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ORIGINAL ARTICLE

Bathymetric and morphometric surveys of the Montebello Lakes, Chiapas

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ABSTRACT

This study presents the first bathymetric surveys and descriptions of the morphometric parameters of the major lakes of the national park and Ramsar Convention site Lagunas de Montebello*, Chiapas, Mexico and represents the first contribution on these limnologically unknown lakes. The morphology of lacustrine basins has an important influence on the physical, chemical and biological dynamics, and limnological research must consider the bathymetry and the related morphometric parameters of the lakes. Of the more than 50 lakes that make up this karst lake system (including dolines, uvalas and poljes), 18 representative lakes were selected along a NW-SE transect. The lakes have widely varying dimensions and include small and deep, small and shallow, large and deep, and large and shallow lakes. The shapes of the lakes vary from circular to elliptical, and the basin resembles an inverted truncated cone. The orientation of the main axis follows the structural orientations of the karst landscape (*i.e.*, faults, fractures and folds). The maximum lengths range from 0.14 to 3.2 km, the surface areas range from 1.1 ha to 306.6 ha, and the lake volumes range from 0.00004 to 0.08852 km^3. Six lakes are among the deepest lakes in Mexico and have an average maximum depth of more than 50 m; the deepest lake has a maximum depth of 198 m. These depths favor prolonged stratification, which increases the probability of accumulating pollutants.*

Key words: Bathymetry; morphometry; karst; solution lakes; tropical lakes; Mexico.

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INTRODUCTION

The morphology of lake basins has important effects on most of the physical, chemical and biological parameters of the lakes. The diverse morphologies of lake basins are a result of their origin and subsequent modifications that are caused by the movement of water within the lake as well as sedimentary inputs from the drainage basin (Wetzel, 2001). The interplay between the physical dimensions of a lake and climatic and edaphic factors determines the environmental conditions of the lake as well as its inhabitants (Cole, 1979). For example, the area of the lake bottom as a function of depth is an important characteristic because a lake that is deep over a large proportion of its area has a delayed biological cycle and is less productive (Margalef, 1983). The morphology of a lake basin greatly regulates the nutrient dynamics, oxygen regime, heat budget and general productivity of the lake (Fee, 1979; Fee *et al*., 1994). Depth dominates over the natural tendency towards eutrophication (Rawson, 1960) and leads to *morphometric oligotrophy* (*sensu* Lundbeck, 1934 in Ryder, 1982). Morphometric parameters must be characterized to identify several limnological processes, such as erosion, nutrient intake rate, mass chemical balance, caloric content, thermal stability, biological productivity and growth effectiveness as well as many structural and functional components of aquatic ecosystems (Wetzel and Likens, 2000).

The *Lagunas de Montebello* National Park is located in the municipalities of La Trinitaria and Independencia in the state of Chiapas and was declared a protected natural area by a presidential decree that was published by the Diario Oficial de la Federación on December 16, 1959. Subsequently, the area was acknowledged as Ramsar Convention site number 1325 on November 27, 2003. In spite of the name of the national park and Ramsar site (*Lagunas de Montebello*), the limnological characteristics of the lakes are essentially unknown. Because the shape of the basin determines many of its limnological characteristics and represents basic information that is required for follow-up studies and because only limited information is available for the Chiapas lakes, the goal of this study was to identify the bathymetric and morphometric parameters that are associated with the main water bodies of the *Lagunas de Montebello* lake complex.

Since this study is strictly exploratory, it does not posit a hypothesis; however, it provides a foundation of information that can be used as the basis of a complete limnological study of the lakes because several changes have occurred to the lakes since 2003, such as a change in the color of the water from crystal clear to yellowish-green and the occurrence of a yellowish-white supernatant, fetid odors from sulfur compounds, and fish mortality.

METHODS

Study area

The study area covers 64.25 km^2 and is located in the physiographic province of Altos de Chiapas, which is also known as the Macizo Central Chiapas. The study area extends from 16°04'40'' N to 16°10'20'' N and from 91°37'40'' W to 91°47'40'' W (Fig. 1). Hydrologically, the basin is endorheic, is part of the RH30Gl sub-basin of the Comitán River, and is superficially fed by the Grande River. This sub-basin is part of the Lacatún River Basin, which is within hydrological region 30, Grijalva-Usumacinta. Data from the meteorological station in Tziscao (16.1°N, 91.63°W; 1475 m asl) indicate that the mean annual temperature is 17.3°C, the mean annual precipitation is 2,279 mm, and the mean annual evaporation is 948 mm. According to García (1988), the climate of the region is Cb(m)(f)ig, which represents a long cool summer that is humid and has a typical summer precipitation regime. More than 10.2% of the annual precipitation falls during the winter. The climate is isothermal (less than 5°C) of a Ganges type. Lithologically, the entire area of interest is covered by a Lower Cretaceous limestone that is associated with the formation of a lake complex of karst origin; it includes solution lakes (Hutchinson, 1957) with dolines, uvalas and poljes. More than 50 lakes are present in the area. According to the classification of Hutchinson (1957), the dolines (type 43a) are funnel-shaped depressions with varied morphologies from round to elliptical, while some lakes have irregular shapes. The uvalas (type 43b) primarily have elliptical shapes; however, the more developed uvalas may be irregular because they are formed by the coalescence of two or more dolines. The poljes, which are tectono-karstic lakes (type 44) that form mainly by solution in tectonic basins, are elongated and irregular depressions with flat bottoms and steep walls. The dolines, uvalas and poljes are aligned in a NW-SE orientation that coincides with the orientation of the main tectonic units (Durán Calderón, 2013).

