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HYDROLOGIC BALANCE OF LAKE ZAPOTLÁN, MEXICO

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Lake Zapotlán has undergone significant hydrologic imbalances in recent times, because of the increase in urban population and associated anthropogenic activities in the basin, and because of the endorheic (closed basin) features and shallow depth of the lake. These activities have put the economic and ecological survival of the lake and its ecosystem at risk. Over exploitation of the water resource, deforestation of the mountains surrounding the lake, and the poor treatment of sewage discharging into the lake have impacted its trophic status and hydrodynamics. Climatic patterns in the basin have also had a strong impact on the lake.

BACKGROUND

Location of the basin

The Lake Zapotlán Basin is located in the southern region of Jalisco State, Mexico, between 19° 34' and 19° 53' north latitude and 103° 24' and 103° 38' west longitude (Figure 1). The basin is bounded to the north by Lake Sayula and the Usmajac Hills, to the east by the Los Manzanitos and El Tigre Mountains, to the west by Media Luna Mountain, and to the south by the Apaxtépetl and Nevado de Colima volcanos. The latter is the highest mountain in the area with an elevation of 4,240 m amsl. The lake is located in the counties of Zapotlán el Grande, the second most populated area in the State of Jalisco, and Gómez Farías, both counties having a total population of about 150,000 inhabitants.

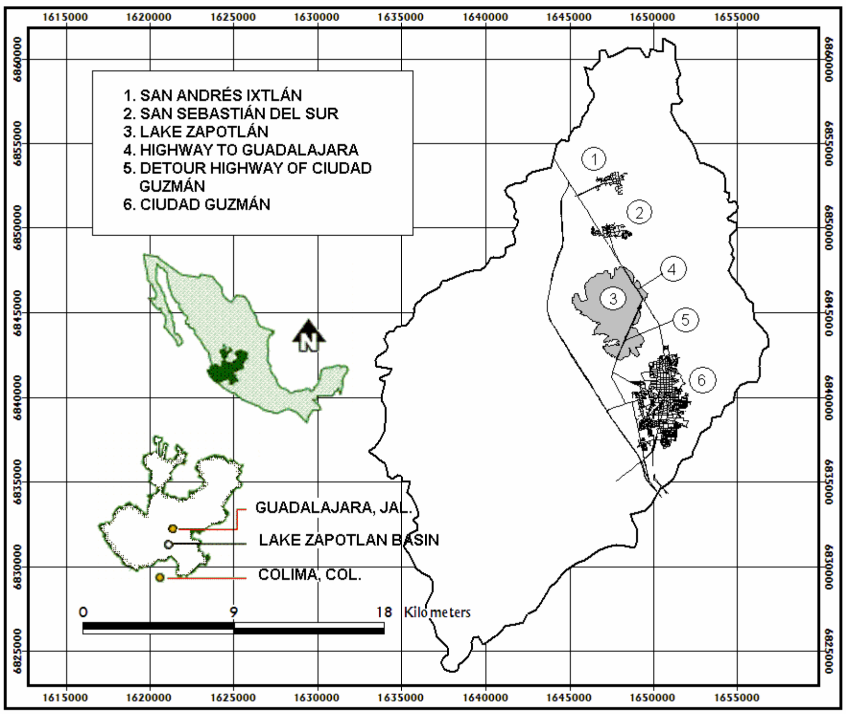

Figure 1. Geographical location of the Lake Zapotlán Basin.

Importance of the lake

The Lake Zapotlán Basin is especially important because it contains the second largest city in Jalisco State, Ciudad Guzmán. The city has a population close to 100,000 inhabitants with a population increase rate of about 1.5% (INEGI, 2000). In the last few decades the basin has undergone strong economic development in services, commerce, and the manufacturing sectors. In contrast, agriculture and cattle farming have decreased in recent years (INEGI, 1980, 1990, 2000).

The economic potential of the lake is based on the fishery production of two main nonnative species; common carp (68%), and aureus tilapia (32%). In spite of the increase in fishing effort, the severe eutrophication of the lake has caused a significant catch reduction of 50% for the year 2002 in comparison to 1998 data. As a result, some former fishing families have resorted to the production of handmade products using the invasive plant commonly called bullrush cotton tail (*Typha latifolia*) (CUSUR, 2002).

The basin has several potentially attractive recreational areas (aquatic sports, fishing and eco-tourism) that could be developed for tourism for the people of Guadalajara City, the capital of the

State located only 100 km to the north of the basin. Furthermore, the lake is considered as a priority area to study migratory waterfowl such as the high plateau duck (*Anaz diazi*), the pintail (*Anas acuta*), a species protected by Mexican environmental law, the white pelican (*Pelecanus erythrorihynchos onocrotalus*), the grey crane (*Grus canadensis*), the great white heron (*Ardea occidentalis*), and the common egret (*Casmerodius albus*) amongst others. In Lake Zapotlán there are two endemic fishes considered endangered species; *Goodea atripinnis* and *Poeciliopsis infans*. The first one has also been found in the Lerma-Santiago Basin and the second one in the Ameca, Magdalena, Armería, Coahuayana and Balsas Rivers.

Human activities in the basin and in the lake

As result of the climate, location in a closed basin, and shallow depth, Lake Zapotlán has undergone significant hydrologic imbalances throughout its history. However, the current anthropogenic activities in the basin are putting at risk the survival of the lake, and the economic and ecological sustainability of the lake and its basin. Of particular note is the construction of municipal roads that cross the lake. These have physically segmented the lake into three quasi-independent water bodies.

This segmentation, together with nutrient contamination, has caused changes in the morphometry, hydrodynamics, aeration and water quality of the lake, resulting in floating aquatic vegetation known as water hyacinth (*Eichhornia crassipes*) and bullrush cotton tail (*Typha latifolia*), which grew uncontrollably until 1994. In 1995, a program of water hyacinth elimination was implemented, resulting in the reductions in weed abundance noted in Figure 2. There have also been recent blooms of a blue green alga, possibly *Anabaena flos-aquae*, a cyanobacterium species that may cause health and odor problems. The primary sources of the nutrients supporting these nuisance blooms of aquatic plants derive from discharges of municipal waste waters that have been poorly treated, runoff from agricultural activities (crops and cattle), and urban runoff from Ciudad Guzmán, San Sebastián del Sur, and San Andrés Ixtlán. The over exploitation of the forest resource in the hills surrounding the lake has also contributed to acceleration of the erosion process in the basin, increasing the solids transport into the lake. The adverse environmental impacts are clearly reflected in the considerable reduction of native and migratory fauna, and in frequent flooding. In particular, commercial fishing has diminished since 1998 (CUSUR, 2002). Figure 2 shows the distribution of aquatic weeds along the lake from Landsat TM satellite images (1989, 1994).

