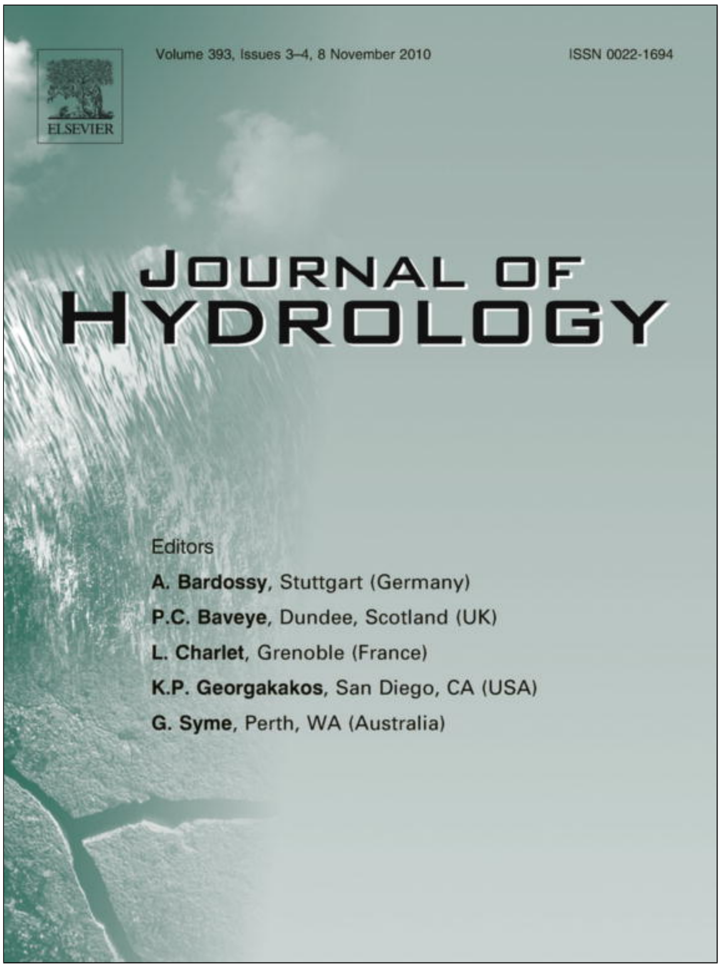

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Hydrological modelling of a closed lake (Laguna Mar Chiquita, Argentina) in the context of 20th century climatic changes

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SUMMARY

A major hydroclimatic change occured in southeastern South America at the beginning of the 1970s. This change was recorded in Laguna Mar Chiquita (central Argentina), the terminal saline lake of a 127,000 km^2 catchment as a dramatic rise in lake level larger than any observed over the past 230 years. Based on available continuous lake level monitoring since 1967, our study aimed to develop a lake water balance model for investigating the link between climate and lake level variations. Since un-gauged downstream surfaces represented approximately 80% of the catchment, the main challenge of the model development and implementation came from estimating the magnitude of catchment inputs from sparsely available gauge data. We determined a strongly negative water balance in the un-gauged part of the catchment that can be attributed to evapotranspiration in two large surface water hydrosystems. The chloride balance indicated that the lake is hydrologically closed, without significant groundwater outflows. Using contrasted hydroclimatic conditions, the robustness of the model calibration was evaluated with the model residual, and a short validation proposed for the 1998–2006 time period. Sensitivity analyses were performed in order to identify the main forcing factors of lake variations. We determined that the abrupt lake level rise in the early 1970s could be attributed to increased runoff in the upper northern sub-basin, suggesting a tropical climatic influence. Based on available hydroclimatic data, we propose a continuous lake level simulation for the 1926–2006 time period which could be used as a reference curve for better constraining paleohydrological reconstructions from sedimentary proxies.

1. Introduction

In southeastern South America (SESA), the hydrologic cycle is known to be characterized by substantial variability over the 20th century (Garcia and Mechoso, 2005; Pasquini et al., 2006). A wet period resulting from a well-documented significant increase in precipitation and streamflows in both the Paraná-Plata Basin and central Argentina occurred from the early 1970s until the beginning of the 21st century (Garcia and Vargas, 1998; Genta et al., 1998; Planchon and Rosier, 2005). This substantial increase in precipitation is associated to higher frequency and severity of extreme hydrologic events (Camilloni and Barros, 2003; Berbery and Barros, 2003). Since this region is highly dependent on agricultural and hydroelectricity, changing conditions have had important and immediate impacts on the local economy and society. Currently, a debate concerns the processes that govern precipitation variability in SESA which induces increasing hydroclimatic trends, as well as the understanding of their link to anthropogenic activities (CLARIS-LPB project, http://www.claris-eu.org/).

Laguna Mar Chiquita (30°54′S–62°51′W) is an extensive saline lake located in central Argentina, west of the Paraná-Plata Basin (Fig. 1a), and has clearly undergone 20th century hydrologic changes through abrupt lake level fluctuations. The lake is a unique site in South America because continuous lake level measurements, collected since 1967, record significant increases in water level since the early 1970s. Historical information, based on limnological studies which began at the end of the 19th century (Harperath, 1887; Von Grumbkow, 1890; Frank, 1915; Kanter, 1935; Bertoldi de Pomar, 1953; Reati et al., 1997), had allowed a semi-quantitative reconstruction of lake evolution prior to the instrumental period (Fig. 1b). Additionally, based on lake sediment proxy data, lake variations have been reconstructed for the last 230 years (Piovano et al., 2002, 2004, 2006, 2009), and have shown that the lake was characterized by dominant dry conditions until the beginning of the last quarter of the 20th century, with the highstand from the early 1970s the most important in length and magnitude. During the dry period, the lake surface was reduced to less than 2000 km^2, whereas in 2003 it reached an area of approximately 6000 km^2, making it not only the largest saline lake in South America but also one of the largest saline lakes in the world.

