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SIMPLIFIED HYDROLOGIC CORRELATIONS TO FORECAST THE NATURAL REGIME OF LAKE CHAPALA

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Lake Chapala is the most important lake in Mexico and the main water supply for Guadalajara, the second biggest city in the country. Presently the lake contributes more than 65% of the daily water needs of the city. The main tributary to the lake is the Lerma River. After a severe drought period in the 1950's, the water inflow to the lake from the Lerma River during the period 1960-1980 was on average 1,769 Mm^3/yr. This raised the average storage volume of the lake to 6,940 Mm^3. During the period 1980-2000 the water supply of the Lerma River was drastically reduced, to only 425 Mm^3/yr diminishing the storage volume of the lake to 2,163 Mm^3 in 2000. The present work provides a simplified statistical analysis of the official historical hydrologic and hydrometric data and illustrates what the water level of the lake would have been under a natural flow regime for the period of 1934-2003, and also shows the natural hydraulic residence time for the lake. This information allows calculation of water deficits, and also quantifies certain parameters of the lake hydrologic regime, allowing for better decisions to be made about the management of the Lerma-Chapala Basin.

INTRODUCTION

The Lerma River-Lake Chapala-Santiago River basin is located between 19° and 23° North latitude and between 99° and 105° West longitude. Historically, Lake Chapala has had an average length of about 77 km in the east-west direction; an average north-south width of about 22.5 km, and a mean depth of 7.20 m (de Anda et al., 1998). Lake Chapala has a nominal water surface elevation of 1,524 m amsl (meters above mean sea level) (SARH, 1981). Figures 1 and 2 show the geographical location of the basin and the lake. The morphometric parameters for the lake were extensively discussed in de Anda et al. (1998).

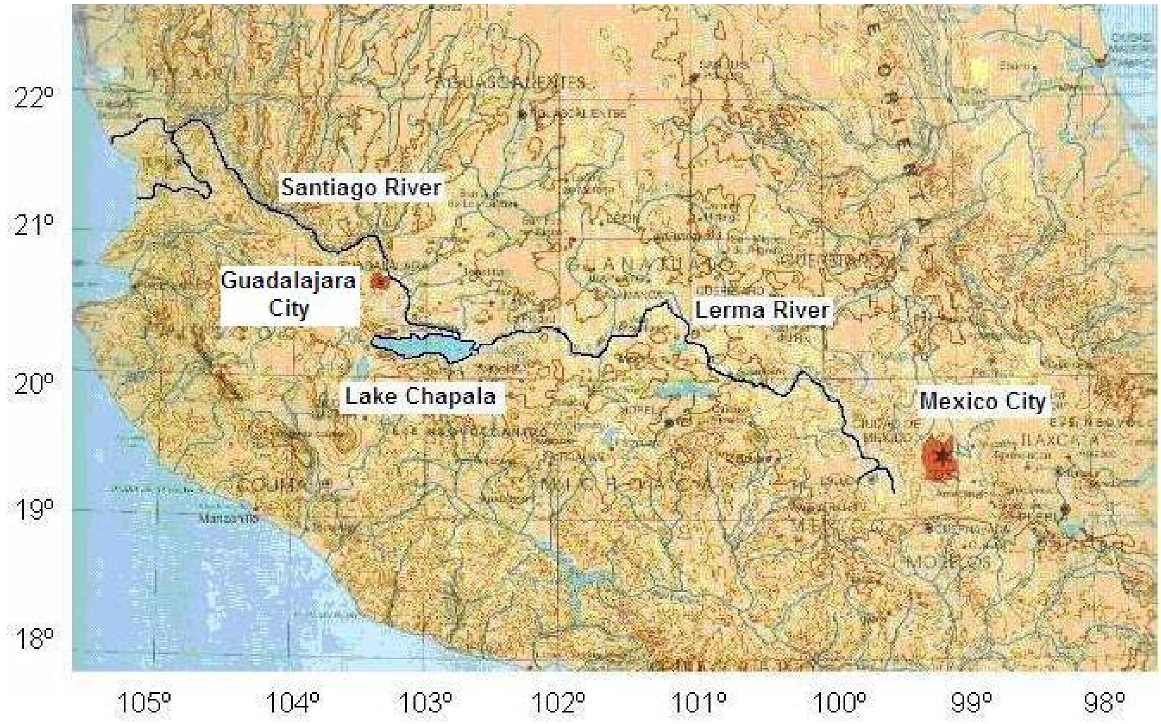

Figure 1. Location of the Lerma-Chapala-Santiago Basin.

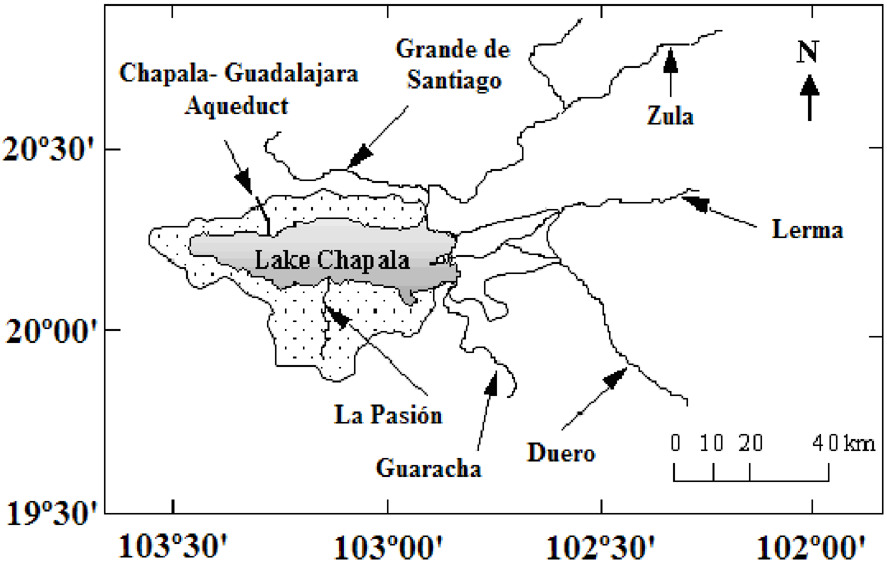

Figure 2. Lake Chapala basin and its main tributaries.

