Morphometric study of Lake Dom Helvécio, Parque Estadual do Rio Doce (PERD), Minas Gerais, Brazil: a re-evaluation

Estudo morfométrico do Lago Dom Helvécio, Parque Estadual do Rio Doce (PERD), Minas Gerais, Brasil: uma reavaliação

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Abstract: Lake Dom Helvécio is located within the limits of the State Park of Rio Doce, in the eastern part of the state of Minas Gerais. This park, one of the largest natural reserves of the Atlantic Rain Forest in Brazil, is a hotspot of tropical biodiversity, and, Lake Dom Helvécio is one of the largest and deepest natural freshwater lakes in Brazil. The objective of this investigation was to update existing information on the bathymetry and morphometric features of the lake, using differential GPS (DGPS) technology for data collection, coupled to a digital echosounder. The bathymetry was based on the acquisition of 54,084 points, where the depth as well as the geographic coordinates were obtained. The total volume calculated for the lake was 59.6×10^6 m^3, with a surface area of 5.27 km^2. The new study allowed refinement of existing morphometric data. The most striking feature of this investigation was the correction proposed for the lake's maximum depth of 39.2 m, in contrast to the maximum depth of 32.5 m according to a previous study.

Keywords: Lake Dom Helvécio, morphometry, bathymetric mapping, lake area, lake volume.

Resumo: O lago Dom Helvécio está localizado nos limites do Parque Estadual do Rio Doce (PERD), na região leste do estado de Minas Gerais. Este parque, uma das maiores reservas naturais da Mata Atlântica no Brasil, é um hotspot da biodiversidade tropical e o lago Dom Helvécio é um dos maiores e mais profundos lagos naturais de água doce do Brasil. Este trabalho tem por objetivo elaborar um novo mapeamento batimétrico e descrever as características morfométricas deste ambiente utilizando a tecnologia do GPS diferencial (DGPS) para coleta dos dados de localização geográfica em conjunto com uma ecossonda digital, equipamento para coleta das informações de profundidade. O levantamento batimétrico do Lago Dom Helvécio foi baseado num total de 54.084 pontos com profundidade e localização conhecidas, obtidas com precisão submétrica. O volume total do lago foi estimado em $59,6 \times 10^6$ m^3 e a área superficial de 5,27 km^2. O novo estudo permitiu o refinamento dos dados morfométricos existentes até então. A característica mais evidente desta investigação é a correção proposta para a profundidade máxima do lago que passa a ser 39,2 m em contraste com o valor de 32,5 m para este parâmetro obtido anteriormente.

Palavras-chave: Lago Dom Helvécio, morfometria, mapeamento batimétrico, área do lago, volume do lago.

1. Introduction

Morphometry is associated with practically all physical, chemical and biological properties of lakes and reservoirs (Wetzel, 2001). Morphometric features define the heat content, the water retention time and the circulation patterns of lakes (Håkanson, 2005). These properties, in turn, are fundamental to understand the functioning of aquatic ecosystems. The volume and water retention time, for example, are essential for estimating the carrying capacity for fish production, or even to detect the fate of nutrient and contaminants in a lake (Sampaio et al., 2007). Fee (1979) demonstrated that the mean depth is a critical factor controlling the magnitude of primary production in most lakes. Several authors have proposed that lake area is a determinant parameter to define the depth of the thermocline (e.g., Patalas, 1984; Hanna, 1990; Fee et al., 1996). The shape of a given lake or reservoir regulates the sedimentation and oxygen dynamics in the hypolimnion (Johansson et al., 2007). Thus, the availability of a bathymetric inventory is a key step in the establishment of a sustainable management plan for most aquatic systems.

In the last decade, the technological capacity for bathymetric mapping has vastly improved. Innovations include the use of differential global positioning systems (DGPS) in combination with echosounders to effect accurate mapping, and the exportation of the data to geographical information systems (GIS). However, these new tools have so far not been applied in most freshwater systems of Brazil. This can be partially explained not only by the high cost of the equipment, but also by the lack of trained personnel. The equipment and software needed for bathymetric studies

require intensive training of a working team of researchers. In addition, this new technology must be applied in a scientific context.