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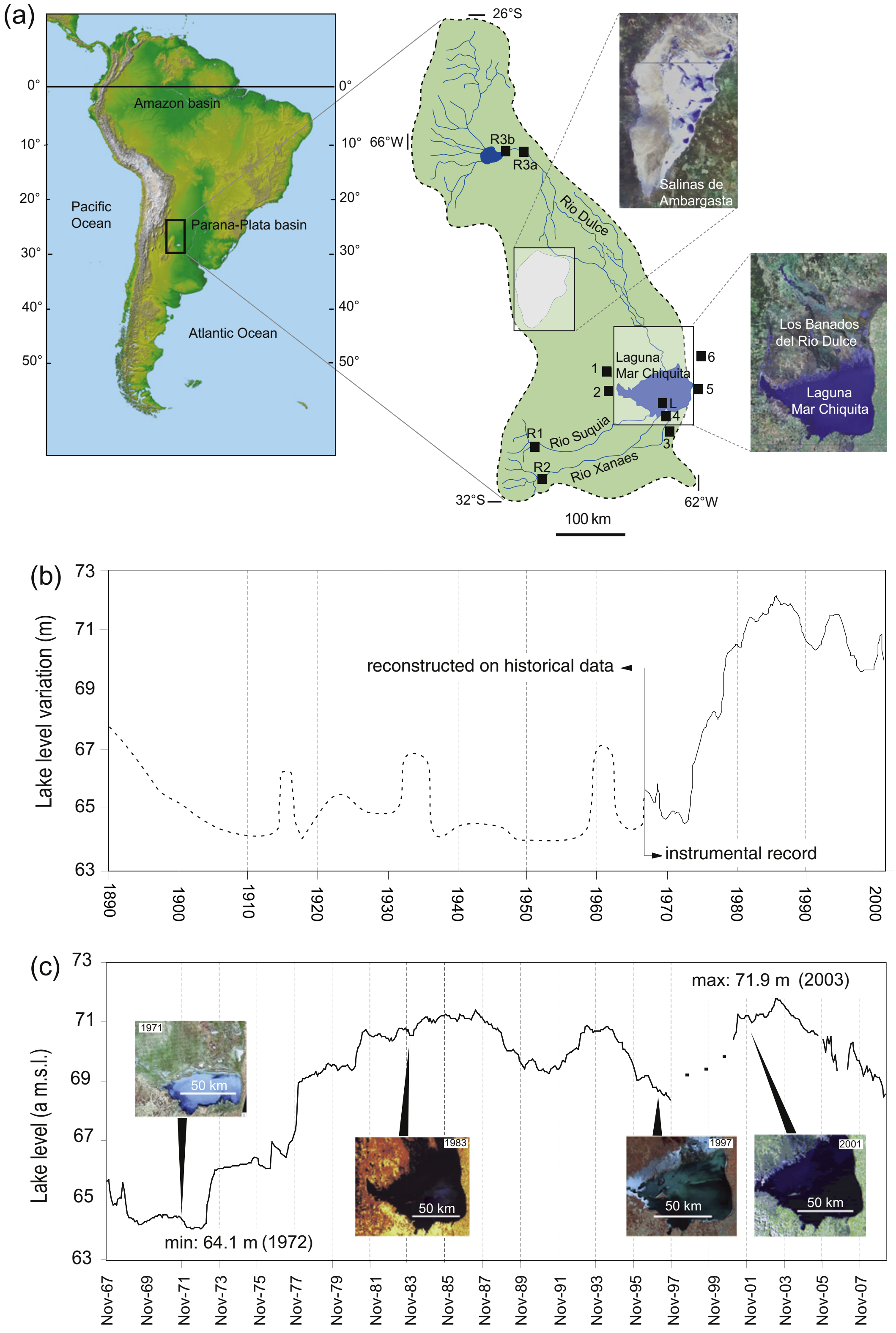

Fig. 1. (a) Location of Laguna Mar Chiquita and its catchment at the west of the Paraná-Plata Basin. Black squares shows the location of rainfall (1–6), discharge (R1, R2, R3a, and R3b) and lake level (L) measurement stations. The two satellite images show the Salinas de Ambargasta and the Bañados del Rio Dulce in the delta of Rio Dulce (*source*: http://earth.google.fr); (b) Lake level variation curve modified and corrected from Piovano et al. (2002): the interval 1890–1966 was reconstructed from a corpus of historical information (low level instrumental records over 1967–1975 were corrected *a posteriori* by Hillman (2003)); (c) Monthly lake level record of Lake Mar Chiquita during the 1967–2009 time period and corresponding satellite images of lake surface variations (http://conae.gov.ar excepting the image of 1976 taken from Bucher (2006)).

The link between climate variability and the hydrologic changes that occurred in the early 1970s in Laguna Mar Chiquita has never been investigated. At the regional scale and from comparisons with data obtained from the La Plata Basin, it has been suggested that increased lake levels could be attributed to an increase in precipitation and river discharge (Piovano et al., 2002). Questions still remain as to whether lake level changes in Mar Chiquita are mainly the result of climatic forcing or whether they are due to an influence from anthropogenic activities.

In this study, a mass balance model is used in order to investigate the link between climate and lake level variations. Calibration of this model, based on lake level measurements, allowed us to investigate lake water balance and its variations within the last quarter of the 20th century. Sensitivity analyses were then developed to identify the main factors responsible for the forcing of lake level variations. Finally, based on available river discharge and precipitation data, the lake model was used to simulate monthly lake levels for the period prior to lake monitoring, and to provide an extended lake level curve that could be utilized to constrain sedimentary proxy data reconstructions.