Of the >50 lakes that make the *Lagunas de Montebello* karst lake complex, 18 were selected for this study; they cover the entire length of the NW-SE-oriented lake complex. This karst system extends beyond the Mexican border into Guatemala. The following 18 lakes (in alphabetical order) were studied: Agua Tinta (Aguatinta), Balantetic, Bosque Azul, Chajchaj, Cinco Lagos, Dos Lagos (Dos Lagunas), Ensueño, Esmeralda, Kichail, La Encantada, Liq-

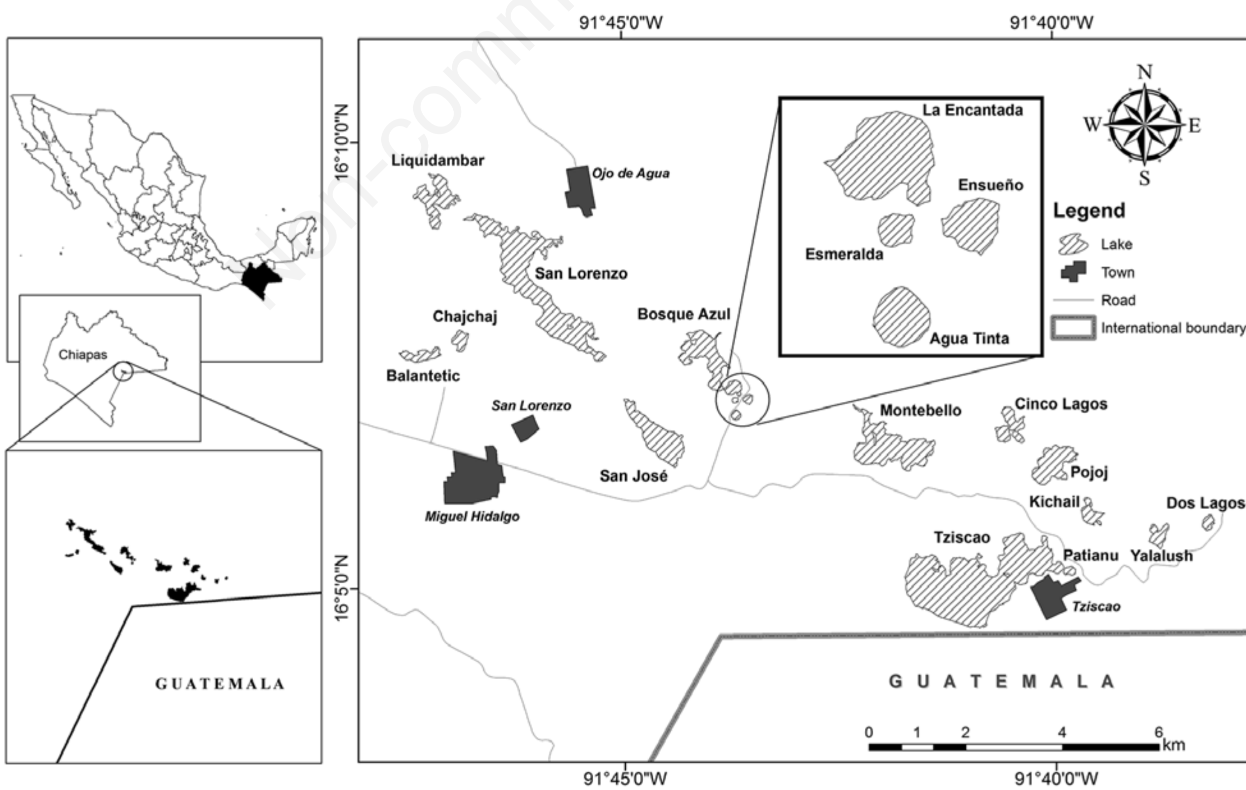

Fig. 1. The *Lagunas de Montebello* Lake District, Chiapas, Mexico. The lakes in this study are marked.

uidambar, Montebello, Patianu (Patianú), Pojoj, San José, San Lorenzo, Tziscao and Yalalush (Fig. 1).

Bathymetric survey of the Montebello lakes

The sampling platform that was used to determine the bathymetry of the lakes was a 10-foot-long (approximately 3 m) aluminum boat with a flat bottom that has a 36-inch (approximately 0.9 m) beam and a 15-cm water line. A 30 lb thrust Minn Kota (Fargo, North Dakota) electric transom trolling motor was used to propel the boat.

Equidistant transects were conducted on perpendicular grids that covered the entire surface of each lake. The number of transects varied based on the length and width of the lake. Transects were parallel to the maximum length and maximum width of the lakes. The bottom position (latitude, longitude and depth) was recorded using a Garmin (Lenexa, Kansas) echo-sounder model GPSMap 526S, which was equipped with an external remote antennae to improve satellite signal reception. The geo-positioning has an accuracy of 1-5 m depending on the number of available satellites (up to 12 available parallel channels) at the time of recording.

The depth sounder has a precision of 95%, a recording speed of 0.5 m s^{-1}, a frequency of 200 KHz, a cover angle of 8° and a transmission power of 150 watts (RMS) and 1200 watts (peak to peak). The coastlines were delineated by collecting GPS data (latitude, longitude and elevation) from the boat as it passed around the perimeters of the lakes. This GPS (Garmin GPS model eTrex Vista) has a precision of <10 m (95%) with an acquisition speed of 0.1 m s^{-1}. Elevations were obtained by averaging all of the recorded points.

The data that were collected in the field by the Garmin GPSMap 526S echo-sounder and the Garmin GPS eTrex Vista were downloaded with the MapSource software version 8.0, which allows the bottom profiles and the outlines of the lakes to be determined. These data (latitude, longitude and depth) were subsequently exported to a worksheet. The bathymetric charts of the lakes were developed based on the echo-sounder records and outline data. Polygons of the coastlines (perimeters) were delineated based on the outline data using the software ArcGis 10.0 (ESRI Inc., Redlands, CA, USA), and the isobaths of the lakes were obtained using the software Surfer 11.0.642 (Golden Software Inc., Golden, CO, USA). This software was also used to create the XYZ files, which include contour and depth data. The data were interpolated by the kriging geostatistical method, and maps of the lake outlines were obtained with the same software.