In Brazil, several lakes have been intensively studied over the past decades. Good examples are the lakes situated in the Middle Rio Doce Lake District in the state of Minas Gerais, and in particular Lake Dom Helvécio. The present study had the main objective to redevelop the bathymetric map of Lake Dom Helvécio using the differential GPS (DGPS) technology for collection of data on geographical location, together with state-of-the-art equipment for collecting depth data. Additionally, this contribution re-evaluated the basic morphometric features and discussed the differences between the new estimates and existing information.

2. Material and Methods

2.1. Study area

Lake Dom Helvécio is located in the eastern portion of the state of Minas Gerais, within the limits of the State Park of Rio Doce. The park has an area of 36,000 ha, and preserves the largest remaining fragment of the Atlantic Forest in the state (Latini and Petreri, 2004). This lake (geographical coordinates of the central station 19° 46' S and 42° 35' W) is the largest and deepest lake of the Middle Rio Doce Lake District, and one of the deepest natural lakes in Brazil (Tundisi and Saijo, 1997). According to Matsumura-Tundisi and Tundisi (1995), it can be classified as oligotrophic and warm monomictic, with one circulation period usually occurring between May and August.

Lake Dom Helvécio is not only one of the most-studied freshwater ecosystems of Brazil, but is also one of the lakes selected by several Brazilian limnologists to initiate large-scale limnological projects. A list of articles and research reports about limnological studies in Lake D. Helvécio and other lakes in the region was given by Pinto-Coelho (2006). These studies intensified after 1976, the date of creation of the first postgraduate courses in Ecology and Limnology in Brazil. Several dissertations and Ph.D. theses were based on data from this lake (e.g., Okano, 1980; Barros, 2003; Missagia, 2006). Dozens of scientific articles, research reports and popular brochures have been published, with this lake as the major study area. One of the most important contributions to the limnology of Lake Dom Helvécio was the Brazil-Japan Limnological Project. This project selected the Rio Doce lakes as the main study area. A synthesis of this international project was the book edited by Prof. Tundisi and Prof. Saijo, published several years ago (Tundisi and Saijo, 1997). This publication contains several articles dealing with physical, chemical and biological aspects of Lake Dom Helvécio, among other lakes.

The first bathymetric study of Lake D. Helvécio was published only in 1986 (Tundisi and Musarra, 1986). In this article, the reader can find a bathymetric chart as well as a table with the basic morphometric parameters of this lake. The study was quite innovative for that time, since it used an echo-sounder to obtain the depth data. Three other lakes were also investigated by these authors: Carioca, Barra and Jacaré, all of them belonging to the lake system of the Middle Rio Doce.

2.2. Data collection

The bathymetric data for Lake Dom Helvécio were collected on 29 and 30 May 2007. The soundings were made from a boat using a Biosonics DT-X (Biosonics Inc.) acoustic device equipped with a 200 KHz split-beam 6.6° digital transducer. The 200 kHz split-beam transducer was positioned vertically, 0.5 m below the water surface. Positional data was acquired with a differential global positioning system (DGPS) AgGPS 132 (Trimble Co.) and linked with the Biosonics unit. The DGPS receiver was corrected in situ, by satellite differential correction (OmniSTAR Inc.). Thus, the data collected by positioning unit was corrected in real time, to provide a horizontal positional accuracy of plus or minus 100 cm. For each update of the DGPS position (every 2 seconds), the X and Y coordinates were recorded from the DGPS together with the Z-value (depth) from the digital echosounder.

The transducer of the echosounder and the kinematics antenna of the DGPS were set on opposite ends of the same metal tube, with the goal of reducing errors in positioning due to the inclination of the boat. Survey transects were conducted in a zigzag fashion from one side of the lake to the other, with one transect starting where the previous transect ended. A conventional GPS, GPS 76 (Garmin Ltd.), was also used to assist with navigation and to control the boat speed, which was maintained at less than 8 km/h. Single depth measurements were taken where navigation was not possible (macrophyte beds) or where the maximum depth was less than 1.0 m.

