Lake Atotonilco morphology and first approach to its ecological volume

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ABSTARCT

Lake Atotonilco is a shallow saline waterbody located in the center-west portion of Mexico. The lake is in the low plain of an endorheic watershed. it is shallow with a large area of surrounding wetlands and is a refuge for dozens of native and migratory waterfowl. Its extremely flat morphometric features coupled with the precipitation and runoff regime from the watershed cause significant changes in the lake surface area and storage volume throughout the year. In recent years, the lake has behaved as an intermittent lake, remaining practically dry in June and reaching its highest storage volume in October. An ecological

water volume that the lake must have to support its biodiversity was estimated. This minimum lake storage volume can only be achieved if public policies are implemented to rationalize the use of water resources in the basin and to protect the few forest areas that remain in the watershed.

Keywords: Lake Atotonilco, Lake Villa Corona, endorheic watershed, intermittent lake, playa lake, Mexico.

INTRODUCTION

Lake Atotonilco is a shallow lake located at 20°18’25.49” N and 103°39’04.11” W and at an altitude of 1352 m a. m. s. l. It is in the center-west of Mexico and to the southwest of the Guadalajara Metropolitan Area, the second largest city in the country (Figure 1). Officially Lake Atotonilco is known as “Laguna de Villa Corona” and, for the purposes of technical hydrological studies, its catchment has been subdivided as Laguna de Villa Corona “A” (337 km^2) and Laguna de Villa Corona “B” (390 km^2), the total catchment area is approximately 727 km^2 (DOF, 2016) (Figure 1). The Spanish word “laguna” is used to refer to small shallow lakes. In fact, the size of the lake fluctuates with the seasons, depending on temperature and rainfall. According to historical records, its maximum surface area is 2,252 ha and the maximum depth of the lake is around 1.00 m during the wet season (SEMADET, 2005).

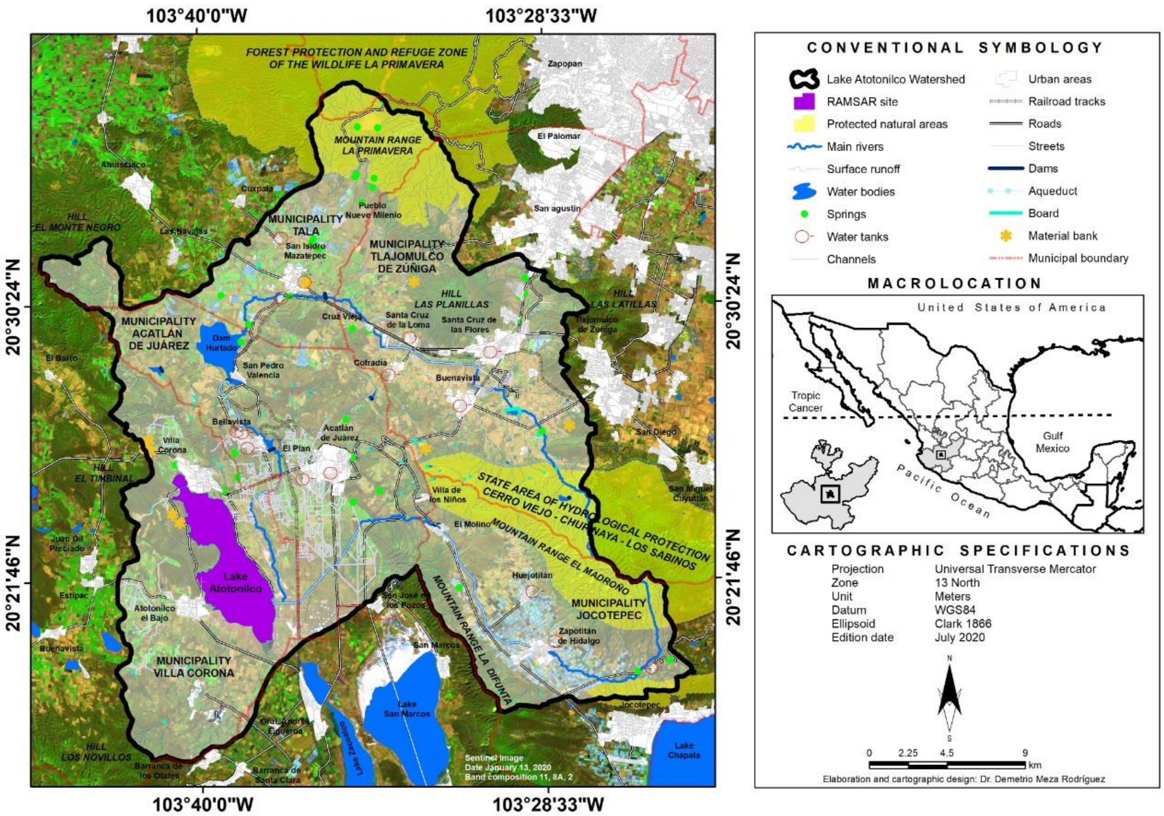


Figure 1. Location of Lake Atotonilco and its catchment area.

According to Mexican regulations, Lake Atotonilco has a medium level of ecological importance, which means that there is a presence of populations of several species of regional relevance due to their contribution to ecosystem services or socioeconomic development (SE, 2012). In Lake Atotonilco and its surroundings, there are around 241 species of birds, fish, reptiles and rodents, in addition to a significant range of insects (GBIF, 2022). Of the total number of species reported, 13 are in some degree of threat or in danger of extinction (SEMARNAT, 2010). The catchment area and habitat are moderately altered. They retain to some extent their operation, structure, and basic services, despite having undergone physical changes. The presence of anthropogenic infrastructure is evident in the lake since there is a road that fragmented the lake in its northern part. Obvious and significant alterations, but certain components of the hydrological regime remain. According to the National Water Commission, the pressure for the use of water in the basin is classified as very high because the volume allocated for the different uses between the average annual availability in the basin and the aquifer exceeds 80% (REPDA, 2022). On the other hand, the conservation actions of the lake are still very limited compared to the serious pollution problems and the overexploitation of its water resources; which is why the watershed has been classified as a very high priority for attention, so actions that contribute to its recovery or rehabilitation should be considered.

In the region where this lake is located, there is a series of small shallow lakes of tectonic origin (Atotonilco, Cajititlán, Zacoalco, San Marcos, Sayula, and Zapotlán), aligned from north to south and characterized by the Lakes' endorheic features (INEGI, 2001) (Figure 2). As shown in Figure 2, the elongated Lake Zacoalco and Lake San Marcos are located in the named San Marcos watershed. According to recent geological studies, these lakes originally were interconnected with Lake Chapala covering an extensive region of western Mexico. They were divided because of volcanic and geological processes that occurred since Late Miocene to Early Pliocene (Zárate-Del Valle et al., 2005; Alatorre-Zamora et al., 2015). In particular, Lakes Atotonilco, San Marcos, and Sayula can be considered as playa (beach) lakes because when they are dry during the dry season, there are large visible areas of plains that give the appearance of being beaches (Last, 2002; Arche, 2007). In recent years, it has been observed that periods of drought in these lakes have been extended due to increased exploitation of underground water resources and the effects of climate change in the central and northern regions of the country (de Anda-Sánchez, 2020).