Hydrologic features of the system

The hydrology of the Lerma-Chapala Watershed was discussed recently by several authors (de Anda et al., 1998; Aparicio, 2001; Filonov et al., 2001). Additionally, there has been some discussion of the ecological and economic implications of the dramatic water level drop of Lake Chapala in recent years (Valdez-Zepeda et al., 2000). The lake has seen important changes in both inflows and outflows through the two main rivers in the Lake Chapala basin, the Lerma River and the Grande de Santiago River (de Anda et al., 1998).

Prior to 1990, the primary potable water supply for Guadalajara had been the outflow from Lake Chapala via the Grande de Santiago River. In 1990, the Mexican National Water Commission (CNA) initiated operation of the closed Chapala-Guadalajara Aqueduct, which now supplies more than 65% of the water needs of the City (see Figure 3) directly from Lake Chapala to Guadalajara (SIAPA, 1994). This aqueduct is located close to the City of Chapala at the mid northern shore of the lake. The Grande de Santiago River continues to carry water from the terminus of the Zula River (Figures 1 and 2) and provides irrigation water to downstream areas such as the Poncitlan and the Atequiza irrigation districts.

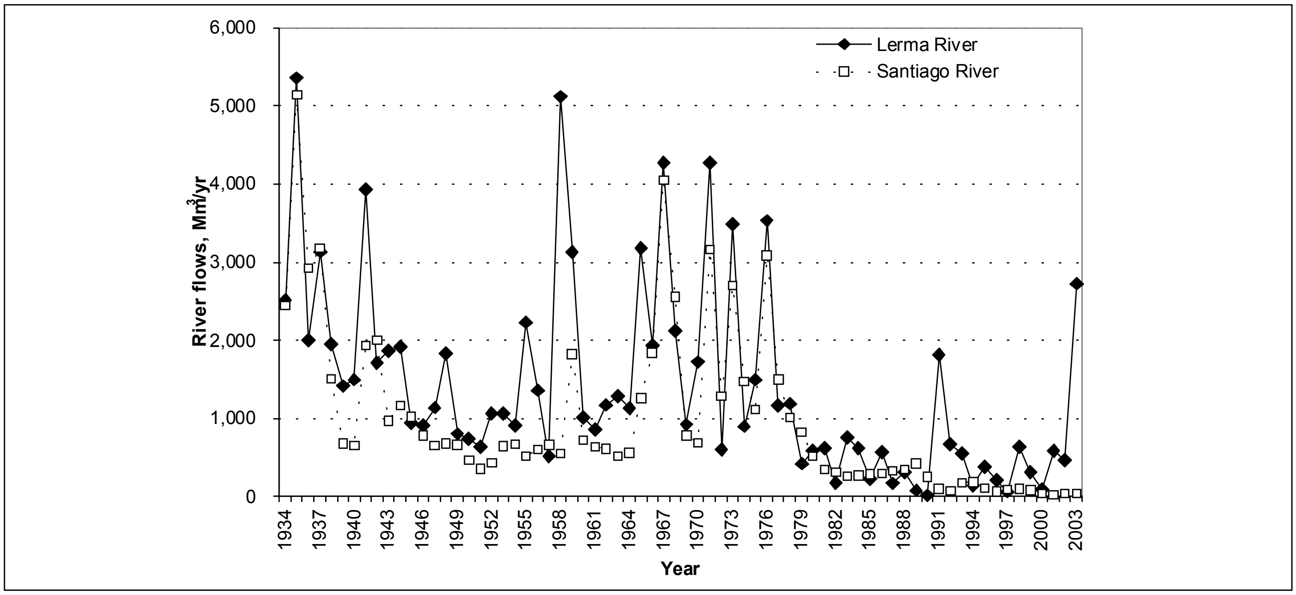

Figure 3. Water pumped to Guadalajara through the aqueduct.

The aqueduct was built to avoid evaporation and infiltration losses that had taken place in the Grande de Santiago River, and to improve the quality of the potable water supplied to the City. For the period of 1991-2003, the potable water flow from Chapala to Guadalajara through the aqueduct was maintained at an average flow of 13.62 Mm^3/month. Figure 4 shows the annual average inflow from the Lerma River and the annual average outflow through the Grande de Santiago River for the period 1934-2003. This Figure shows a trend towards a considerable reduction in flow starting in the second half of the 1970s.

After the start up of the Aqueduct, the Santiago River was no longer used to carry water to Guadalajara. It is important to note that the outflow through the Santiago River is fully controlled by the Mexican National Water Commission (CNA) at the Poncitlan dam. Its flow has been reduced from 1,467.50 Mm^3/year in the period of 1960-1980 to 193.21 Mm^3/year in the period 1980-2003. The lake water no longer drains naturally through the Santiago River due to lower water levels at the east end of the lake. Water has to be pumped into the river channel, where it is then used for irrigation.

