Batimetría y análisis morfométrico del lago de Atitlán (Guatemala)

Bathymetry and morphometric analysis of Atitlán Lake

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Received: May 25th, 2017 Approved: October 9th, 2017

Resumen

La cuenca del lago de Atitlán es de tipo endorreica y cuenta con el cuerpo de agua más profundo de Centroamérica, sin embargo, desde el año 1975 no se tiene información actualizada de su batimetría ni de su morfometría. El objetivo de desarrollar un estudio batimétrico en el lago de Atitlán, fue determinar su morfometría, y así poder comprender en el futuro algunos procesos físicos, químicos y biológicos. Para el levantamiento batimétrico del lago de Atitlán, durante 2014 se tomaron datos de profundidad a lo largo y ancho de todo el espejo de agua con una ecosonda de multi-frecuencia. Posteriormente la información fue procesada y se obtuvieron 16 parámetros morfométricos, tales como volumen, área, perímetro, profundidad máxima, fetch efectivo, longitud y ancho máximo, entre otros. El área superficial del lago obtenida fue de 125.77 km^2, el perímetro de 101.67 km y un volumen de 25.46 km^3. El lago de Atitlán es un sistema tropical profundo y de forma cóncava, según la curva hipsográfica, tiene una profundidad máxima de 327.56 m, una media de 203.21 m. El mapa batimétrico del 2014, presenta pocas diferencias morfométricas y morfológicas en comparación con el que se realizó en el año 1975.

Palabras clave: morfometría, mapa batimétrico, curva hipsográfica, fetch efectivo, sistema tropical profundo.

Abtract

The lake Atitlan basin is endorheic and is the deepest body of water in Central America. Information regarding its bathymetry and morphometry has not been updated since 1975.The objective of a bathymetric study in Lake Atitlán was to determine its morphometry and in the future, understand some physical, chemical and biological processes. For the bathymetric survey of Lake Atitlán, during 2014, depth data were taken along the lake with a multi-frecuency echo sounder. Later, the information was processed and 16 morphometric parameters were obtained, such as volume, area, perimeter, maximum depth, effective fetch, length and maximum width, among others. The surface area of the lake obtained was 125.77 km2, perimeter of 101.67 km and a volume of 25.46 km3. Lake Atitlan is a deep tropical system with a maximum depth of 327.56 m, an average depth of 203.21 m and concave; according to the hypsographic curve. The bathymetric map of the year 2014, presents few morphometric and morphological differences compare with the one that was realized in 1975.

Keywords: morphometry, bathymetric map, hypsographic curve, effective fetch, deep tropical system.

Introduction

The morphometric characterization of a body of water should be the starting point of limnological investigations (Margalef, 1983), since it allows knowing the depths and relief of the bottom of a body of water, thus facilitating conservation and management strategies of the basin. Some morphometric studies date from 1888 in Scotland (Murray, 1988), but it was not until 1957, when Hutchinson (1957) developed the subject in depth, followed by Wetzel (1983), Cole (1979), Håkanson (1981) and Kalff (2002), who established the main morphometric parameters that a body of water must have. The geomorphology of a lake determines the characteristics of its drainage, the entry of nutrients and solids, and the residence time. The shape, volume, area and depth of the cuvette have an effect on the temperature, the thermal balance and the stratification of the water column (Lewis, 1996). For example, the depth and area of a lake can affect the oxygenation rate and the availability of nutrients in the water column, therefore, it can be used to infer the metabolism of a body of water, (eg lakes of tectonic or volcanic origin, which are usually very deep) have low values of primary productivity (Wetzel, 2001).

The morphology of a lake is described by means of a detailed bathymetric map, necessary for the evaluation of the main morphometric parameters. The importance of the study of bathymetry and morphometry in lakes resides mainly in the influence that climatological, geological and anthropogenic factors may have on the physical, chemical and biological processes that occur within water bodies (Alcocer et al., 2016) , Oseguera, Sánchez, González, Martínez, & González, 2016). In America and in other regions of the world, some morphometric investigations have been carried out in lagoons (Fornerón, Piccolo, & Carbone, 2010), reservoirs, (Hernani & Ramírez, 2002) and lakes

(Wirrmann, 1991; Takano et al., 2004; Montoya , 2005; Anzidei et al., 2008., Yesuf, Alamirew, Melesse, & Assen, 2013; Alcocer et al., 2016). In Central America, there are no current bathymetry studies detailing the morphometry of other lakes in the region, nor bathymetric maps.