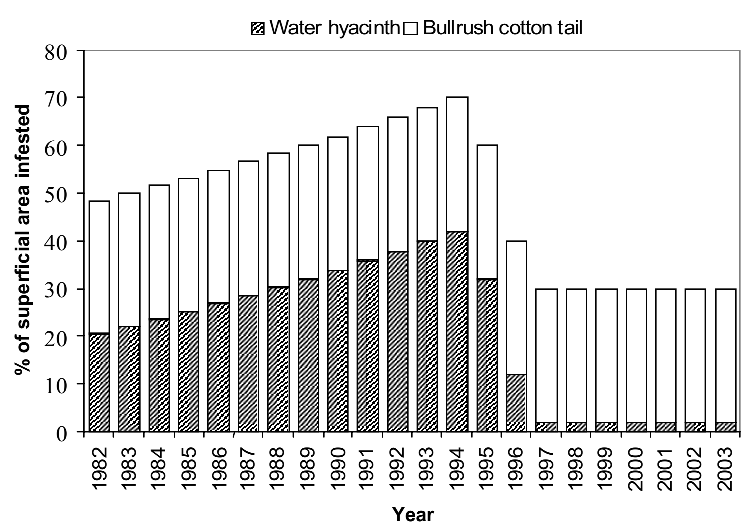

Figure 2. Area covered by aquatic weeds in Lake Zapotlán.

There are historical records dating from the Spanish colonial period showing major water level fluctuations in the lake from a completely dry lake to flooding above 1,515 m amsl covering agricultural areas around the lake. Today the main water discharges from the lake are direct water extractions and pumping from water wells located close to the lake. In both cases the water is used for irrigation of local crops covering more than 1,500 ha (CEASJ, 2003). The anthropogenic activities in the basin, the over exploitation of the surface water and groundwater, the deforestation in the basin, and the direct discharges of sewage have also impacted the climatic patterns in the basin and have produced a hydraulic imbalance in the lake, causing flooding affecting more than 75% of the cultivated land on the margins of the lake.

This paper provides a detailed water balance of the lake for the period of 1982-2003, based on the existing hydrologic and meteorological information from the basin measured by the Mexican National Water Commission (CNA, 2004) and the State Water Commission of Jalisco State (CEASJ, 2003). Due to the limited information about water levels in the lake, we applied a simulation model to quantify the level, volume and surface water of the lake, using as primary data the water level of the lake registered in June 1982.

Climate

According to the climate classification of Köpen, the climate of the basin belongs to the type (A)c(Wo)(w) a (i). This translates to fairly warm, fairly wet with rains during the summer season, and with average winter rain less than 5% of the annual total precipitation. The average annual temperature is 19.6°C with a variation of ±5.9°C. The maximum temperatures are in July and the minimum temperatures are in January (INEGI, 2001).

The yearly mean hailstorm frequency is two days and there are on average 10 days of frost per year. The average annual rainfall in the basin is 813 mm with most rainfall occurring from June to September. The maximum precipitation in the basin is 1,100 mm, and occurs in the northwest in the El Tigre Mountains, while the minimum precipitation occurs in the east and southeast part of the Basin, reaching only 700 mm (CEASJ, 2003).

The month of maximum precipitation is July, with between 340 and 350 mm, whereas February is the driest month with 10 mm or less (SPP, 1981). The mean annual evaporation in the basin is 611 mm, with a maximum evaporation of 179 to 252 mm during the months of March, April and May. The minimum evaporation occurs in December, with a mean value of 87.8 mm (CCT-UdG, 1995). The main wind directions are south-southeast then north-northeast with an average wind speed of 8.64 km/h and gusts of winds to 15.6 km/h (CNA, 2002).

Geomorphology

The Lake Zapotlán Basin is located in the physiographic province of the Mexican Transvolcanic Belt (MTVB), a volcanic arc that emerged during the Tertiary Pliocene and continued until the Quaternary era. This volcanic event was caused by the subduction of the Rivera Plate and the Cocos Plate over the North American Plate. The main geological components of the basin are limestone, a sequence of volcanic sedimentary, and sand-lutite belonging to the Lower Cretaceous, a sand-lutite from the Upper Cretaceous, granite from the Cretaceous, andesite from the Lower Tertiary, and a sand-conglomerate from the Upper Tertiary. The Zapotlán Basin is classified as a tectonic *graben*, filled with hundreds of meters of volcanic ash and pyroclastic spills alternating with lacustrine sediments (diatomaceous) from the Tertiary and covered by alluvial and lacustrine sediments from the Quaternary era.

The basin is bounded on the north by a mountain of pyroclastic origin, to the east by a group of mountains arising from the fold of sedimentary marine rocks, to the south by a monogenetic volcano, and to the west by a geological formation of lavas of dacitic origin, and to the southeast by a volcano of basic andesitic origin. According to geological, hydrological and biological studies, it has been suggested that around one million years ago, at the western part of the MTVB there existed a primitive internal lake, named Xalisco Lake, having a probable surface area of about 70,000 km^2. The intensive volcanic activity of the MTVB subdivided this enormous lake into different closed basins such as Lake Chapala (de Anda et al., 1998), Lake Sayula-Zacoalco, and Lake Zapotlán (SARH, 1972).

HYDROLOGY

General features of the basin

The basin has a maximum length of 39.5 km in the northeast-southwest direction, a maximum width of 23.11 km in the north-south direction, a shoreline length of 110 km, and a total surface area of 45,500 ha. The topography varies from an elevation of 1,497 m amsl at the surface of the lake, to 3,900 m amsl at the El Águila Peak located in the volcano Nevado de Colima. The main slopes are greater than 15%. The principal soil types in the basin are haplic feozem (43%), chromic cambisol (30%), and euritic regosol (20%) (INEGI, 2001). Due to the high and medium permeability features of the soil, there are very few surface streams. Table 1 shows the land uses in the basin.

Table 1. Land uses in the Lake Zapotlán Basin.

Land use	Hectares	Percentage
Irrigated agriculture area	1,576	3.7
Temporal agriculture area	17,425	41.0
Seeded pasture	2,834	6.7
Coniferous forest	11,960	28.1
Tropical deciduous forest	3,278	7.7
Secondary vegetation	3,020	7.1
Urban zone	845	2.0
Lake and wetlands	1,562	3.7
Effective surface area	42,500	100.0

Lake Zapotlán Basin

The Lake Zapotlán Basin is integrated into a group of neighboring closed basins such as Lake Sayula, Lake San Marcos, and Lake Atotonilco, together covering a surface area of 318,000 ha. Lake Zapotlán is the main water reservoir in its basin. In the recent past, some of the creeks that drained into the lake, that are presently intermittent, were considered as important perennial streams. Because of these inflows, the lake covered a larger surface area compared with the present one.