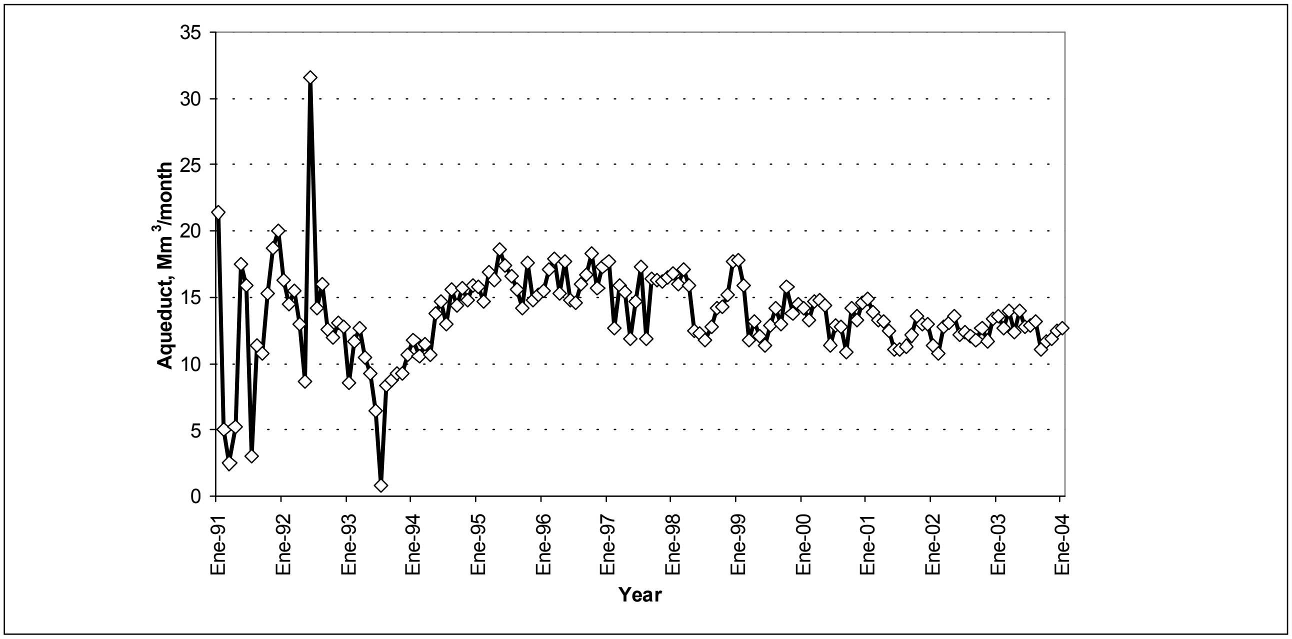

Figure 4. Inflow from the Lerma River and outflow through the Santiago River.

This change in the outflow regime since 1991 has required using a different approach to calculate the hydrologic balance of the Lerma-Chapala basin.

Figure 5 shows the annual average rainfall and evaporation for the period 1934-2003. It should be noted that from 1980-2003, rainfall remained relatively consistent at about 867 Mm^3/year, and well within the long-term average range. The frequencies for rainfall are shown in Figure 6, and the highest frequencies are in the range of 700-1,000 Mm^3/year. The Mexican National Water Commission uses evaporation pans to measure the potential evaporation rate in Lake Chapala. These instruments are located at three different points around the lake. An empirical pan coefficient of 0.77

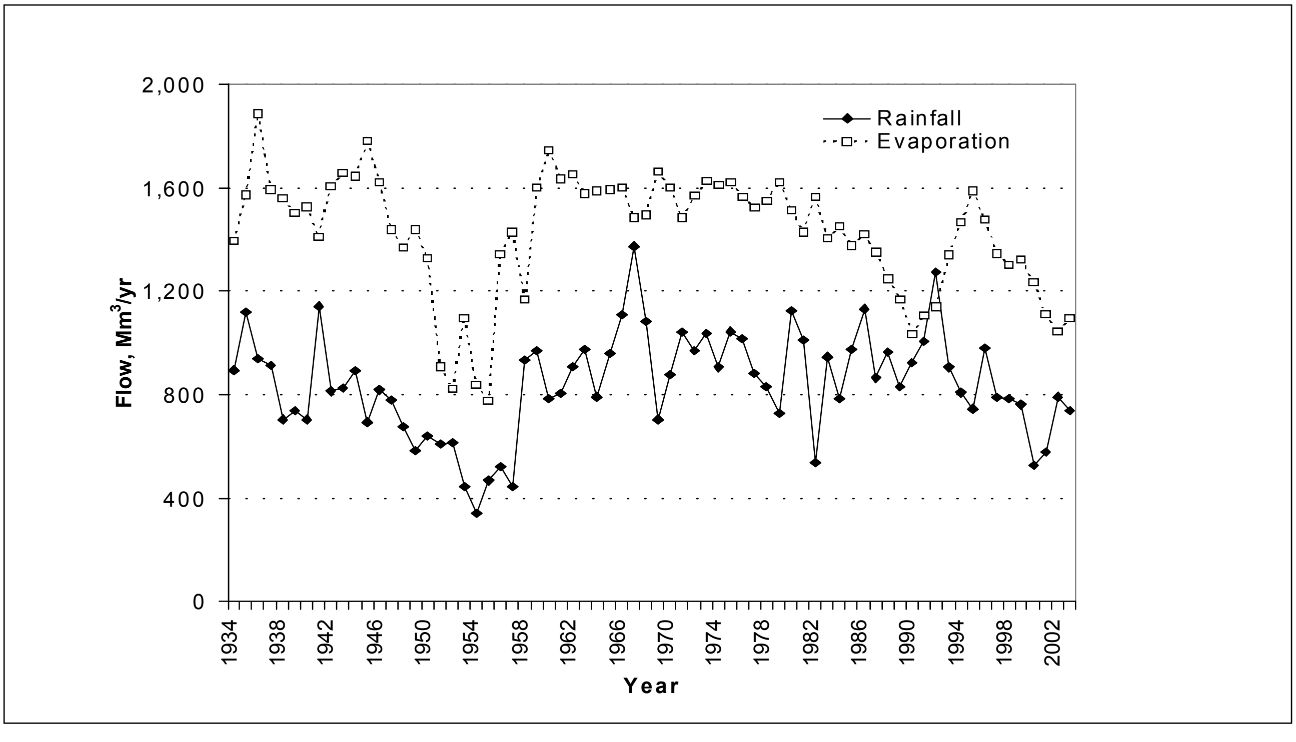

Figure 5. Annual rainfall and evaporation in Lake Chapala.