2. General description of the study area

2.1. The lake watershed

Laguna Mar Chiquita (30°54′S–62°51′W) is a terminal lake occupying a tectonic depression that formed during the middle Pleistocene (Kröhling and Iriondo, 1999). The lake is limited at its eastern shore by a fault (Bordo de Los Altos) that forms a small cliff that prevents surface outflow towards the Parána-Plata Basin. The lake catchment is estimated (based on the digital elevation model (DEM)) to comprise roughly 127,000 km^2 from 26°S to 32°S and from 62°W to 66°W (Fig. 1a), with a relatively low relief except for its mountainous borders on the northwest and southwest. The catchment is part of the Chaco-Pampean Plain, a larger lowland area where grasslands and shrublands have been modified for agricultural activities during the last century (Gavier and Bucher, 2004). The southernmost portion of the lake watershed is characterized by the fertile lowlands of the so-called "Pampas".

In its northern part, the watershed includes two surface water systems. The first one, called Salinas de Ambargasta (~5000 km^2 estimated from the DEM; Fig. 1a), is an extensive area of salt pans containing numerous small lakes that become linked during the wet season. The Salinas are fed by groundwater and short-lived ephemeral streams from the Rio Dulce during the wet season. Water loss is dominated by evaporation during the dry season although a small river outflow, draining salty evaporated water, is seasonally joined to the Rio Dulce. Before reaching the lake, the Rio Dulce feeds the second system, a large floodplain called the Bañados del Rio Dulce (~13,000 km^2; Pagot, 2003) that is characterized by a very low gradient forming marshy zones, ponds, small lakes, and large wetlands (Fig. 1a). An attempt to quantify the extension of open water surfaces within the wetlands was performed from satellite images by Pagot (2003), who found evidence for large variations from 325 to 3400 km^2. However, no clear link between surface variations and Rio Dulce discharge or lake level was determined.

2.2. Hydrology and chemistry of Laguna Mar Chiquita

Laguna Mar Chiquita is fed by three rivers (Fig. 1a) and likely receives substantial groundwater inputs. Groundwater is omnipresent in the plain surrounding the lake and the water table lies a few meters below the soil surface. However, no piezometric monitoring was available for the region to allow quantification of groundwater lake inputs. The main surface water inflow is from the Rio Dulce which drains the northern basin. Other important inflows to the lake, draining the southwestern part of the basin and coming from the Sierras Pampeanas region, are the Rios Xanaes and the Suquía. The lake system has no surface outlet and the only significant water loss is evaporation, which is favoured by the pan-like shape of the lake. Possible groundwater losses from the lake itself, which can occur at the lake's eastern border towards the Parána-Plata Basin, are discussed in Section 5.2.1.

Lake salinity undergoes strong interannual variations that are associated with lake volume changes. Throughout the 20th century, salinity has fluctuated between 27 and 360 g/l, a range 139% greater than the widest range of salinities recorded for a series of salt lakes in the world (Williams, 1993). The lake water is alkaline (pH > 8) due to a chloride-sulphate sodium alkalinity. During lowstands, the system is supersaturated in both calcite and gypsum, whereas during highstands it remains supersaturated in calcite and only occasionally in gypsum (Martinez et al., 1994). The shallow depth of the lake (~10 m of the maximum water depth during highstands) results in a well-mixed water column.

2.3. Regional climate

The studied area corresponds to a transition between different climatic influences. The lake catchment presents from North to South a subtropical to warm-temperate climate with a mean annual precipitation and temperature varying from 1300 mm and 20 °C, respectively, in the northern area of the basin, to 806 mm and 18 °C, respectively, close to the lake. A minimum in precipitation and temperature occurs between June and August, with a maxima occurring between December and March.

Another precipitation gradient appears from East to West characterized by the intensification and duration of an austral dry winter, and a decrease in the rainy period during the austral summer (Planchon and Rosier, 2005). Hence, a climatic gradient appears from the wet Pampa plains to the sub-Andean basins successively defining a wet climate without a pronounced dry season at the eastern side of the lake, and a semi-arid climate in the western part of the catchment area.

Regional climate is mainly defined by one of the major atmospheric features driving seasonal climatic variability in the SESA, the South American Monsoon System (SAMS). The SAMS extends southward from the tropical continental region from December to March (austral summer) connecting the tropical Atlantic Inter Tropical Convergence Zone (ITCZ) with the South Atlantic Convergence Zone (SACZ) via the large scale atmospheric circulation containing a low-level jet (Zhou and Lau, 1998). The South American low-level jet begins in the northern part of South America at the foot of the Andes and provides moisture for southeastern South America, bringing vapor from the tropics to the subtropical latitudes (Labraga et al., 2000; Barros et al., 2002).

3. Data

3.1. Lake level measurements

Monthly measurements of water lake levels spanning the 1967–2006 time period were obtained from the Laboratorio de Hidráulica at the Universidad Nacional de Córdoba (the location of lake level measurements in Fig. 1a). Lake level records have been conducted continuously since 1967, except for a gap between November 1997 and January 2001 for which only three monthly measurements of water lake levels were available. Large hydrologic changes occurred during the 1967–2006 time period with a significant lake level rise between 1973 and 1987 (Fig. 1c). Maximum lake levels were observed in 1987, 1993, and 2003 and were followed by a rapid drop that began after 2003 and that is still ongoing. Lake level rise between November 1967 and May 2003 ($\Delta h = 7.8$ m) was associated with an important increase in the lake's surface ($\Delta S = 2.71 \times 10^9$ m^2) and a change in volume (ΔV) of 8.22×10^9 m^3 (Fig. 1c).

