# Response of lake Mar Chiquita in Argentina to climate change: data analysis and application of a lake model

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**Abstract**

Lake Mar Chiquita (30°54'S-62°51'W), a closed, shallow, hypersaline-lake in Central Argentina (30°S, 62°W) has recorded hydrological changes for the 20th century in Southern South America (SESA) by sharp variations in its water-level. The lake, located at the lowermost end of an endorheic basin, has a large catchment area (37,570 km$^2$) situated in the western part of the Parana-La Plata basin. It is also a part of the Chaco-Pampean plain, an zone of forests and grasslands that has been extensively cleared for agricultural activities since the end of the nineteenth century. During the hydrological changes that occurred during the 70's in SESA, the lake has undergone a significant water-level rise. Historical and instrumental data, combined with sediment core studies (sedimentological, isotopic, and diatom analysis) showed that Mar Chiquita is an ideal site for recording high- and low-frequency changes in hydrological budget. Therefore, this lake can be considered as a regional and temporal integrator of its catchment water balance. A detailed hydrological study was initiated through a modelling approach in order to determine lake level variations in response to climate changes. In this paper, we present preliminary results, based on hydroclimatic records (precipitation and river discharge data) covering the last quarter century.. The lake water balance model is used to determine the lake hydrological behaviour and to quantify its water balance. From available hydroclimatic data, an important overestimation of the simulated lake level was evidenced. We discuss the possible processes involved in this discrepancy.

Key words: Argentina, climate change, saline lake, water balance

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## 1. Introduction

In SESA (Southern South America), important hydrological variations have been observed during the last century (Georgi, 2002). Dry intervals characterized the first 75 years of the 20$^{th}$ century while a significant increase in precipitation has occured after 1970s. The Lake Mar Chiquita, a closed, shallow, hypersaline-lake in Central Argentina (30°S, 62°W, Fig. 1), responds to these climatic fluctuations through lake level and salinity variations. For example, during the 1923-73 period, the lake has tended to dry out which has induced a dramatic salinity increase. But since 1973-74, the situation was reversed. Now, the lake lies at its maximum extension, being not only the largest saline lake in South America (≈ 6000km$^2$) but also one of the world's largest saline lake.The high sensitivity of Lake Mar Chiquita to climatic fluctuations is illustrated by various authors (Reati, G.J. et al., 1997, Martinez D.E. 1995, Pasquini A. *et al.*, 2006), and makes it a very attractive site to study the hydrological response to climate change (Piovano *et al.*, 2002, 2004a, 2004b).

A detailed hydrological study of the lake-catchment system has been initiated in order to analyse the response of lake level and salinity to climate changes through a modelling approach. The objectives of this work are (1) to provide a quantified climatic interpretation of lake variations reconstructed for the last centuries and (2) to help understanding the magnitude and mechanisms of the past changes. In this paper, we present the preliminary results of this study, based on hydroclimatic records from the last quarter century. These data are from different stations and localized in the catchment area of Lake Mar Chiquita. A lake water balance model is used to simulate the lake level in response to precipitation and river discharge data over the 1975-1995 period. In this study, the modelling approach is used to help understanding the lake water balance and hydrological behaviour.

## 2. Site and climate description

The lake Mar Chiquita (30°54’S-62°51’W) is located at the lowermost end of an endorheic basin. It has a large catchment area located in the west of the Parana-La Plata basin covering 37,570 $km^2$ from 26°S to 32°S and 62° to 66°W (Fig. 1). It is part of the Chaco-Pampean plain, an extensive area of forests and grassland that has been extensively modified by deforestation for agricultural activities since the end of the nineteenth century. Approximately 200 km north-west of Mar Chiquita lie the Salinas de Ambargasta, an extensive area of salt pans.