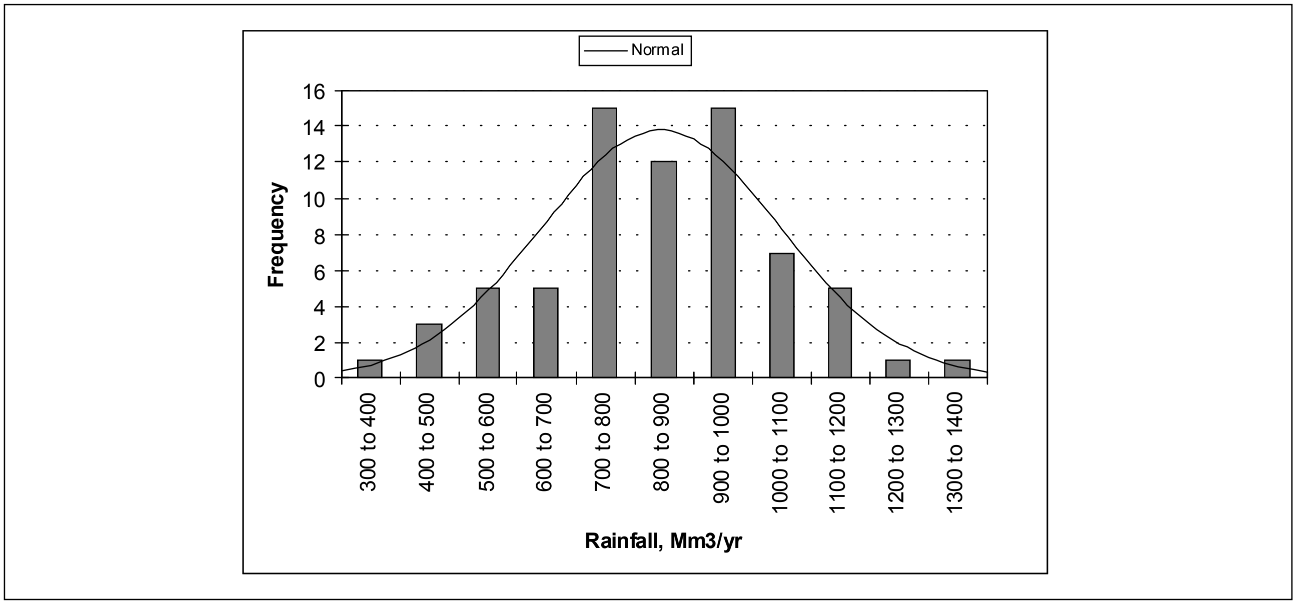

Figure 6. Rainfall frequency curve in the period 1934-2003.

is used to estimate the evaporation rate for the lake. Evaporation has remained at the long-term average of about 1,315 Mm^3/year during the same period, with the exception of 1990, when the evaporation dropped to 1,035 Mm^3/year, likely the result of the significant reduction of the evaporative surface area of the lake.

Lake levels and lake volumes are shown in Figure 7. The lake surface area decreases significantly with a decrease in water level because of the shallow bathymetry of the lake (de Anda et al., 1998). Most apparent in Figure 7 is the extremely low lake level in the mid 1950s, the result of a severe drought (see Figure 5). Other low levels occurred in 1990, and again in 2001 and 2002, but the reason for these low levels does not seem attributable to decreased rainfall, or increased evaporation, since these have both remained relatively consistent, as just noted.

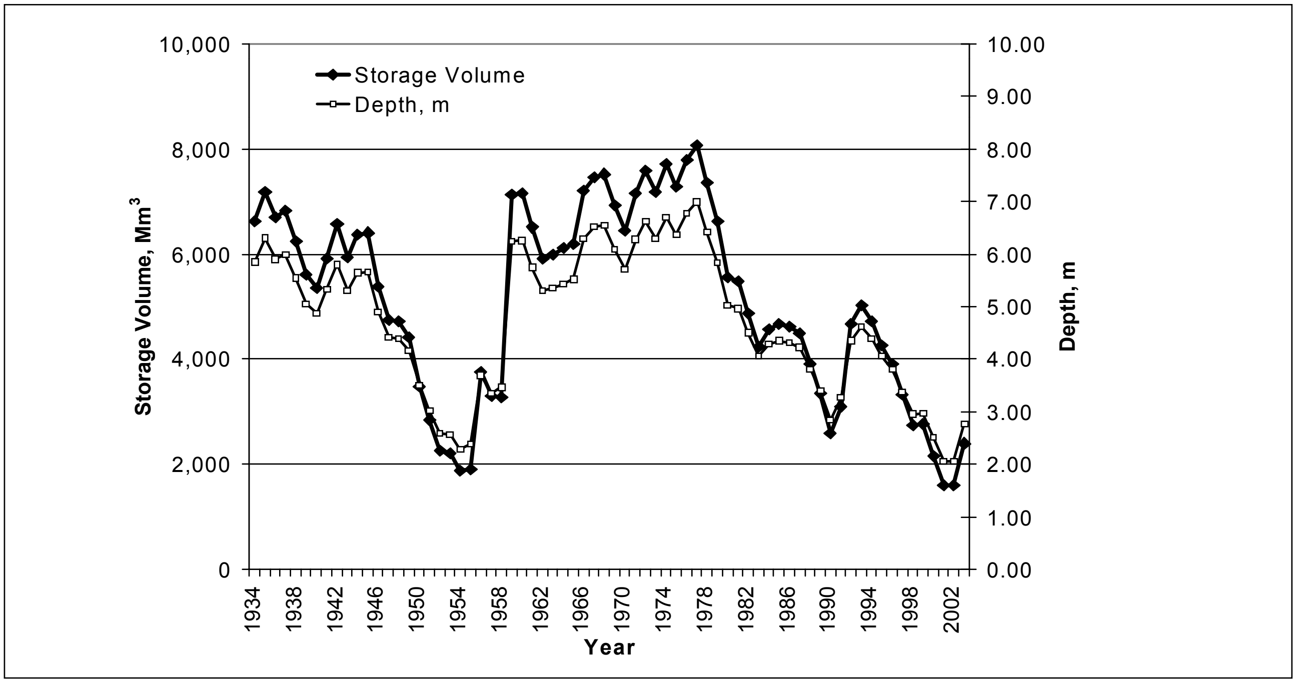

Figure 7. Storage volume and level variations of Lake Chapala.

Our analysis is based mainly on management policies for water distribution that favor agriculture in the Lerma River Basin, (León-Vizcaíno et al., 1994; CNA, 1999) and that favor the provision of water for the future needs of Guadalajara City. The goal of our work is to discuss the relationship between rainfall and the Lerma River flow (including the Duero River contributions) and also the lake storage volume, and its implications for lake ecology and water management.

METHODOLOGY

The historical hydrologic and hydrometric information collected at three different stations located in the Lake Chapala Basin, during the period 1934-2003, were used to estimate the hydraulic residence time of the lake (CNA, 2003). This parameter normally has low variability under different climatic conditions when the water body is well managed. This parameter was selected to analyze when the water body started to demonstrate anomalous behavior due to poor management practices upstream. During the time when the hydraulic residence time was maintained within a small range of variation, we looked for correlations with rainfall as the independent variable, and Lerma River inflow and Lake Chapala volume as the dependent variables. To estimate the statistical trends and the correlation coefficients we used the program WinSTAT® (2002). With the correlations that we obtained, we calculated the dependent variables to estimate the behavior of the lake under "natural" conditions until 2003. The differences that we found between the present "controlled" status of Lerma River and the natural behavior of the river are discussed with respect to management policies.