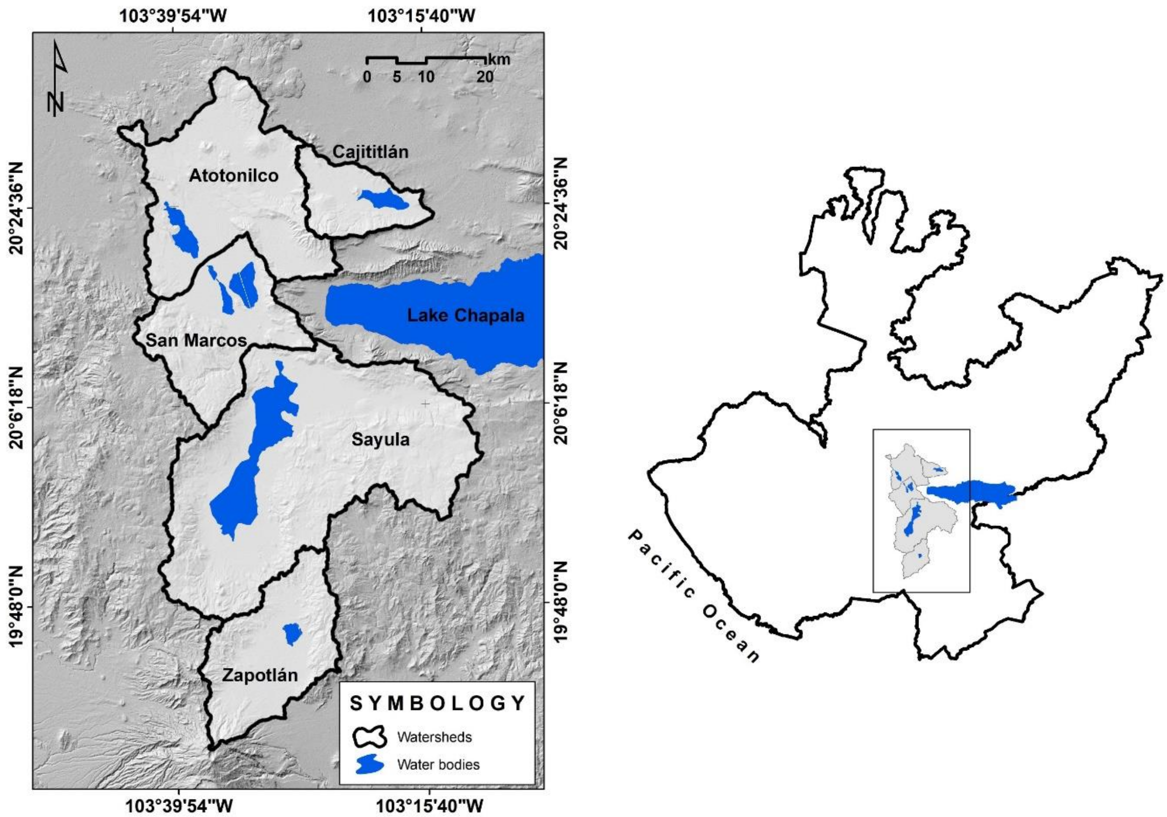


Figure 2. Geographic location of the closed watersheds Atotonilco, Cajititlán, San Marcos, Sayula, and Zapotlán, in the state of Jalisco, Mexico.

In particular, Lakes Atotonilco, Zacoalco, San Marcos, and Sayula show significant reductions in water storage volume due to natural sedimentation processes that have occurred over thousands of years. This has resulted in saline soils with high concentrations of sodium and high electrical conductivity (1.0769 mS/cm in Lake Sayula, 6.7151 mS/cm in Lakes Zacoalco and San Marcos, and 6.9680 mS/cm in Lake Atotonilco) (INEGI, 2001). The high levels of salinity of the soil means that the waters of these lakes are not suitable for agricultural use (Richards, 1954).

To protect the integrity of the ecosystem, Lake Atotonilco was recognized as a wetland of international importance and designated as a Ramsar site on March 16, 2006 (SEMADET, 2005; CONANP, 2006, p.63). Its protection area covers around 2,850 hectares. In this protected area, the typical biodiversity of the continental wetlands of western Mexico is well represented. The area has been the habitat for a wide variety of endemic and migratory waterfowl. This shallow lake and its marshes are the sanctuary of dozens of endemic and migratory bird species, such as the cinnamon teal (*Anas cyanoptera*), the northern shoveler (*Spatula clypeata*), the northern pintail (*Anas acuta*), the roseate spoonbill (*Platalea ajaja*), the snow goose (*Chen caerulescens*), and the American white pelican (*Pelecanus erythrorhynchos*) among many others. The site offers protection to some species in the Federal Register such as the Cane Toad (*Bufo marinus*), the Mexican Garter Snake (*Thamnophis eques*), the Common Stripped Whiptail lizard (*Cnemidophorus communis*), the Bigfoot Leopard Frog (*Rana megapoda*), and the White-nosed Coati (*Nasua narica*) (CONANP, 2006). More recently some otters (*Lontra longicaudis*) have been sight in the western shore of the lake.

Despite the ecological importance of this lake, its bathymetry, the hypsographic curves, and morphometric features of the lake and its watershed, were unknown. Likewise, there is no criterion to determine the minimum ecological volume that this lake must have to ensure the conservation of its biodiversity. This work describes the main morphometric features of Lake Atotonilco and its watershed. It includes the hydrographic characteristics of the catchment area, the monitoring of the temporary variations of the wet surface extension of the lake and its corresponding storage volume in the period from August 2020 to September 2021 and proposes a method to determine the ecological volume required to sustain the lake's biodiversity.

METHODS

Precipitation

Lake Atotonilco watershed has an extreme variation of monthly rainfall by season. Table 1 shows the calculated mean monthly precipitation in the basin from1963 to 2019.The rainfall period comprises 6 months starting in May and ending in October. The month with the most rain is July, with an average rainfall of 197.47 millimeters. The dry period of the year lasts for 6 months, from November to April 15. The month with the least rainfall is March, with an average rainfall of 2.37 millimeters. Figure 3 shows the distribution of mean monthly precipitation in Lake Atotonilco according to the data reported on Table 1.

Table 1. Mean monthly precipitation in Lake Atotonilco basin in the period of 1963 to 2019.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Minimum	-	-	-	-	0.81	46.99	114.11	101.28	59.92	1.17	-	-
Mean	6.56	7.49	2.37	3.52	21.19	158.04	197.47	156.05	138.86	53.12	15.53	12.21
Maximum	32.65	43.75	30.13	38.94	66.05	239.09	308.18	229.61	250.70	125.00	90.82	72.65

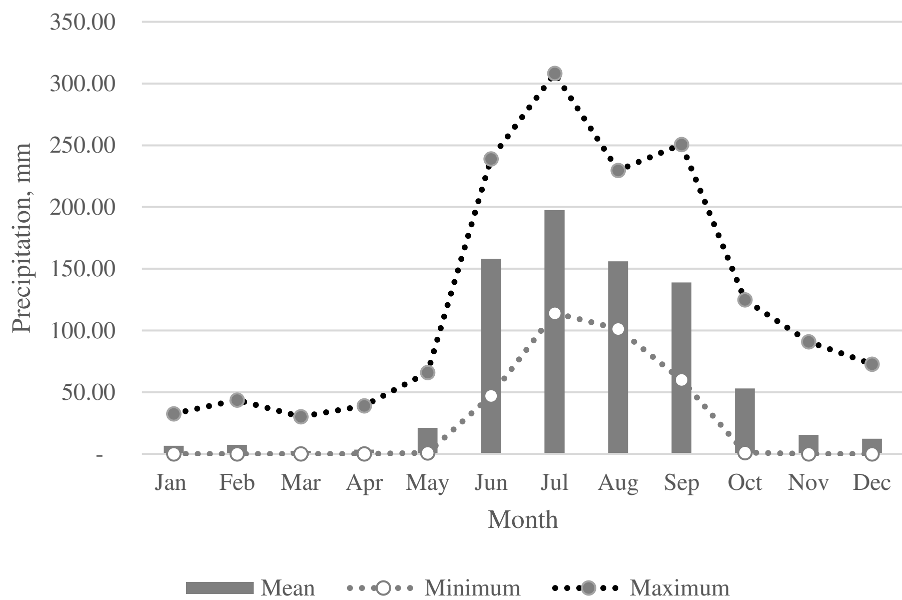


Figure 3. Distribution of mean monthly precipitation in Lake Atotonilco basin from 1963 to 2019.