In Guatemala, there are no bathymetric studies except for a bathymetric study prepared by the National Geographic Institute (IGN, by its acronym in Spanish) in 1975, on Lake Atitlán. However, the bathymetry of Lake Atitlán had not been updated since 1975, despite the importance of morphometric studies of limnetic environments. For this reason, the main objective of this work was to estimate the main morphometric and bathymetric features of Lake Atitlán, in order to use them for future planning of the activities carried out in the lake and implement an integral management strategy for the basin.

Materials and Methods

The study area is located in the country's highlands, within the Lake Atitlán Basin Multiple Use Reserve (RUMCLA, by its acronym in Spanish), which was created in 1997 by Decree 64-97 and is administered by the National Council of Areas Protected (CONAP, by its acronym in Spanish) (Santizo & Secaira, 2007), in coordination with the Authority for the Sustainable Management of the Lake Atitlán Basin and its Environment (AMSCLAE, by its acronym in Spanish).

The Lake Atitlán basin is an endorheic system located at coordinates 425,000 X and 1,625,000 Y. The area of the basin is 124.5 km2 and is divided into two main sub-basins (Quiscab River and San Francisco River and several micro-basins of the San Buenaventura River, the Catarata river and the Tzununá River). The lake is located at an altitude of 1,556 meters above sea level, in the department of Sololá, in the western region of Guatemala (Figure 1).

The bathymetry of Lake Atitlán was carried out by taking depth data using a Hydrotrac multi-frequency echo sounder and the sites were georeferenced with a DGPS Hemisphere global positioning system (GPS). During the months of May and June 2014, 270 main navigation lines were made with a separation between lines of 100m, navigating with an orientation of 140º outward and 320º return; and 13 secondary navigation lines, with a separation of 1,000m between each one, navigating with an orientation of 247º outward and 67º return. For the processing of the data obtained in the field, the Hypack® Max, 3d Surfer® 12 and Arc Gis® 10.2 programs were used, which resulted in the bathymetric map and the main morphometric parameters of Lake Atitlán, such as volume, area, perimeter, maximum depth, maximum length and width.

To obtain the result of the maximum distance of the wind acting on the waves in the water mirror from a certain point (effective fetch), the data of the wind direction of the five climatological stations of the AMSCLAE, located in the northern (3) and southern (2) parts of the Lake Atitlán basin. After obtaining the average wind action orientation, the length was estimated using digitized plans.

Figure 1. Location map of the study area of Lake Atitlán.

Results

The bathymetric map of Lake Atitlán from 1975 and the one made in 2014 are presented in Figures 2 and 3, respectively.

Table 1 shows the values of the main morphometric parameters for Lake Atitlán, which describe the shape and physical characteristics of the lake.