Hydraulic residence time

The "hydraulic residence time" (τ) represents the number of years that Lerma River water remains in the lake. This parameter was previously proposed for Lake Chapala by de Anda et al. (1998). The relationship between lake volume and Lerma River flow provides the hydraulic residence time of the lake according to Equation (1).

$$\tau\,[\mathrm{yr}] = V_{\mathrm{lake}}\,[\mathrm{Mm}^3] \,/\, Q_{\mathrm{Lerma}}\,[\mathrm{Mm}^3/\mathrm{yr}] \qquad (1)$$

Where V_{lake} is the lake volume in millions of cubic meters, Q_{Lerma} is the Lerma River flow including the Duero River contribution in millions of cubic meters per year and τ is the hydraulic residence time of the lake in years. Figure 8 shows the behavior of the hydraulic residence time in the period of 1934-2003. The Figure reveals that after 1980, this parameter frequently exceeded its lower and upper limits of between 1 and 10 years that had been maintained during the previous 45 years. From 1979 to 2003 the hydraulic residence time increased, often exceeding 50 years, showing that the lake's long-term natural hydrologic regime had been altered, likely due to the significant reduction of the Lerma River flow.

Statistical correlations

According to Figure 8, the hydraulic residence time of the lake started to increase after 1979; therefore, we correlated the yearly Lerma River flows and Lake Chapala volumes as dependent variables with yearly rainfall as independent variable only during the period 1934-1978. By using several correlation Equations, the best trends are represented by the Equations shown in Figures 9 and 10.

RESULTS

Using the correlations shown in Figures 9 and 10, we have calculated the values of Lerma River flow and lake volume for the period of 1934-2003. Measured and calculated values for both dependent variables are shown in Figures 11 and 12.

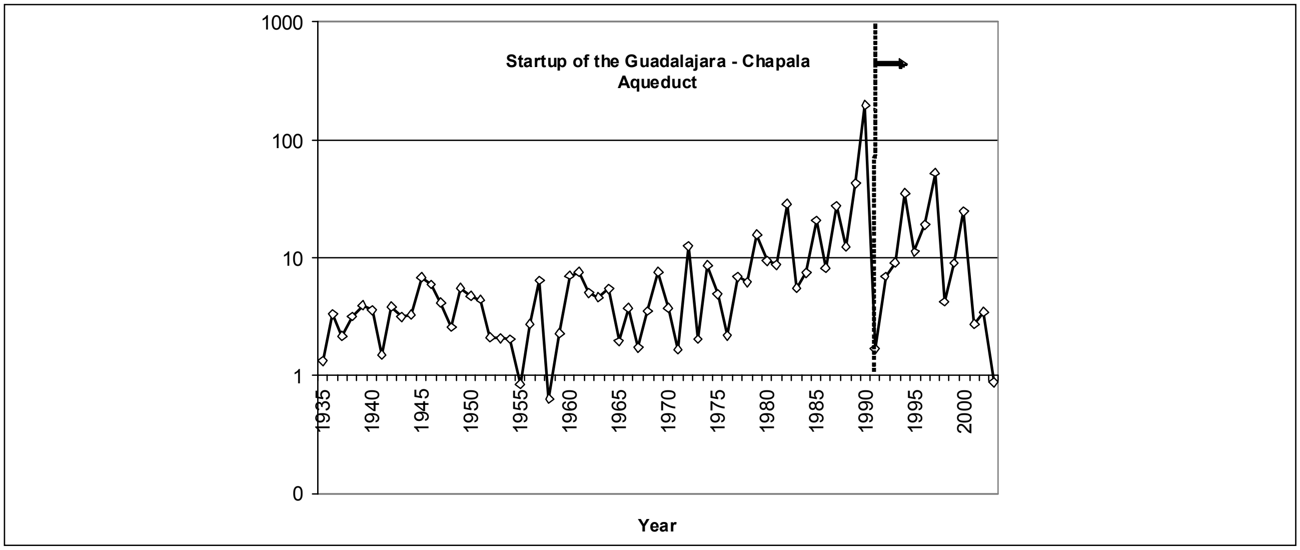

Figure 8. Hydraulic residence time in Lake Chapala.

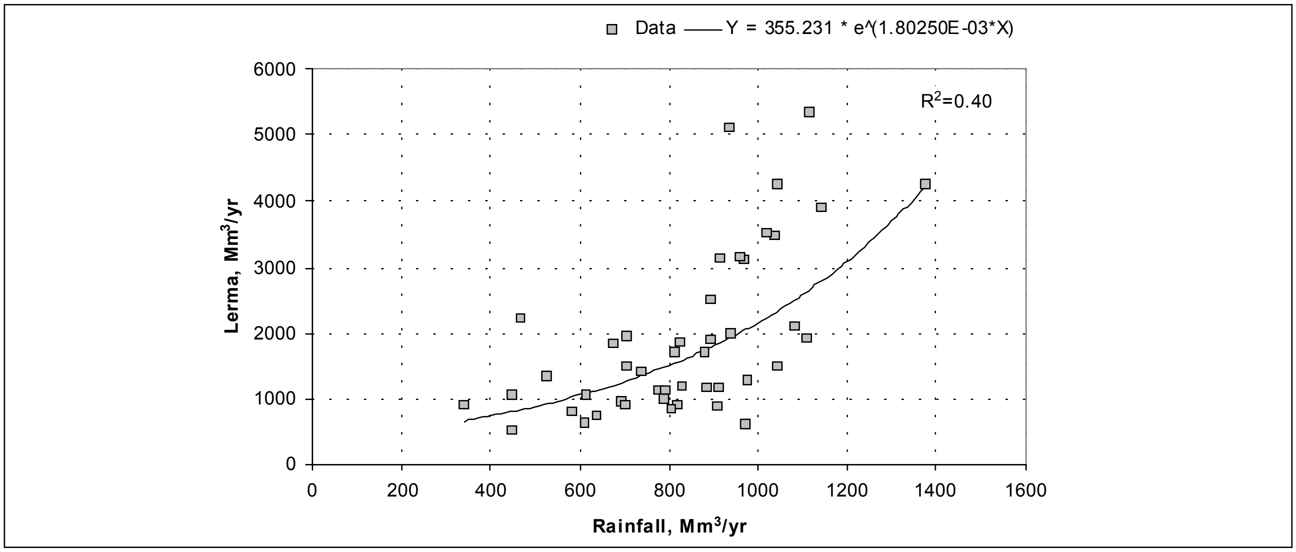

Figure 9. Correlation between Lerma River flow and rainfall (1934-1978).