Lake Bathymetry

To generate the topographic and bathymetric maps of Lake Atotonilco a portable water level gauge was used to take direct measures of the water column depth in selected sites described in Figure 4. To measure altitude and geographical location a portable GPS System was used. The field work was carried out in October 2020. With the ArcGIS 10.8 program, a bathymetric model classification was performed every 0.10 meters from which the depth weighted average value was obtained.

Hypsographic curves are graphs used to provide a visual representation of the relationship between the surface area of a lake basin and its depth (Håkanson, 1977; Florida LAKEWATCH, 2001). To generate the area-volume curve, it was necessary to use the ranges indicated above (0.10 m), to estimate the volumes of water for each class considered. The

Golden Software Surfer 20 software was used with the "Grid Volume" function (Surfer®, 2021) to generate the graphs. The area (ha) was defined on the abscissa axis and the volume (Mm^3) was defined on the ordinate axis.

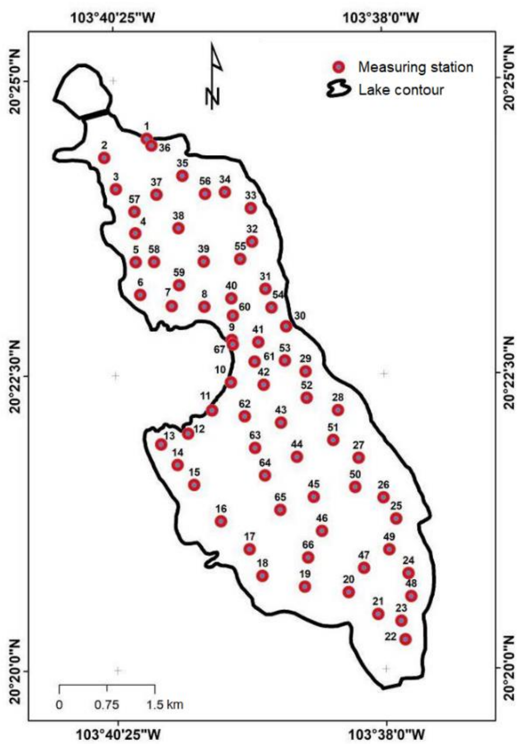


Figure 4. Measurement sites used to determine the topography and bathymetry of Lake Atotonilco.

Morphometric parameters

Basin area

The area of Lake Atotonilco watershed was estimated using the ArcMap program. The catchment area is probably the most important morphometric and hydrological characteristic of a watershed. According to Jiménez & Materón (1986), the size of the hydrographic basin can be classified according to the criteria established in Table 2.

Table 2. Proposed basin classification according to its size (Jiménez & Matrón, 1986).

Basin size (km²)	**Description**
< 25	Very small
25 a 250	Small
250 a 500	Intermediate-Small
500 a 2,500	Intermediate-Large
2,500 a 5,000	Big
> 5,000	Very Large

Perimeter

The perimeter (*P*) is the length of the watershed dividing line (Campos, 1987). The area and perimeter of the basin are closely related to the present lithology; a soft rock gives rise to a well-drained basin with relatively large area and tendencies to rounded shapes. On the contrary, resistant rock gives rise to an elongated basin, with steep slopes, low drainage density and small areas (Díaz *et al.,* 1999). The perimeter was calculated by using the ArcMap program.

Slope of the basin

Slope (*S*) is one of the main parameters that characterizes the relief of basin and allows comparison between basins (Guilarte, 1978). The slope of the basin is important in the relationship amongst infiltration, surface runoff, soil moisture and underground flows to the flow of the surface channels. This concept is representative of different slopes and is closely related to the erosive phenomena that manifest themselves on the surface. Table 3 shows the slopes classification according to Guilarte (1978).

Table 3. Basin topography classification according to the degree of slopes.

Slope %	Type of Land
0 – 2	Plain
2 – 5	Smooth
5 – 10	Medium rough
10 – 15	Rough
15 – 25	Heavily Rugged
25 – 50	Steep
> 50	Very steep

The Digital Elevation Model (DEM), necessary to estimate the slope, was generated using the information of six digital topographic charts that encompass the basin of Lake Atotonilco at a scale of 1:50000 of the National Institute of Statistics and Geography (INEGI). The interpolation of the ordinary Kriging model was used. The spatial data structure was quantified using linear variogram. It is assumed that the closest data have greater weight or influence on interpolation, decreasing as the data move away from the point of interest (Schloeder *et al*., 2001). The estimate the slope was obtained from the DEM applying the Horn method (1981). This method is used for the calculation of the value of the nearest neighbors and the diagonal neighbors, the former having greater weight. The value is assigned to the central point, even if its elevation is not used in the calculation (Meza et al., 2017).

Average height

The average height, H, is the mean elevation referred to the level of the gauging station at the mouth of the basin. The elevational variation of a hydrographic basin has a direct impact on its hydrological regime, thermal distribution, and therefore on the existence of characteristic microclimates and habitats according to prevailing local conditions (Rentería-

Guevara et al., 2019). This parameter was obtained from the DEM by using the ArcMap program.

Relief

The relief parameter (*R*) represents the difference of the greater height and the lower height of the basin. The influence of the relief on the surface runoff is even more evident. A higher slope corresponds to a shorter duration of runoff water in the drainage network and tributaries of the main stem (Campos, 1987). This parameter was obtained from the DEM by using the ArcMap program. It is represented by the equation (1).

$$R = H_{max} - H_{min} \qquad \text{Eq. (1)}$$

Where:
H_{max}: Maximum basin height (m),
H_{min}: Minimum basin height (m)

Length of the basin

In endorheic watersheds, the watershed length is defined as the largest dimension that exists along a straight line from the mouth of the mainstream that discharges into the lake to the dividing line parallel to the mainstream (Schumn, 1956; Campos, 1987). This parameter was estimated by using the ArcMap program.

Compactness Index

The compactness index (*C*) corresponds to the relationship between the perimeter of the basin and the circumference of the circle that has the same surface of the basin (Sánchez, 1987). The closer the index is to 1.0 it is closer to be of circular form and therefore more compact and increases as compactness decreases. This coefficient can reach values of 3.0 in the case of very elongated basins (Sánchez, 1987; Campos, 1987). It is represented by equation (2) and are classified according to Table 4.

$$C = 0.282\frac{P}{\sqrt{A}} \qquad \text{Eq. (2)}$$

Where:

P: Basin Perimeter in (km),

A: Basin Area (km²),

Constant: 0.282.

Table 4. Shape classification table, determined by the compactness index parameter.

Class	Values of values	Forms
K1	1.00 a 1.25	Almost round to oval - round
K2	1.26 a 1.50	Oval round to oval - oblong
K3	1.51 a 1.75	Oval – oblong to rectangular oblong

Shape index

The shape index (R_f) is very often used to define the unit ideograph of the basin. When the value of the shape index is less than 0.5 or tending to zero , it represents the known characteristics of the basin with long slopes and canyoned shaped hydrological network with high sloped gradients and high drainage density. When the shape index is less than 0.5 the basin is elongated, runoff predominates and the regime is usually of the torrential type because there is more runoff concentrated in these basins, and when it presents values greater than 0.5 it indicates that they are rounded or compacted basins, with less torrential runoff and (Sánchez, 1987). It is represented by the equation (3).

$$R_f = \frac{A}{La^2} \qquad \text{Eq. (3)}$$

Where:

A: Basin area in (km²),

La: Basin length (km).