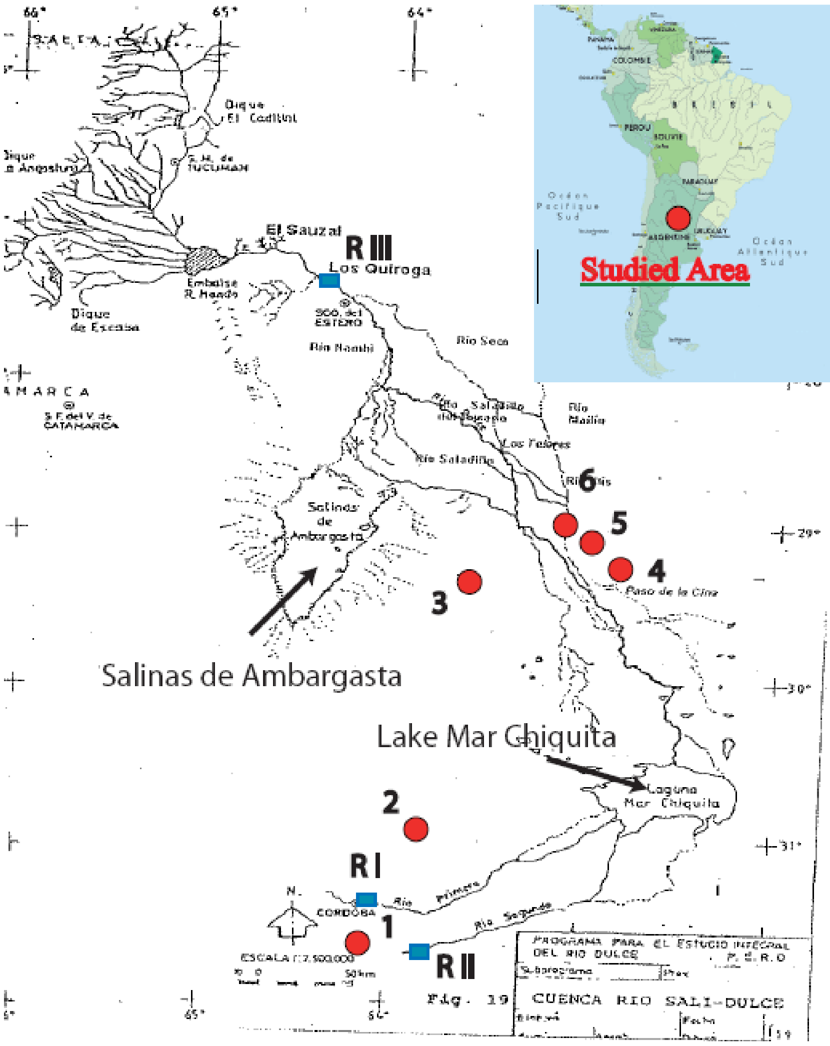


Figure 1: Map of the study area showing the location of rainfall (filled red circles) and discharge gauging (filled blue rectangles) stations. The names of the stations (indicated by numbers) are listed in Table 1

In the Mar Chiquita catchment, summers are hot and wet, whereas winters are cold and dry. Humid winds derive from the anticyclone of the South Atlantic Ocean and precipitation decreases from east to west. Dominant winds blow from the south-west and north-east. Average annual temperature is 18-19°C.The monthly average temperature is maintained above 20°C over 5 months (November to March), with a maximum value of 25°C during January). This warm season also corresponds to the highest monthly rainfall: monthly average exceeds 100 mm and totals 600 mm for these 5 months (66-75% of the annual total) (Capitanelli, 1979).

This terminal lake is fed by three major rivers (Fig. 1). The rivers drain part of the Gran Chaco (Río Dulce basin to the North) and Sierras Pampeanas regions (Ríos Primero and Segundo basins to the South). The Río Dulce alone has an average annual discharge of 3000 $10^6$ $m^3$; whereas Ríos Primero and Segundo have a combined annual discharge of 725 $10^6$ $m^3$. The rivers partially infiltrate the soil and recharge groundwater before reaching the lake basin. However, the importance of groundwater inputs to Mar Chiquita has never be clearly estimated (Martinez, 1995). The system has no surficial outlet and water is loss through evaporation only, which is additionally favoured by the pan-like shape of the lake. Limnological studies in this area began as early as the end of the nineteenth century, which is relatively unusual in this area of South America. Historical and instrumental data show that the lake surface was reduced to ~1,000 $km^2$ during dry periods whereas it covered an area of up to 6,000 $km^2$ during intervals with a positive hydrological balance. During highstands, maximum length and width may reach 120 km and 80 km, respectively, while the maximum water depth is ~10 m. At present, the lake is at its maximum extension making it not only the largest saline lake in South America but also one of the largest in the world.