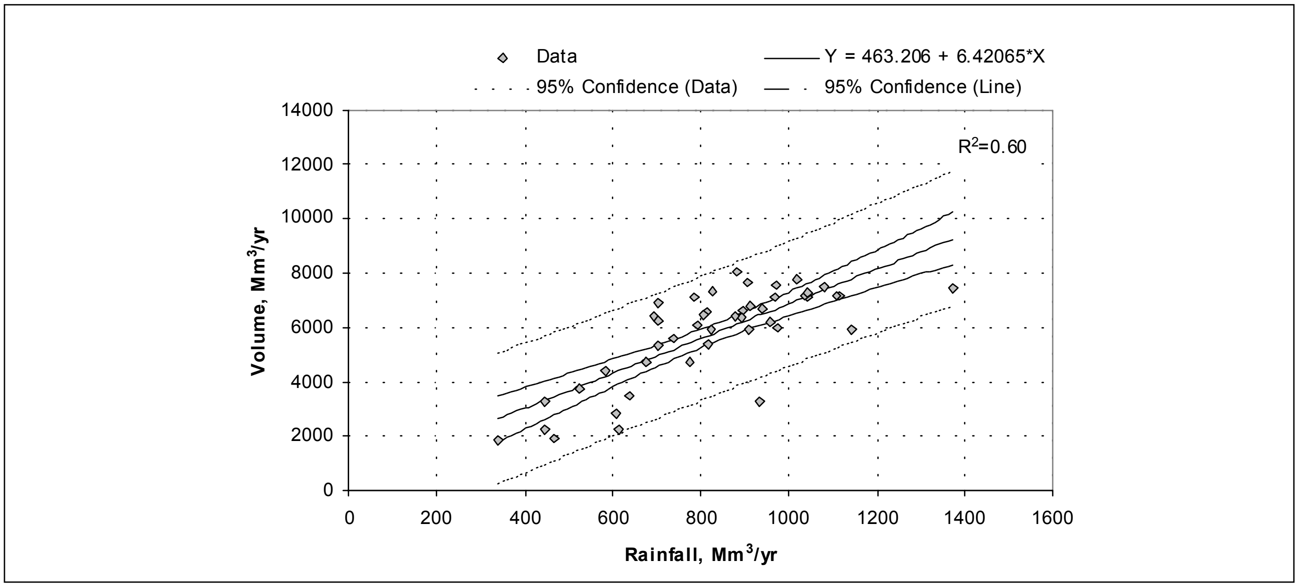

Figure 10. Correlation between lake volume and rainfall (1934-1978).

As shown in Figures 11 and 12, the calculated values follow the measured hydrologic regime of the Lerma River flow and lake volume up to 1978. After 1978, both correlations fail because the calculated values are above those actually measured. In the case of the Lerma River flow, the mean difference between measured and calculated flows was 1,241.08 ± 795.46 Mm^3 /yr, and in the case of the storage volume the mean difference was 2,104.20 ± 1,358.37 Mm^3.

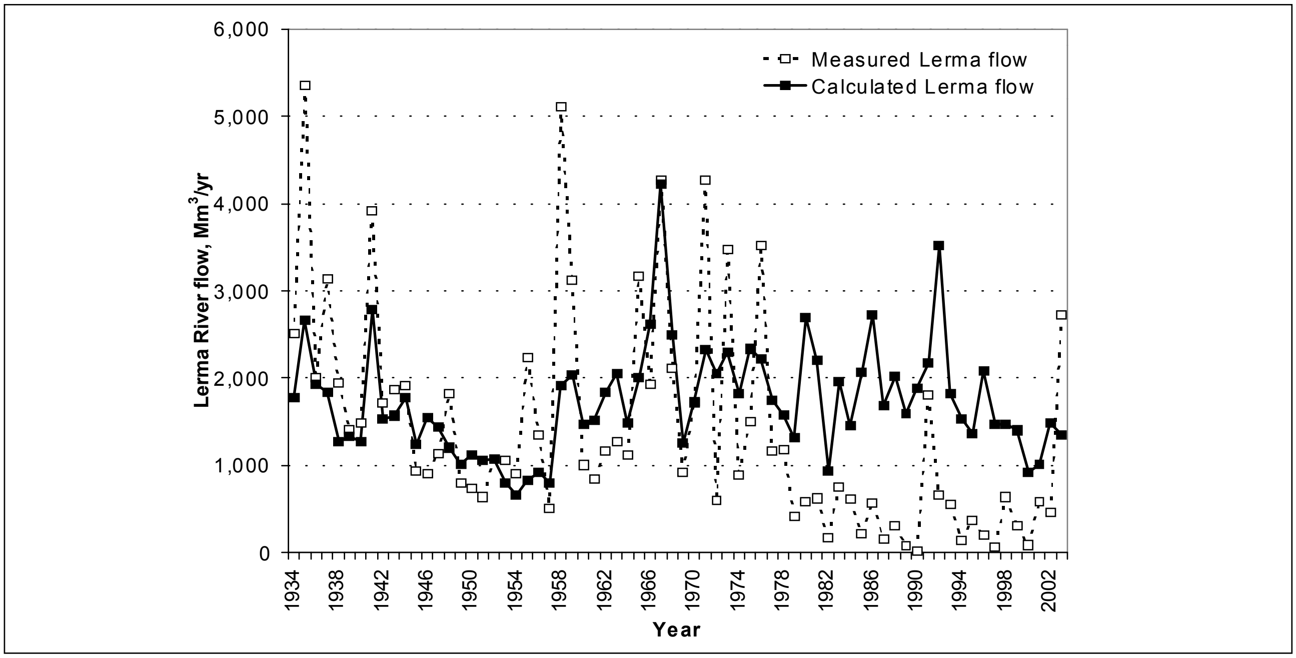

Figure 11. Calculated values of the Lerma River flow.