Deforestation at higher altitudes of the basin results in an increase in surface runoff and a decrease in groundwater recharge, which may in turn amplify water level fluctuations in the lake. The Lake Zapotlán Basin is divided into eight sub-basins, with drainage patterns classified as sub-dendritic, denditric and sub-parallel, having a density of 0.34 streams/km^2 in the plains and 3.89 streams/km^2 in the hills (UdeG, 2002). The sub-basins located in the northeast and east part of the lake are the main water contributors to the lake during the rainfall period. Unfortunately, today the only permanent water source discharging into the lake is the sewage coming from Ciudad Guzmán, San Sebastián del Sur, and San Andrés Ixtlán.

Morphometric description of Lake Zapotlán

The highway to Guadalajara crosses the lake, drastically modifying the shoreline, and severely affecting the ecosystem. The road changed the hydrodynamic patterns of the lake, resulting in stagnant zones with poor water quality. Around 30% of the surface area is a littoral zone occupied by waterweeds located mainly in the south and west part of the lake.

The deepest zone is located in the mid-eastern part of the lake. The water column is considered completely mixed due to the permanent winds. Despite being located in a closed basin, the lake has a short residence time of about seven months. On average, the main outflows of the lake are water extractions for irrigation (37.4%), evapotranspiration (33.6%) and evaporation (29%). Table 2 shows the average morphometric parameters of the lake as estimated using hydrologic records for the last 22 years, and a simulation program to calculate the water balance of the lake.

Table 2. Morphometric Parameters of Lake Zapotlán

Parameter	Value
Maximum length (NW-SE)	5,271 m
Maximum wide (East-West)	4,300 m
Surface area	1,109.3 ha
Volume	19.612 Mm^3
Maximum depth	4.8 m
Mean depth	1.66 m
Shore line length	25,060 m

Bathymetry of Lake Zapotlán

Recently the State Water Commission (CEASJ, 2003) carried out a bathymetric study of the lake using transverse paths and topo-bathymetric curves for every 0.25 m depth. Figure 3 shows the hypsographic and volume curves of the lake. Equation 1 was used to estimate the volume of the lake as a function of its coverage area.

$$V_{i,i+1} = \int_{H_i}^{H_{i+1}} A(z)dz \quad (1)$$

where:

z = elevation, m amsl

$A(z)$ = area in every level curve, m^2

$V_{i,\, i+1}$ = volume of the segment between two successive elevations, m^3

$H_i,\, H_{i+1}$ = successive elevations.

We used the trapezoidal rule to estimate the integral equation (1)

$$V_{i,i+1} = \left[\frac{A(H_i) + A(H_{i+1})}{2}\right](H_{i+1} - H_i) \quad (2)$$

Where $A(H_i)$ and $A(H_{i+1})$ are the areas of the level curves corresponding to the elevations H_i and H_{i+1}, respectively. The accumulated volume from the maximum depth of the lake to the elevation H was calculated by using following equation:

$$V_H = \sum_{j}^{H} \left[\frac{A(H_j) + A(H_{j+1})}{2} \right] (H_{j+1} - H_j) \quad (3)$$

Results obtained from this numerical method are shown on the right vertical axes on Figure 3.

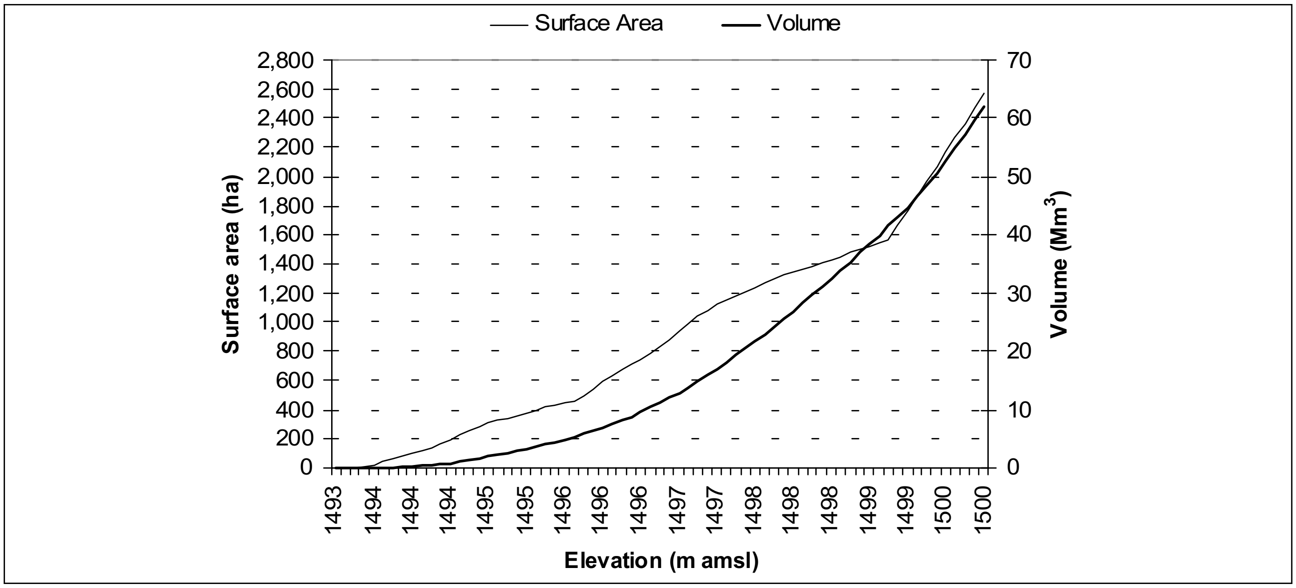

Figure 3. Hypsographic curves of Lake Zapotlán.

Accumulated sediment

The main factors contributing to high accumulated sediments in the lake include the high slopes around the basin, the erodible features of the soil, the uncontrolled deforestation in the higher parts of the mountains surrounding the lake, the substitution in the lower part of the basin of endemic species by agriculture, and the increase of the urban area of Ciudad Guzmán. This results in an increase in surface water velocity to the lake, carrying solids and contaminants and affecting water quality. It was estimated that the maximum discharges draining to the basin carry about 550,000 tons of sediments per year to the lake (UdG, 2002). The shape of the shoreline of the lake shows that all the streams discharging to the lake deposit large quantities of sediments at their mouths.