The recent (1968-2001) instrumental record of lake levels from Mar Chiquita shows a clear increase since 1973 (Fig. 2). This increase is associated with important extension of the lake surface (Fig. 3) and has had disastrous effects on the lakeside town of Miramar, which lost a significant portion of its urbanized area due to permanent flooding. During the 1977-1985 period the number of inhabitants in Miramar, the only village settled on the lake side, fell from 6000 to 1600. Although the hydrological change started in 1973, it was only after 1977 that the lake extension went beyond the historical record producing drastic consequences on the tourism-based local economy.


Figure 2. Available water level records for Lake Mar Chiquita

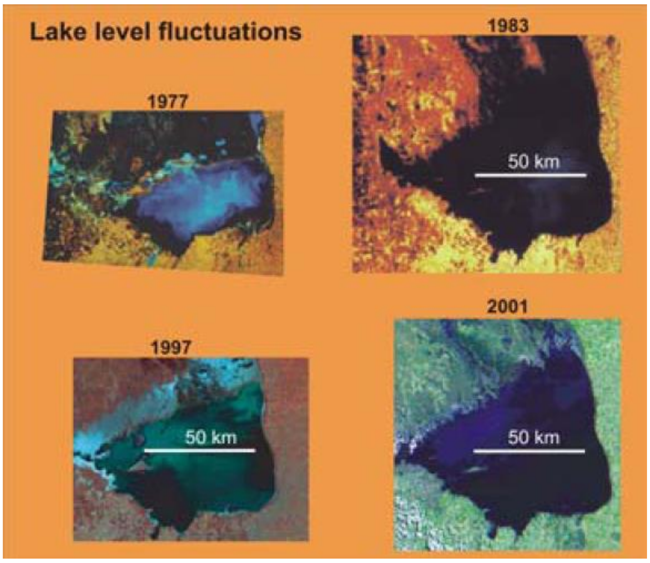


Figure 3: Satellite images of the lake surface variations encountered since the 1970's in association with lake level variations.

## 3. Analysis of available hydrometeorological data

### *3.1. Data*

Monthly total rainfall and monthly mean river discharge records used in this study were obtained from different sources. Table 1 lists rainfall and gauging stations, and includes information on locations and length of the records. Argentina's Subsecretaría de Recursos Hídricos (http://www.obraspublicas.gov.ar/) supplied all rivers discharge records. The Dirrección Provincial de Agua y Saneamiento (DIPAS) in Argentina's Córdoba Province and the Instituto Nacional de Tecnologia Agropecuaria (http://www.inta.gov.ar/) supplied most of the rainfall data.

The annual rainfall from our 6 stations varies from 546 mm/year to 926 mm/year (Table 1). Important seasonal variations are observed in precipitation and river discharge (Fig. 4), the highest precipitation rates occur in December-January, while the maximum river discharge occurs in February-March.

| | Station | Catchment location | Variable | Record period | Latitude (S) | Longitude (W) | Catchment area (km²) | Annual value | Missing data (%) |
|---|---|---|---|---|---|---|---|---|---|
| RI | Dique San Roque | South | Discharge (Rio Primero) | 1926-1998 | 27°39' | 64°21' | 1350 | 126 m³/s (242 mm) | 21 |
| RII | Santa Ana | South | Discharge (Rio Segundo) | 1926-2004 | 31°40' | 64°34' | 465 | 77 m³/s (428 mm) | 0.5 |
| RIII | Los Quiroga | North | Discharge (Rio Dulce) | 1975-1997 | 27°39' | 64°21' | 20200 | 1339 m³/s (172 mm) | 0 |
| 1 | Manfredi | South | Rainfall | 1931-2007 | 31°49' | 63°46' | | 757mm | 0 |
| 2 | Quebrada | South | Rainfall | 1974-2003 | 31°11' | 64°20' | | 926mm | 0 |
| 3 | Villa Ojo de Agua | North | Rainfall | 1948-1995 | 29°30' | 63°41' | | 628mm | 33 |
| 4 | Pinto | North | Rainfall | 1948-1996 | 31°22' | 64°27' | | 715mm | 2 |
| 5 | Villa Union | North | Rainfall | 1974-1996 | 29°25' | 62°47' | | 692mm | 0 |
| 6 | Sumampa | North | Rainfall | 1948-1995 | 29°23' | 63°28' | | 546mm | 5 |

