facilita a ocupação por organismos aeróbios em toda sua extensão. O fato de serem lagoas rasas e as profundidades medianas do volume muito baixas são fatores limitantes para a gestão sustentável dos recursos hídricos. As características morfológicas das lagoas costeiras tornam muito difícil uma avaliação adequada do seu estado trófico e uma gestão sustentável dos seus recursos hídricos baseadas em critérios comumente utilizados.

Palavras chave: lagoas costeiras, morfologia, planície costeira, Rio Grande do Sul, Brasil.

1. Introduction

Comparative studies in limnology often aim to search out general factors that explain why lakes differ in fundamental properties, such as humic and trophic levels (Hakanson and Peters, 1995). The study of lake morphology is fundamental not only for the knowledge of its shape, but also for understanding the processes referred to internal currents and the structuring of strata that exert influence on the transport of nutrients and the distribution of biological communities (Hakanson, 1977, 1982, 2005; Fee, 1979; Blais and Kalff, 1995; Fantin-Cruz et al., 2008; Nõges, 2009; Liu et al., 2010, 2011; Lawniczak et al., 2011; Stefanidis and Papastergiadou, 2012; Murdoch and Power, 2013; Kolada, 2014). Thienemann (1927) already established that morphology is important for the classification of the trophic state of lakes, ranking shallow lakes as eutrophic and deep lakes as oligotrophic. This is due to the fact that shallow lakes have usually a greater productive layer than deep lakes, if they are not limited by light (Magyar et al., 2013). Shallow lakes are characterized by their high dynamic of ecological conditions. Most of them are holomictic and polymictic, with short stable stages (Crisman et al., 2005).

The coastal plain of Rio Grande do Sul was formed by erosion and deposition processes during marine transgressions and regressions in the Pleistocene and Holocene, associated with fluvial and wind erosion, which formed four depositional systems, so called lagoon-type barriers. The systems I to III were originated during the Pleistocene and system IV in the Holocene (Schwarzbold and Schäfer, 1984; Villwock et al., 1986; Tomazelli and Villwock, 2000; Dillenburg et al., 2004). Due to its origin, the coastal lakes of Rio Grande do Sul are characterized by their low depth. Its location near the Atlantic Ocean causes a very strong influence of regular winds, predominantly from the northeast. This exposure has a decisive influence on nutrient balance, rate of eutrophication, structure of banks and siltation of the water bodies. Many coastal lakes show a morphologic asymmetry between the east and west banks. In the east, migrating dunes are encroaching on the lakes and form a very unstable substrate with high slope, preventing the permanent settlement of submerged and emerged macrophytes. Along the other shores there are belts of dense macrophyte communities occupying the low slope banks. These peculiarities elucidate the essentially of morphological for understanding the structure and ecological functioning of coastal lakes in southern Brazil (Schäfer et al, 2009a; Ahlert et al., 2013). The first morphological classification of the freshwater costal lakes of Rio Grande do Sul was performed between 1979 and 1983, and it included 48 lakes along the entire coastline of Rio Grande do Sul and differentiating four morphological types based on size and depth (Schwarzbold and Schäfer, 1984; Schäfer et al., 1985; Schäfer, 1988, 1992). The present study aimed at characterization of the morphology of 18 coastal lakes of Rio Grande do Sul, based on GPS oriented echo sounder measurements, remote sensing, GIS applications and statistical data processing.

2. Material and Methods

2.1. Study area

The geomorphologic province "Coastal Plain of Rio Grande do Sul", so called by the first time by Nogueira (1948), represents an area of approximately

37,000 km^2, in which 22,740 km^2 are terrestrial area and 14,260 km^2 are covered by waterbodies, including 620 km of the coastline between the state of Rio Grande do Sul and the Atlantic Ocean (Schäfer, 1992). This region comprises about 100 freshwater lakes next to the Atlantic Ocean and long beaches bounded by a undulated barrier of migrating sandy dunes, generally oriented northeast to southwest (Dillenburg et al., 2004). The present study includes 18 coastal lakes located in the municipalities of Cidreira, Balneário Pinhal and Palmares do Sul in the northern and middle part of the coastal plain of Rio Grande do Sul (Figure 1 and Table 1).

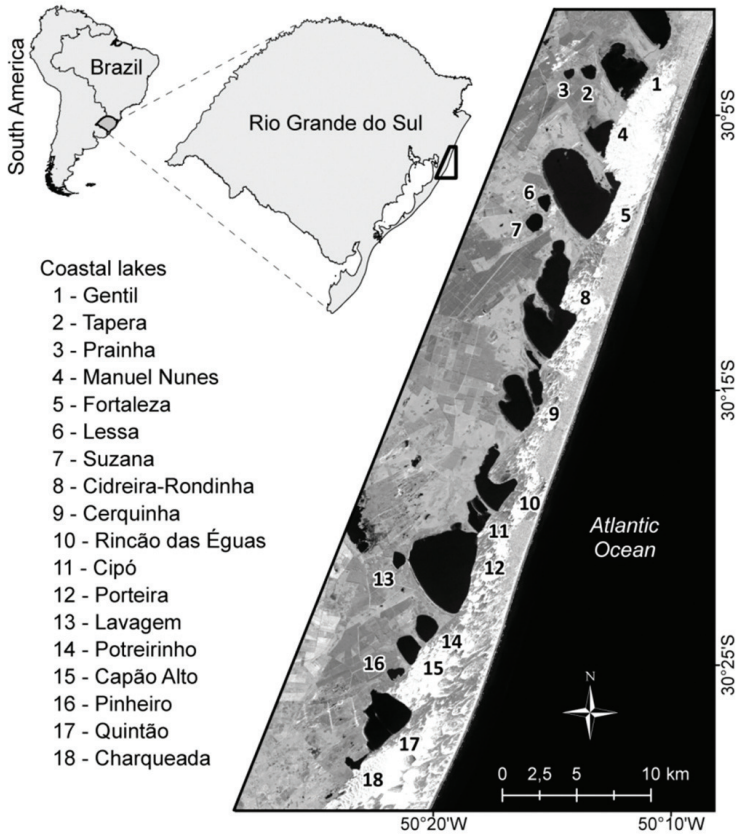

Figure 1. Name and geographical location of the 18 studied coastal lakes.