3.2. Meteorological and hydrological data

Available monthly rainfall and discharge data span the 1926–2006 time period. Monthly rainfall was obtained from the Dirección Provincial de Agua y Saneamiento (DIPAS) in Argentina's Córdoba Province, and from the Instituto Nacional de Tecnologia Agropecuaria (INTA) for six stations surrounding the lake (Fig. 1a and Table 1). As mentioned above, seasonal rainfall distributions showed a wet austral summer between November and March, and a dry austral winter between June and August with a positive gradient from West to East (Fig. 2). Stations 1–3 that are located at the western and southern part of the lake recorded lower annual rainfall (Table 1). Station 4, located near the southern shoreline of the lake, showed the same seasonal pattern but with comparatively higher rainfall amounts during the year (Fig. 2 and Table 1). The two eastern stations (stations 5 and 6) that recorded the highest annual rainfall (Table 1) displayed an intensification of the rainy period. Station 5 recorded higher annual rainfall, in particular at the end of the rainfall season, with a maximum occurring in March (Fig. 2). A shift in the rainfall season at station 6 was observed through an earlier rainfall increase during spring (Fig. 2).

Monthly river discharge was obtained from Argentina's Subsecretaría de Recursos Hídricos and the Laboratorio de Hidráulica at the Universidad Nacional de Córdoba (Table 2). The two southern rivers, the Rios Suquía (R1) and the Xanaes (R2) were gauged at Dique San Roque and Santa Ana, respectively, both being located at approximately 160 km upstream of the lake shore. The northern river, Rio Dulce (R3), was gauged at Los Quiroga (R3a) and Dique Rio Hondo (R3b); the stations are located at approximately 360 and 410 km upstream from the mouth of the river, respectively (Fig. 1a). The R3b time series was obtained by combining two neighbouring gauging stations, which were well correlated during the 1967–1982 common time period ($r^2 = 0.99$). Together, the three gauging stations R1, R2, and R3a cover 20% of the total lake catchment area (Fig. 1a and Table 2).

3.3. Time series analysis

In order to reconstruct a complete time series spanning the 1926–2006 period, missing precipitation data were replaced using statistical regressions between nearby stations (station 1 *versus* 2, $r^2 = 0.60$, $n = 635$; station 3 *versus* 4, $r^2 = 0.74$, $n = 825$; and station 5 *versus* 6, $r^2 = 0.56$, $n = 734$) and completed using mean monthly values when data from the reference station was missing (the latter case represents for stations 1 and 2: 7.7%; for stations 3 and 4: 5.6%; and for stations 5 and 6: 3.3%). The R3b time series was completed using mean monthly values (gaps during the first 8 months and the last 9 months of the 1926–2006 time period).

Annual average precipitation indexes for the 1926–2006 time period exhibited a relatively low variability although wetter conditions could be observed since the early 1970s (Fig. 3a). By comparison, the annual normalized index of river discharge (Fig. 3b), and in particular for the northern river, showed higher interannual variability than for precipitation, with alternating periods of relatively drier and wetter conditions. Annual river discharge indices exhibited relatively long dry conditions from the early 1930s to the early

Table 1
The name, location, and main characteristics of the six precipitation stations.

	Rainfall station	Latitude (S)	Longitude (W)	Altitude (m)	Period: 1926–1966		Period: 1967–1997		Period: 1998–2006	
					Annual value (mm)	Proportion of monthly missing data (%)	Annual value (mm)	Proportion of monthly missing data (%)	Annual value (mm)	Proportion of monthly missing data (%)
1	Arrias	30°20	63°36	190	609	22	720	2	674	45
2	La Posta	30°25	63°40	158	694	24	660	30	678	64
3	Balnearia	31°00	62°41	83	693	1	743	8	743	47
4	Miramar	30°54	62°40	75	728	1	824	17	824	49
5	Morteros	30°44	62°00	98	796	19	990	9	990	51
6	Ceres	29°53	61°57	90	819	12	965	0	998	0

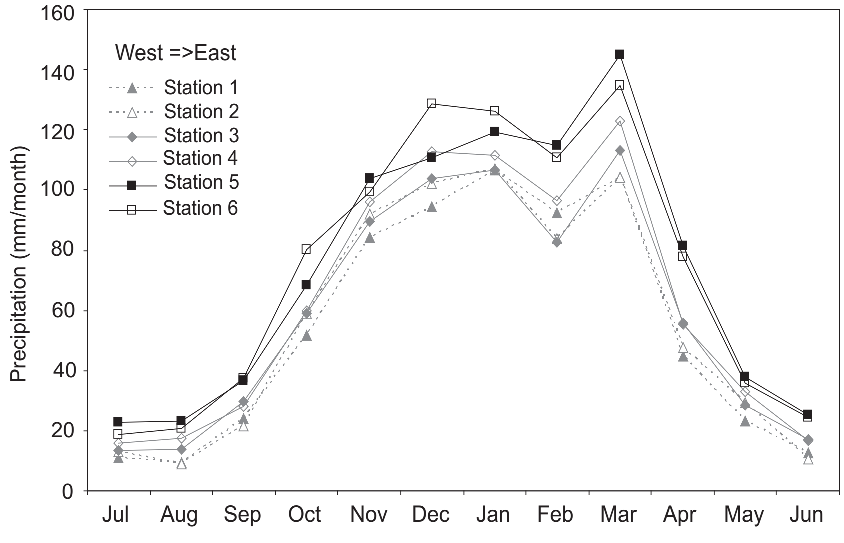

Fig. 2. Mean monthly rainfall from the six stations around Laguna Mar Chiquita over the 1926–2006 time period.

Table 2
The name, location, and main characteristics of the river discharge stations.