Table 1: Name, location and record periods of available precipitation and river discharge data

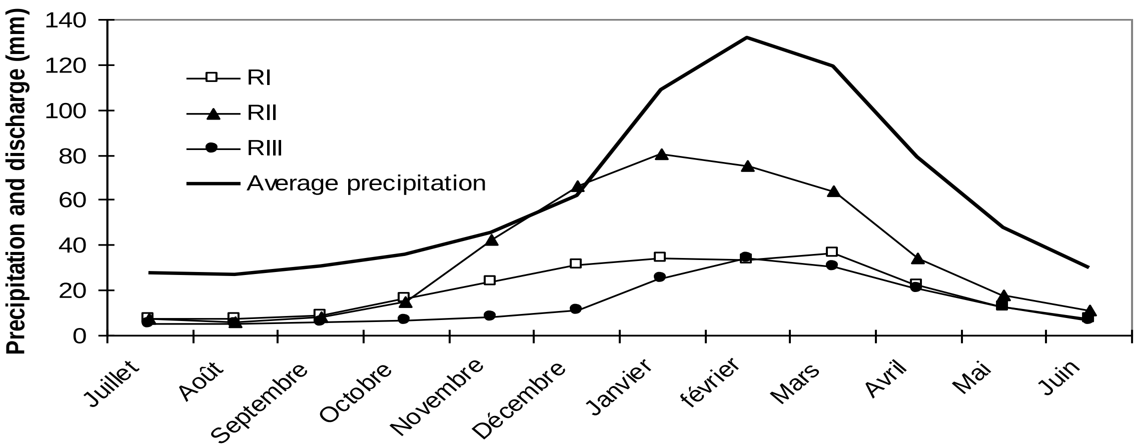


Fig 4: Monthly data of precipitation (average from stations 1 to 6) and River discharge of Rio Primero (RI) Rio Segundo (RII) and Rio Dulce (RIII) (specific discharge in mm/month).

### *3.2. Trends analysis*

The cumulative sum technique is a valuable tool to detect intermediate-terms changes in the mean value of a sequence of regularly spaced observations (Crapper *et al.*, 1996). We use cumulative anomalies $s_i$ of a variable $x_i$ as defined by:

$$s_i = \sum_{1}^{i} (x_i - \bar{x}) \qquad \text{Eq. (1)}$$

Applied to time series analysis, $s_i$ provides a normalised distribution and reveals runs of observations greater than the longterm average with a positive slope and those lower than the long-term average with a negative slope. Note that in such a graph, the slope is informative but not the absolute ordinate values.

Calculation of cumulative anomalies needs a complete time series. Our longest precipitation time series (Manfredi station) illustrates the main trends over the period 1931-2007 (Fig. 5). The humid periods (positives slopes, underlined in grey) appears more frequent during the second half of the time series (after 1976), while drought periods are particularly important between 1941 and 1956, and between 1962 and 1973. In this preliminary study, we focus on the 1975-1995 period, when the whole set of data is complete. The globally positive slope observed for this period in Fig. 5 suggests particularly humid conditions.