Table 1. Name, municipality and UTM coordinates of geographical location of the studied coastal lakes.

Name	Municipality	UTM coordinates (Fuse 22)	
Lagoa do Gentil	Cidreira	576770	6674684
Lagoa do Manuel Nunes	Cidreira	575216	6670173
Lagoa da Tapera	Cidreira	574499	6674574
Lagoa da Fortaleza	Cidreira	573770	6666619
Lagoa da Prainha	Cidreira	573151	6674455
Lagoa da Cidreira-Rondinha	Cidreira/Balneário Pinhal	571838	6658900
Lagoa do Lessa	Cidreira	571485	6665830
Lagoa da Suzana	Cidreira	570822	6664467
Lagoa da Cerquinha	Balneário Pinhal	569940	6652696
Lagoa do Rincão das Éguas	Palmares do Sul	567994	6646974
Lagoa do Cipó	Palmares do Sul	566966	6644851
Lagoa da Porteira	Palmares do Sul	564814	6641406
Lagoa do Potreirinho	Palmares do Sul	563479	6637262
Lagoa do Capão Alto	Palmares do Sul	562325	6635820
Lagoa da Lavagem	Palmares do Sul	561656	6641804
Lagoa do Pinheiro	Palmares do Sul	561446	6634204
Lagoa do Quintão	Palmares do Sul	560686	6631070
Lagoa da Charqueada	Palmares do Sul	558713	6628150

2.2. Morphometric parameters

The following morphometric parameters were used for the characterization of the coastal lakes: surface area (km^2), maximum depth (m), average depth (m), volume (10^6 m^3), relative depth (%), median depth of volume (% of maximum depth), perimeter (km), perimeter development, relative fetch (%), length (km) and width (km). The parameters surface area, length, width, perimeter and volume were obtained by remote sensing and the bathymetric data. The calculation of the other parameters followed Hakanson (1981) and Schäfer (1985).

2.3. Echo sounding

The field sampling period was from December 2011 to February 2012. The measurements of depths were conducted with a single-frequency echo sounder 500c Fish Elite Eagle (Lowrance Electronics Inc.) which relates the depth data with geographic positioning through associated GPS receiver. The survey followed the lines of margin and covered the whole lake area as regularly as possible. The depth data and its positioning were automatically saved in digital form by the echo sounder. The depth profiles were analyzed by Sonar Viewer 1.2.2 software.

2.4. Remote sensing and GIS processing

The surface form and the edge delimitation of the lakes were obtained by interpretation of LANDSAT 5/TM satellite images provided by the Brazilian National Institute for Space Research (INPE). For this study, a scene from November 6, 2011, clear of clouds, was selected and the software ENVI 4.5 used for the georeferencing based on Image Geocover (RGB742) provided by the National Aeronautics Space Administration (NASA). False-color composition (RGB 453) and the band 4 were exported to software ArcGIS 10 (ESRI), where the parameters surface area, perimeter, length and width were obtained. Surfer 8.0 software was used for the generation of bathymetric maps and volume calculations.

2.5. Statistical treatment of data

The following statistical procedures were applied: Kolmogorov-Smirnov Test of Normality, Coefficient of Variation, Cluster Analysis (measure Euclidean Distance and unweighted cluster combining) for the identification of morphological lake groups, Discriminant Analysis to confirm the results of cluster analysis and identify the most important morphological variables for grouping, Regression Analysis between width, area, transparency and relative depth and Principal Component Analysis (PCA) to identify groups of correlated variables. The calculations and graphical presentations were performed with IBM SPSS statistics 21.

3. Results

First of all, it may be underlined here that all the studied coastal lakes are shallow (major depth only 9.3 m) with relative depths far below the upper threshold of 2% for unstable water bodies (Wetzel, 1981). The differentiation of the morphological characteristics is, therefore, only relative within the general classification of depth and stability of lakes.

The set of results explores the morphology of 18 lakes. All of them are associated with the Holocene lagoon-barrier system IV. Although having the same geological origin and age, approximately 5,500 years BP, they present a high diversity of morphological features (Table 2). To exemplify the lake types proposed by this study, five lakes are presented with aerial photo and bathymetric map.

3.1. Lagoa da Tapera (Type A1)

The lake is situated in the northern part of the study area, in the municipality of Cidreira. It has a surface area of 0.74 km^2 and a volume of 0.7 *$10^6 m^3$ (Figure 2). The whole shore line is occupied by belts of macrophyte communities. The bottom is uniform with maximum depth of 2.1 m. The relative depth is 0.38% e the transparency 0.8 m. The lake is completely covered by emerge and floating macrophyte species (*Potamogeton ferrugineus, Schoenoplectus californicus, Cabomba caroliniana*). Dense plant communities indicate an advanced stage of biological aging or natural eutrophication. The lake is not situated near migrating dunes.

3.2. Lagoado Capão Alto (Type A2)

This lake takes part of a group of three small coastal lakes which were formed by the segmentation of a former extended water body. Its area is 2.25 km^2 and the volume 4.3*10^6 m^3 (Figure 3). The relative depth is 0.19% and the transparency 0.9 m. Because of the influence of migrating dunes on the east bank, the lake has a slight morphological asymmetry with the highest depth (3.3 m) in the southwestern part of the water body. The banks formed by dunes are not occupied by macrophyte communities. On the opposite side of the lake there are belts of emerged and submerged water plants.

Table 2. Morphometric and transparency data of the 18 coastal lakes.