Morphometry of the Montebello lakes

Tab. 1 shows selected morphometric parameters using the nomenclature of Wetzel and Likens (2000). The morphometric parameters were calculated using the software ArcGis 10.0 (ESRI Inc.) and Surfer 11.0.642 (Golden Software, Inc.) and the criteria proposed by Wetzel and Likens (2000) except for the index of basin permanence (IBP), which followed the criteria of Kerekes (1977).

A hierarchical cluster analysis (HCA) was performed using the Ward method with the square of the Euclidian distances to classify the Montebello lakes based on their morphology (form and dimensions) using all of the morphometric parameters. In addition, a principal component analysis (PCA) was used to identify the most important parameters for the ordination (García de León Loza, 1988). For the multivariate analyses (HCA and PCA), the morphometric data were Z-transformed to avoid high values that would bias the results and maintain the values within an acceptable scale for comparison (Spatz, 2011). The multivariate analysis and data standardization were performed with the software SPSS v21 (IBM, Armonk, NY, USA).

RESULTS

Tab. 2 shows the precise coordinates of the limits of the Montebello lakes and Tab. 3 shows the corresponding morphometric parameters. The bathymetric charts of the lakes are provided as supplementary files (Supplementary Figures 1-18).

Based on the orientation of their major axis (L_{max}), most of the lakes have NE-SW (38.9%) or NW-SE (33.3%) orientations, and lower percentages are oriented W-E (16.7%) and N-S (11.1%). As shown below, the orientations clearly reflect the structural alignment of the relief. The Montebello lakes have a wide variety of dimensions. The maximum lengths (L_{max}) of the lakes vary between 0.14 km and 3.2 km (mean value ($\bar{x}$)=0.99 km). The maximum widths (b_{max}) fluctuate between 0.11 km and 1.48 km ($\bar{x}$=0.55 km), and the mean widths (b_{mean})

Tab. 1. List of measured morphometric parameters, including the symbols and methods of the morphometric characterization, for the Montebello lakes, Chiapas.

Parameter	Symbol	Reference
Maximum length	L_{max}	ArcGis 10.0
Maximum width	b_{max}	ArcGis 10.0
Mean width	b_{mean}	Wetzel and Likens (2000)
Surface area	A	ArcGis 10.0
Volume	V	Wetzel and Likens (2000)
Shoreline length	S_L	ArcGis 10.0
Maximum depth	Z_{max}	Wetzel and Likens (2000)
Mean depth	Z_{mean}	Wetzel and Likens (2000)
Relative depth	Z_r	Wetzel and Likens (2000)
Shoreline development	D_L	Wetzel and Likens (2000)
Volume development	D_V	Wetzel and Likens (2000)
Index of basin permanence	IBP	Kerekes (1977)

vary between 0.08 km and 0.96 km ($\bar{x}$=0.31 km). The perimeters or coastlines (S_L) have a mean of 15 km and vary in length from less than a kilometer (0.42 km) to more than 15 km for Esmeralda and San Lorenzo, respectively. The maximum surface area is approximately 306.6 ha at Tziscao, and the lowest is 1.1 ha at Esmeralda. The

Tab. 2. Location (extreme coordinates in decimal degrees and elevations in m asl) of the Montebello lakes in this study. (The lakes are ordered from west to east).

Name	Lat (°N)		Long (°W)		Alt. (m asl)
Balantetic	16.1255	16.1284	91.7932	91.7852	1,466
Liquidambar	16.1505	16.1609	91.7812	91.7903	1,461
Chajchaj	16.1275	16.1315	91.7798	91.7830	1426
San Lorenzo	16.1256	16.1533	91.7531	91.7807	1,455
San José	16.1057	16.1185	91.7384	91.7499	1,454
Bosque Azul	16.1199	16.1313	91.7290	91.7392	1,458
Esmeralda	16.1176	16.1186	91.7277	91.7289	1461
Agua Tinta	16.1144	16.1163	91.7272	91.7291	1,465
La Encantada	16.1189	16.1218	91.7270	91.7307	1,454
Ensueño	16.1173	16.1191	91.7249	91.7268	1,430
Montebello	16.1048	16.1172	91.6897	91.7055	1490
Cinco Lagos	16.1099	16.1165	91.6724	91.6781	1,486
Tziscao	16.0753	16.093	91.6649	91.6957	1,490
Patianú	16.0851	16.0867	91.6627	91.6651	1,484
Pojoj	16.1020	16.1095	91.6621	91.6710	1,499
Kichail	16.0943	16.0995	91.6570	91.6615	1,475
Yalalush	16.0898	16.0946	91.6447	91.6484	1,452
Dos Lagos	16.0932	16.0961	91.6358	91.6382	1,427

Tab. 3. The main morphometric parameters of the Montebello lakes, Chiapas.