Visual Acquisition 5.1 software (Biosonics Inc.) was used to integrate the data, and Visual Bottom Typer 2.0 software (Biosonics Inc.) was used to determine depth from the echo-sounding data. Database files were created that included latitude, longitude, and depth. Before exporting to the GIS software, all coordinates were transformed from spherical coordinates to UTM projections using the horizontal datum WGS-84 (World Geodetic System).

2.3. Surface interpolation and contour map

The spatial data collection of this survey can be considered as sampling values, and to obtain regular grid data for the entire area of the lake, the data must be interpolated. The process of finding data values for unknown locations between observed data locations is known as interpolation. In this process, the original data collected in the field (XYZ file of location and depth) are used to generate calculated data points on a regularly spaced grid (Awulachew, 2006).

Various interpolation methods include inverse distance, kriging, minimum curvature, nearest neighbor, polynomial regression, radial basis functions, Shepard's method, and triangulation with linear interpolation. These interpolation methods were explored to determine the method that provides the best surface estimation. Kriging was chosen since the surface that it generated passed through nearly all sample points and produced the best predictive output of actual bathymetric contouring for Lake Dom Helvécio. The program Surfer 8.0 (Golden Software, Inc.) was utilized to interpolate the data, and then to create the contour (bathymetric) and the wireframe (3D) maps.

The next step was to overlay two different geographic information plans (maps): a) the shoreline of Lake Dom Helvécio; and b) the contour map of different depth lines generated by the software Surfer 8.0. The shoreline definition is an important element in the process of creating a bathymetric chart. This line is made of many points (geographic coordinates) that assume the value of Z is zero. Since this array of coordinates cannot be produced by an echosounder, we used another approach. The shoreline points were obtained from calibrated high-precision 1:10,000 aerial photos (orthophotos) published by Cemig, Inc. (Cemig, 1989). We used a sub-routine from the software Didger 3.0® (Golden Software Inc.) for (re)calibrating this image with the required accuracy (sub-metric precision). The calibration of this high-definition raster TIFF image was done using an array of georeferenced control points obtained in the terrain, using another differential GPS model GTR-A (Tech Geo, Ltda.). The precision of the calibrated shoreline image was less than 1.0 m.

2.4. Estimating the morphometric parameters

The morphometric features were estimated directly from the field data. The maximum depth was read directly from the field-data matrix. The perimeter (P), maximum effective length (Le), and the maximum effective width (We) were estimated directly in the bathymetric chart by means of the image-analyzer program Scion Image® (Scion Corporation). The lake surface (A), the bottom area (Ba) and the lake volume (V) were estimated from Surfer 8.0 subroutines. This program uses three different methods for estimating the lake volume: trapezoidal, Simpson and 3/8 Simpson rules. We took the arithmetic mean of all three estimates for the volume of Lake Dom Helvécio. The volumes of each 4.0 m depth layer, which were needed for constructing the hypsographic curves (according to Cole, 1994), were also estimated using the Surfer program.

All other secondary parameters, mean depth ($\overline{Z}$), relative depth (Z_R), volume development index (D_V), perimeter development index (D_P), mean width (L_m), and mean slope (α) were estimated according to Von Sperling (1999).

3. Results and Discussion

A total of 54,084 depth points were obtained with the DT-X echosounder in Lake Dom Helvécio. All points were synchronized to their geographical coordinates with sub-metric precision. This data matrix was processed by the Surfer program, using the Kriging interpolation method. After this procedure, a bathymetric chart with depth curves (isobaths) every 6 m was generated. This chart corresponds to the beginning of the dry season (May, 2007) when the lake was at its maximum level (Figure 1). According to the state park staff members, the lake surface reaches its minimum level, roughly to 1.0-1.5 m below the maximum level, in late October. The lake usually reaches its maximum level just after the rainy season (November-March). During our sampling, no depletion was noticeable along the shoreline, and we can assume that the lake was then at its maximum level.

The contours of the lake bottom are surprisingly complex. This pattern is typical in many man-made reservoirs, which suggests that the lake probably originated from damming of an ancient branch of Rio Doce (Meis and Tundisi, 1997). This large data matrix generated by the many sampling points made possible a detailed description of the lake basin. According to Cole (1994), the accuracy of every bathymetric chart is directly dependent on the number of sampling points.