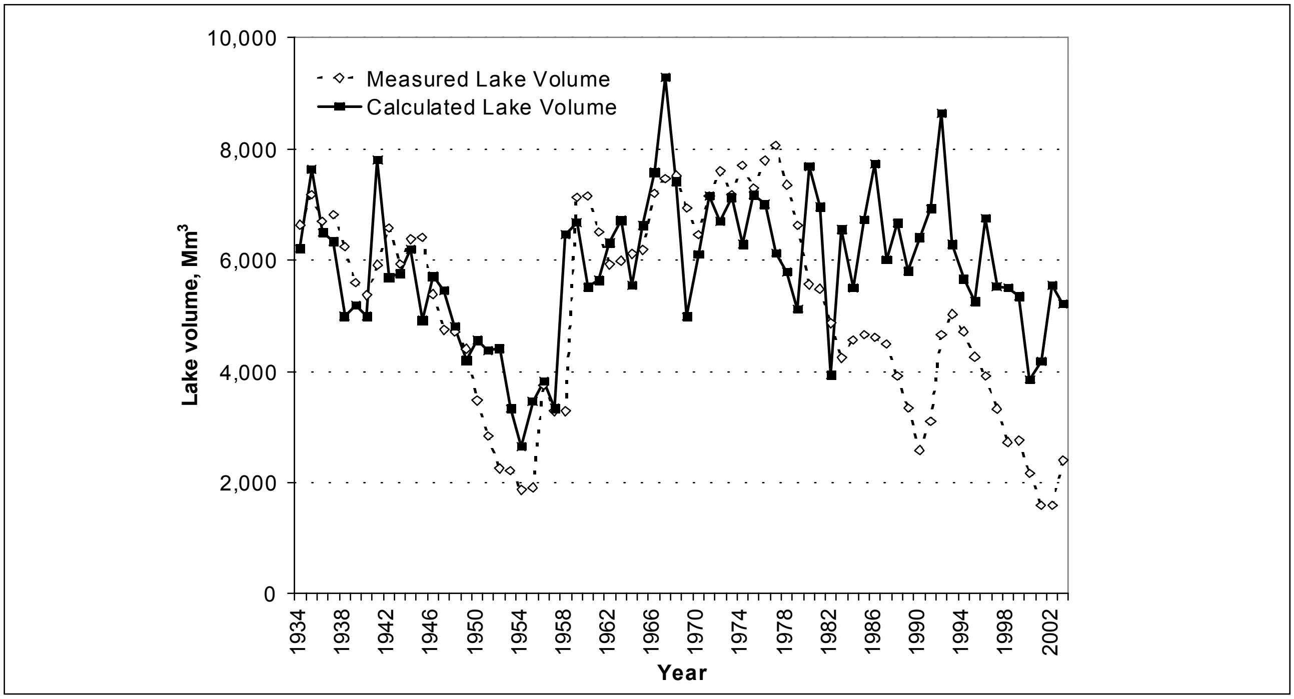

Figure 12. Calculated values of the lake volume.

If we analyze the hydrologic process by using only calculated values for the Lerma River flow and storage volume, we can estimate the hydraulic residence time for the entire period of 1934-2003. By using the calculated hydraulic residence time we have built a quality control chart (see Figure 13) to show the process (WinSTAT®, 2002; Montgomery, 2004) where every point represents individual values. The control chart demonstrates that the process is under control for the entire period of study with a mean value of 3.57 ± 0.57 years, and with lower and upper limits of 2.22 and 4.90 years respectively. Comparing this result with the measured hydraulic residence time for the period 1934-1978 we get a mean value of 4.07 ± 2.40 years, values very close to the calculated ones. However, considering the measured hydraulic residence time for the period 1979-2003, this mean value reaches 22.71 ± 38.96 years. In this last case the hydraulic residence time is significantly out of control.

DISCUSSION

Hydrologic regime

Our analysis shows strong fluctuations in the lake level and in the lake storage volumes for the period 1934-2003 (see Figure 7). During the period 1934-2003, it was evident that the lake had gone through two periods of extremely low water level. The first period during the mid-1950s, is associated with extreme drought in the Lerma-Chapala basin. The second one, which occurred during the late 1980s, cannot be fully associated with climatic events, since there were normal rainfalls during the 1980s and 1990s (see Figure 5). In addition, the evaporation rate from the lake has decreased from the long-term average, the result of a lower lake level, and a decreased evaporative surface area.

Up to 1978, there appears to be a close correlation between the rainfall in Lake Chapala and the water inflow through the Lerma River and lake volume (see Figures 11 and 12). After 1978, the system appears to have been severely perturbed, and this correlation no longer holds. It is clear from the evidence presented here that the second period of low lake levels is associated with reduced inflow from the Lerma River. This reduction is likely the result of excessive extraction of water within the Lerma River basin, and not the increased withdrawal of water from Lake Chapala to Guadalajara (see Figure 4) (CNA, 2003). The increase in population since the 1970s in the Lerma-Chapala Basin (the main hydrologic basin located in the central part of Mexico) has resulted in a social crisis due to critical water competition. This competition for water in the Lerma-Chapala Basin is widely discussed in Scott and Silva-Ochoa (2001). These authors demonstrated in a quantitative way that the basin has total consumptive water demands that significantly exceed average water supply.

Figure 11 shows that under natural climatic conditions, the average Lerma River flow should have been 1,765.8 Mm^3/year during the period of 1979-2003 instead of the 524.7 Mm^3/year actually measured during this period. Figure 12 shows that in the same period, the lake volume should have had an average value of 5,991.4 Mm^3 instead of the 3,887.2 Mm^3 estimated during this period. Finally the hydraulic residence time should have remained at an average value of 3.53 years instead of the 22.71 years estimated during this period. The calculated hydraulic residence time also shows that the values of this parameter have to be controlled if the natural water regime of the Lerma-Chapala Basin is to be maintained. According to Figure 13, the limits for the hydraulic residence time have to be between 2.22 and 4.90 years to consider the system under control. The consequences of an uncontrolled residence time, as shown by the quality control charts, are well known as discussed earlier.

Lake Chapala is a very shallow lake whose morphometric features have a strong influence on its water level and on its water quality (Limón et al., 1989; Limón et al., 1990). Lower water levels result in bottom sediments being resuspended (de Anda et al., 2004). Recently de Anda et al. (2004) worked on developing an indicator that suggests the minimal water depth of the lake based on the total dissolved solids. According to this criterion, the lake should have a minimum water storage capacity of 5,000 Mm^3, representing a mean depth of 4.6 m.