Lake	Orientation	L_{max} (km)	b_{max} (km)	b_{mean} (km)	A (ha)	S_L (km)	V (km^3)	Z_{max} (m)	Z_{mean} (m)	Z_r (%)	D_L	D_V	IBP
Agua Tinta	N-S	0.21	0.20	0.14	3.0	0.65	0.00044	24	14.7	13.7	1.07	1.81	0.670
Balantetic	W-E	0.81	0.23	0.17	13.6	2.33	0.00023	3	1.7	0.7	1.79	1.65	0.099
Bosque Azul	NW-SE	1.32	0.82	0.40	52.5	5.81	0.01050	58	20.0	7.1	2.26	1.04	1.808
Chajchaj	N-S	0.45	0.31	0.21	9.2	1.33	0.00048	12	5.3	3.5	1.23	1.30	0.365
Cinco Lagos	NW-SE	0.82	0.60	0.29	23.7	3.78	0.01006	162	42.5	29.5	2.19	0.79	2.660
Dos Lagos	NE-SW	0.34	0.23	0.16	5.2	0.99	0.00132	42	25.2	16.4	1.22	1.78	1.341
Ensueño	NE-SW	0.22	0.19	0.12	2.7	0.66	0.00058	35	21.6	19.0	1.13	1.84	0.884
Esmeralda	NE-SW	0.14	0.11	0.08	1.1	0.42	0.00004	7	3.6	5.8	1.11	1.57	0.097
Kichail	NW-SE	0.58	0.44	0.21	12.5	2.38	0.00119	22	9.5	5.5	1.90	1.29	0.499
La Encantada	W-E	0.39	0.31	0.21	8.2	1.28	0.00241	89	29.4	27.5	1.26	0.99	1.880
Liquidambar	NW-SE	0.95	0.70	0.43	40.5	5.68	0.00453	24	11.2	3.3	2.52	1.42	0.797
Montebello	NE-SW	1.69	1.14	0.57	96.2	7.84	0.01186	45	12.3	4.0	2.26	0.83	1.513
Patianu	W-E	0.26	0.18	0.13	3.4	0.73	0.00037	26	10.8	12.5	1.12	1.25	0.504
Pojoj	NE-SW	1.06	0.74	0.41	43.7	3.61	0.01538	198	35.2	41.6	1.54	0.53	4.258
San José	NW-SE	1.76	0.66	0.34	60.6	4.54	0.00623	30	10.3	7.3	1.64	1.03	1.372
San Lorenzo	NW-SE	3.09	1.29	0.59	181.3	15.01	0.02147	67	11.8	4.4	3.14	0.53	0.001
Tziscao	NE-SW	3.20	1.48	0.96	306.6	13.22	0.08852	86	28.9	11.7	2.13	1.00	6.695
Yalalush	NE-SW	0.54	0.33	0.21	11.5	1.87	0.00114	23	9.9	19.6	1.56	1.29	0.607
X		0.99	0.55	0.31	48.6	4.01	0.00982	53	16.9	12.9	1.73	1.22	1.447
Max		3.20	1.48	0.96	306.6	15.01	0.08852	198	42.5	41.6	3.14	1.84	6.695
Min		0.14	0.11	0.08	1.1	0.42	0.00004	3	1.7	0.7	1.07	0.53	0.001

L_{max}, maximum length; b_{max}, maximum width; b_{mean}, mean width; A, surface area; V, volume; S_L, shoreline length; Z_{max}, maximum depth; Z_{mean}, mean depth; Z_r, relative depth; D_L, shoreline development; D_V, volume development; IPB, index of basin permanence.

mean surface area is 48.6 ha. Esmeralda has the lowest water volume (0.040 hm^3), whereas Tziscao has the maximum volume of 88.521 hm^3 ($\bar{x}$=9.819 hm^3). The maximum depth (Z_{max}) recorded in the Montebello lakes is 198 m at Pojoj followed by 161.8 m at Cinco Lagos. In contrast, several lakes are shallow, such as Balantetic (3 m) and Esmeralda (7 m); the average depth is 53 m. The average of the mean depths (Z_{mean}) is 16.9 m, and the minimum mean depths are also at Balantetic (1.7 m) and Esmeralda (3.6 m), whereas Cinco Lagos has the maximum mean depth (42.5 m).

Figs. 2 and 3 show the distribution (from largest to smallest) of the lakes based on their morphometric parameters. The white bars indicate lakes with magnitudes that are greater than the global mean, and the black bars indicate lakes with magnitudes that are less than the global mean. The distribution is log-normal; approximately one third of the lakes (6-8) have distributions that are greater than the mean, whereas two thirds of the lakes (10-13) are less than the mean. The only morphometric parameter that does not conform to this trend is the volume development (D_V), for which 11 of the lakes are greater than the mean; thus, the lakes have conical shapes, which is typical of karst lakes. In the HCA dendrogram, which was constructed with the morphometric parameters, three groups are observed with a cut at half the similarity distance. The first group (A) contains the largest number of lakes, which are clustered into three groups with Agua Tinta isolated. The second group (B) contains three lakes, which is the smallest number of lakes, and the third group (C) contains