Name	Area (km^2)	Perimeter (km)	Length (km)	Width (km)	Volume (m^3*10^6)	Maxi-mum depth (m)	Ave-rage depth (m)	Relative depth (%)	Peri-meter development	Relative fetch (%)	Secchi depth (cm)	Volume median depth (%)
Gentil	6.52	12.4	3.91	2.81	4.0	1.45	0.62	0.05	1.37	68	75	47
Tapera	0.74	3.3	1.03	0.98	0.7	2.12	0.89	0.22	1.07	91	80	24
Prainha	0.36	2.2	0.77	0.62	0.5	4.42	1.40	0.65	1.05	98	120	10
Manuel Nunes	2.91	7.4	2.62	1.78	2.7	1.96	0.91	0.10	1.23	86	45	28
Fortaleza	17.96	20.9	5.77	4.22	30.8	2.98	1.72	0.06	1.39	76	70	33
Lessa	0.71	3.2	1.15	0.89	0.8	1.80	1.06	0.19	1.08	81	80	17
Suzana	1.06	3.8	1.21	1.07	1.1	2.58	1.04	0.22	1.04	99	60	13
Cidreira-Rondinha	15.53	25.0	8.00	3.49	19.5	3.26	1.26	0.07	1.79	44	95	30
Cerquinha	8.67	21.1	3.89	3.03	9.2	1.80	1.06	0.05	2.02	84	90	30
Rincão das Éguas	5.63	14.1	3.58	2.81	12.2	3.76	2.17	0.14	1.67	73	90	39
Cipó	2.36	9.3	2.25	1.69	2.4	2.08	1.02	0.12	1.70	68	70	26
Lavagem	0.75	3.3	1.19	0.92	1.0	2.61	1.38	0.27	1.06	83	50	27
Porteira	19.07	17.5	6.15	4.47	55.2	5.04	2.89	0.10	1.13	85	60	30
Potreirinho	2.23	5.5	1.90	1.69	3.6	2.91	1.62	0.17	1.04	85	80	28
Capão Alto	2.25	5.6	2.03	1.61	4.3	3.27	1.92	0.19	1.06	71	90	30
Pinheiro	0.64	3.6	1.14	0.72	1.4	6.35	2.23	0.70	1.27	100	110	8
Quintão	8.41	12.5	3.99	3.23	30.5	9.34	3.63	0.29	1.22	99	200	22
Charqueada	0.76	4.6	1.46	1.24	2.0	4.65	2.61	0.47	1.47	99	120	32

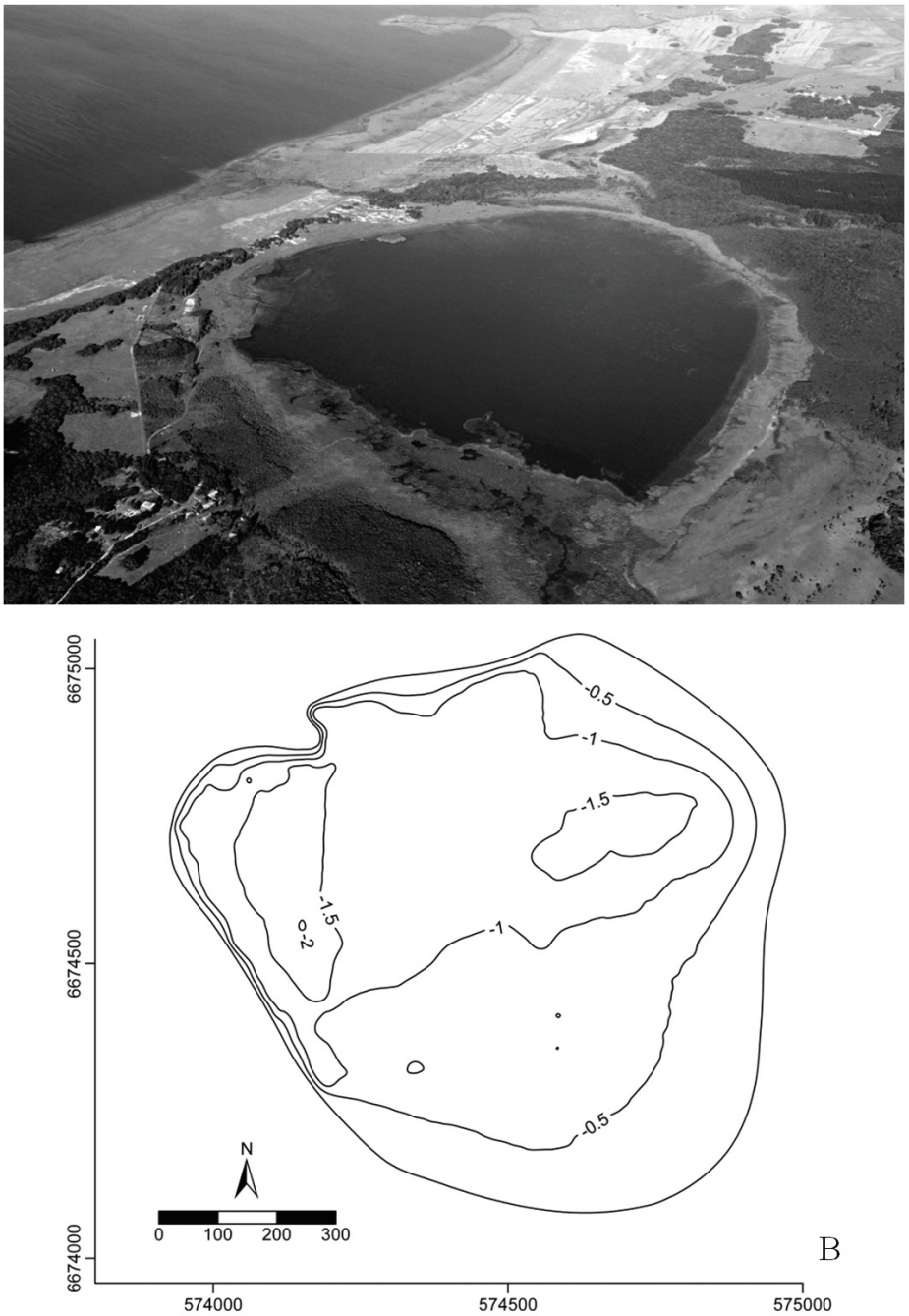

Figure 2. Lagoa da Tapera. A: aerial photo; B: bathymetric map.

3.3. Lagoa do Pinheiro (Type A3)

This lake with a surface area of only 0.64 km² has a maximum depth of 6.4 m, being the deepest of the small lakes (Figure 4). The bottom form is funnel-shaped, not uniform as in the other studied lakes. The high relative depth (0.7%) causes a transparency of 1.1 m. There is no direct contact between the margins and migrating dunes because of the *Pinus* plantation around the whole lake. The only source of suspended matter is a channel to the adjacent Lagoa do Quintão.