Hypsometric curve

This curve represents the drained area varying with the height and surface of the basin, these elevation data are significant in the behavior of temperature and precipitation, and graphically represent the elevations of the terrain as a function of the corresponding surface (Campos, 1987). The hypsometric curve can be modified according to the relative height and thus allows an estimation of the potential dynamic equilibrium state of the basin. According to Strahler cited by (Llamas, 1993), these show the characteristic curves representing the geological stage, as well as the erosive cycle of the basin and the type of basin, with different evolutionary potential. To estimate this parameter, it was necessary to classify the elevations using the ArcMap program.

Order number

It is the number that has a close relationship with the number of branches found in a drainage network of a basin, where the mainstem has the highest order. Where the order number is greater, the erosive potential will be greater, the sediment transport will be greater and therefore the direct runoff will also be greater than in another basin of the same area (Campos, 1987). Horton (1945) pointed out that the higher the order of the basin, the greater its degree of river development. To estimate the following parameter, the ArcMap program was used under the Geographic Information System.

Number of runoffs

It is represented by the total number of channels of order *N1 + N2 + N3*... etc., which we can find in a basin, this parameter indicates the number of branches found in the basin (Campos, 1987). To count the runoff, the ArcMap program was used under the Geographic Information System.

Length of runoff

This represents an indicator of the degree of slope of the basin, as well as the degree of drainage density. Areas with slopes or very steep slopes present a greater degree of branching of tributary currents, unlike valley areas with deep soils present long and perennial tributary currents (Guerra & González 2002). To estimate the length of the runoff, the ArcMap program was used.

Length of main runoff

The length of the main river represents the distance between the mouth and the source of the stream (Klohn, 1970). To estimate the length of the runoff, the ArcMap program was used to identify the main channel.

Drainage density

This physical parameter reflects the dynamics of the basin, the stability of the hydrological network, and the type of surface runoff, in general, is the relationship between the length of all river streams and the area of the basin (Sánchez, 1987; Llamas, 1993). In this way high values reflect a strong runoff, mountainous relief, with scarce vegetation cover and impermeable soils. High drainage density results in faster runoff and increases the peak of the hydrograph (Campos, 1987). It is represented by the equation (4).

$$Dd = \frac{Le}{A} \qquad \text{Eq. (4)}$$

Where:
Le: Total length of runoff (km),
A: Basin area (km²).

Hydrological density

The hydrologic density (C_f) represents the number of flow channels per surface unit. This parameter is interpreted as the number of channels per square kilometer that we find in the basin and that must be maintained to have stable hydrological conditions (Díaz *et al*., 1999). It is represented by the equation (5).

$$C_f = \frac{Nw}{A} \qquad \text{Eq. (5)}$$

Where:
Nw: Number of Runoffs,
A: Basin area (km²).

Branch ratio

Horton (1945), developed a system to order the networks of the surface streams of rivers. This was modified by Strahler (1964); the system known as Horton-Strahler is the best known and widely used method (Campos, 1987). Strahler's numerical criterion considers that the bifurcation relation (RB) is a dimensionless property and that drainage systems in homogeneous materials tend to show geometric similarity (Campos, 1987).

The value of the bifurcation from Horton's method is defined as the relationship between the number Ni of channels of order i and the number Ni +1 of channels of order i + 1. Horton found that the relationship is relatively constant from one order to another. It is represented by the equation (6).

$$R_B = \frac{N_i}{N_{i+1}} \quad \text{Eq. (6)}$$

On the other hand, obtaining the value of the bifurcation of the basin by means of the numerical criterion of Strahler, shows the order of the currents in the abscissas and the algorithm of the frequencies of the currents in the ordinate, where the simple regression between both variables is obtained the relation of the algorithms and with an anti-logarithm of value of the slope of the line is obtained the bifurcation relationship for the basin (Sánchez, 1987).

Slope of the mainstem

This average slope of the main channel is directly related to erosion at depth and to the transport capacity of suspended sediments (Campos, 1987). The value of the slope of the mainstream is obtained from the DEM.

Concentration time

The concentration time (*Tc*), also called equilibrium time, is defined as the time it takes a drop of rain to move from the furthest point of the basin to the exit of the basin. Very short concentration times have intense flows and very fast sections, while longer concentration times determine attenuated flows and sustained recessions, considering that there is no evaporation and that the surface is impermeable (Kirpich, 1940). It is represented by the equation (7).

$$Tc = \left(\frac{0.87C_f^3}{D_a}\right)^{0.385} \quad \text{Eq. (7)}$$

Where:

Cf: Mainstream length (km),

D_a: Maximum height – Minimum height,

Constants: 0.87, 3, and 0.385.

Lake surface area method

According to Browne (1981) and Shang (2013) the lake surface area is an appropriate index for the habitat protection of lake ecosystems because the biodiversity increases with the surface area. Besides, lake storage is taken as an index of water quantity. Both lake surface area and storage volume increase with water level. The relationship between lake mean depth (Z) and surface area (S) can be expressed by $Z= Z(S)$, and the relationship between surface area (S) and the storage volume (V) can be expressed by $S=S(V)$. The lake surface area method was proposed to define minimum ecological lake level from lake level–area–storage volume curves, with detailed calculation procedures. The relationship between lake surface area and storage can be expressed by equation (8).

$$S = S(V) \quad \text{Eq. (8)}$$

Where S is the lake surface area, and V is the lake storage. To eliminate the scaling effect of lake surface area and storage, dimensionless lake surface area (S) and storage volume (V) are used instead, which are defined as:

$$s = \frac{S}{S_{max}} \qquad \text{Eq. (9)}$$

$$v = \frac{V}{V_{max}} \qquad \text{Eq. (10)}$$

Where s and v are dimensionless lake surface area and storage volume, respectively, and S_{max} and V_{max} are maximum lake surface area and lake storage volume, respectively. Then s can be expressed as a function of v, which is:

$$s = s(v) \qquad \text{Eq. (11)}$$

Using the slope method described by Shang (2013), the dimensionless minimum ecological lake storage volume (v_e) is determined by the breakpoint of the dimensionless lake surface area-storage volume curve with the slope equal to a specified value, usually equal to 1:

$$\left.\frac{ds}{dv}\right|_{v=v_e} = 1 \qquad \text{Eq. (12)}$$

After the determination of v_e, minimum ecological lake storage (V_e) can be calculated from

$$V_e = v_e V_{max} \qquad \text{Eq. (13)}$$

From equations (2), (3) and (5), V_e can also be defined directly from:

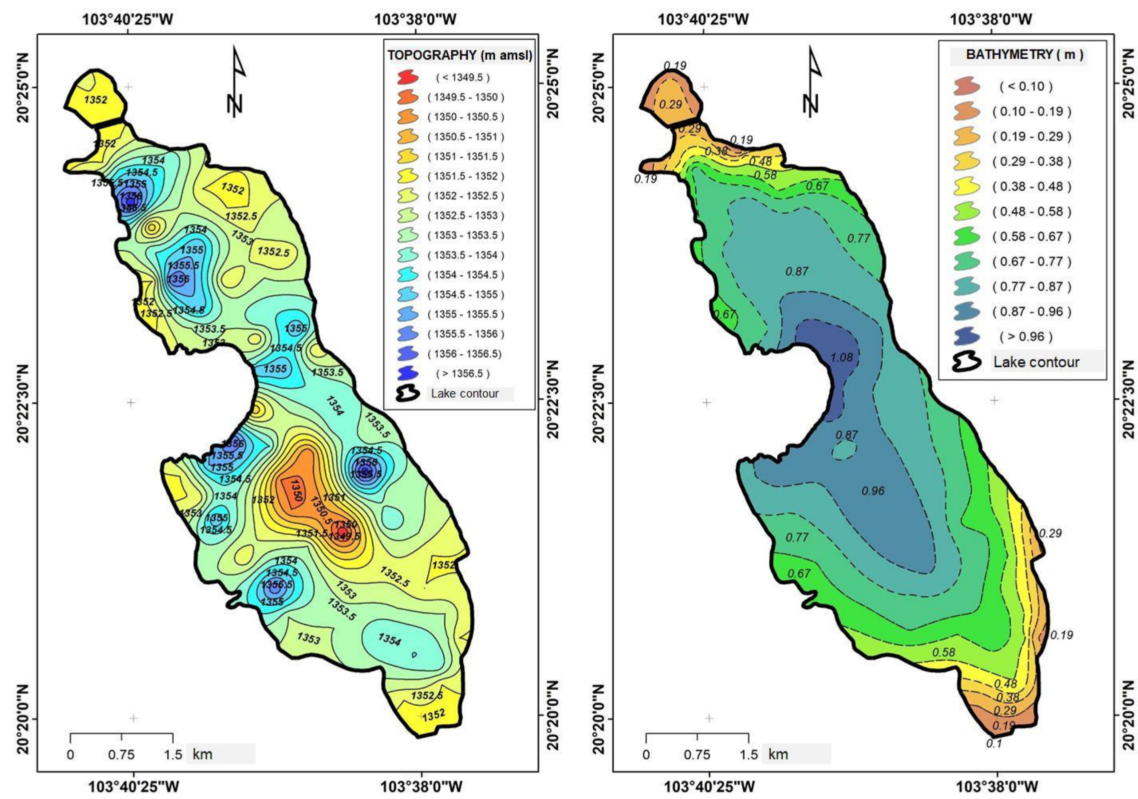
$$\left.\frac{dS}{dV}\right|_{V=V_e} = \frac{S_{max}}{V_{max}} \qquad \text{Eq. (14)}$$

Therefore, the minimum ecological lake storage volume is that one at which the slope of the S-V curve (dS/dV) equals to the average value of lake surface area per unit storage volume namely the ratio of maximum lake surface area to maximum lake storage, S_{max}/V_{max} (Shang, 2013).

RESULTS

Lake topography and bathymetry

Figure 5 shows the results of the topography (A) and bathymetry (B) of Lake Atotonilco after processing the data obtained during the measurement campaigns at the sites described in Figure 4.



(A) (B)

Figure 5. Topography (A) and bathymetry (B) of Lake Atotonilco.

Morphometric and hydrographic parameters of the lake watershed

Table 5 shows the morphometric and hydrographic parameters of Lake Atotonilco watershed. From this table the shape of Lake Atotonilco watershed is intermediate-large and oval-oblong to rectangular oblong with a dendritic drainage. The total area of the watershed was estimated in 755.32 km^2 with a perimeter of 170 km. The average slope of the basin is 12% and its maximum length is 30 km.

Table 5. Morphometric and hydrographic parameters of Lake Atotonilco watershed.

Parameter	Symbol	Units	Value
Watershed name			Lake Atotonilco
Elevation		m a. m. s. l.	1364 - 2956
Watershed description			Intermediate-Large
Classification			Endorheic
Watershed shape			Oval - oblong to rectangular oblong
Drainage type			Dendritic
Area	*A*	km^2	755.32
Perimeter	*P*	km	170
Average height	*H*	m a. m. s. l.	1,581
Relief	*R*	m	1,592
Slope of the basin	*S*	%	12
Basin length		km	30
Compactness index		[-]	1.74
Form factor		[-]	1.90
Hypsometric curve			Valley basin
Order number		No.	6
Number of runoffs		No.	2,147
Runoff length		km	1,426
Length of main runoff		km	59
Drainage density		km/km^2	1.88
Hydrological density		n/km^2	2.84
Bifurcation ratio		[-]	3.13
Main river slope		%	1.15
Concentration time		h	6.17

Morphometric features of Lake Atotonilco

Table 6 shows the estimated morphometric parameters for Lake Atotonilco. According to the reported figures, the lake has a maximum area of 26.45 km^2 with a maximum depth of 1.87 m and a storage capacity of 62.47 hm^3. The perimeter of the lake at its maximum water level is 45.71 km with a maximum length of 12.44 km and average slope of 0.64%. According to Håkanson (2004) the shape of the lake could be classified as convex (Cx). The transparency of the lake waters is very low because the shallowness of the lake and the clay soil that comprises its bottom, which are in constant resuspension due to wind.

Table 6. Morphometric features of Lake Atotonilco.

Parameters	Symbol	Units	Value
Maximum width	W_{max}	km	4.55
Average width	W	km	2.13
Watershed area	Ac	km^2	755.32
Lake area	AL	km^2	26.45
Light attenuation coefficient	K	[-]	1.05
Rivera development	DL	[-]	0.68
Elongation index	Ia	[-]	5.85
Coast development index	Dl	[-]	2.51
Insularity	IA		0.00
Maximum length	P	km^2	12.44
Average slope	S	%	0.64
Perimeter	P	km	45.71
Photic zone depth		m	0.06
Maximum depth	Z_{max}	m	1.87
Medium depth	Z_m	m	0.99
Average depth		m	1.10
Relative depth	Z_r	%	3.49
Major axis direction			N – S
Lake shape			Cx
Schindler relationship		[-]	12.45
Transparency		m	0.02
Volume	V	hm^3	62.47
Development volume	DV	[-]	1.60
Z_m / Z_{max}		[-]	0.53

Ac/A		[-]	33.55
Ac/V		[-]	12.09

Development of depth, area, and volume of the lake

Table 7 shows the temporary variations of perimeter, surface area, and storage volume of the lake calculated from the topographic and bathymetric vector data processed in a Geographic Information System.

Table 7. Variations of the surface area, perimeter, maximum depth, and storage volume of Lake Atotonilco in the period from August 2020 to December 2021.

Month	Year	Storage volume (hm^3)	Storage volume (m^3)	Surface area (km^2)	Surface area (m^2)	Perimeter (km)	Maximum depth (m)	Mean depth (m)
Aug	2020	34.54	34,541,507.53	20.90	20,899,190.00	32.15	1.04	0.38
Sep	2020	36.74	36,736,729.68	21.94	21,940,000.00	32.54	1.08	0.42
Oct	2020	42.52	42,521,800.36	23.10	23,097,210.00	35.80	1.27	0.61
Nov	2020	41.05	41,046,806.62	22.87	22,873,120.00	33.10	1.22	0.56
Dec	2020	37.90	37,900,457.08	23.07	23,069,580.00	32.82	1.06	0.39
Jan	2021	33.41	33,407,384.26	20.51	20,505,885.00	31.30	0.98	0.34
Feb	2021	30.30	30,295,388.60	19.65	19,647,160.00	31.27	0.87	0.29
Mar	2021	28.01	28,012,489.53	19.03	19,025,870.00	30.53	0.78	0.25
Apr	2021	21.29	21,294,320.79	16.54	16,537,090.00	26.87	0.54	0.14
May	2021	12.76	12,760,909.34	11.67	11,670,000.00	20.71	0.30	0.03
Jun	2021	1.32	1,319,115.93	1.28	1,284,812.00	12.71	0.22	0.01
Jul	2021	28.52	28,517,090.07	18.99	18,988,120.00	33.76	0.84	0.26
Aug	2021	33.77	33,765,195.16	21.09	21,090,000.00	33.99	1.13	0.47
Sep	2021	46.51	46,508,037.82	24.15	24,147,470.00	41.31	1.38	0.72
Oct	2021	62.47	62,469,385.11	26.45	26,450,310.00	45.72	1.87	1.10
Nov	2021	54.03	54,034,143.42	25.44	25,443,000.00	42.11	1.61	0.84
Dec	2021	47.38	47,384,660.30	25.20	25,200,000.00	42.10	1.36	0.61

According to the data reported in Table 4 and in Figure 6A and 6B, from August 2020 to December 2021, Lake Atotonilco had a maximum depth of 1.87 m with a maximum surface area of 26.45 km^2 and a maximum storage volume of 62.47 hm^3 in October 2021. The minimum values during the period were in June 2021, corresponding to the end of the dry season, where the depth diminished to scarcely 0.22 m, the wet surface area was 1.28 km^2 and the storage volume was barely 1.32 hm^3.