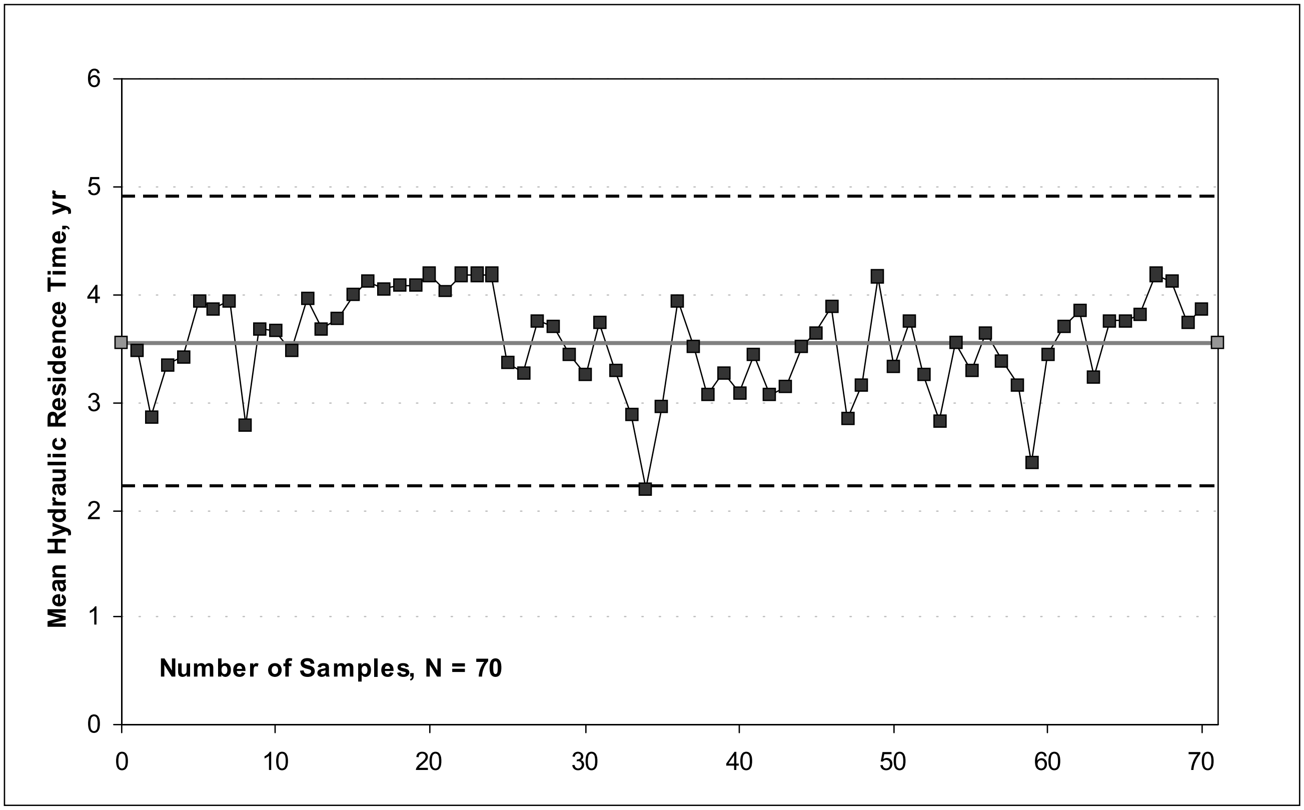

Figure 13. Control chart for the calculated hydraulic residence time in the period 1934 – 2003.

Lake management policies

In Mexico, basin councils coordinate the activities and agreements between the federal, state and municipal government, and also between the users of the water resources. Their main goal is to work on the planning, execution and control of different projects for the development of hydraulic infrastructure, and their associated services. Their goals are concentrated on basin cleanup, establishing water use regulations between users, achieving the efficient use of water, management and conservation of basins and streams, and contribution to the appreciation of water as an economic, social and environmental value (Diario Oficial, 1992, 1994). Even though Mexican laws and regulations allow for consensus between stakeholders, there are severe conflicts of interest between users, mainly farmers, who use more than 60% of the surface water for agriculture, employing poor management practices that use water inefficiently because of a lack of technology and appreciation of the value of the water resource. The future of Lake Chapala depends on the agreements adopted by the different Mexican federal states, municipal governmental entities, and the users, to manage the water resources in the Lerma-Chapala Basin appropriately. Unfortunately it will take time to conclude agreements that can solve the different problems in the basin.

As a consequence of the uncertainty of assuring the volume of the lake, in the near future Lake Chapala may not be a reliable source of water for Guadalajara. To deal with this possibility, the municipalities located in the Metropolitan Zone of Guadalajara are at present planning a new reservoir to supply water to Guadalajara. This reservoir, named “Presa de Arcediano” (Arcediano Dam), is under discussion because the goal is to treat and recycle sewage waters from the city to supply the main water demands of Guadalajara. Arcediano will be located in the Santiago River Basin north of Guadalajara City (see Figure 1). It represents one of the most important water works in Mexico with an investment of around $600 million US dollars.

CONCLUSIONS

The correlation equations that we have used in this paper permitted us to model the hydrologic behavior of the Lerma River flow and lake volume. Present public demands for the sustainability of the Lake Chapala Basin focus the discussion on the lake itself, not considering that the entire basin works as a hydrologic unit. Our work demonstrates that the water demands have to be considered in both the lake volume and the inflow of the Lerma River, as manifested by changes in the hydraulic residence time, in order to restore the natural behavior and hydrologic balance of the basin.

Since Lake Chapala cannot be hydraulically sustained without the Lerma River inflow, it is evident that better water resource management policies and technology to treat and reuse the water used in agriculture need to be implemented for the entire Lerma-Chapala Basin. These policies must take into account not only water quality and better water distribution policies, but also a change in land use and agricultural practices throughout the entire basin.

The conflict between rural water use and urban water supply that is discussed in this paper may have analogies elsewhere. Probably one of the most important questions to answer is whether there could be any alternatives to the construction of new infrastructure; that is, the proposed Arcediano reservoir and wastewater recycling. Could the same funds be used to improve the efficiency of agricultural water use upstream of the lake where efficiency is poor due to a lack of technology and appreciation of the value of the water resource?

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