HYDROGEOLOGY

The materials that have filled the Zapotlán graben developed the existing aquifer system. Generally the volcanic rocks are fractured and are permeable, although they show impermeable horizons. Andesitic spills form a geological basement located at approximately 700 m depth.

Alluvial and lacustrine materials having high permeability compose the main lithology present in the aquifer, but there are also some intercalated horizons of materials having low permeability such as clay, lavitic spills, and pyroclastic materials.

The thickness of these materials under the lake is about 250 m and about 300 m around the lake. The first aquifer is located in geological materials between 170 and 300 m depth. The materials encountered in this horizon are sand, gravel, clay, and clasts, but some lateral variations have been noted due to intercalated and confined volcanic ashes. In other places close the lake, a second aquifer was located at about 170 m in basaltic altered rock. The depth of static water levels varies from 1 to 106 m (INEGI, 2001).

Considering the aquifer flow directions, it is possible that there is groundwater communication between the Lake Zapotlán Basin and Lake Sayula located to the north, and also with the Zapotiltic Valley located to the south (UdG, 2002). About 50 wells, 12 waterwheels, and 6 springs, including La Catarina Spring, are located in the basin. The over exploitation of the groundwater resources of the basin has produced an annual average drop of 0.50 m in the static water levels during the last ten years (INEGI, 2001) causing cracking and subsidence in the basin (CUSUR, 2002).

The basin has about 1,576 ha of irrigated land, of which 700 ha are irrigated with lake water, and the remainder with groundwater (CEASJ, 2003). Due to frequent earthquakes in the region from both volcanic and tectonic origin, the sewage system of Ciudad Guzmán has been affected by leaks that allow flows to the aquifers, contaminating them by infiltration (INEGI, 2001). The main water uses of groundwater and lake water in the basin are irrigation and watering (90%), industrial use (7%) and urban use (3%) (INEGI, 2001).

HYDROGEOCHEMISTRY

As a result of geothermal factors, the temperature of groundwater in the Basin is about 30°C (INEGI, 1996), but this does not have any apparent implications for groundwater quality. The Mexican National Water Commission classifies the chemical quality of groundwater as suitable for drinking, having a mean total dissolved solids concentration of 396 ppm. However, some traces of methane have been found in some wells used for irrigation and water supply for the urban areas causing some health problems among the population (UdG, 1999). The hardness of the lake is about 192 mg $CaCO_3$/L, which is considered a high value for urban uses. The mean pH value in the lake is relatively high (up to 9.3). This pH value frequently leads to the conversion of dissolved ammonium ion to ammonia gas, thus degrading water quality, and resulting in fish kills because of its toxicity.

HYDROLOGIC ANALYSIS

Hydrologic simulation of Lake Zapotlán was carried out using observed meteorological data in the Zapotlán Basin during the period June 1982 to December 2003. Monthly data were calculated considering the hypsometric model of the lake (Figure 3) and the lake level recorded in June 1982 as initial conditions. A General Purpose Simulation System (GPSS) was also used as a simulation language (Minuteman Software, 2000) (Table 3). To estimate the evaporation and evapotranspiration of the lake waters, it was necessary to assume that the water weeds in the lake are static around the shoreline of the lake in a certain fixed amount, and also that the water surface area is constant, with a value of 1,240 ha. The amount of water evaporated monthly in the non-vegetated portion of the lake $\hat{Q}_{5,ij}$ at year i and month j in Mm^3 was calculated using the following equation:

$$\hat{Q}_{5,ij} = \frac{k_p E_{ij}\left(A_{ij} - M_{ij}\right)}{100{,}000} \qquad (4)$$

where:

k_p = 0.92, a non-dimensional net evaporation factor of Lake Zapotlán (CEASJ, 2003).

E_{ij} = monthly evaporation measured at the Ciudad Guzmán meteorological station in year i and month j, in mm/month.

A_{ij} = total surface area of the lake in the year i and month j, obtained from Figure 3, in ha.

Table 3. GPSS Model for Hydrological Balance of Lake Zapotlán

10	ELEVA	FUNCTION P1,C69
DATA…		
20	AREA	FUNCTION P2,C137
DATA…		
30	PRECG	FUNCTION X1,L247
DATA...		
40	PRECCA	FUNCTION X1,L247
DATA…		
50	EVAPO	FUNCTION X1,L247
DATA…		
60	DESRES	FUNCTION X1,L247
DATA...		
70	COBER	FUNCTION X1,L247
DATA…		
80	CESC	FUNCTION X1,L247
DATA...		
90	EXTR	FUNCTION X1,L247
DATA…		
110	TAP	FVARIABLE (FN$COBER-(1240-FN$AREA))#X$KEY
120	ESC	FVARIABLE FN$PRECCA#FN$CESC#.425000
130	LLZ	FVARIABLE FN$PRECG#FN$AREA/100000
140	DAR	FVARIABLE FN$DESRES
150	INF	FVARIABLE 0.4
160	TIN	FVARIABLE V$ESC+V$LLZ+V$DAR+V$INF
170	ELZ	FVARIABLE (FN$EVAPO#0.92)#(FN$AREA-X5)/100000
180	ETM	FVARIABLE (V$ELZ#X5)#2/(FN$AREA-X5)
190	EXT	FVARIABLE FN$EXTR
200	TSA	FVARIABLE V$ELZ+V$ETM+V$EXT
210	ALF	FVARIABLE P1+V$TIN-V$TSA
220	VOL	EQU 10.285700
230		GENERATE 0
240		ASSIGN 1,VOL
250		OPEN ("MILAGO.TXT"),,
260		WRITE (POLYCATENATE(“labels”)),,
270		CLOSE
280	BUCLE	TEST L X1,261,FIN
290		OPEN ("MILAGO.TXT"),,
300		SAVEVALUE 1+,1
310		SAVEVALUE KEY,1
320		SAVEVALUE 2,P1
330		ASSIGN 2,FN$ELEVA
340		SAVEVALUE 3,P2

The surface area of the water weeds, M_{ij}, on Lake Zapotlán in year i and month j, in ha, was estimated using following equation:

$$M_{ij} = \left[1{,}240S_i - J\left(1{,}240 - A_{ij}\right)\right]I \qquad (5)$$

where:

S_i= fraction of water surface area of the lake, having a standard surface of 1,240 ha, invaded by water weeds in year i estimated by using Figure 2, and the following relationships:

$$I = \begin{cases} 0, \text{ if } 1240S_i < 1240 - A_{ij} \\ 1, \text{ if } 1240S_i > 1240 - A_{ij} \end{cases} \qquad (6)$$

$$J = \begin{cases} 0, \text{ if } A_{ij} > 1{,}240 \\ 1, \text{ if } A_{ij} < 1{,}240 \end{cases} \qquad (7)$$

The monthly volume evapotranspired in the vegetated portion of the lake $\hat{Q}_{6,ij}$ at year i and month j, in Mm^3, was estimated using following equation:

$$\hat{Q}_{6,ij} = \frac{\hat{Q}_{5,ij} M_{ij} k_t}{A_{ij} - M_{ij}} \qquad (8)$$

where:

k_t = 2.0, the evapotranspiration factor measured in bullrush and aquatic hyacinth (*http://aquat1.ifas.ufl.edu*).