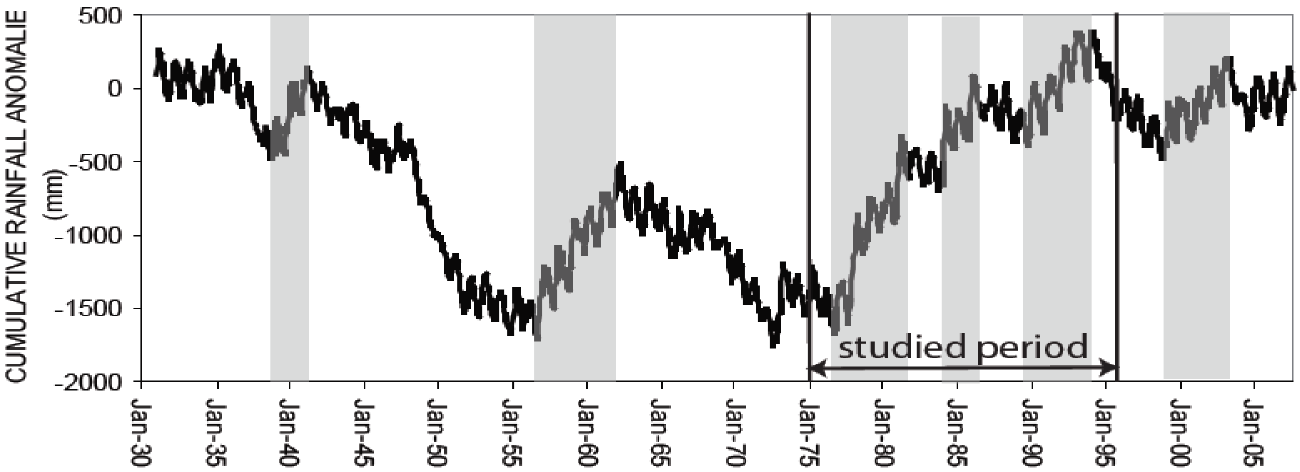


Figure 5: Cumulative rainfall anomalies of station 1 (Manfredi Station) over the 1931-2007 period. The grey areas represent the humid periods (increasing slope). The arrow indicates the period for which the lake model is applied.

## 4. Lake water balance model

### *4.1. Basic equations and method*

The dynamic lake water balance equation is given by:

$$\frac{\Delta V}{\Delta t} = A(V)(P - E) + Q_i + G_i \qquad \text{Eq. (2)}$$

Where, for the time step $\Delta t$ (one month in this study), $\Delta V$ is the lake volume variation; $A$ is the lake area ($m^2$), as a function of lake volume $V$; $P$ is the precipitation (m) above the lake; $E$ the evaporation (m) from the lake surface; $Q_i$, $G_i$ the surface and groundwater inputs ($m^3$) respectively. There are no outputs from Lake Mar Chiquita except evaporation. The corresponding lake level is then estimated as a lake volume function:

$h$ = f($V$), following the morphometric relationship (Fig. 6) established from the lake bathymetry (Hillman 2003). Note that strong variations of the lake surface are associated with the lake level changes, because of the pan-like shape of Lake Mar Chiquita. The lake water balance models were developed under *Matlab* (The Mathworks) programming environment.

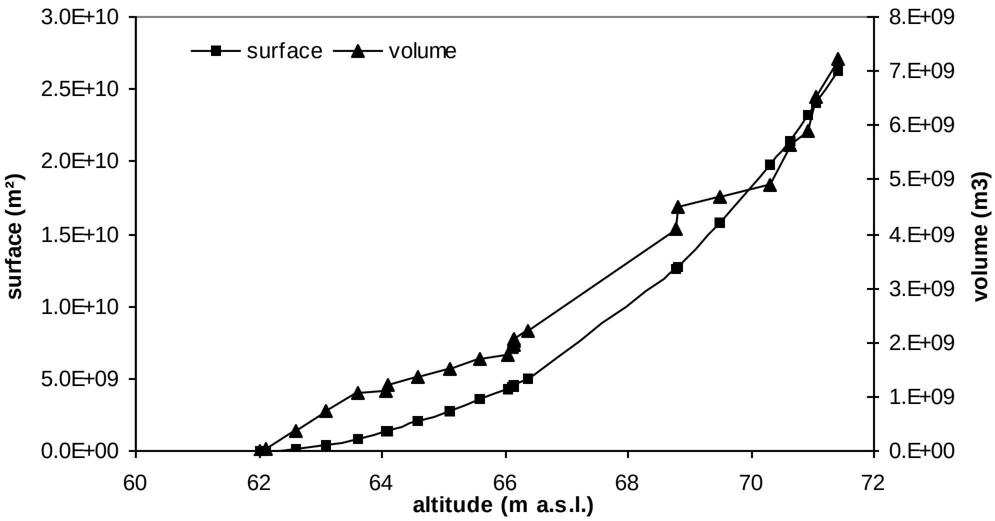


Figure 6: Relationships between altitude of water level, area and volume (from Hillman 2003)