	River discharge station	Latitude (S)	Longitude (W)	Catchment area (km^2)	Period: 1926–1966			Period: 1967–1997			Period: 1998–2006		
					Average value (m^3/s)	Specific discharge (mm/year)	Proportion of monthly missing data (%)	Average value (m^3/s)	Specific discharge (mm/year)	Proportion of monthly missing data (%)	Average value (m^3/s)	Specific discharge (mm/year)	Proportion of monthly missing data (%)
R1 (Rio Suquía)	Dique San Roque	31°36′	64°45′	1350	9	209	0.6	13	293	0	14	316	11
R2 (Rio Xanaes)	Santa Ana	31°40′	64°34′	465	5	305	35	6	404	0	12	815	38
R3a (Rio Dulce)	Los Quiroga	27°39′	64°21′	23,810		No data		94	125	0		No data	
R3b (Rio Dulce)	Hondo	27°30′	64°52′	19,700	103	161	1.6	132	211	0	190	304	41

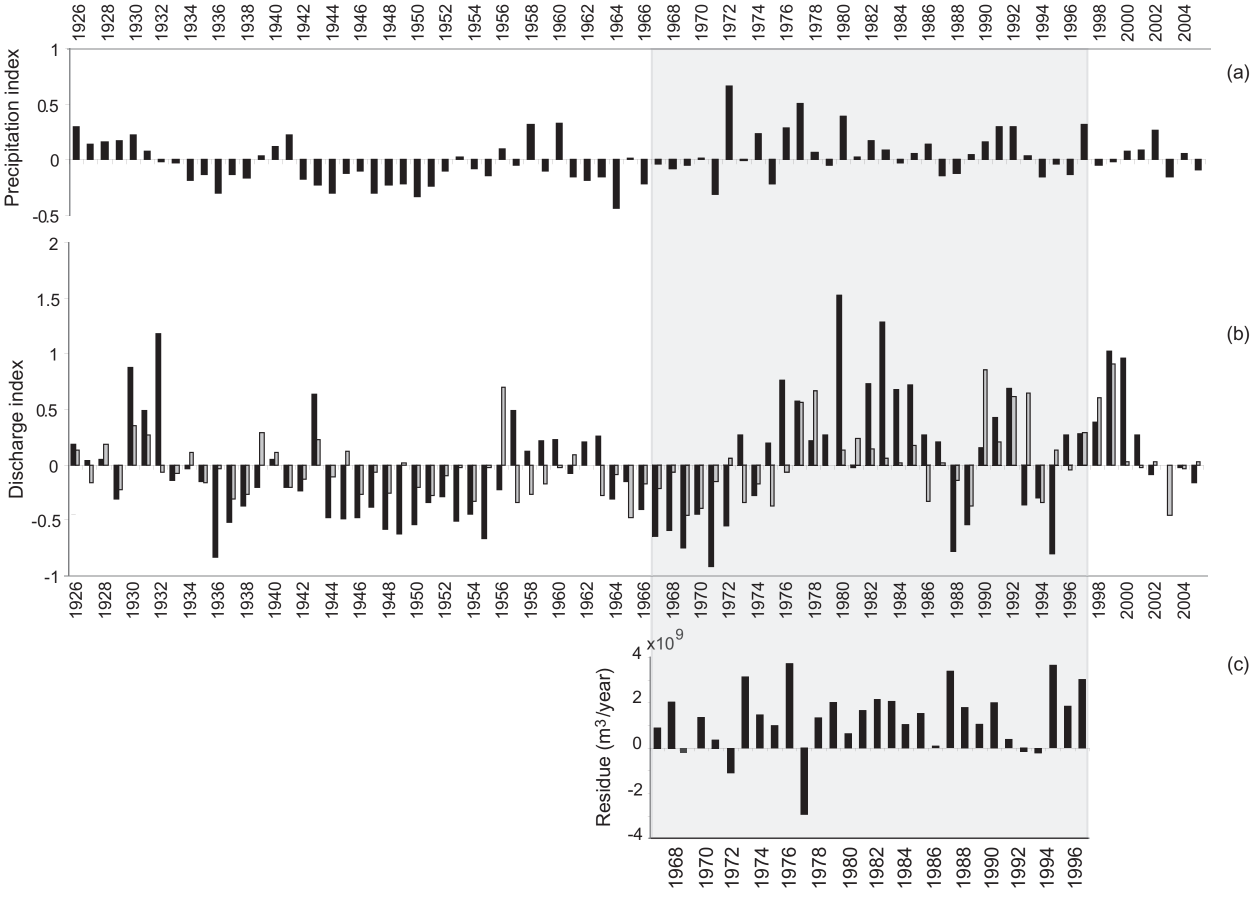

Fig. 3. (a) Annual normalized precipitation and (b) discharge (south: R1 + R2 in grey bar; north: R3b in black bar) indexes over the 1926–2006 time period; (c) annual values of the model residue calculated from Eq. (6).

1970s, including short wet periods. Since the early 1970s, a longer period of wetter conditions occurred until the middle-to-late 1980s, followed by shorter alternating periods of dry and wet conditions until 2006.

Based on available data (Table 2), we delineated three time periods: 1967–1997 (the most complete data set, including available R3a time series), 1998–2006 (available lake level data, but many gaps in the R3b time series), and 1926–1966 (no lake level data). The three times series were utilized for model calibration, model validation, and lake level extrapolation, respectively.

3.4. Chemical data

Lake chemical data available since 1926 were compiled from several sources (Kanter, 1935; Bertoldi de Pomar, 1953; Durigneux, 1978; Martinez et al., 1994; and Piovano et al., 2004) and completed by lake water sampling in 2005 (Table 3). Since 1976 and 1977, a clear decrease in lake salinity and chloride concentrations was observed, respectively, for salinity (TDS < 80 g/l) and chloride (C_L < 36.5 g/l) due to lake water dilution associated with lake level rise. River and groundwater

Table 3
Measured lake total dissolved solids (TDS) and chloride concentrations during the 1926–2005 period. The historical documented record of TDS and chloride concentrations are documented since several sources: Kanter (1935); Bertoldi de Pomar (1953), Durigneux (1978), Martinez et al. (1994) and Piovano et al. (2004).