The new morphometric information differs substantially from previously published values (Tables 1 and 2). The estimated total volume (59.6×10^6 m³) is 614% higher than the volume published by Tundisi and Musarra (1986). They estimated a volume of only 8.31×10^6 m³ (Table 2). We believe that there must have been a typographical error in their estimates: probably the authors intended to write 83.1×10^6 m³. However, even considering this possibility, there would be a difference of 28% between this new figure and the present estimate. The estimated lake area is also quite different between the two studies. We estimated a lake area of 5.27 km² (Table 1), whereas Tundisi and Mussara (1986) gave a higher figure of 6.87 km². This corresponds to a difference of 23% (Table 2). Because lake volume and lake area are primary morphometric parameters, these parameters are used in the estimations of all other secondary morphometric features of a lake (Cole, 1994, von Sperling, 1999). Thus, large differences were also noted between the estimations of the secondary morphometric parameters (Table 2).

A three-dimensional view of Lake Dom Helvécio (Figure 2) shows the heterogeneous nature of different lake compartments. The deepest zone (>25 m) of the lake is in the central/ northeastern part. The other lake arms are shallower, with depths of 6 to 8 m. These differences are clearer in lateral view (Figure 3). This figure also shows that the deepest point is located in the northeastern part
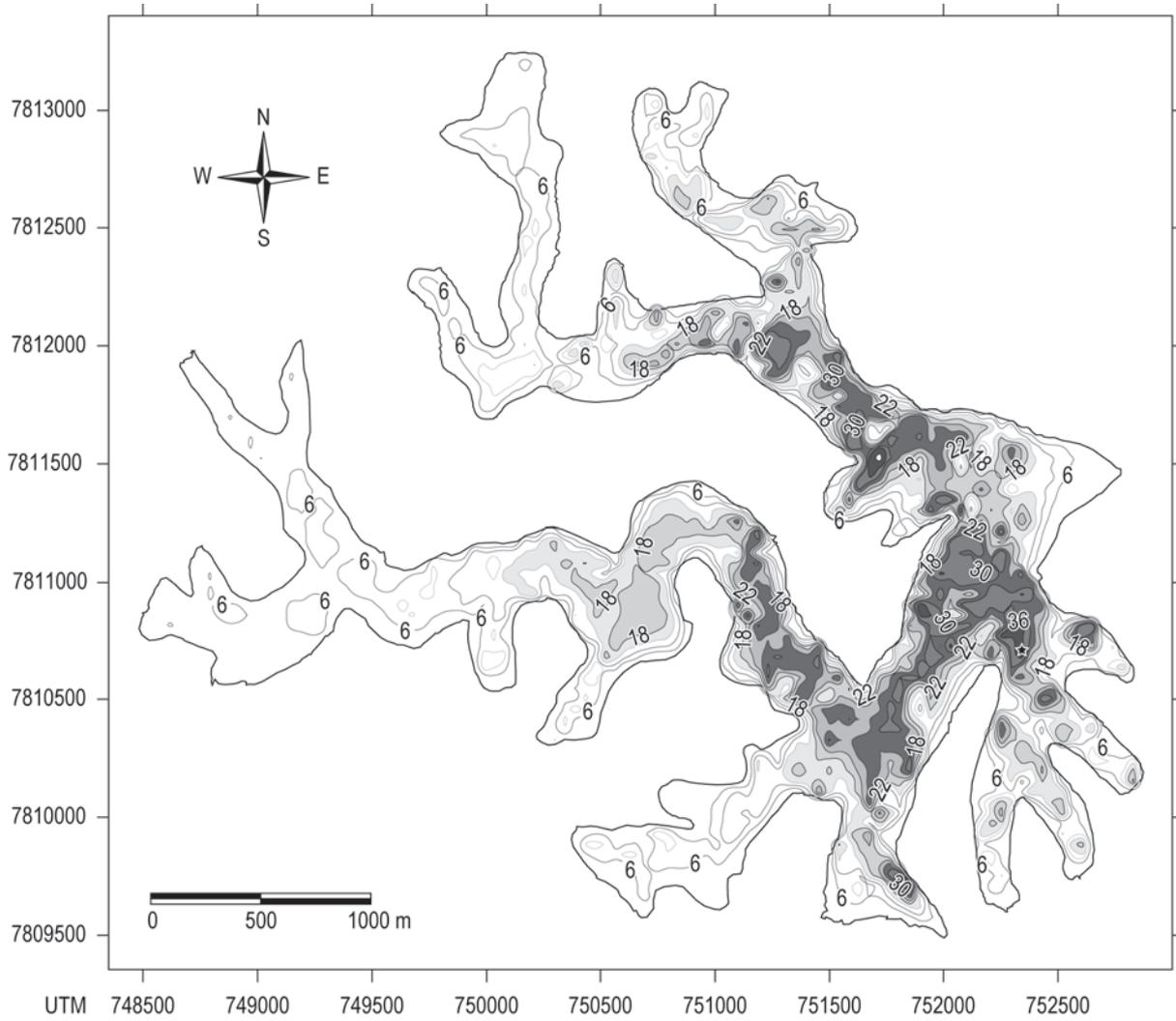
Figure 1. Bathymetric map of Lake Dom Helvécio, Parque Estadual do Rio Doce, state of Minas Gerais. Black star indicates the location of maximum depth (39.3 m).
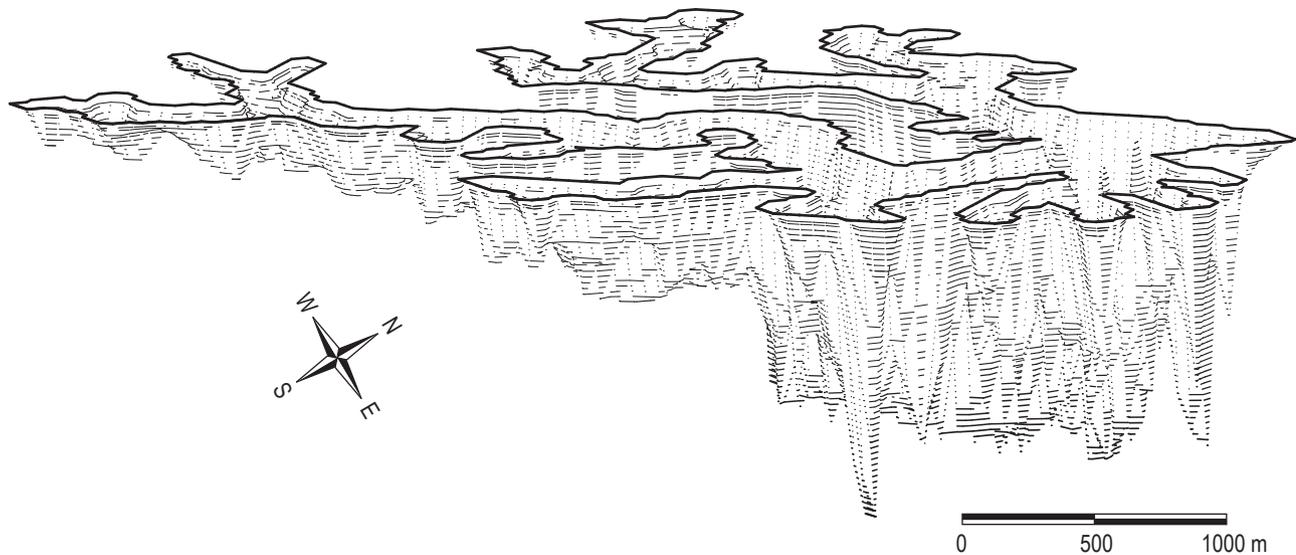