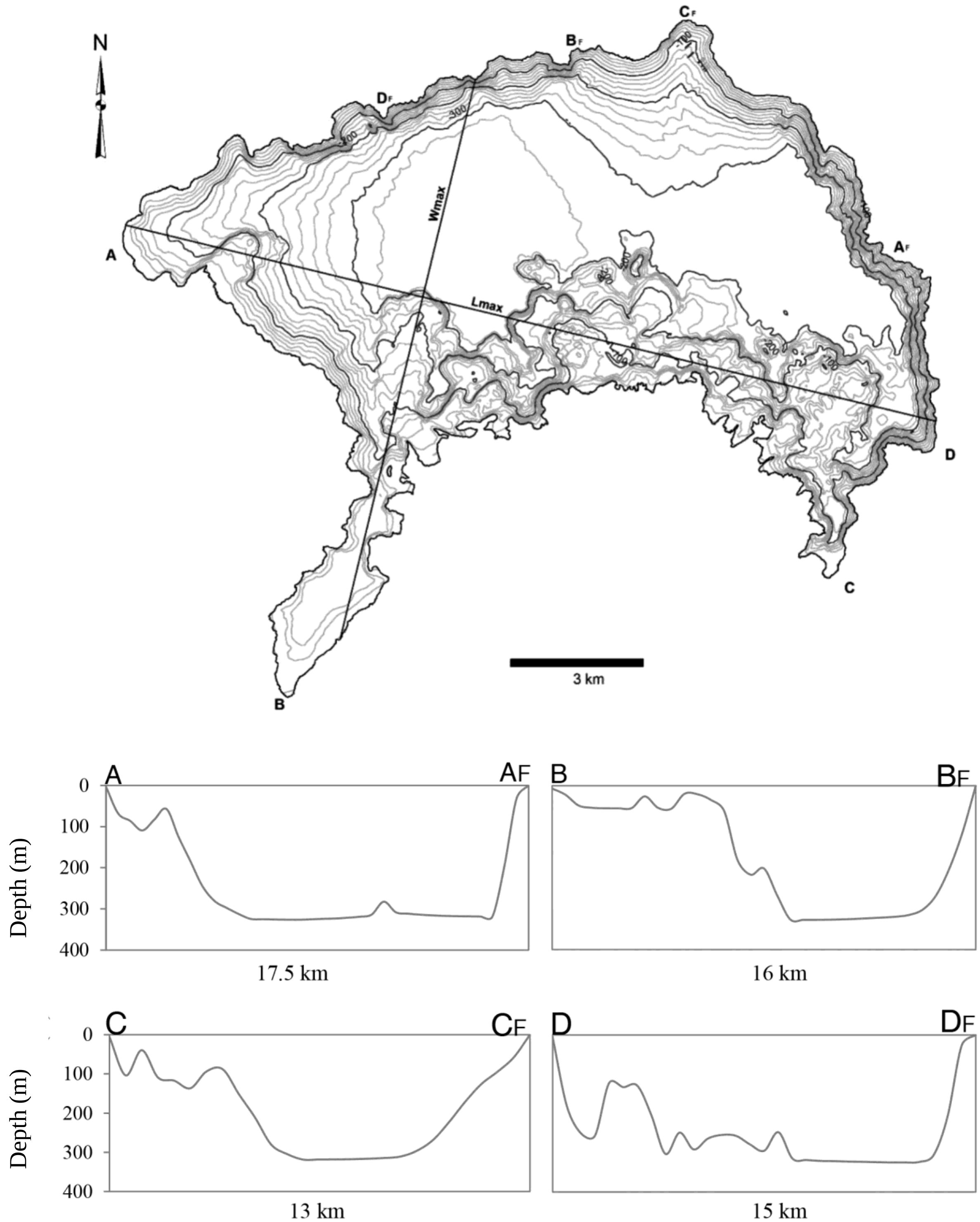

Figure 2. Bathymetric map and profiles corresponding to transects A, B, C and D of Lake Atitlán, 2014.