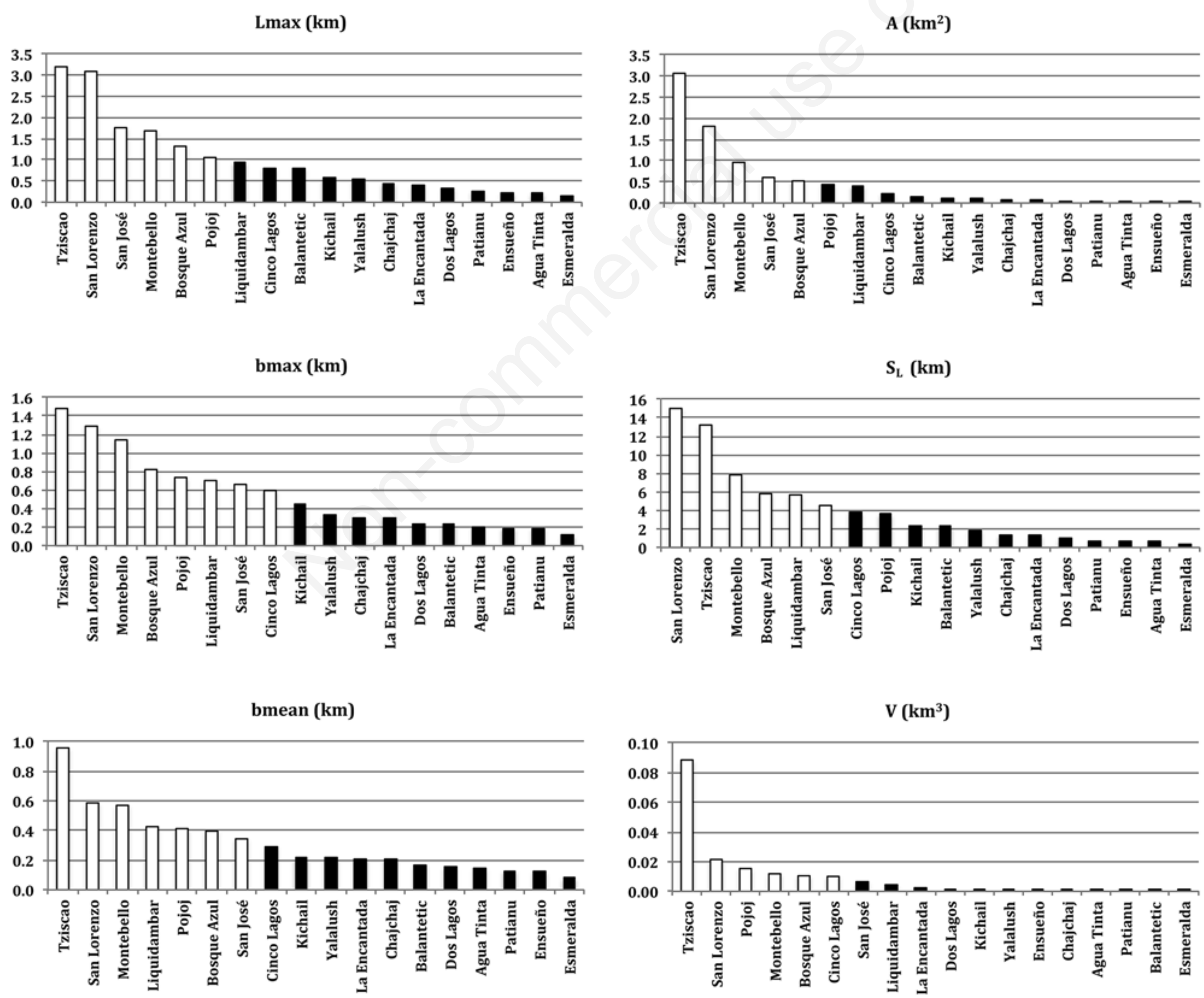

Fig. 2. Graphical representation of the dimensions of the sampled Montebello lakes from greatest to smallest based on their morphometric measurements. White bars, values greater than the mean; black bars, values less than the mean; L_{max}, maximum length; b_{max}, maximum width; b_{mean}, mean width; A, surface area; V, volume; S_L, coastline or perimeter.

five lakes, of which Tziscao is the least similar to the others (Fig. 4). In the PCA, the first two principal components (PC) explain almost 70% of the total variance (68.9%); the first PC explains 47.8%. For PC 1, b_{max} and b_{mean} were the most heavily loaded variables (0.156 and 0.154, respectively). The widest lakes are in the positive part of the first PC. However, the relative depth (Z_r, 0.355) and the mean depth (Z_{mean}, 0.353) had the greatest influence on PC2. The highest values of these variables are in the positive part of the component. The same three groups as in the HCA are identified in the PCA. Group A includes lakes with the lowest values of b_{max}, b_{mean}, Z_{mean} and Z_r. Group B includes lakes with the largest values of Z_{mean} and Z_r, and group C contains lakes with the largest values of b_{max} and b_{mean} (Fig. 5).

DISCUSSION

The Montebello lakes include several types of solution lakes or karst structures, including dolines (Type 43a from the classification of Hutchinson, 1957), uvalas (Type 43b) and poljes (Type 54), which have an increasing degree of dissolution and structural complexity. The directions of the major axes of the lakes are consistent with the structural alignments of the relief (faults, fractures and folds), which indicates a close relationship with the main tectonic alignments and fracture network (Durán Calderón, 2013). Based on the bathymetry, the Montebello lakes can be classified into the three categories of karst lakes (Tab. 4). In addition, the lakes can be classified into two groups based on their main dimensions [L_{max}, b_{max}, b_{mean}, A (sur-