Figure 4 shows that after 1996 the evaporation is greater than the evapotranspiration because of the reduction in the abundance of water hyacinth. The precipitation in 1991 and 1992 was classified as atypical because it was influenced by the climatic phenomenon called El Niño, that produced abnormally heavy precipitation between December 1991 and January 1992.

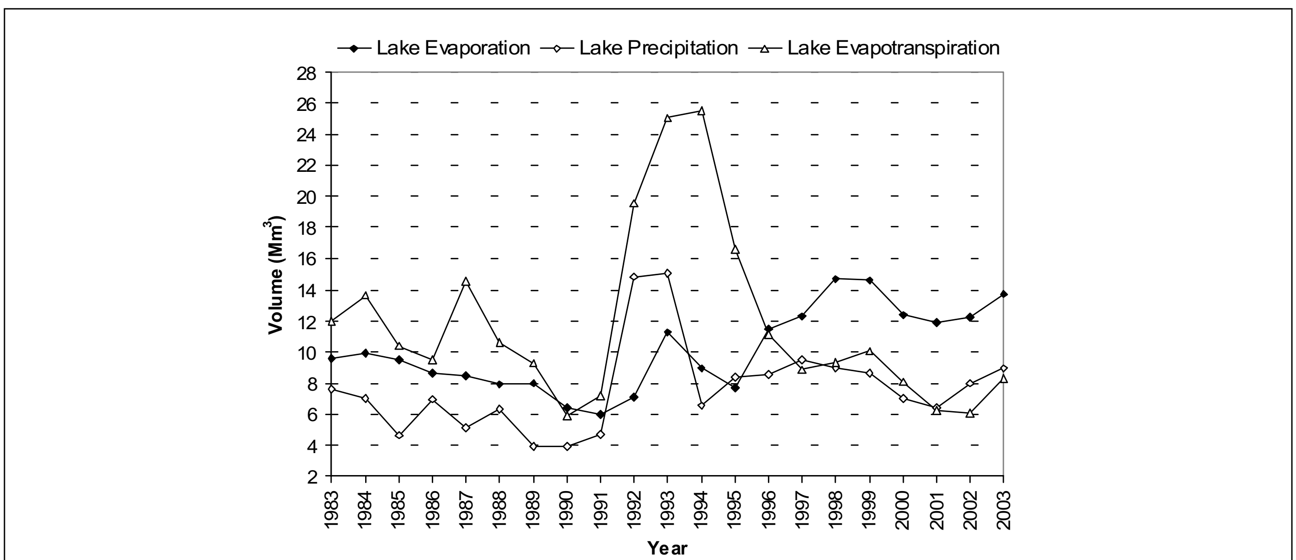

Figure 4. Annual precipitation, evaporation, and evapotranspiration in Lake Zapotlán.

Given the available information, the water balance equation for Lake Zapotlán can be expressed as follows:

$$S(t)\frac{dV}{dt} = \left[Q_1(t) + Q_2(t) + Q_3(t) + Q_4(t)\right]_{inlets} - \left[Q_5(t) + Q_6(t) + Q_7(t)\right]_{outlets} \quad (9)$$

where:

$S(t)$ = storage water volume in the lake in month t, in Mm^3/month

V = lake volume in month t, in Mm^3

$Q_1(t)$ = surface runoff to the lake in month t, in Mm^3/month

$Q_2(t)$ = direct precipitation onto the lake in month t, in Mm^3 /month

$Q_3(t)$ = sewage flows discharged in the lake in month t, in Mm^3 /month

$Q_4(t)$ = groundwater flows discharged to the lake in month t, in Mm^3 /month

$Q_5(t)$ = evaporation rate in the non-vegetated portion of the lake in month t, in Mm^3 /month

$Q_6(t)$ = evapotranspiration in the vegetated portion of the lake in month t, in Mm^3 /month

$Q_7(t)$ = surface and adjacent groundwater extractions from the lake in month t, in Mm^3/ month

To calculate the runoff coefficients in the basin, a runoff-weighted factor K of 0.161 was used. The Thiessen polygon method was used to weight the precipitation measured at the meteorological stations located in Atoyac (3%), San Gregorio (16%) and Ciudad Guzmán (81%). The groundwater infiltration to the lake was calculated adjusting the predicted lake levels with Equation (9) with the empirically observed water levels of the lake. Unfortunately there is no record of observed levels, and the only credible lake level was recorded in June 1982.

Figure 5 shows the interaction between the inlet and outlet annual mean flows of the lake. When both flows are correlated in year *i*, a correlation factor $R = 0.44$ was obtained, but when the inlet mean flow in year *i* was correlated with the outlet mean flow in year *i*+1, a correlation factor of 0.82 was obtained. Consequently we established a rule of thumb for Lake Zapotlán: the water inflow to the lake in year *i* is equal to the outflow in year *i*+1. Figure 6 and Table 4 show in detail, the components in the water balance of the lake.