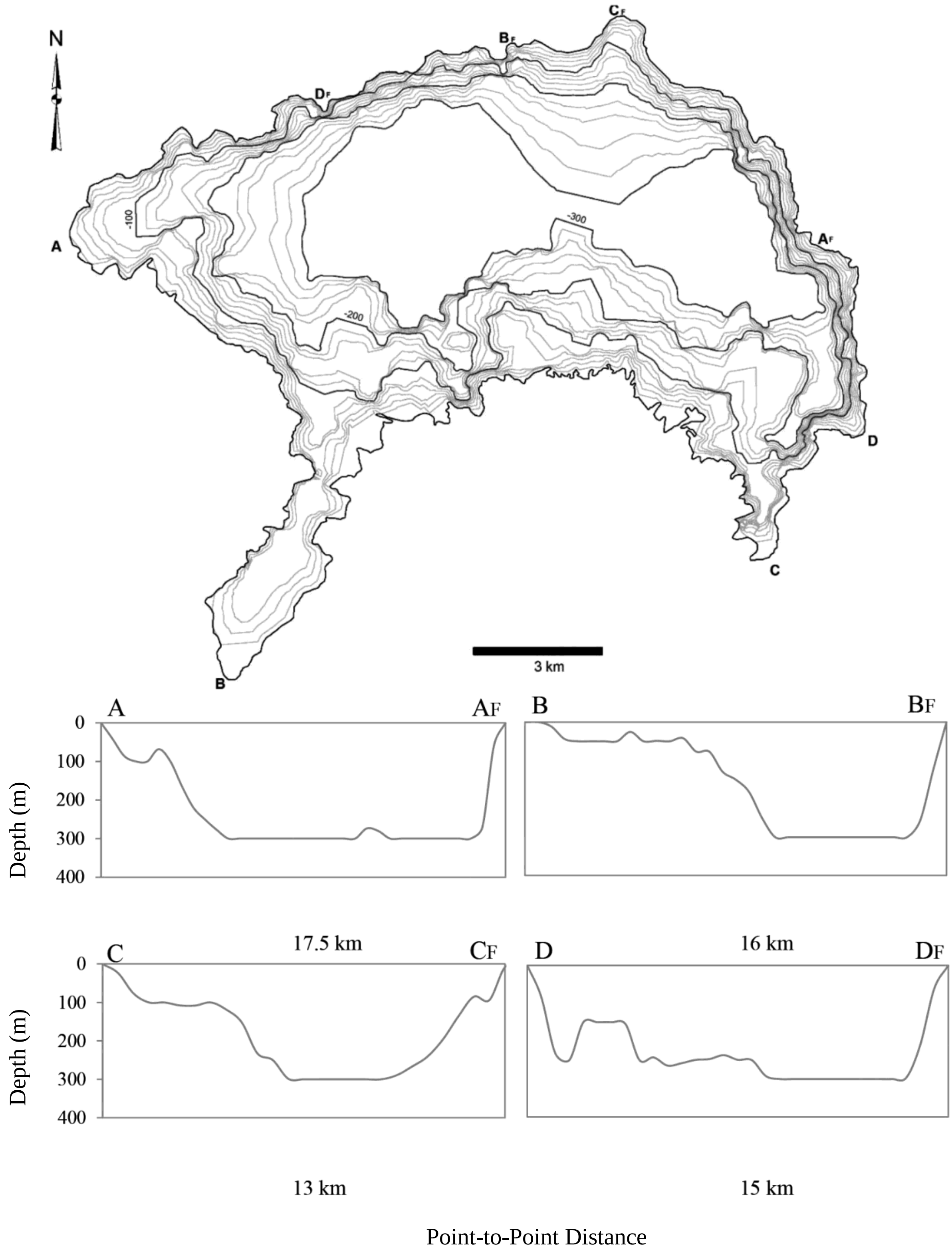

Figure 3. Bathymetric map and profiles corresponding to transects A, B, C and D of Lake Atitlán, 1975 (IGN, 1975).

Table 1. Morphometric Parameters of Lake Atitlán.

Parameter	Acronym	Value	Paremeter	Acronym	Value
Basin area (km^2)		546.03	Perimeter (km)	I_o	101.67
Total area (km^2)	a	125.78	Maximum width (km)	$W_{máx}$	13.04
Superficial area (km^2)	A	125.77	Average width (km)	W	6.65
Volume (km^3)	V	25.46	Max deep (m)	$D_{máx}$	327.56
Coast development index	F	2.56	Average depth (m)	D_m	202.40
Volume development index	V_d	1.85	Relative depth (%)	D_r	2.59
Maximum length (km)	$L_{máx}$	18.91	Effective fetch (km)	L_f	9.58
Maximum effective length (km)	L_e	18.91	Lake shape		Concave

The bathymetric map shows that the lake is a deep (327 m) and extensive (125 km2) body of water, which consists of a single basin and two bays. The maximum slopes are located in the northwest and east; the smallest slopes occur in the southern zone (Figure 2).