Figure 2. Bathymetric profiles in three-dimensional perspective of Lake Dom Helvécio, Parque Estadual do Rio Doce, state of Minas Gerais, south-north view.
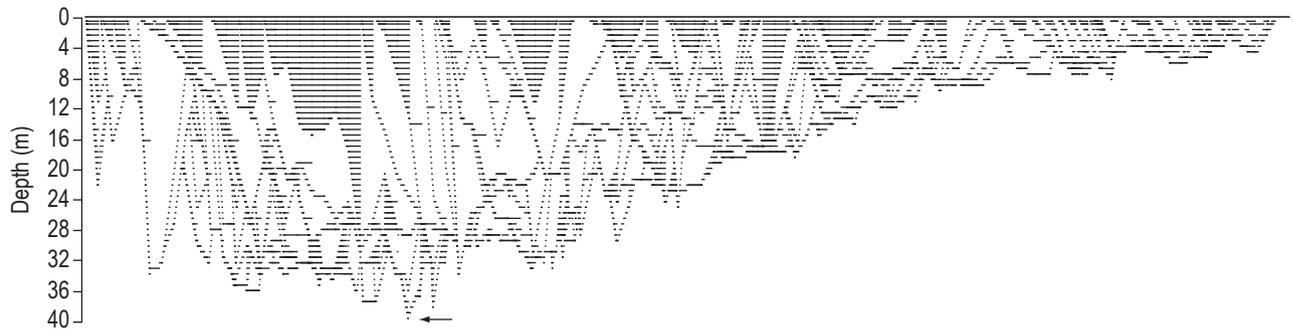
Figure 3. Lateral view of Lake Dom Helvécio, Parque Estadual do Rio Doce, state of Minas Gerais showing the point of maximum depth (arrow), north-south view.

Table 1. Morphometric characteristics of Lake Dom Helvécio, Parque Estadual do Rio Doce, state of Minas Gerais.

Morphometric Parameters	
Surface area (A)	5.27 km²
Volume (V)	59.4 x 10⁶ m³
Shoreline length (P)	37.7 km
Bottom area (Ba)	11.4 km²
Effective maximum length (Le)	3.1 km
Effective maximum width (We)	1.2 km
Maximum depth (Z_{max})	39.2 m
Mean depth ($\bar{Z}$)	11.3 m
Relative depth (Z_R)	1.52%
Mean width (L_m)	1.69 km
Volume development (D_V)	0.86
Shoreline development (D_L)	4.61
Mean slope (α)	3.04

Table 3. Information from the area and volume data by stratum of Lake Dom Helvécio, Parque Estadual do Rio Doce, state of Minas Gerais.

Depth (m)	Area (m²)	Area (%)	Layer	Volume (m³)	Volume (%)
0	**5266336.34**	**100.0**	0-4	17581250.44	29.57
4	4034813.77	76.62	4-8	13560758.03	22.82
8	2955879.74	56.13	8-12	9860782.17	16.59
12	2171642.04	41.24	12-16	7289225.44	12.24
16	1596208.77	30.31	16-20	5111083.60	8.60
20	1034701.79	19.65	20-24	3279174.63	5.51
24	680224.25	12.92	24-28	1981092.47	3.32
28	320446.21	6.08	28-32	679329.99	1.13
32	61549.6	1.17	32-36	89890.54	0.21
36	3174.39	0.08	36-39.3	2669.80	0.02
39.3	0.62	0.00	Total	**59435257.13**	**100.00**

Table 2. Comparison of morphometric data collected in 2007 with data collected by Tundisi and Musarra in 1986.

Parameters	This study	Tundisi and Musarra (1986)	Percentage difference
Volume (x10⁶ m³)	59.40	8.31	+614.0
Maximum depth (m)	39.20	32.50	+20.6
Surface area (km²)	5.27	6.87	–23.3
Mean depth (m)	11.30	12.10	–6.6
Shoreline length (km)	37.70	45.00	–16.2
Shoreline development	4.61	5.45	–15.4

of the lake (39.2 m). The coordinates of this point are 19° 46' 59.67" S and 42° 35' 29.54" W. The present study also identified several depression zones in the lake. These depressions usually have depths greater than the 32.5 m that was the previous deepest point noted by Tundisi and Musarra (1986). The same Surfer subroutine was used to calculate the volume of different depth layers of the lake. In this study, each layer was 4 m thick. These estimates made it possible to construct a hypsographic curve (depth x area lines) (Figure 4). More than 50% of the total lake area has depths greater than 7.8 m (Table 3).