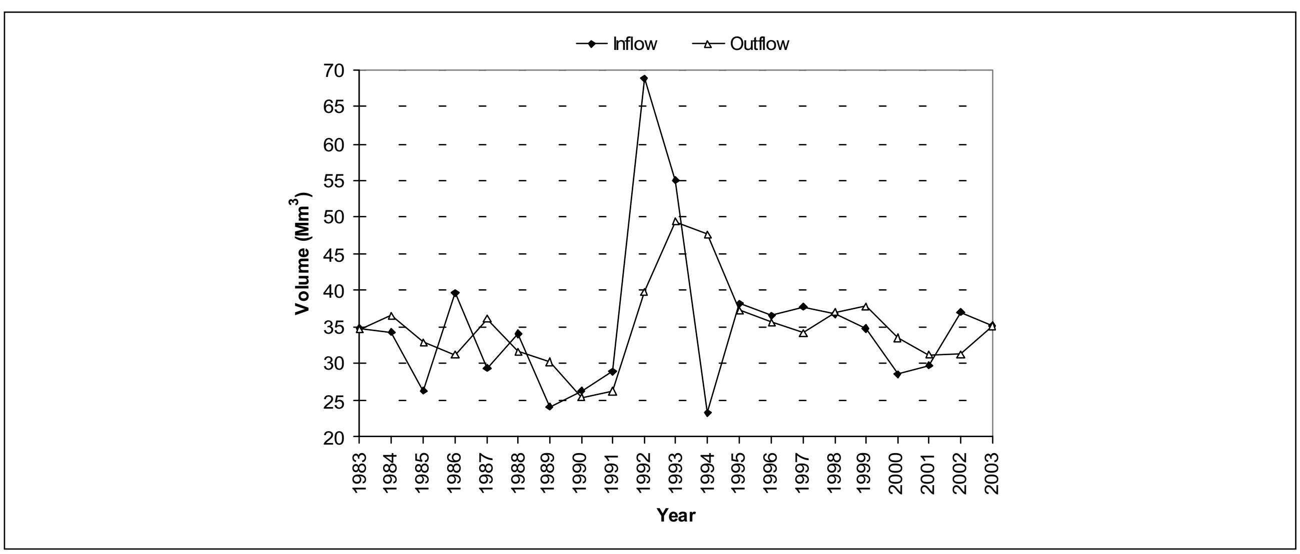

Figure 5. Annual inlet and outlet flow in Lake Zapotlán.

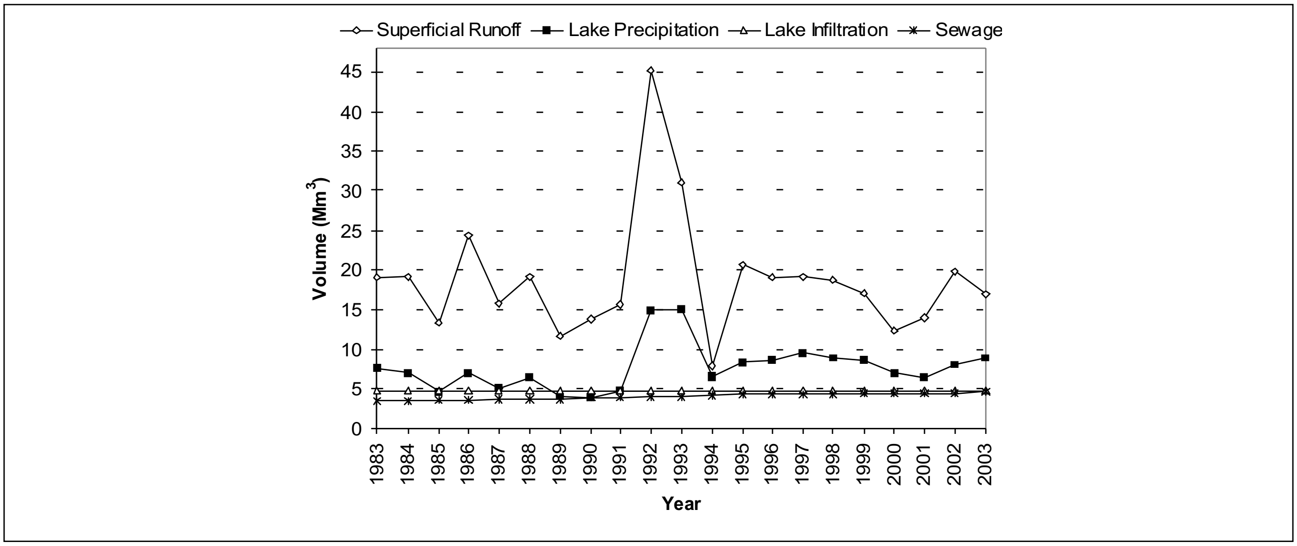

Figure 6a. Main annual inlet flows in Lake Zapotlán.

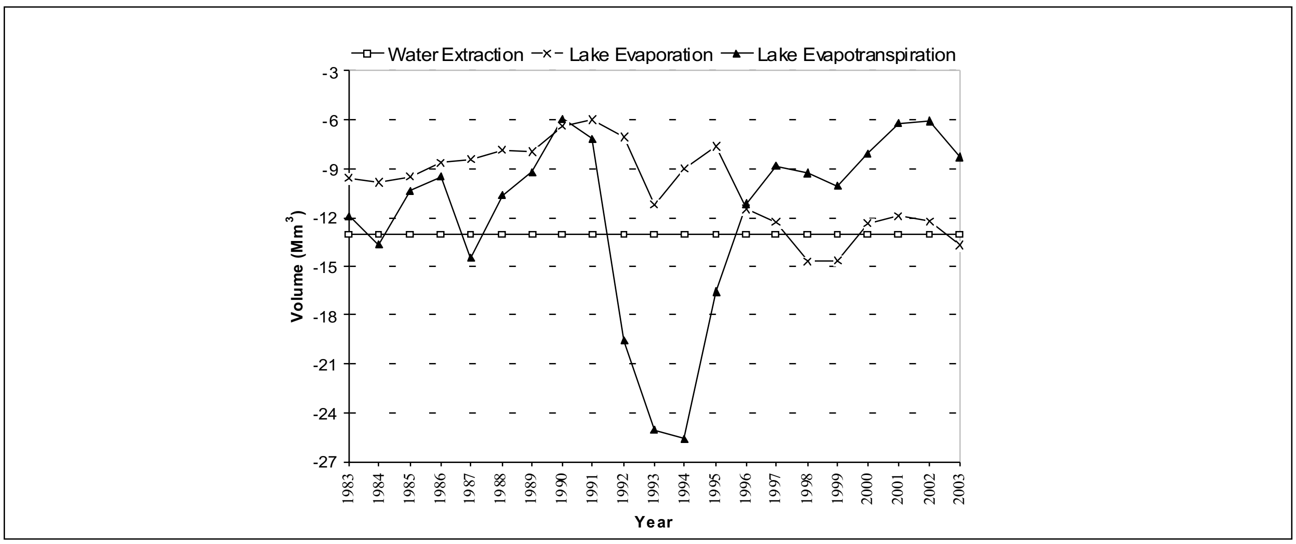

Figure 6b. Main annual outlet flows in Lake Zapotlán.