Qi corresponds to the sum of discharge of the three main rivers: Rio Primero (RI), Rio Segundo (RII) and Rio Dulce (RIII). The precipitation is estimated from the average between available rainfall stations around the lake (stations 1 to 6). Evaporation from the lake surface is calculated by the CRLE model (Morton, 1983b; DosReis and Dias, 1998). This approach is based on the postulate of a complementary relationship between actual and potential evapotranspiration. This model can be considered as a simplified application of the Bouchet's theory (1963) for monthly estimates of lake evaporation. The advantage of using this model is that it only requires monthly data of air temperature, humidity and solar radiation. The model calculates an 'equilibrum temperature' by solving vapor transfer and energy balance equations simultaneously in conditions of potential evapotranspiration. This equilibrum temperature is then used in the Priestley-Taylor equation, (Morton, 1983b; DosReis and Dias, 1998). The explicit influence of wind speed in the term of Penman equation is replaced by an empirical coefficient, which does not require any site-specific calibration. The model has been applied previously for different lakes with an accuracy superior at 10% in the evaporation estimates (Morton, 1983b; DosReis and Dias, 1998; Vallet-Coulomb *et al.*, 2001). The application of the CRLE model at Lake Mar Chiquita provides an annual evaporation rate of 1145 mm.

The lake model is firstly applied with available data of P, Q, and calculated data of evaporation. Then, an adjusment parameter $\gamma$ is estimated with a "trial and error" process (Fig. 7), based on the comparison between measured ($H$) and simulated ($h$) values of lake level, following the Nash criteria $r^2$:

$$r^2 = \frac{\sigma^2 - \chi^2}{\sigma^2} \quad \text{with} \quad \chi^2 = \sum (h_i - H_i)^2 \quad \text{and} \quad \sigma^2 = \sum (H_i - \overline{H})^2 \qquad \text{Eq. (3)}$$

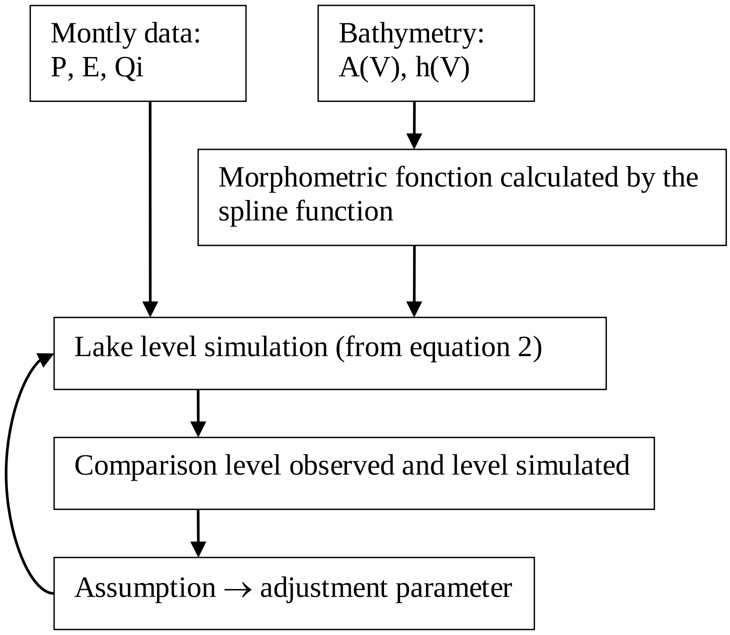


Figure 7: Scheme of the lake model approach

*4.2. Results and discussion*

The lake model is applied over the 1975-1995 period, for which our time series are complete. Applied with available hydroclimatic data, the model overestimates the lake level for most of the simulation period (Fig. 8) (Note that since the year 1982, the simulated lake level becomes higher than the measured values used for establishing the lake morphometry (Fig. 6), and the application of the spline function used for $h$ = f($V$) becomes irrelevant).

In order to estimate the order of magnitude of the discrepancy, we introduce a constant value of $\gamma$. The optimisation process (trail and error) provides a value of $\gamma = 1.25\ 10^8\ m^3$/month with $r^2 = 0.9143$ (Fig. 9). Relative to the average lake water surface (≈ 6000 km²), this value corresponds to 250 mm/year.