4. Conclusions

This study used a new procedure that makes it possible to obtain all basic morphometric parameters and to generate a bathymetric chart very rapidly, with sub-metric accuracy. Additionally, this is a low-cost method, provided the echosounder is available. The most difficult step was to obtain an affordable cartographic basis, since it is crucial to calibrate the shoreline for this kind of investigation.

The present study was able to show that the existing data concerning Lake Dom Helvécio morphometry, as well as its old bathymetric chart, needed new adjustments. Considering the differences observed in lake area and volume between our and the previous study (Table 3), we also suggest a revision of some aspects of lake function, such as heat content or lake stability and oxygen deficit, that have been published based on the older estimations (e.g., Henry and Barbosa, 1989; Henry et al., 1989).

The complex spatial distribution of depths in Lake Dom Helvécio suggests a high spatial variability in several ecological properties of the lake. Thus, there must be large spatial (longitudinal) differences in properties such as lo-
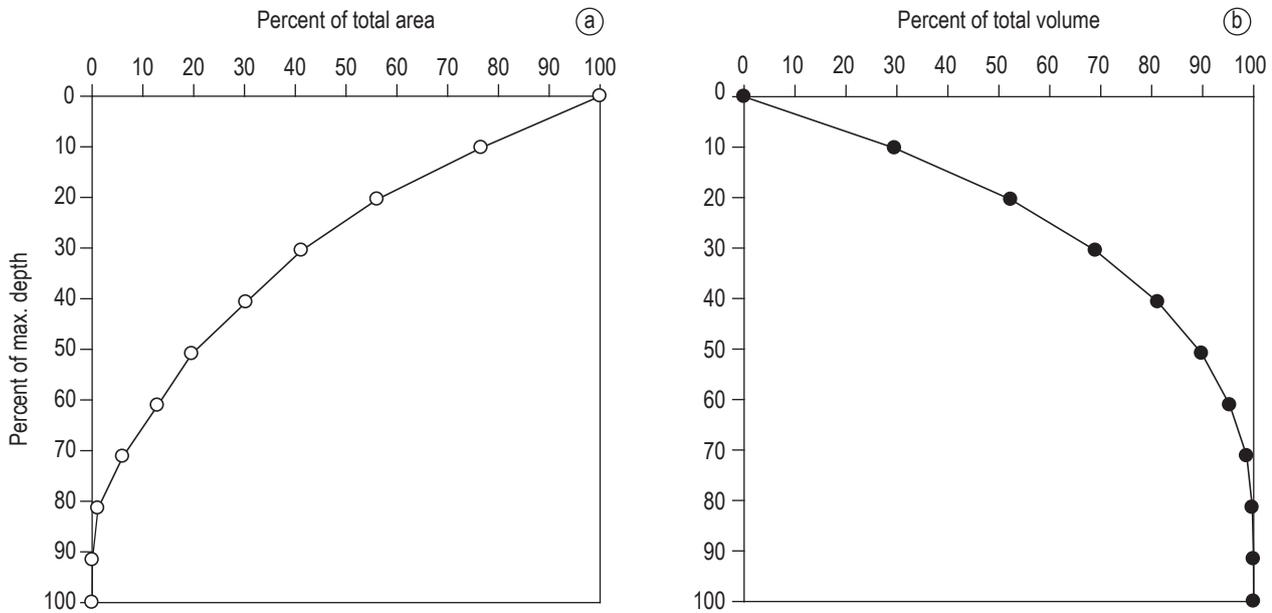
Figure 4. a) Hypsographic curves of percent total surface area and percent maximum depth, and b) percent total volume and percent maximum depth of Lake Dom Helvécio, Parque Estadual do Rio Doce, state of Minas Gerais.

cal availability of limiting nutrients, primary production of phytoplankton and macrophytes, and fish abundance. Therefore, it is also necessary to develop new research efforts aiming to identify the existence of longitudinal (horizontal) patterns in different limnological variables such as chlorophyll *a*, plankton community and fish assemblage. This kind of information is certainly essential for the establishment of a truly sustainable management plan for this important lake.

Acknowledgements

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