	Year	Measured TDS (g/l)	Measured chloride concentration (g/l)
Documented record	01/1926	186	/
	01/1951	251	/
	01/1953	290.6	/
	01/1970	270	143.7
	01/1972	270	/
	01/1973	218	/
	01/1976	80	/
	12/1977	78.7	36.5
	01/1978	50	/
	01/1981	33	/
	02/1982	30	13.6
	01/1983	30	/
	08/1984	29.2	/
	11/1984	27.2	/
	01/1985	28.5	/
	11/1986	29.2	13.40
	11/1987	29.7	/
	07/1988	30	/
	12/1988	35	/
	01/1989	38	16.65
	03/1989	40	/
	10/1989	45	/
	12/1989	50	/
	01/1990	51	/
	04/1990	47	/
	08/1990	45	/
	01/1991	50	/
	02/1992	40	/
	01/1993	30	/
	02/1994	30	/
	08/1994	35	/
	01/1995	40	/
	01/1996	42	/
	04/1996	45	/
	01/1997	57.6	/
	01/2000	40	/
Analysis of water samples	03/2005	22.2	14.41
	11/2005	32	15

chloride concentrations were also obtained in 2005, 2007, and 2008 (Table 4).

4. Lake water balance

4.1. Basic equation

Monthly changes in lake level were calculated using the water balance equation combined with quantitated area–volume-level relationships. The dynamic lake water balance equation can be expressed as follows:

$$\frac{\Delta V}{\Delta t} = A(V)(P - E) + Q_{in} - G_{out} \qquad (1)$$

where for the monthly time step Δt, ΔV is the lake volume variation (m^3); A is the lake area (m^2), as a function of lake volume V; P is the on-lake precipitation estimated from the six rainfall stations (m); E is the evaporation from the lake's surface (m); Q_{in} is the water inflow from the catchment (m^3); and G_{out} is the groundwater outflow (m^3). The corresponding lake level is then estimated as a function of lake volume, $h = f(V)$, following the morphometric relationship (Fig. 4) established using lake bathymetry (Hillman, 2003).

Lake water model performance was evaluated using the Nash–Sutcliffe modelling efficiency index (EF; Nash and Sutcliffe, 1970):

$$EF_n = \frac{\sum_{i=1}^{n}(V_i - \overline{V})^2 - \sum_{i=1}^{n}(V_s - V_i)^2}{\sum_{i=1}^{n}(V_i - \overline{V})^2} \qquad (2)$$

where V_i is the observed lake volume (m), V_s is the simulated lake volume (m), and $\overline{V}$ is the mean observed lake volume (m). We have chosen to base the model efficiency on volume instead of lake level, in order to put less weight on low levels, which are very sensitive to water balance uncertainties (Fig. 4). The lake water balance model was developed using the *Matlab* (Mathworks) programming environment.

4.2. Evaporation estimate

Evaporative flux is a major component of lake water balance, but determination of this variable is challenging due to the lack of detailed measurements above the lake surface. Based on our previous experience in lake evaporation estimates from limited input data (Vallet-Coulomb et al., 2001, 2006), we used the Complementary Relationship Lake Evaporation Model (CRLE model; Morton, 1983; DosReis and Dias, 1998) to estimate monthly evaporation for the surface of Laguna Mar Chiquita. The approach is based on the postulate of a complementary relationship between actual and potential evapotranspiration. For monthly estimates of lake evaporation, the model can be considered as a simplified application of Bouchet's theory (1963). The advantage of this model is that it only requires monthly values of air temperature, relative humidity, and solar radiation. The model calculates an 'equilibrium temperature' by solving vapor transfer and energy balance equations simultaneously using conditions of potential evapotranspiration. The equilibrium temperature is then used in the Priestley–Taylor equation (Morton, 1983; DosReis and Dias, 1998). The explicit influence of wind speed in the term of the Penman equation is replaced by an empirical coefficient, which does

Table 4
Measured chloride concentrations of the three rivers (R1, R2, and R3) and groundwater between 2005 and 2008.

	Year	Measured chloride concentration (g/l)			
		Rio Suquia River (R1)	Rio Xanaes River (R2)	Rio Dulce River (R3)	Groundwater
Analysis of water samples	11/2005	0.02	0.02	/	/
	04/2007	0.05	0.01	0.10	0.14
		0.12	0.03	0.09	0.06
				0.12	0.13
					0.09
					0.12
	03/2008	0.07	0.06	0.07	/
		0.19		0.33	
				0.08	
				0.07	
				0.06	
	Average	0.09 ± 0.06	0.03 ± 0.02	0.12 ± 0.09	0.10 ± 0.03

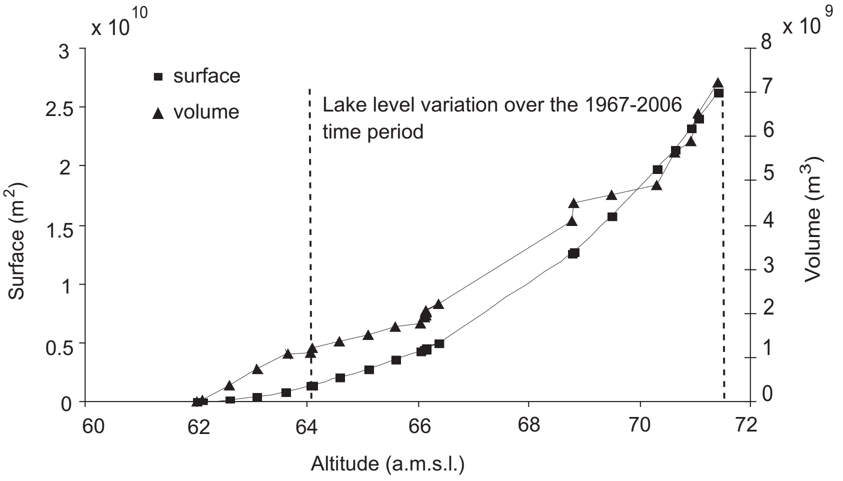

Fig. 4. Relationships between lake water level, area, and volume (from Hillman (2003)).