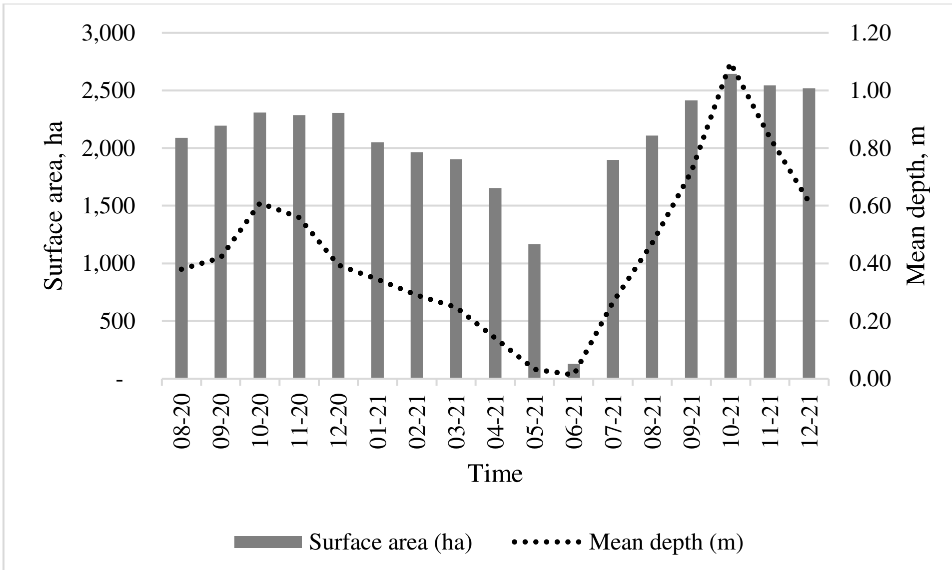


Figure 6A. Temporary variations of surface area and mean depth in Lake Atotonilco during the period of August 2020 to December 2021.

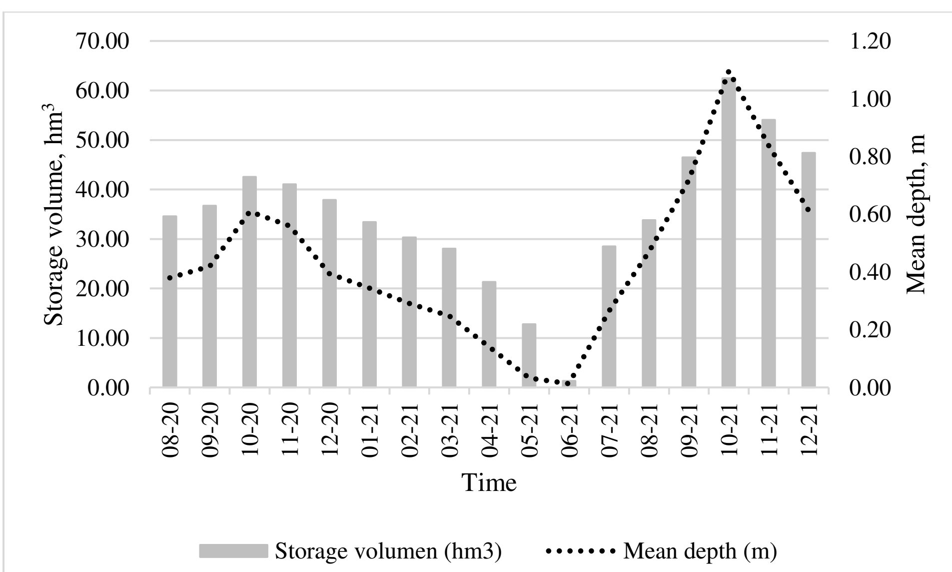
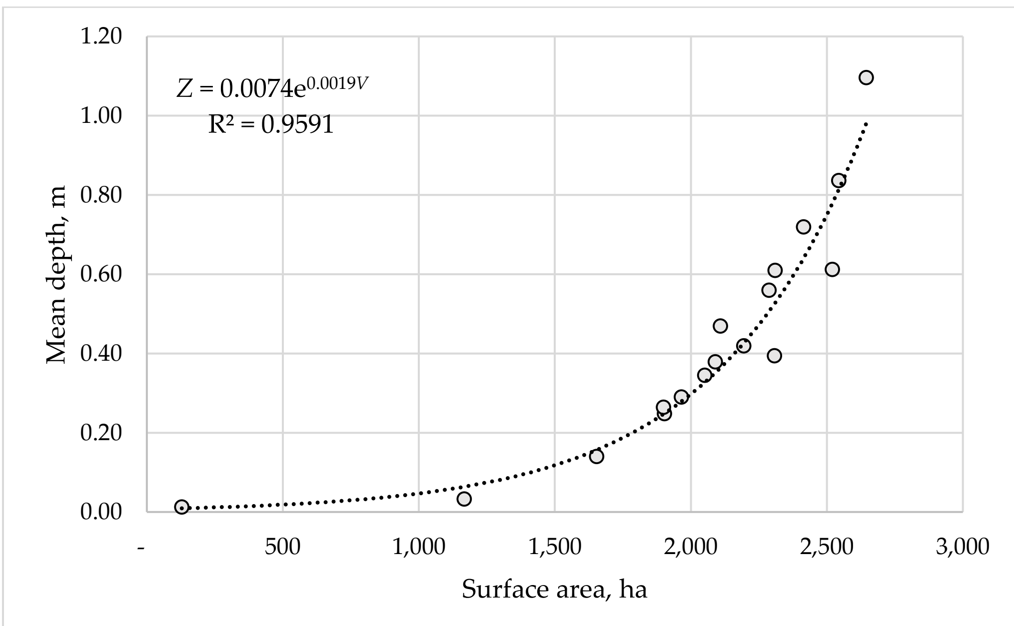


Figure 6B. Temporary variations of storage volume and maximum depth in Lake Atotonilco during the period of August 2020 to December 2021.

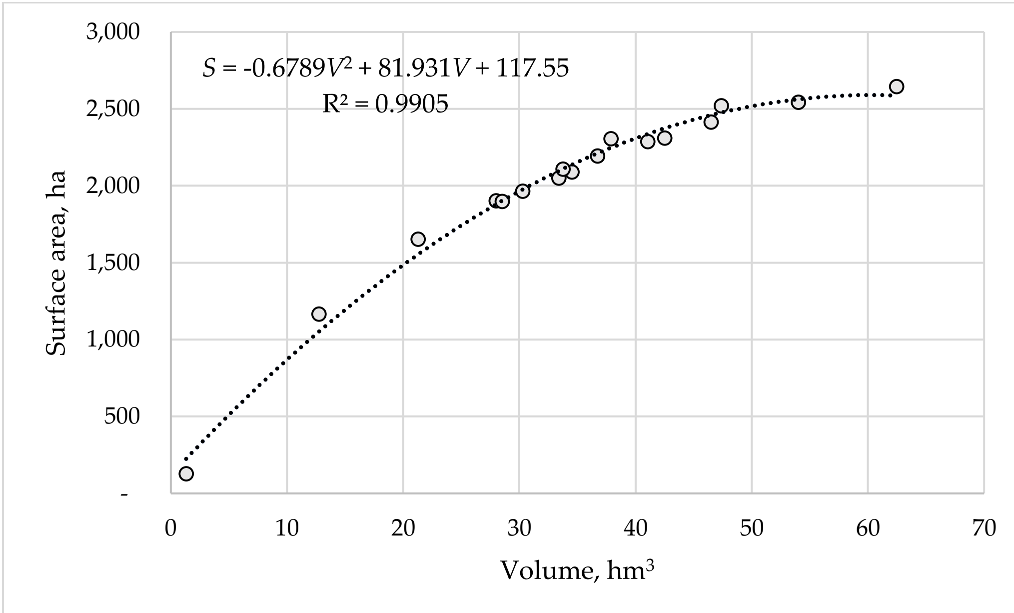
DISCUSSION

Hypsographic and volume curves

The respective hypsographic and volume curves namely mean depth (Z) - area (S) curve, and the area-volume (S-V) curve with its respective fitting equations are shown in figures 7A and 7B respectively.