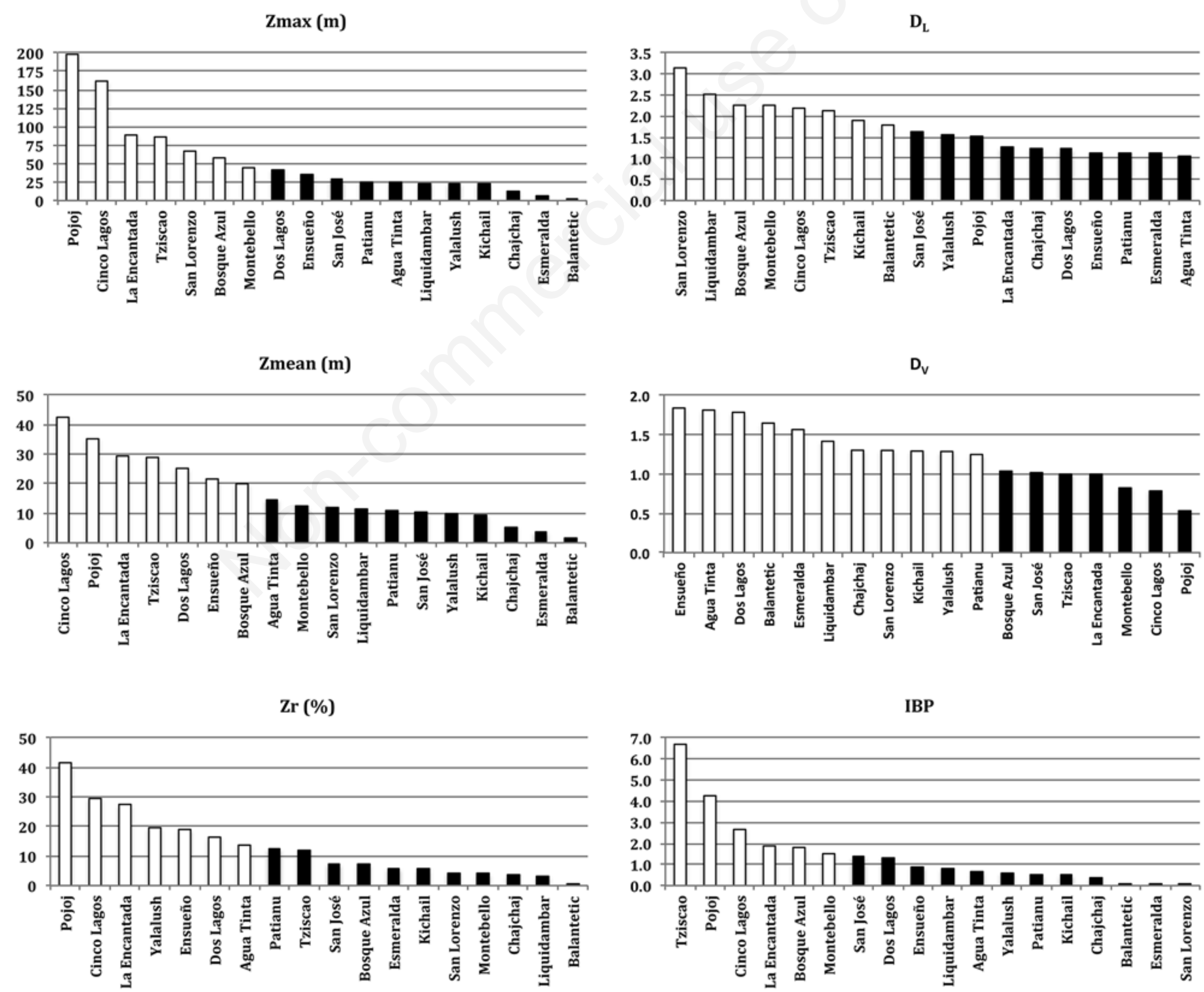

Fig. 3. Graphical representation of the sampled Montebello lakes from greatest to smallest based on their morphometric measurements. White bars, values greater than the mean; black bars, values less than the mean; Z_{max}, maximum depth; Z_{mean}, mean depth; Z_r, relative depth; D_L, development of the coastline; D_V, development of volume; IBP, index of basin permanence.

face area), S_L (shoreline length), and V (volume)]: a) *large* lakes, where all or most (at least four out of six) measurements are greater than the mean, and b) *small* lakes, where all or most of the dimensions (at least three) are less than the mean. The large lakes are Bosque Azul, Montebello, Pojoj, San José, San Lorenzo and Tziscao, and the small lakes are Agua Tinta, Balantetic, Chajchaj, Cinco Lagos, Dos Lagos, Ensueño, Esmeralda, Kichail, La Encantada, Liquidambar, Patianu and Yalalush. The lakes are also divided into two groups based on their depths (Z_{max}, Z_{mean} and Z_r): a) *deep* lakes, in which the values of at least two of the three parameters are greater than the mean, and b) *shallow* lakes, with parameter values that are less than the mean. The deep lakes are Bosque Azul, Cinco Lagos, Dos Lagos, Ensueño, La Encantada, Pojoj and Tziscao, and the shallow lakes are Agua Tinta, Balantetic, Chajchaj, Esmeralda, Kichail, Liquidambar, Montebello, Patianu, San José, San Lorenzo and Yalalush. In summary, the Montebello lakes are classified into four categories based on their dimensions and depth (Tab. 5). This simple classification, which only considers a few morphometric variables, is consistent with the multivariate analyses (HCA and PCA), where the lakes were classified in three groups according to their dimensions (represented mainly by b_{max} and b_{mean}) and depths (represented mainly by Z_r and Z_{mean}). However, each type of lake (dolines, uvalas and poljes) has a wide range of values, so it appears that the mode of origin has little influence on the morphometry (*i.e.*, the HCA and PCA groups do not appear to be related to the mode of origin). The geomorphological study of Durán Calderón (2013) provides information that may explain this lack of concordance. While one group of lakes is closely related to the main fracture network in the area, the other is more closely related to the solution and collapse of ancient caverns. Furthermore, it appears that most

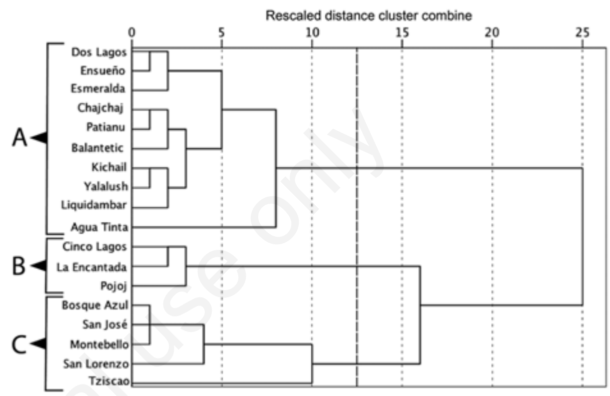

Fig. 4. Classification (Hierarchical Cluster Analysis, Ward method) of the Montebello lakes, Chiapas, based on their morphometric parameters.