3.4. Lagoa da Cerquinha (Type A4)

Situated in the central part of the study area, in the municipality of Balneário Pinhal, the Lagoa da Cerquinha is morphologically the most irregular. It has a sinuous shape and a surface area of 8.67 km²

Figure 3. Lagoa do Capão Alto. A: aerial photo; B: bathymetric map.

(Figure 5), low maximum depth (1.8 m) and low water volume of $9.2*10^6$ m^3. The relative depth is only 0.05%. The aging process is accelerated due to the advanced stage of segmentation, because it is almost divided into three parts by a deposition of sediments, covered by macrophytes. Because of this segmentation, the lake has very expanded perimeter and the highest perimeter development among the 18 lakes (2.02). Despite of these characteristics, mainly the small volume, the lake is used to supply the city of Balneário Pinhal.

3.5. Lagoa do Quintão (Type B)

Situated in the southern part of the study area, in the city of Palmares do Sul, the Lagoa do Quintão has an area of 8.41 km^2 and stands out for being the deepest (9.3 m) between the studied lakes and the third in volume ($30.5*10^6$ m^3). Its morphology

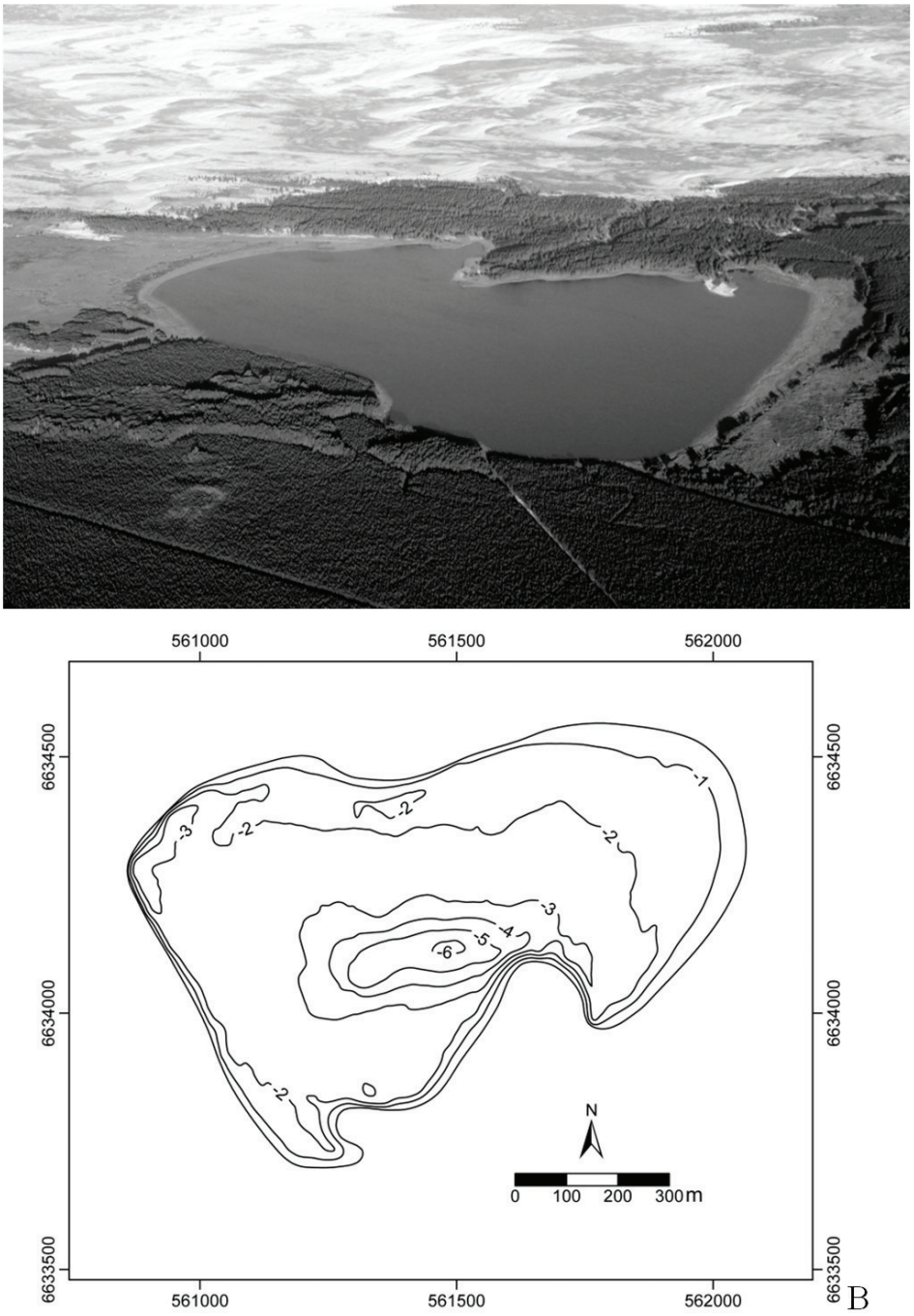

Figure 4. Lagoa do Pinheiro. A: aerial photo; B: bathymetric map.

presents an internal barrier of sediments, in the depth of approximately 2 m, which gradually begins to delineate the division of the lake into two bowls, a deeper in the east and a shallower in the west (Figure 6). The lake presents an early and less advanced stage of segmentation due to its high depth.