(A)



(B)

Figure 7. Hypsographic (*Z*-*S*) curve and area-volume (*S*-*V*) curve for Lake Atotonilco.

To have a first approximation to the ecological volume of Lake Atotonilco, the data from Table 7 were used to build the curve shown in Figure 7A, which shows the best fit achieved correlating the average depth of the lake (*Z*) and the surface of it (*S*), which follows an exponential expression:

$$Z = 0.0074e^{0.0019S} \quad \text{Eq. (15)}$$

This equation has a correlation coefficient R^2 of 0.9591. In the same way, Figure 8B shows the behavior of the lake surface area data (*S*) with those of its volume (*V*), which follows a quadratic expression:

$$S = -0.6789V^2 + 81.931V + 117.55 \quad \text{Eq. (16)}$$

This equation has a high correlation coefficient achieving a R^2 de 0.9905.

According to Table 7, in October 2021 the conditions with the highest storage volume were reached during the monitoring period, with a Z_{max} of 1.87 m, a maximum surface area of S_{max} = 2,645 ha, and a maximum storage volume of V_{max} = 62.47 hm^3. With these data and applying Eq. (14) on the correlation Eq. (16), an ecological volume for Lake Atotonilco of V_e = 29.16 hm^3 was obtained. This ecological volume corresponds to an ecological surface of S_e = 1,929.23 ha (19.29 km^2). The ecological mean depth for Lake Atotonilco could also be calculated with Eq. (15) giving a value of Z_e = 0.29 m.

CONCLUSION

According to results the lake is currently practically without water in June. The storage volume and the surface area of the lake depends in an important way on the precipitation regime and the runoff of the watershed. It has been mentioned that the water pressure in the basin is very high because the volume in concession of the available surface and underground water exceeds 80%. This fact allows to assume that if there are no policies to protect the water resource, the lake may soon enter an intermittence regime with even longer periods of drought affecting the lake as a refuge of local and migratory bird species. In this work, a relevant indicator is proposed, which is the ecological volume of the lake, which determines to what extent protection measures for surface and groundwater should be implemented to ensure the minimum storage volume that the lake need to ensure the conservation of the aquatic and terrestrial species. It is important to highlight, this is one of the first research works where an ecological volume is proposed for a lake in Mexico, which originally didn't have any specific bathymetric information.

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References

Alatorre-Zamora, Miguel Angel, Campos-Enríquez, José Oscar, Rosas-Elguera, José Guadalupe, Peña-García, Laura, Maciel-Flores, Roberto, & Fregoso-Becerra, Emilia. (2015). Chapala half-graben structure inferred. A magnetometric study. *Geofísica internacional*, 54(4):323-342. Retrieved from http://www.scielo.org.mx/scielo.php?script=sci_arttext&pid=S0016-71692015000400323&lng=es&tlng=en.

Arche, A. (2008). Some precisions on the use of the term playa in the geologic literature. *Journal of Iberian Geology*, 34(1), 5-9. Retrieved from https://digital.csic.es/handle/10261/5470

Browne, R. A. (1981). Lakes as Islands: Biogeographic Distribution, Turnover Rates, and Species Composition in the Lakes of Central New York. *Journal of Biogeography*, 8(1):75-83. https://doi.org/10.2307/2844594

Campos, A. 1987. Procesos del ciclo hidrológico. Universidad Autónoma de San Luís Potosí. Vol. 1, t. 1/2. San Luís Potosí. México. pp. 2-52.

CONANP (2006). *Mexico's priority wetlands*. Comisión Nacional de Áreas Naturales Protegidas. Secretaría de Medio Ambiente y Recursos Naturales. México. 80 p.

de Anda-Sánchez, J. (2020) Precipitation in Mexico. In: Raynal-Villasenor J. (eds) Water Resources of Mexico. World Water Resources, vol 6. Springer, Cham. https://doi.org/10.1007/978-3-030-40686-8_1

de Anda, J., Díaz-Torres, J. de J., Gradilla-Hernández, M. S., & de la Torre-Castro, L. M. (2019). Morphometric and Water Quality Features of Lake Cajititlán, Mexico. *Environmental Monitoring and Assessment*, *191*(2):92. doi: 10.1007/s10661-018-7163-8.

Díaz, C., Mamado. K., Iturbe. A., Esteller. M. V., y Reyna. F. 1999. Estimación de las Características Fisiográficas de una cuenca con la ayuda de SIG y MEDT: Caso del curso alto del Río Lerma, Estado de México. Ed. Ciencias Ergo Sum. Julio. Volumen 6. Número dos. Universidad Autónoma del Estado de México. Toluca. México. pp. 124–134.

DOF (2016). *ACUERDO por el que se dan a conocer los resultados de los estudios técnicos de las aguas superficiales en las cuencas hidrológicas Laguna Villa Corona A, Laguna Villa Corona B, Laguna San Marcos-Zacoalco, Laguna de Sayula A y Laguna de Sayula B, mismas que forman parte de la Subregión Hidrológica Cuencas Cerradas de Sayula, de la Región Hidrológica número 12 Lerma-Santiago*. 07 de abril de 2016. Diario Oficial de la Federación. Secretaria de Medio Ambiente y Recursos Naturales. Estados Unidos Mexicanos. Retrieved from https://dof.gob.mx/nota_detalle.php?codigo=5432307&fecha=07/04/2016

ESRI (2021). ArcGIS Desktop. Retrieved from https://www.esri.com/en-us/arcgis/products/arcgis-desktop/resources

Florida LAKEWATCH, 2001. *A Beginner's Guide to Water Management - Lake Morphometry*. 2nd Edition. University of Florida, USA. 39 p. https://edis.ifas.ufl.edu/pdf/FA/FA08100.pdf

GBIF. (2022) *Global Biodiversity Information Facility*. IF Occurrence Download https://doi.org/10.15468/dl.ueet6n

Gradilla-Hernández, M.S., de Anda, J.*, García-Gonzalez, A., Meza-Rodríguez, D., Yebra Montes, C., Perfecto-Avalos, Y., 2020. Multivariate water quality analysis of Lake Cajititlán, Mexico. *Environmental Monitoring and Assessment*. 192(5):1-22. https://doi.org/10.1007/s10661-019-7972-4

Guerra, F. y González. J. 2002. Caracterización morfométrica de la cuenca de la Quebrada La Bermeja, San Cristóbal, Estado Táchira, Venezuela. Geoenseñanza. Vol. 7. Universidad de los Andes, Táchira. Departamento de Ciencias Sociales. Táchira. Venezuela. pp. 88-108.

Guilarte, R. 1978. Hidrología Básica. Facultad de Ingeniería. Universidad de Caracas Venezuela. Caracas-Venezuela. 667 p.