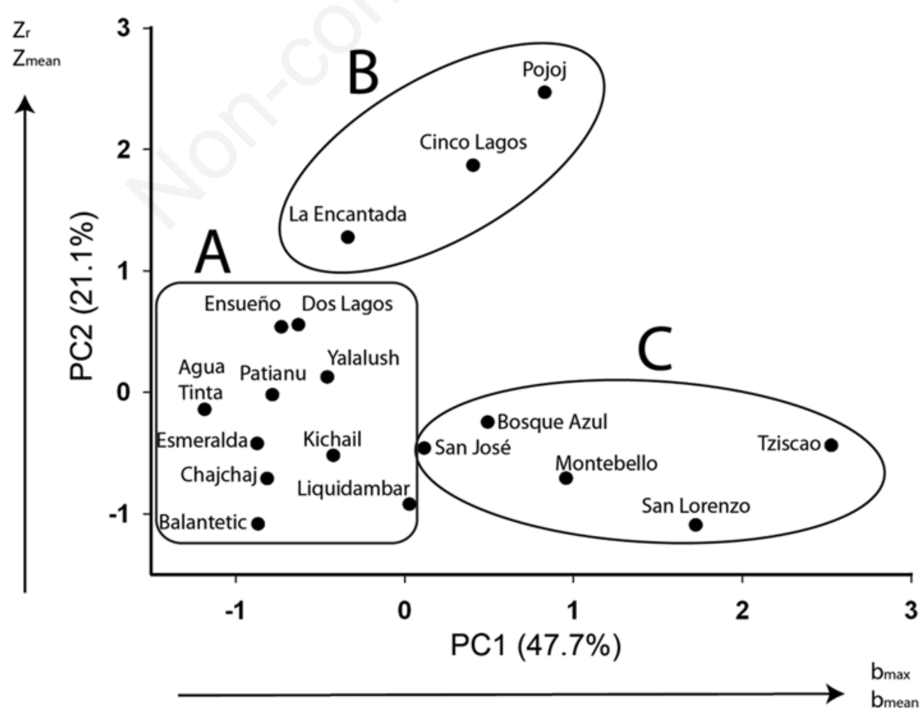

Fig. 5. Ordination (Principal Components Analysis) of the Montebello lakes, Chiapas based on their morphometric parameters.

of the dolines developed on Cretaceous strata, the uvalas formed on Cretaceous and Quaternary strata, and the poljes formed on Quaternary strata.

As previously described, some of the Montebello lakes are deep. Five of the 18 Montebello lakes in this study are the second to sixth deepest (Z_{max}) in Mexico. The deepest lake in Mexico is called *El Zacatón*; it formed from a hydrothermal karst, is 339 m deep and is located in the municipality of Aldama, NE of Tamaulipas (Gary *et al*., 2008). The next deepest lakes are Pojoj (198 m), Cinco Lagos (162 m), La Encantada (89 m), Tziscao (86 m) and San Lorenzo (67 m). The next two deepest lakes are crater lakes or maars: Santa María del Oro in Nayarit (65.5 m; Serrano *et al*., 2002) and Alchichica in Puebla (62 m; Filonov *et al*., 2006).

In general, Z_{max} is positively correlated to Z_{mean} (the larger the value of Z_{max}, the larger the value of Z_{mean}) (Fig. 6). Pojoj had the largest Z_{max} (198 m), but Z_{mean} was only 35 m, which differs from the general trend (dotted line in Fig. 6). However, Pojoj had the second highest value of Z_{mean}. The average Z_{max} of all of the Montebello lakes was equal to only 27% of the largest Z_{max}. A similar relationship for Z_{mean} shows that the mean value of Z_{med} is 40% of the maximum Z_{med}. In most lakes around the world, Z_r <2%; Z_r >4% indicates a deep lake with a small surface area, which reflects resistance to mixing (Hutchinson, 1957; Wetzel and Likens, 2000). The Montebello lakes have a mean Z_r of 12.9% and show a marked trend towards stratification. The highest values of Z_r above the mean are at Agua Tinta, Cinco Lagos, Dos Lagos, Ensueño, La Encantada, Pojoj and Yalalush, and Balantetic has the lowest value (0.7%). The D_L values indicate that most of the Montebello lakes are nearly circular (≈1), including Agua Tinta (D_L=1.07), or subcircular to elliptical (≈2), although some lakes are more irregular, such as San Lorenzo (D_L=3.14). The mean D_L value of the lakes is 1.73. Irregular coastlines (high values of D_L) favor the growth of littoral macrophytes and general productivity of the lake (Hutchinson, 1957). This parameter indicates the potential habitat that is available for wildlife in the lake. The highest values above the mean D_L are at Balantetic, Bosque Azul, Cinco Lagos, Kichail, Liquidambar, Montebello, San Lorenzo and Tziscao.

According to Hutchinson (1957), most of the lakes have a development of volume (D_V) >1, which indicates a conical depression. Lakes that are located on rocks that are easily eroded have D_V values between 1 and 1.5. These conditions occur in the Montebello lakes because they are karst type lakes, and only five (Cinco Lagos, La Encantada, Montebello, Pojoj and San Lorenzo) of the 18 lakes

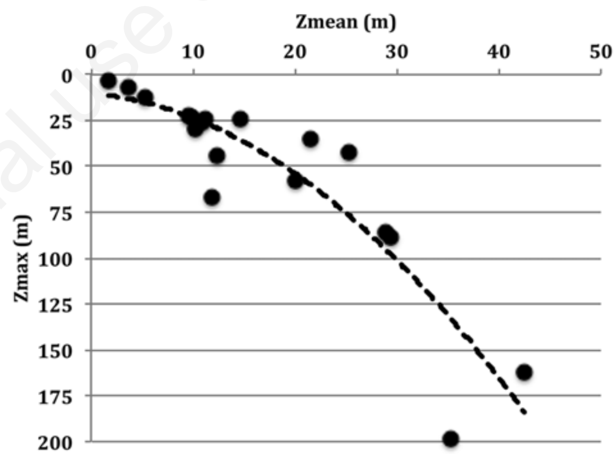

Fig. 6. Relationship between Z_{max} and Z_{mean} for the Montebello lakes (the dotted line indicates the general trend).

Tab. 4. Classification of the type of origin (Hutchinson 1957) of the Montebello lakes based on the morphometric parameters.

Category	Lakes
Doline	Agua Tinta, Dos Lagos, Ensueño, Esmeralda and Patianu
Uvala	Chajchaj, Balantetic, Cinco Lagos, Bosque Azul, La Encantada, Liquidambar, Kichail, Montebello, Pojoj, Yalalush and San José
Polje	San Lorenzo and Tziscao

Tab. 5. Categorization of the Montebello lakes based on their dimensions and depths.