3.6. Morphometric differentiation of the coastal lakes

Comparing the variation of data it can be noticed that the parameters that describe the size of the lakes were more distinctive than those that describe the depths, with the exception of relative depth, showing a high variation

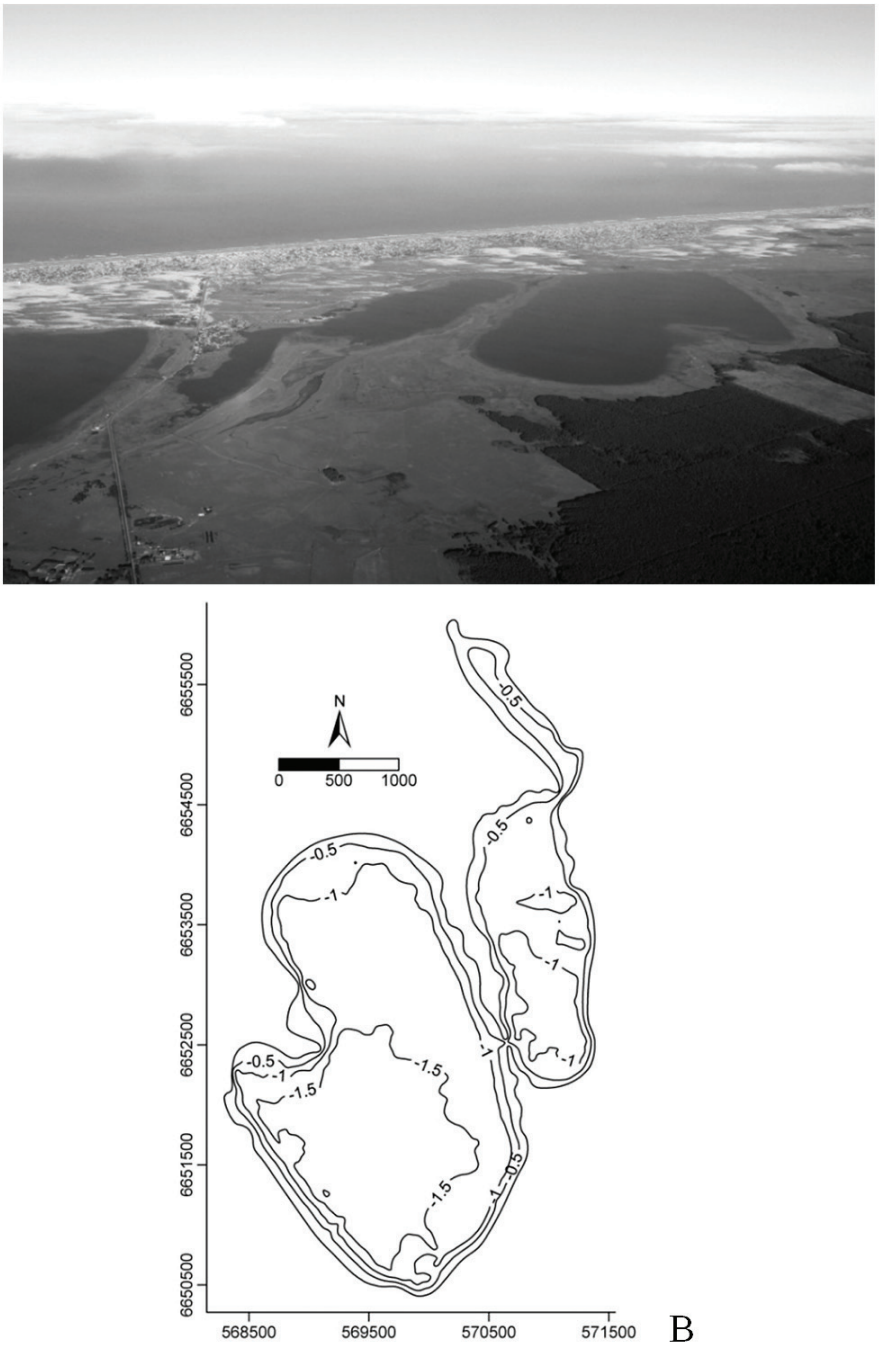

Figure 5. Lagoa da Cerquinha. A: aerial photo; B: bathymetric map.

because it represents the ratio between maximum depth and area (Table 3). Figure 7 shows, in descending order, the coefficients of variation of the morphometric parameters. This result indicates that a morphological differentiation is more related to size than to the depth of the lakes.

3.7. Cluster analysis

The next step of the morphological characterization was a cluster analysis in order to identify morphologically differentiated groups of lakes (Figure 8). The dendrogram distinguishes two main groups: small (A) and big (B) lakes.