Table 4. Hydrologic Balance of Lake Zapotlán in Mm^3 (Annual Average 1982-2003)

Component	**Inflow**		**Outflow**		**Net Accumulation**
	Qty	%	Qty	%	
Runoff	18.91	53.25			
Precipitation	7.76	21.85			
Groundwater Infiltration	4.80	13.52			
Sewage	4.04	11.38			
Water Extraction			13.00	37.36	
Evapotranspiration			11.70	33.62	
Evaporation			10.10	29.02	
TOTAL	35.51	100.00	34.80	100.00	+0.71

Figures 7 and 8 show that after the appearance of the El Niño phenomenon in December 1991, a recovery of the water level of the lake of 1 m occurred, equivalent to 11 Mm^3 of water storage. To estimate the hydraulic residence time of the lake τ_i in year i in relation to the total annual inflow to the lake in year i, the following equation was used:

$$\tau_i = \frac{V(i)}{Q_1(i) + Q_2(i) + Q_3(i) + Q_4(i)} \tag{10}$$

Results of this equation are reported on Figure 9. Figure 10 shows the difference between the total annual inflow to the lake and total annual outflow from the lake.

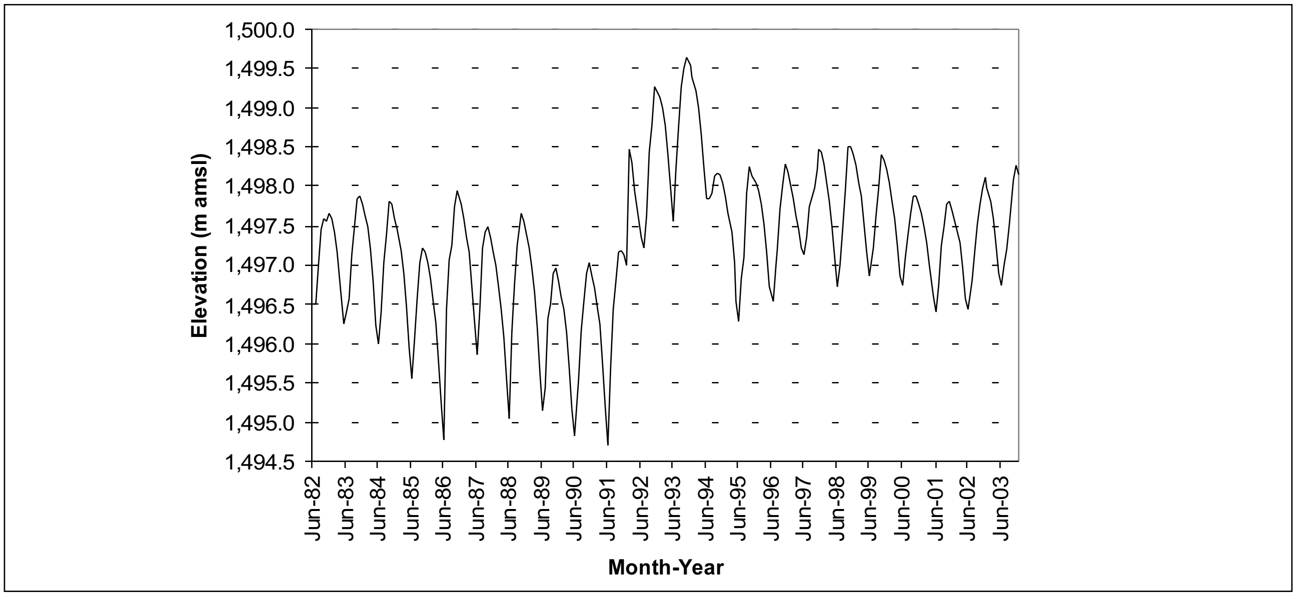

Figure 7. Calculated monthly surface level in Lake Zapotlán.

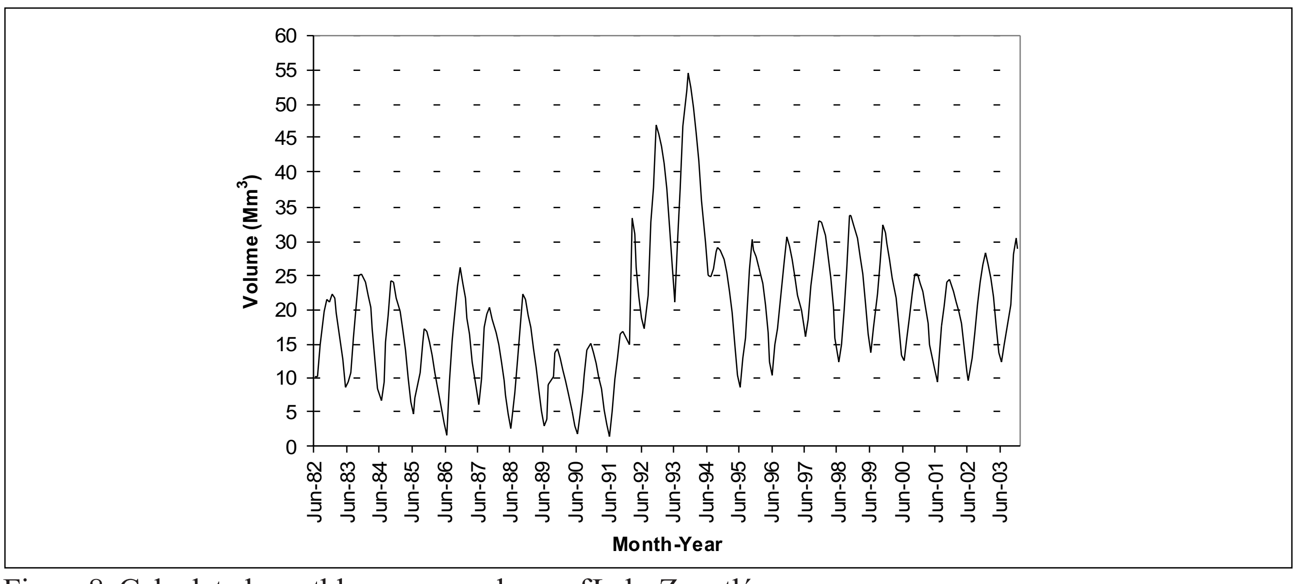

Figure 8. Calculated monthly average volume of Lake Zapotlán.

CONCLUSIONS AND COMMENTS

Results of the simulation model show large water level variations in the lake (Figure 7) and consequently in its storage volume during the period of study (Figure 8). The influence of El Niño as a climatic phenomenon influencing the water balance of the water body is also evident.

In the 1980s, the water levels in the lake were quite low. This could be the result of low precipitation in the basin (Figure 4), although in the neighboring basin of Lake Chapala, precipitation maintained its mean values without significant changes during this period (de Anda et al., 1998). Water extractions for agriculture could have contributed to the decrease in water levels.