Table 5

Monthly climatic data from the CRU 30′S latitude/62′W longitude data set (New et al., 2002), and results of the CRLE model of evaporation (Ta = air temperature; Rh = relative humidity; Rs = solar radiation; and *E* = lake evaporation).

	Ta (°C)	Rh (%)	Rs (W/m²)	*E* (mm)
January	24	81	184	176
February	23	81	195	184
March	22	82	205	185
April	19	81	214	149
May	16	77	226	107
June	12	72	233	76
July	11	69	241	49
August	12	64	256	36
September	13	57	290	38
October	17	56	287	64
November	19	61	254	102
December	22	76	202	146
Annual value	18	72	232	1313

not require any site-specific calibration. The model has been applied previously for different lakes. Using monthly averaged data from the Climatic Research Unit database (CRU; Table 5), application of the CRLE model at Laguna Mar Chiquita provided an annual evaporation rate of 1313 mm, with a minimum in August (36 mm) and a maximum in March (185 mm). For comparison, potential evaporation rates estimated using the Penman (Shipper, 2005) and Priestley–Taylor (Pozzi et al., 2005) methods lead to values of 1277 mm/year and 1405 mm/year, respectively, that were 3% lower and 7% higher, respectively, than the evaporation calculated by the CRLE model. The difference was found in the magnitude of the range for evaporation uncertainties. A global comparison between output from the CRLE model and evaporation estimated from lake water budgets showed a difference in the estimates of ±7% (Morton, 1983). Differences on the same order of magnitude (±8%) have been observed in other studies (DosReis and Dias, 1998; Vallet-Coulomb et al., 2001).

5. Calibration of the lake model: the 1967–1997 time period

5.1. Evidence and quantification of a water loss

First, the lake level simulation was performed by neglecting groundwater outflows G_{out}, and estimating Q_{in} from the sum of measured river discharges ($Q_{in} = Q_{R1} + Q_{R2} + Q_{R3a}$). The results showed a significant lake level overestimation, on average, ~1.3 m above the observed lake level (Fig. 5; EF = 0.70). Then, in order to estimate this discrepancy in terms of water volume, we introduced a constant calibration parameter γ in the lake model as follows:

$$\frac{\Delta V}{\Delta t} = A(V)(P - E) + Q_{in} - \gamma \qquad (3)$$

The adjustment was determined through a trial and error process that was based on the Nash–Sutcliffe efficiency index, and led to $\gamma = 9.8 \times 10^7$ m³/month, corresponding to 1.2×10^9 m³/year (Fig. 5; EF = 0.93). We are aware that this calibration parameter accounted for all of the uncertainties in the input time series construction. However, the large magnitude of γ compared with each water balance component (22% of *E*, 35% of *P*, or 33% of Q_{in}) suggests the existence of additional hydrological processes which induce water losses in the water balance.

5.2. Origin of the water loss

As described above, gauging stations are located far from the lake and only 20% of the total lake catchment is covered by river discharge records. The northern part of the un-gauged lake catchment corresponds to a plain where surface and subsurface water were omnipresent: the river network is poorly organized and numerous wetlands closely interact with the shallow water table through infiltration or groundwater resurgence. Evapotranspiration could thus lead to a negative water balance. Although agricultural and urban water uses could also be involved but cannot explain the magnitude of γ since this region includes sparse urban zones with a low population density and essentially non-irrigated crops (Zak et al., 2008). In the following sections, we discuss the main hydrological processes able to explain the water loss in the lake water balance: groundwater infiltration and water loss from evaporation and evapotranspiration in the un-gauged part of the catchment.

5.2.1. Groundwater loss: insights from the chloride balance

Water infiltration in un-gauged surfaces mainly feeds the phreatic aquifer. However, since the Laguna Mar Chiquita represents the terminal water body of the catchment, shallow groundwater is expected to join the lake and, therefore, should not induce a water loss in the lake water balance. Only groundwater seepage from the lake body itself could explain a significant water deficit, and could occur at the lake's eastern border towards the Parána-Plata Basin. We evaluated the magnitude of potential groundwater loss using a chloride balance, which has proven to be useful in lake

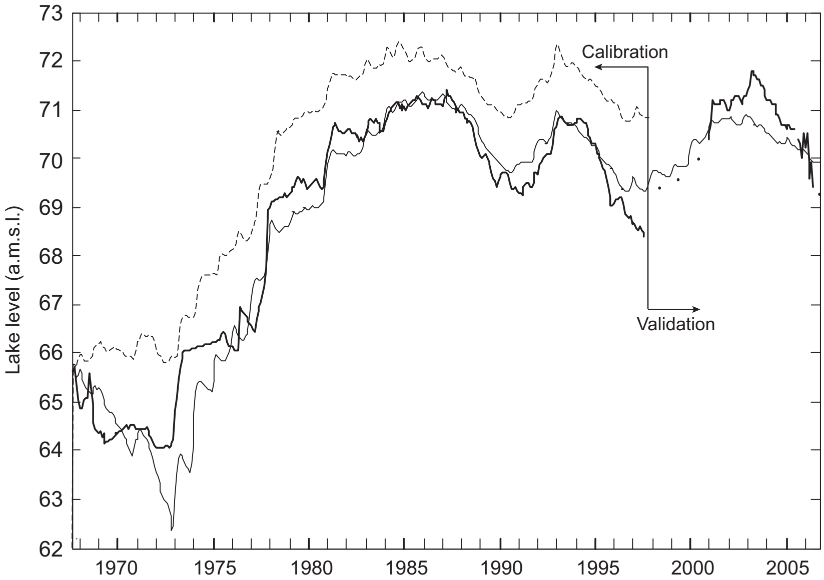

Fig. 5. Observed (bold line) and simulated lake levels of Laguna Mar Chiquita. Dotted line: first simulation obtained by neglecting groundwater outflows G_{out} and using the constructed river discharge time series for estimating Q_{in} (EF = 0.70). Thin line: simulation obtained with $\gamma = 9.8 \times 10^7$ m^3/month (Eq. (3); EF = 0.93) and by using R3a during the calibration period, and the correlation between R3a and R3b during the validation period (see text).

water balance studies (Vallet-Coulomb et al., 2001, 2006; Legesse et al., 2004). Although sparse chloride data was available, the occurrence of groundwater loss from the Laguna Mar Chiquita should be easily detectable since the lake chloride concentration was more than a hundred times that of water inflows.