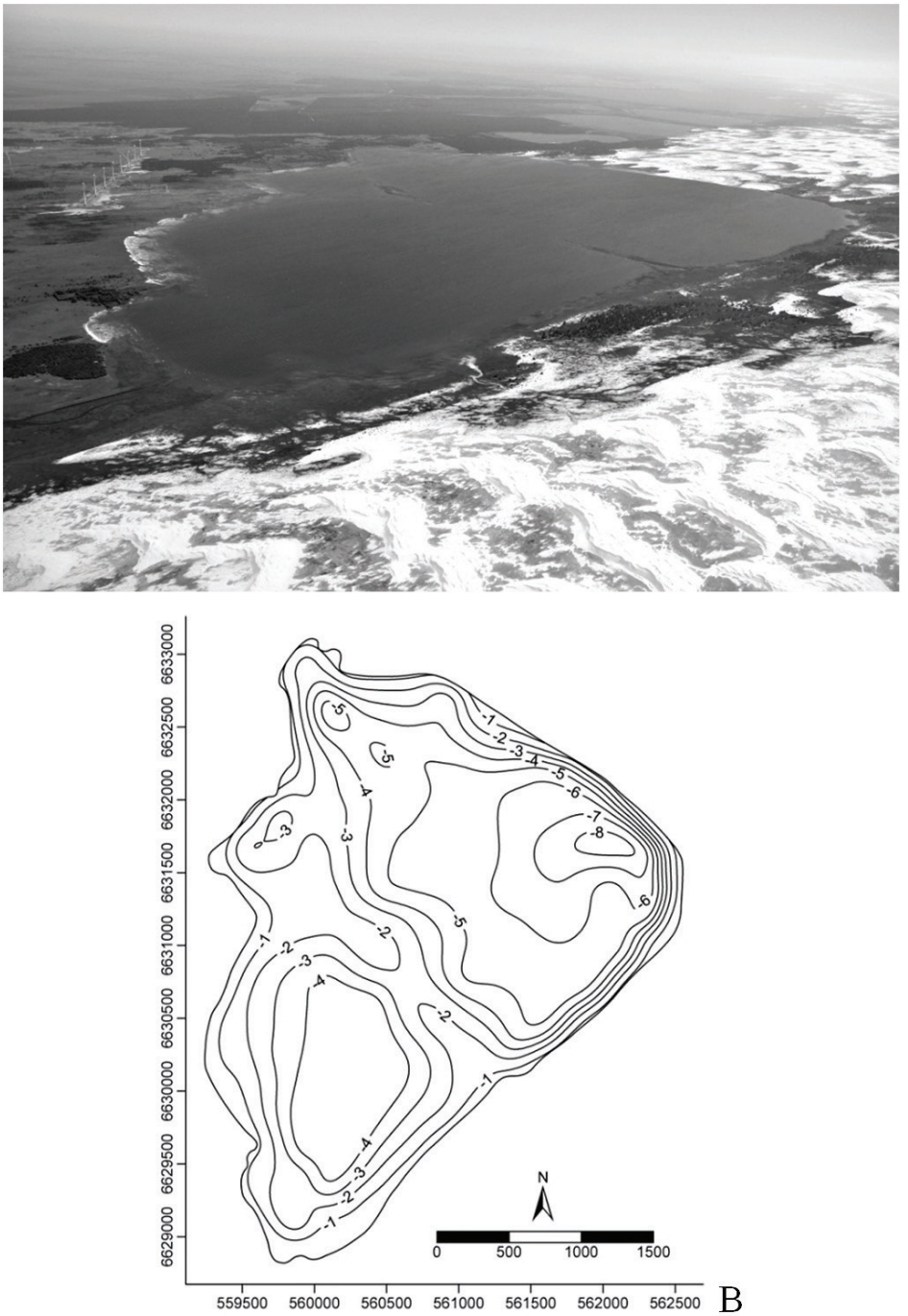

Figure 6. Lagoa do Quintão. A: aerial photo; B: bathymetric map.

The group of the smaller lakes can be subdivided into four subgroups:

Subgroup A1: very small lakes with surface areas of 0.71-1.06 km^2, maximum depths around 2 m and low relative depth near 0.2%; lakes with highly unstable water body and very regular shape (perimeter development 1.04 – 1.08).

Subgroup A2: lakes with areas between 2.2 and 2.9 km^2, maximum depths from 2 to 3 m, small lakes with low relative depth (around 0.2%) and highly unstable water body and regular shape (perimeter development 1.04 – 1.23).

Subgroup A3: very small lakes (0.4 – 0.8 km^2) with the highest relative depths (0.47 to 0.7%), they

Table 3. Minimum and maximum values, difference factor, name of the lake with minimum and maximum value and coefficient of variation (CV) of 10 morphometric parameters.

	Max	Min	Difference Factor	Lake max	Lake min	CV
Surface area	19.07	0.36	53	Porteira	Prainha	116
Perimeter	20.9	2.2	9.5	Porteira	Prainha	75
Length	8.0	0.77	10.4	Cidreira-Rondinha	Prainha	72
Width	4.47	0.62	7.2	Porteira	Prainha	60
Volume	55.2	0.5	110.4	Porteira	Prainha	147
Maximum depth	9.34	1.8	5.2	Quintão	Cerquinha	57
Average depth	3.63	0.62	5.9	Quintão	Gentil	49
Relative depth	0.7	0.05	14	Pinheiro	Gentil	86
Perimeter development	2.02	1.04	1.9	Cerquinha	Suzana/ Potreirinho	23
Relative fetch	100	68	1.8	Pinheiro	Gentil/Cipó	18

Max: maximum value, Min: minimum value; lake max: name of the lake with maximum; lake min: name of the lake with minimum.

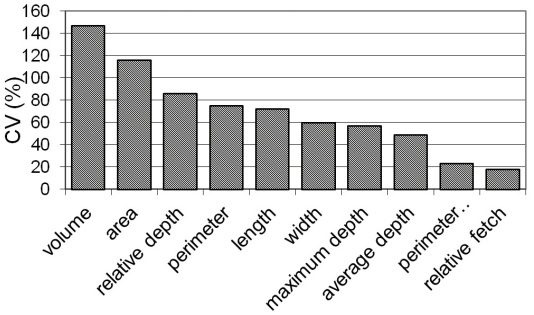

Figure 7. Coefficient of Variation (CV) of 10 morphometric parameters in 18 coastal lakes. perimeter . . . = perimeter development.

are the less unstable of the studied lakes because of their small surface area combined with maximum depths between 4 and 6.4 m; they have regular shapes (perimeter development 1.05 – 1.47)

Subgroup A4: lakes with the most irregular surface form, the highest perimeter development (between 1.4 and 2.0), a heterogeneous subgroup of shallow lakes with medium sizes.

Group B: big lakes, with areas between 8.4 and 19.1 km^2 and irregular shapes. The separate position of the Lagoa do Quintão in the dendrogram is due to the minor area and the highest maximum depth.

The morphological characterization of the groups is given in Table 4.

3.8. Discriminant analysis

A discriminant analysis was performed to test if the relationships between the variables show the same group memberships and to identify the parameters that best explain the grouping. The analysis confirms the grouping of the lakes. The width and relative depth were identified as most important for the differentiation of morphological groups (Figure 9). The width explains 58.4% of variance, relative depth 37.1% and development of perimeter 4.5%. As the width is not commonly used to characterize the morphology of lakes but the surface area, it was performed a log-log regression between these two variables. The calculation showed a very high correlation, where the surface explains 97.5% of the variance in width ($r^2 = 0.975$; $p < 0.001$). Consequently, the width can be used as an indicator variable for the size of the lakes.

3.9. Principal Component Analysis

The Principal Component Analysis (PCA) extracted two significant factors, the first represents mainly four positively correlated variables that describe the size (area, length, width and perimeter) of the lakes and, negatively related to these, the relative depth and relative fetch. The second component represents the maximum and average depths (Figure 10). The two components explain 83% of variance of the data set. As the relative depth and fetch are negatively correlated to the size, the big lakes tend to have a low relative depth. The perimeter development is located together with the size parameters (Figure 10). Therefore it is used, jointly with area, relative depth and maximum depth to describe the morphological types (Table 4).