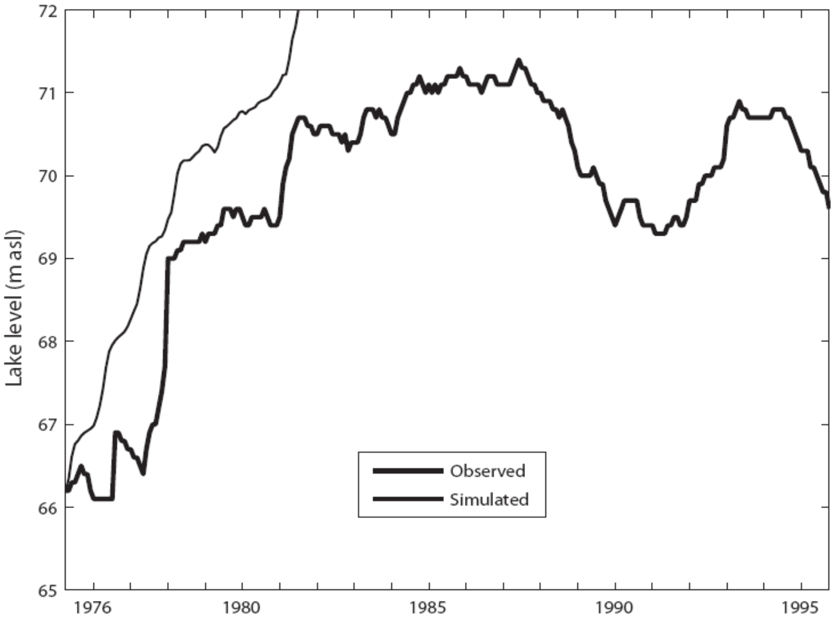


Figure 8: Simulation results on the 1975-1995 period without adjustement parameter

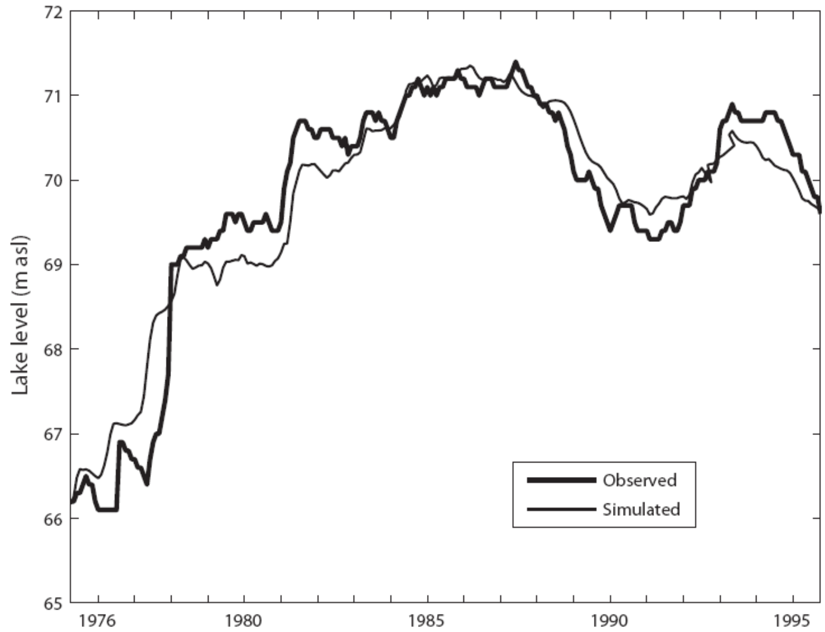

Figure 9: Simulation results on the 1975-1995 period with the constant parameter $\gamma$ = 1.25 $10^8$ $m^3$/mois ($r^2$ = 0.9143)

Despite the high value of $r^2$, we can observe that the model overestimates the lake level for some periods (e.g. 1988-1993), while during others periods (e.g. 1979-1983), the lake level is underestimated. It would be necessary to introduce a time variation of $\gamma$ to improve the simulation.

However, before going further, we have to discuss the possible origin of the lake water balance overestimation by 250 mm/year.