In the relative hyposographic curve of the area versus the depth (Figure 4), it can be seen that half of the depth values are above the average depth value. The shape of Lake Atitlán based on the hyposographic curve is concave, according to the classification proposed by Håkanson (1981).

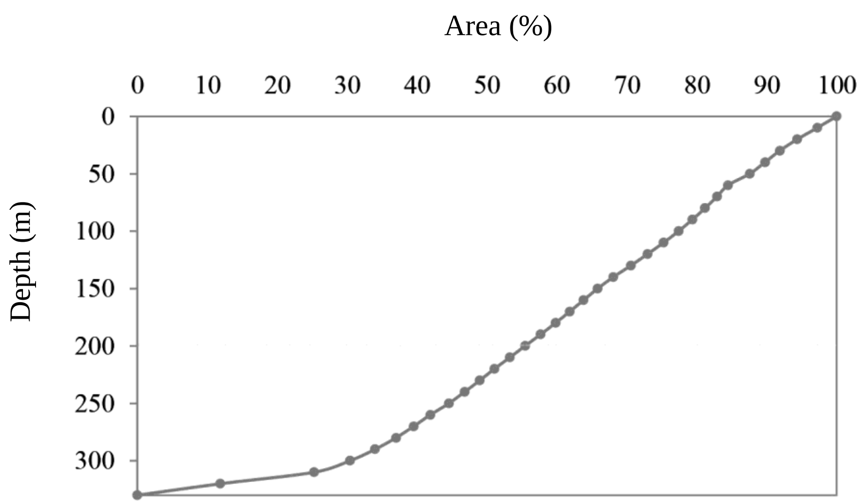

Figure 4. Hypographic curve of Lake Atitlán.

Discussion

The main differences between the 2014 bathymetric map and the one carried out in 1975 are mainly observed in the shallow areas or in the areas near the lake shore. Profiles A - AF and D - DF show that the northern part has steep slopes in the first meters of the coastal zone; in these areas the depth can rise abruptly from 50 m to 300 m. Profiles B - BF and C - CF show how the southern part of Lake Atitlán is an area with gentle slopes that go from the lake shore to the center (Figures 2 and 3). The differences between the two bathymetric maps and between the profiles of the northern and southern zones may be linked to the oscillation of the maximum water level of Lake Atitlán, caused by extreme weather events and the seismic activity of recent years (ie, earthquake , 1976 and 2012; Hurricane Mitch, 1998; Hurricane Stan, 2005; Storm Agatha, 2010), as has occurred in other regions (Anzidei et al., 2008; Yesuf et al., 2013). The currents and waves that originate the north-northwest winds and natural events have had an influence on the transport and deposition of the sediments that enter due to surface runoff in the area parallel to the entire shore of the lake, altering the morphometry and bathymetry of Lake Atitlán, as occurs in Lake Hayq, Ethiopia (Yesuf et al., 2013).

The development of the coast (F), (i.e., the relationship between the perimeter (Io) and the length (Lmax), was 2.56). A lake with a coastal development equal to one indicates that it is a circular lake, and it increases as its shape lengthens or the shore is irregular. Therefore, Lake Atitlán is considered to have a high coastal development index, indicating that the shape of the lake is irregular, therefore, there are greater possibilities for the development of benthic communities and a wide coastal area. (Roldán & Ramírez, 2008; Alcocer et al., 2016).

An important parameter that determines the degree of sedimentation is the volume of the lake *(V)*. Lakes with large volumes are a natural consequence of the evolution of a lake basin, because as it ages, the volume development index increases due to the accumulation of sediments, transforming into a conical or V shape, in the case of young, or U-shaped, lakes in the case of more advanced or older lakes (Benjumea, Wills, & Aguirre, 2007; Fornerón et al., 2010; Roldán & Ramírez, 2008). In the case of Lake Atitlán, the volume (V) and the volume development index (V) were 25.47 km3 and 1.86, respectively, indicating that it is an evolved, concave and U-shaped aquatic environment (Håkanson, 1981; Rico, Chicote, González, & Montes, 1995). However, the total volume of the lake is very dynamic, it can oscillate in ± .088 km3 per year, this due to seasonality, residence times and / or extreme weather events (hurricanes, tropical storms, droughts). The volume development of Lake Atitlán compared to other lakes, e.g. Craterlake (Vd 1.65), Lake Tahoe (Vd 1.87), Lake Baikal (Vd 1.65), is within the value range of deep and volcanic lakes (Byrne, 1962).