All statistical approaches show that the morphological differentiation of the 18 coastal lakes is mainly done by the heterogeneity of the sizes (area and regularity) in association with their relative depths and less by the differences of maximum depths. The grouping by cluster analysis was the baseline for the morphological types of coastal lakes. Figure 11 shows the distribution of the lake types in the study area.

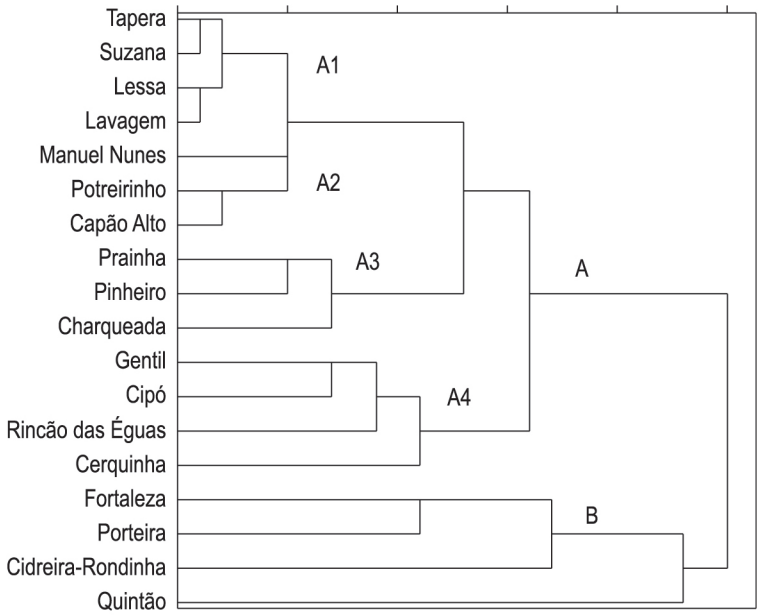

Figure 8. Dendrogram of the morphological groups of the 18 costal lakes, using all standardized morphometric parameters and as measure the Euclidian Distance. There are two main groups, the small lakes (A) with differentiation in four subgroups (A1 to A4) and the big lakes (B) with outstanding Lagoa do Quintão because of its high maximum depth.

Table 4. Morphological lake types based on surface area, stability of water body (relative depth), perimeter development and maximum depth, derived from cluster analysis of 18 lakes with 10 standardized morphometric parameters. A: small lakes; B:big lakes.

Type	Area (km^2)	Relative Depth (%)	Maximum depth (m)	Perimeter development
A	0.7-8.6	0.05-0.7	1.5-6.4	1.0-2.0
A1	0.7-1.06	0.19-0.27	1.8-2.6	1.04-1.08
A2	2.2-2.9	0.1-0.19	2.0-3.3	1.05-1.23
A3	0.4-0.8	0.5-0.7	4.4-6.4	1.05-1.47
A4	2.4-8.6	0.05-0.14	1.5-3.8	1.4-2.0
B	8.4-19.1	0.06-0.29	3.3-9.3	1.1-1.8

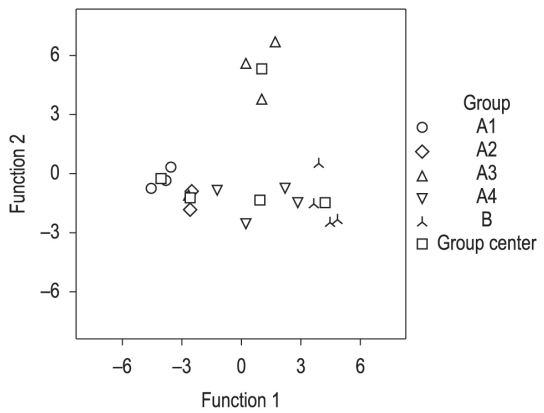

Figure 9. Ordination of the groups of lakes along the two first discriminant functions. The first is related to the width and the second to the relative depth. The group A3 is noted by the high relative depth, while the other four groups follow a size gradient.

4. Discussion

Since the early limnological studies, morphometric peculiarities played an important role in explaining biotic and abiotic phenomena, such as diversity of communities as well as the dynamic of substances cycling. The main problems of the morphological lake characterization were the precision of depth measurements, particularly because of the lack of the exact localization of the sampling sites, and the quality of surface data, limited by the accuracy and scale of the cartographic material. The use of echo sounder coupled with GPS allows an increase in the precision of depth data sampling and permits a review of former assessments of lake structure and functioning (Bezerra-Neto and Pinto-Coelho, 2008; Bezerra-Neto et al., 2010). The satellite image interpretation increases the spatial

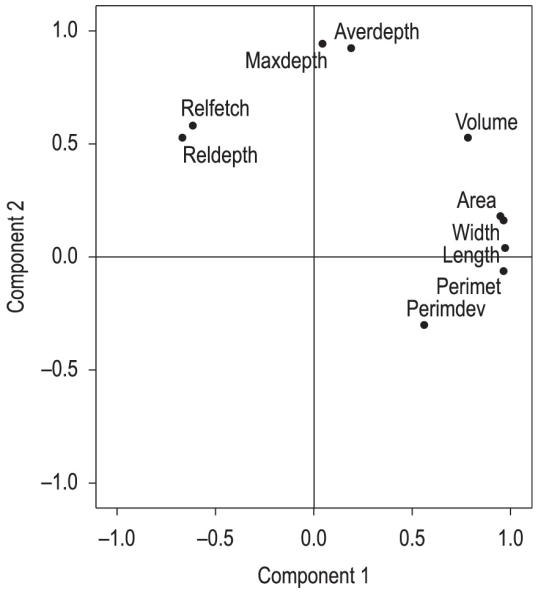

Figure 10. Loading plot of the two significant components extracted by PCA of 10 morphometric parameters. The first component is characterized by a positively related group of four size describing parameters and the negative correlated relative depth and related fetch. The second component shows the maximum and average depths as positively correlated parameters. relfetch = relative fetch; reldepth = relative depth; maxdepth = maximum depth; averdepth = average depth; perimet = perimeter; perimdev = perimeter development.