**Uncertainty in the lake evaporation rate**

The accuracy of the lake level simulation greatly depends on the validity of evaporation estimates, since it is the only loss of water from the lake. However, a precise quantification of evaporation is difficult, especially when detailed climatic data above the lake surface is lacking. For comparison, potential evaporation calculated by the FAO Penman method, from three meteorological stations located in the northern Mar Chiquita catchment indicates about 1277 mm/year (Shipper 2005), which is 12% higher than the 1145 mm/year estimates from our CRLE approach. An 8% underestimation of evaporation from the CRLE model was observed in a detailed study from a Brazilian lake (DosReis and Dias, 1998). We could assume that the CRLE model would tend to underestimate the evaporation rate. However, the value of $\gamma$ (250 mm/year) would correspond to a 22% underestimate. Thus, even if a better estimate of the lake evaporation rate would be necessary, we do not believe that it would resolve the actual discrepancy between simulated and measured lake levels.

Moreover, we did not take into account the effect of the water salinity on the evaporation rate. During the studied period, the lake salinity has varied from 79 g/l in 1977 to 28 g/l in 1986 (Martinez, 1995). Because the evaporation rate is lower for saline water than for freshwater (Oroud, 1998), this would tend to reduce the calculated evaporation rate and to increase the lake level overestimation.

**Uncertainty in river flow estimates; influence of the northern wetlands (Los Bañados)**

The river discharge stations are situed between 160 and 366 km from the lake shore (Fig. 1). A water loss in the catchment area located between the gauging stations and the lake shore could also explain the lake level overestimation. Infiltration of river water may be involved, but the phreatic aquifer lying in the lake area probably feed the lake and this process should not induce a water loss for the lake, except in case of important groundwater pumping. This point has to be checked, even if it seems that irrigation is not widespread in this cultivated area. Evaporation of surface water between the gauging stations and the lake is another process that could explain a water loss. This process may be important especially in the northern wetlands (Los Bañados) an area with a particular hydrological behaviour, located in the Dulce River delta (Fig. 10). Satellite images have shown that the flooded area in this zone is large and varies within an important range (Pagot 2003). Evaporation from these wetlands, which is not taken into account in our simulation, may thus affect the lake water balance. In order to introduce this influence in the lake model, we have to understand the factors which control the variation of flooded surfaces, and the hydraulic relations between the wetlands and the lake.

**Uncertainty in the morphometric relationships.**

As a very flat lake, important variations of the water surface are associated to the lake level variations (Fig. 3). In particular, abrupt water invasion may occur in some parts of the lake shore during the lake level rising, influencing the $S = f(h)$ function. The "Laguna del Plata", a small lake ("satellite lake") located southern to Lake Mar Chiquita (Fig. 10) provides an example of this phenomenon. During the beginning of the modelling period, the Laguna del Plata was a small lake overflowing towards Mar Chiquita through a small river channel. After the lake level rising, it has been completely connected to Lake Mar Chiquita, and is now completely included in the lake water body. Such phenomena should be taken into account in the morphometric relation used in the lake model.


Figure 10: Satellite image of Lake Mar Chiquita, showing the Northern wetlands (Los Bañados) and the small "satellite lake" Laguna del Plata

## 5. Conclusions

In SESA, available precipitation records indicate that rainfall has increased significantly during the second half of the 20th century, particularly since the middle 1970's (Piovano *et al.* 2002; 2004a, 2004b). These recent changes in precipitation regimes have greatly influenced the hydrological cycle (Barros, 2004), and the present-day positive hydrological balance has produced important social and economic consequences.

Lake Mar Chiquita is a good recorder of climatic changes in its catchment. As for other closed saline lakes (e.g. Vallet-Coulomb *et al*. 2006), an hydrological modelling approach will allow a quantitative interpretation of the past hydrological changes reconstructed from lake sediments, and the assessment of the lake sensitivity to climate change. In order to estimate its water balance and to analyse the hydrological processes which control its fluctuations, we have applied a lake water balance model at a monthly time-step. We were not able to simulate the lake level from available hydro-climatic data. An adjustment coefficient was used, and showed that the lake water balance is overestimated by 250 mm/year. In addition to a possible error in the evaporation estimate, and to uncertainties in the morphometric relationships, we suggest that this may be attributed to a water loss in the catchment area located between the gauging stations and the lake shore. A possible mechanism involved in this water loss is the evaporation of surface water, especially in the northern wetlands. Further study is necessary to understand the factors which control the variations of flooded surfaces, and the hydraulic relations between the wetlands and the lake.

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