Category	Lakes
Large and deep	Bosque Azul, Pojoj, Tziscao
Large and shallow	Montebello, San José, San Lorenzo
Small and deep	Cinco Lagos, Dos Lagos, Ensueño, La Encantada
Small and shallow	Agua Tinta, Balantetic, Chajchaj, Esmeralda, Kichail, Liquidambar, Patianu, Yalalush

have D_V <1, although La Encantada (0.99), Bosque Azul (1.04), San José (1.03) and Tziscao (1.0) are close to D_V=1. Pojoj has the lowest D_V (0.53), which clearly identifies it as having a small deep area. IBP values below 0.1 reflect senescent lakes that are dominated by rooted aquatic vegetation (Kerekes, 1977). The most extreme case is San Lorenzo, which has an IBP of 0.001, although Balantetic (0.099) and Esmeralda (0.097) are similar. At values of 0.2, lakes show an improved permanence, but large and deep lakes have much higher IBP values (*e.g.*, Lake Erie at 450 or Lake Superior at 4,000). The Montebello lakes have a mean IBP of 1.5 and show permanence, and Tziscao has the maximum IBP of 6.7. The lakes with the greatest permanence and values above the mean are Bosque Azul, Cinco Lagos, La Encantada, Montebello, Pojoj and Tziscao.

CONCLUSIONS

- The Montebello lakes formed by the dissolution of the material on which they are located, and they include dolines, uvalas and poljes. The orientation of the main axes of the lakes is consistent with the structural alignment of the karst relief (faults, fractures, and folds).
- The lakes have widely varying morphometric dimensions, including large and deep, large and shallow, small and deep, and small and shallow lakes.
- The maximum and mean widths and the relative and mean depths are the morphometric parameters that best distinguish the lakes. Based on these parameters, the 18 lakes that were surveyed were separated into three groups: a) lowest width and depth (Agua Tinta, Esmeralda, Chajchaj, Balantetic, Patianu, Ensueño, Dos Lagos, Yalalush, Kichail and Liquidambar), b) deepest (La Encantada, Cinco Lagos, Pojoj), and c) widest (San José, Bosque Azul, Montebello, San Lorenzo and Tziscao).
- The maximum lengths vary from 0.14 to 3.20 km, the surface areas vary from 1.1 to 306.6 ha, and the volumes vary from 0.040 to 88.521 hm^3.
- Six of the 18 Montebello lakes are among the deepest in Mexico; they are the second to sixth deepest behind *El Zacatón*, which is located in Tamaulipas and is of hydrothermal karst origin.
- Most of the Montebello lakes have high Z_r values, which reflect a marked tendency towards stratification.
- The D_L values indicate that most of the Montebello lakes have circular to sub-circular and elliptical shapes, and the D_V values indicate that the basin has a conical shape; both characteristics are expected based on the origin of the lakes.
- The IBP values indicate that most of the Montebello lakes have high permanence; therefore, they are not considered senescent lakes.

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REFERENCES

Cole GA, 1979. Textbook of limnology. Mosby, St. Louis: 426 pp.

Durán Calderón JL, 2013. [Análisis geomorfológico del Parque Nacional Lagunas de Montebello, Chiapas].[Thesis in Spanish]. UNAM, México: 89 pp.

Fee EJ, 1979. A relation between lake morphometry and primary productivity and its use in interpreting whole-lake eutrophication experiments. Limnol. Oceanogr. 24:401-416.

Fee EJ, Hecky RE, Regehr GW, Hendzel LL, Wilkinson P, 1994. Effects of lake size on nutrient availability in the mixed - layer during summer stratification. Can. J. Fish. Aquat. Sci. 51:2756-2768.

Filonov A, Tereshchenko I, Alcocer J, 2006. Dynamic response to mountain breeze circulation in Alchichica, a crater lake in Mexico. Geophys. Res. Lett. 33:L07404.

García E, 1988. [Modificaciones al sistema de clasificación climática de Köppen].[Book in Spanish]. Instituto de Geografía, UNAM: 217 pp.

García de León Loza A, 1988. [Generalidades de análisis de cúmulos y de análisis de componentes principals].[Article in Spanish]. Divulgación Geográfica 8:7-29.

Gary M, Fairfield N, Stone WC, Wettergreen D, Kantor GA, Sharp Jr. JM, 2008. 3D mapping and characterization of Sistema Zacatón from DEPTHX (DEep Phreatic THermal eXplorer), p. 202-212. Proc. 11th Multidisciplinary Conf. on Sinkholes and the engineering and environmental impacts of karst, Tallahassee, FL, USA.

Hutchinson GE, 1957. A treatise on limnology. 1. J. Wiley & Sons, New York: 1015 pp.

Kerekes J, 1977. The index of lake basin permanence. Int. Rev. Ges. Hydrobiol. Hydrogr. 62:291-293.

Margalef R, 1983. [Limnología].[Book in Spanish]. Omega, Barcelona: 1010 pp.

Rawson DS, 1960. A limnological comparison of twelve large lakes in northern Saskatchewan. Limnol. Oceanogr. 5:195-211.

Ryder RA, 1982. The morphoedaphic index - use, abuse, and fundamental concepts. Trans. Am. Fish. Soc. 111:154-164.

Serrano D, Filonov A, Tereshchenko I, 2002. Dynamic response to valley breeze circulation in Santa María del Oro, a volcanic lake in Mexico. Geophys. Res. Lett. DOI:10.1029/2001GL014142.

Spatz C, 2011. Basic statistics: tales of distributions. Wadsworth Cengage Learning, Belmont: 512 pp.

Wetzel RG, Likens GE, 2000. Limnological analyses. Springer, New York: 429 pp.

Wetzel RG, 2001. Limnology: lake and river ecosystems. Academic Press, San Diego: 1006 pp.