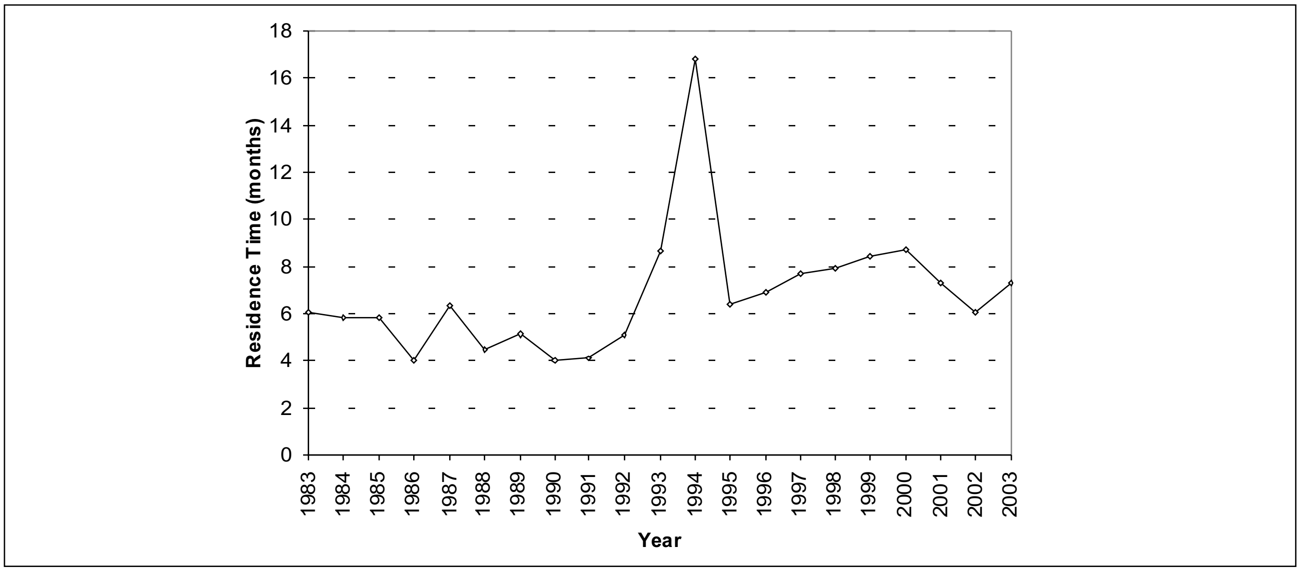

Figure 9. Mean annual inflow residence time in Lake Zapotlán.

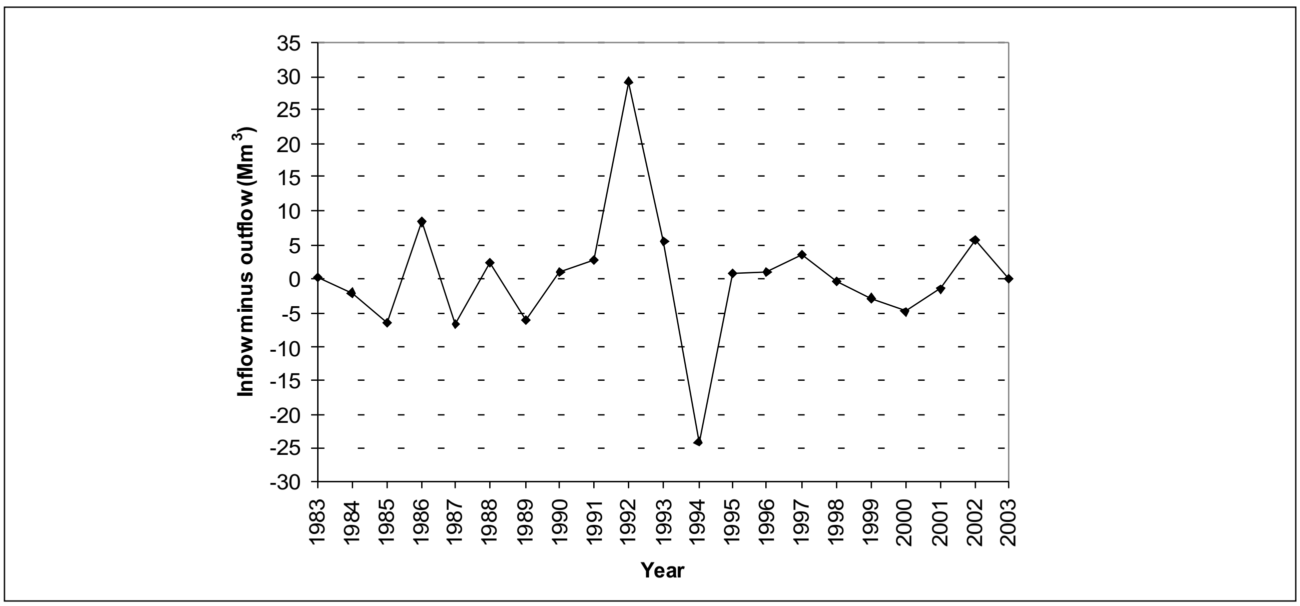

Figure 10. Differences between total annual inflow and outflow in Lake Zapotlán

During the second period (1992-1993) water levels were extremely high, due to an atypically long rainfall season producing flooding water levels on the lake.

The third period has also been associated with high lake levels, because of the increase in the annual mean precipitation, starting in the 1990s and continuing into the first three years of the present century. In 1992 (see Figure 10) one can see a positive difference of 30 Mm^3 between contributions and extractions to the lake; in 1993 this difference was only 5 Mm^3. In contrast, in 1994, this difference was negative reaching an historical record of 24 Mm^3 of water losses from the lake.

This imbalance produced an increase of three times in the mean hydraulic residence time of the lake (Figure 9). This perturbation of the system was the result of the atypical precipitation that occurred in 1991 and 1992, of the historical diminution of runoff throughout the basin, and of the high evapotranspiration in 1994 because of blooms of floating and fixed aquatic weeds in the lake.

As shown in this study, precipitation, groundwater and runoff are the main natural water contributors to the lake. The deforestation of the basin, without doubt, has affected the amount of runoff entering the lake. The sewage discharged directly to the lake with or without partial treatment is unfortunately one of the most important anthropogenic water contributions to the lake.

From this study we conclude that it is necessary to continuously monitor the main climatic and hydrologic variables affecting the water balance of the lake. The hydrologic situation of the lake needs to be analyzed and reported periodically to the public, and decision makers. Since the presence of large amounts of waterweeds in the lake is a symptom of anthropogenic contamination, it is also desirable to measure the behavior of the water quality parameters of the main streams discharging into the lake.

It is evident that the entire basin requires better water and wastewater management policies, regulations for groundwater extraction, control of deforestation, improvement in agricultural practices, and land use planning throughout the basin to create a sustainable environment. The highway that crosses the lake should be relocated to improve circulation within the lake.

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