Håkanson, L. (1977). On Lake Form, Lake Volume and Lake Hypsographic Survey. *Geografiska Annaler: Series A, Physical Geography*, 59(1-2), 1-29. https://doi.org/10.1080/04353676.1977.11879944

Håkanson L. (2004). Lakes: form and function. The Blackburn Press, New Jersey, USA. 201 p. ISBN-10: 1930665245.

Horn, B. K. P. 1981. Hill shading and the reflectance map. *Proceedings of the IEEE*, 69: 14-47.

Horton, R. E. 1945. Erosional development of streams and their drainage basins; hydrophysical approach to quantitative morphology. *Bulletin of the Geological Society of América*, 56:275 – 370.

INEGI (2001). *Estudio Hidrológico del Estado de Jalisco*. Gobierno del Estado de Jalisco. Instituto Nacional de Estadística, Geografía e Informática. Aguascalientes, Aguascalientes, México. 87 p. ISBN 970-13-3561-9.

INEGI (2021a). Edafología. Retrieved from https://www.inegi.org.mx/temas/edafologia/

INEGI (2021b). Uso de suelo y vegetación. Retrieved from https://www.inegi.org.mx/temas/usosuelo/

INEGI (2021c). Modelos Digitales de Elevación de Alta Resolución LiDAR, con resolución de 5m. Superficie. ASCII. E15B87C2. Retrieved from https://en.www.inegi.org.mx/app/biblioteca/ficha.html?upc=702825836184

Jiménez E. H., & Materón, M. H. (1986). *Hidrología Básica*. Tomo III. Univalle 1986.

Kirpich, Z. P. 1940. Times of concentration of small agricultural watersheds. *Civ. Eng*, 10(6):362.

Klohn, W. 1970. Magnitudes fisiográficas e Índices morfométricos relacionados con la hidrología. Publicación Aperiódica No. 12 del servicio colombiano de Meteorología e Hidrología, Bogotá, Colombia. pp. 3-15.

Last, W. M. (2002). Geolimnology of salt lakes. *Geosciences Journal*, 6(4), 347-369. https://doi.org/10.1007/BF03020619

Llamas, J. 1993. Hidrología general. Principios y aplicaciones. Servicio Editorial de la Universidad del País Vasco, Québec, Canadá. pp. 2-20.

Meza-Rodríguez, D. et al., 2017. Régimen natural de caudales del río Ayuquila-Armería en el occidente de México. *Terra Latinoamericana*, 35(3):203-217, DOI: https://dx.doi.org/10.28940/terra.v35i3.224

Meza-Rodríguez, D., Martínez-Rivera, L.M., Mercado-Silva, N., García de Jalón-Lastra, D., González del Tánago-del Rio, M., Marchamalo-Sacristán, M. and De la Mora-Orozco, C. (2017). Régimen natural de caudales del río Ayuquila-Armería en el occidente de México. Terra Latinoamericana, 35(3): 203-217. (CRMCyT), Indizada CONACYT, ISSN: 0187-5779 / E-ISSN: 2395-8030, julio-septiembre. DOI: http://dx.doi.org/10.28940/terra.v35i3.224

National Meteorological Service (SMN) (2021). Información de estaciones climatológicas. Retrieved from https://smn.conagua.gob.mx/es/climatologia/informacion-climatologica/informacion-estadistica-climatologica

Oñate-Valdivieso, F., Bosque-Sendra, J., Sastre-Merlin, A. & Ponce, V. M. (2016). Calibración, validación y evaluación de un modelo hidrológico concentrado en un área montañosa al sur del Ecuador. *Agrociencia*, *50*(8), 945-963. Retrieved September 08, 2021, from http://www.scielo.org.mx/scielo.php?script=sci_arttext&pid=S1405-31952016000800945&lng=en&tlng=es.

Reyes-Trujillo, A., Ulises-Barroso, F., Carvajal-Escobar, Y., 2010. *Guía básica para la caracterización morfométrica de cuencas hidrográficas.* Programa Editorial Universidad del Valle. Cali, Colombia. 92 p. ISBN 9789587654011.

Richards, L. A. (Ed.) (1954). Diagnosis and improvement of saline and alkali soils. United States Department of Agriculture. Agriculture Handbook No. 60. 166 p. Retrieved from https://www.ars.usda.gov/ARSUserFiles/20360500/hb60_pdf/hb60complete.pdf

Rentería-Guevara, S. A., Sanhouse-García, A., & Bustos-Terrones, Y., Rodriguez-Mata, A. E., & Rangel-Peraza, J. G. (2019). A proposal to integrate the legal definition and official delineation of watersheds in Mexico: eight model case studies. *Rev. Ambient. Água*. 14(2):1-21. https://doi.org/10.4136/ambi-agua.2198

REPDA. (2022). *Base de datos del REPDA*. Comisión Nacional del Agua. México. https://www.gob.mx/conagua/acciones-y-programas/registro-publico-de-derechos-de-agua-repda-55190#:~:text=El%20Registro%20P%C3%BAblico%20de%20Derechos,y%20sus%20bienes%20p%C3%BAblicos%20inherentes.&text=Salvaguardando%20los%20derechos%20inscritos%20y,obtener%20constancia%20de%20los%20mismos.

Sánchez, V. A. 1987. Conceptos elementales de hidrología forestal agua, suelo y vegetación. La cuenca hidrográfica. Editorial. División de Ciencias Forestales. Primera Edición. Volumen 1. Universidad Autónoma de Chapingo. pp. 57-97.

Schloeder, C. A., N. E. Zimmerman and M. J. Jacobs. 2001. Comparison of methods for interpolating soil properties using limited data. Soil Science Society of America Journal. 65: 470-479.

Schumn, S.A (1956). Evolution of drainage systems and slopes in Badlands at Perth Amboy. New Jersey. *Geological Society of America Bulletin*, 67, 597-646. https://doi.org/10.1130/0016-7606(1956)67[597:EODSAS]2.0.CO;2

SE. (2012). Mexican Standard NMX-AA-159-SCFI-2012 that establishes the procedure for environmental flow determination in hydrological basins. Secretaría de Economía. México. Retrieved from https://www.gob.mx/cms/uploads/attachment/file/166834/NMX-AA-159-SCFI-2012.pdf

SEMARNAT. (2010). *NORMA Oficial Mexicana NOM-059-SEMARNAT-2010, Protección ambiental-Especies nativas de México de flora y fauna silvestres-Categorías de riesgo y especificaciones para su inclusión, exclusión o cambio-Lista de especies en riesgo*. Secretaría de Medio Ambiente y Recursos Naturales, México. https://www.profepa.gob.mx/innovaportal/file/3552/1/nom-059-semarnat-2010__30-dic-2010.pdf

Shang, S. (2013). Lake surface area method to define minimum ecological lake level from level-area-storage curves. *J. Arid Land*, 5, 133-142. https://doi.org/10.1007/s40333-013-0153-3

SEMADET (2005). *Laguna de Atotonilco. Ficha Informativa de los Humedales Ramsar*. Secretaría de Medio Ambiente y Desarrollo Territorial. Gobierno del Estado de Jalisco. México. Retrieved from https://semadet.jalisco.gob.mx/sites/semadet.jalisco.gob.mx/files/fichalagunadeatotonilco.pdf

Strahler, A. (1966). The Earth Sciences. Harper y Row. Segunda Impresión. Japón. pp. 577-592.

Surfer® (2021). *Surfer. Explore the depths of your data*. Golden Software, LLC. Colorado, USA. Retrieved from https://www.goldensoftware.com/products/surfer

Zárate-Del Valle P.F. et al. (2001) Geology, Sediments and Soils. In: Hansen A.M., van Afferden M. (eds) The Lerma-Chapala Watershed. Springer, Boston, MA. https://doi.org/10.1007/978-1-4615-0545-7_2