The effective fetch, (i.e., distance over which the wind has the possibility of producing waves) (Malhotra & Fonseca, 2007), was 9.58 km above 23 ° NNE. Traditionally, the depth of the thermocline has been related to the size of the lake and, in particular, to the distance on the surface of the water over which the wind or fetch can act, or its maximum length. The effect of the wind on Lake Atitlán is mainly related to the breakdown of the thermal stratification of the water column (thermocline) and the oxygenation of the surface layers (oxycline) (Bejumea, Wills, & Aguirre, 2007; Roldán & Ramírez, 2008).

The average depth (Dm) is the morphometric parameter that best characterizes the functioning and production of a body of water, in addition to the ecosystem structure of an aquatic environment. The lake's D_m/D_{max} ratio was 0.62, which characterizes an ellipsoidal basin, with very low sloping bottoms and sloping coastal walls (Figures 2 and 4) (Fornerón et al., 2010; Roldán & Ramírez, 2008).

The relative depth, (i.e., maximum depth divided by the average diameter of the lake), is considered as an indicator of the stability of the water column (Alcocer et al., 2016). Wetzel (1983) points out that most lakes have a relative depth (Dr) less than 2%, while deep and small-surface lakes generally have values greater than 4%, and are more protected from the wind and have a greater stability. In the case of Lake Atitlán the value of the relative depth was 2.59%, therefore, the stability of the water column is considered to be high. Shallow lakes tend, in relative terms, to form a less stable thermocline than large ones. The thermocline of Lake Atitlán is quite stable (Reyes et al., 2016), since the relative surface of heat exchange with the atmosphere is smaller.

The bathymetry of Lake Atitlán carried out in 2014 allowed to know its bottom profile, its morphology and morphometry compared to the study carried out in 1975. Due to the resolution of the 1975 map and the lack of data, the corresponding morphometric calculations could not be performed. However, the differences are considered to be minimal, as can be seen in Figures 2 and 3. The differences may be due to the oscillation of the maximum water level in Lake Atitlán in a seasonal cycle, which can vary between 0.45m to 0.90m depth (Xaminez & Reyes, 2016). This variation mainly depends on the seasonality of the rainfall, the contributions of surface waters and the processes of evaporation and precipitation within the basin, (e.g. storms, droughts, heavy rains and the period of the heat wave that has occurred during a year).

The morphometric values found for Lake Atitlán are within the typical ranges of lakes with volcanic origin. Most of the limnology principles can be demonstrated based on the comparison between lakes. The comparison between them allows to obtain generalities on the eutrophication processes, characteristics of the basin and management conditions. The morphometry and bathymetry of the lakes of the Americas, Europe and Asia region is influenced by the geological origin and topography of the region.

Lake Atitlán is a deep lake with a U-shaped basin, with a background of very high slopes and a certain irregularity of the coastline. Relative depth is low compared to other deep volcanic lakes. All these characteristics give the lake the evident formation of a physical and chemical vertical gradient that determines the vertical and temporal dynamics of the biological communities, (eg the thermocline and oxycline is located between 25 and 35 m deep and the distribution of phytoplankton between 5 and 15 m depth) (Reyes et al.¸ 2016).

Acknowledgement

This work was carried out thanks to the support of the Ministry of National Defense, Quetzal Port Company, Santo Tomas de Castilla National Port Company, Commandery and lake captaincy of Lake Atitlán, within the framework of the Interinstitutional Commission for Hydro-Oceanographic Research (*CIIHO, by its acronym in Spanish*). Thank you to Captain Oliverio Gonzáles, Juan Carlos Bocel and Julio Méndez of AMSCLAE and to all those people and institutions that supported in one way or another the development of this research so that it would finish.

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