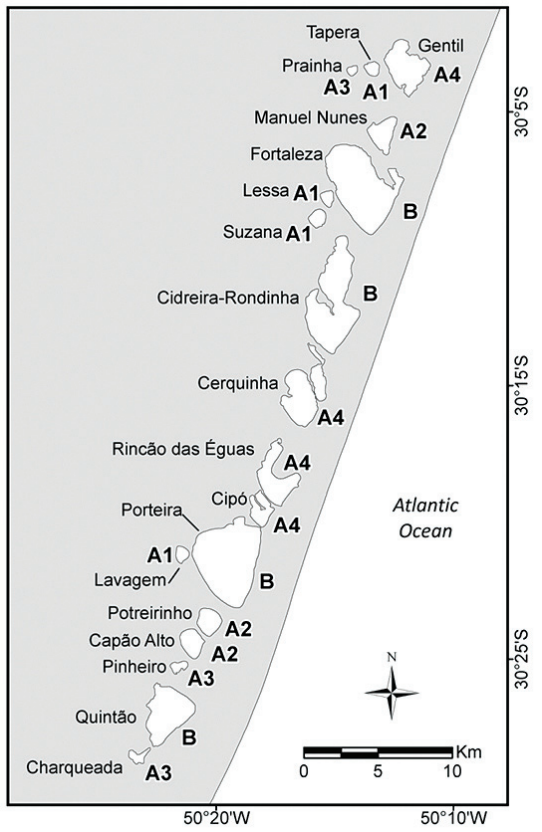

Figure 11. Map of distribution of the five morphological types of the coastal lakes in the study area. Types: A1: very small, shallow and regular shape; A2: small, shallow and regular shape; A3: very small, medium deep, regular shape and high relative depth; A4: medium sized, shallow and very irregular shape; B: big lakes, large and/or deep with irregular shape.

resolution and gives exact information of the actual lake surface. Consequently, the quality of predicting models increases, apart the ecological aspects, with the accuracy of morphometric data of the lakes (Hakanson, 2005; Johansson et al., 2007).

The morphological characteristics play an important role in the trophic state assessment of the coastal lakes. Most of the trophic state indices are based on the light availability for photosynthesis, expressed by Secchi Depth or transparency and its relationship with phytoplankton density (Carlson, 1977; Carlson and Simpson, 1996). In the present case, the light extinction also depends on lake morphology, mainly on the relative depth. The linear regression between transparency and relative depth is highly significant ($p = 0.002$) and explains nearly 50% ($r^2 = 0.48$) of the variance of transparency. The low relative depths and the exposure of the lakes to constant northeastern winds reduce the transparency. Consequently, the lakes are light limited by suspension of inorganic and organic matter. This means that an accurate trophic state assessment must consider the morphological aspects of the coastal lakes. The relative depth is an indicator for the dynamic and the circulation properties of the water body. The lakes have relative depths less than 1%. The shallowness of the lakes and the constant ocean winds permit permanent holomictic circulations all over the year. They are responsible for oxygenated sediment surfaces and saturation of oxygen in the water column. These conditions facilitate the homogeneous settlement of aerobic organisms all over the bottom area. There is no significant relationship between differences of depth, organic matter content of sediment and the composition of macroinvertebrate communities. The aerobic sediment is a criterion for oligotrophic lakes, while the usual trophic state assessments indicate higher trophic levels (Schäfer et al., 2013).

Because of their shallowness and the form of the lake basin, the coastal lakes have a small water volume, contrasting with the surface area and often overestimated by public and private managers. A

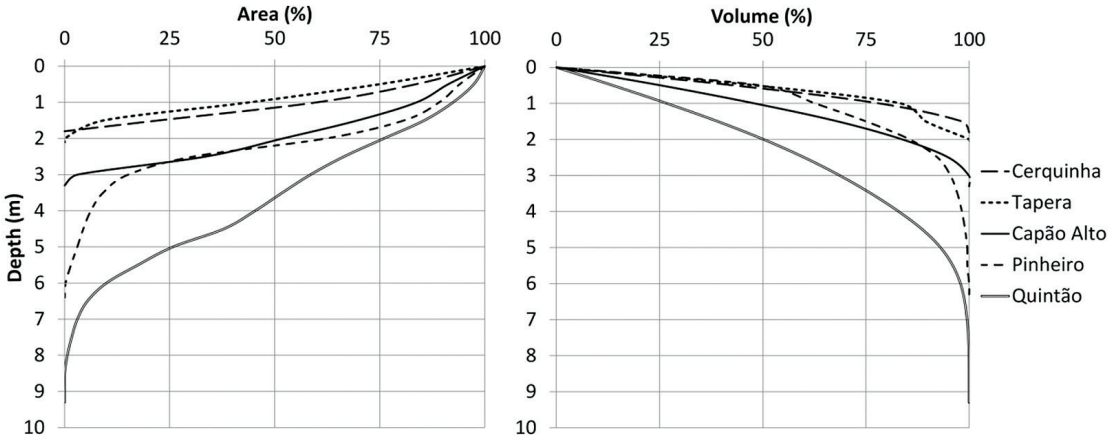

Figure 12. Hypsography of the representatives of the five morphological lake types. The median depths of volume (50%) are situated nearby the surface of the lakes. An exception is the Lagoa do Quintão because of its high maximum depth of 9.3 m.

typical example for that is the Lagoa do Quintão (Figure 6). Among the lakes studied, it shows the most irregular bottom with significant depth variation. This fact explains that it has a lower volume than expected from the surface area and maximum depth. Associated with this irregularity, the high maximum depth differentiates it from the other studied lakes, being a typical feature of the coastal lakes located further south in the middle coast of Rio Grande do Sul (Schäfer et al., 2009b).

The low median depth of volume is a problem regarding the use of water for irrigation and supply (Figure 12). It ranges between 8 and 47% of the maximum depth, with an average of 28.3% ±12.3%. The shallowness and the median depths of volume are a limiting factor for sustainable water supply management. The exaggerated water withdrawal, mainly during summertime, may have negative impacts on fixed riparian vegetation because of the higher wind exposure and desiccation of the upper shore line during low water levels.

5. Conclusion

The specific morphological characteristics of the coastal lakes, mainly its shallowness and the instability of there water bodies, turn an accurate ecological assessment with usual trophic state criterions and a sustainable water resource management based on general guidelines a very difficult approach.

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