By neglecting inputs from precipitation, and assuming that chloride is conservative and the water body is quite homogeneous, the chloride balance can be expressed as follows:

$$\frac{\Delta(vCL)}{\Delta t} = Q_{in}C_{in} - G_{out}CL \qquad (4)$$

where G_{out} is the groundwater outflow and C_L, C_{in}, are, respectively, the chloride content of lake water and the water inflow (g/l).

The homogeneity of the lake water body has been determined from an extensive sampling campaign (Durigneux, 1978), and verified from our *in situ* conductivity measurements. Homogeneity is the result of the shallowness of the water column (max. 10 m during highstands), easily mixed by the wind. The main weakness of the chloride balance approach is the assumption of chloride conservation. Calcite and gypsum precipitation, as well as halite precipitation during low lake level phases, has been determined in sediment cores (Martinez et al., 1994; Piovano et al., 2009). The important volume reduction associated with decreasing lake levels leads to salt precipitation along the lake shore (as observed along the southern and eastern coasts). These salts may further dissolve during subsequent water level rising periods. However, during low lake level stages, it has been observed the development of "dust storms" with noticeable transport of salt efflorescence, that fringes the lake, up to several hundred kilometres from the lake's location. Salt exportation from exposed lake sediments was reported during the most recent lake level drop. All of these processes induce uncertainties in the chloride balance.

The high salinity of Laguna Mar Chiquita is the result of the progressive accumulation of the salt that is naturally present in the inflows of the catchment ($\Delta(vC_L)/\Delta t > 0$), implying that on average, chloride exportation is lower than the inputs: $G_{out}C_L < Q_{in}C_{in}$ (Eq. (4)). The assumption neglects chloride removal from salt precipitation and wind, but such a process makes the G_{out} value even lower.

The C_{in} value was estimated from the average concentration of rivers (Table 4), weighted by the average flows (Table 2): C_{in} = 0.11 g/l. Inflows from the catchment come from both surface and subsurface flows. However, no clear difference appeared between the estimated C_{in} value and the average chloride concentration of groundwater. Therefore, we calculated the average chloride flux from the catchment using the average river discharge during the calibration period ($Q_{in}C_{in} \approx 4.6\ 10^8$ kg/year).

During the calibration period, the C_L value varied significantly (Table 3), which made the meaning of the average calculation questionable. However, based on our rough estimates, we calculated that the maximum G_{out} values varied between 3.22×10^6 and 3.45×10^6 m^3/year for the different C_L values. Therefore, G_{out} represented at most 3% of γ (i.e. less than 1% of water loss due to evaporation).

5.2.2. Impact of evapotranspiration in the catchment

Ruling out the effect of significant groundwater seepage from the lake, water loss was attributed to evapotranspiration. Indeed, the regional climate is characterized by the strong excess of potential evapotranspiration with respect to precipitation, which partly explains the endoreism of the catchment. In this climatic context, the actual evapotranspiration flux is mainly driven by water availability. Evapotranspiration could occur along the lake shore, in the flat area alternatively flooded and emerged during lake surface variations, but the major surface bodies exposed to evapotranspiration in the catchment are Salinas de Ambargasta and Bañados del Rio Dulce (see Section 2.1). We thus concluded that water loss mainly arises from evapotranspiration in the northern part of ungauged surfaces within the catchment.

6. Robustness of the lake model

6.1. Dependence of the model residue on climatic conditions

Despite the statistically significant lake level simulation performed with a constant γ value, discrepancies remained between the simulated and observed lake level curves (Fig. 5). These discrepancies could be related to the uncertainties in input variables (discharge, precipitation, and evaporation times series), measured lake levels, or model structures (the morphometric relation $A(v)$; and the calibration parameter). We analyzed the model residue in order to detect possible trends or biases. Because the model was developed to be used in the context of climate change, it was crucial to assess its applicability to contrasted hydroclimatic conditions.

Annual values for the model residue β were estimated from the following iterative calculation, performed at a monthly time step:

$$\beta_i = A(v)(P - E) + Q_{in} - \frac{\Delta v}{\Delta t} \tag{5}$$

where v is the observed lake volume, calculated as a function of the observed lake level. On average β was found to be $1.3 \times 10^9\ \mathrm{m}^3$/year, close to the γ value, but showed important variations. Negative β values corresponded to the two maxima of P (1972 and 1977), or to the two consecutive years of positive P anomalies in (1991 and 1992, with $\beta > 0$ in 1993) (Fig. 3a), indicating that high precipitation years were associated with a positive catchment water balance. However, the relationship was not clear and we could see a negative water balance in 1982–1983 (Fig. 3a), despite positive P anomalies. A comparison between β and Rio Dulce discharge variations also did not show any consistent relationship.

Therefore, despite the exceptionally high contrast between dry and wet hydroclimatic conditions covered by the calibration period, no trend appeared in the model residue. Additionally, although hydrological processes in the un-gauged catchment are complex, a statistically significant simulation was performed with a constant parameter for both the dry (1967–1972) and wet (1976–1985) periods (Fig. 5), with a maximum error of ±0.61 m in the lake level.

6.2. Short validation during 1998–2006

In the absence of discharge data from station R3a, we used the correlation established between R3a and R3b during their common period ($\mathrm{R3a} = 0.73 * \mathrm{R3b} - 1.2$; $r^2 = 0.78$). The lake level simulation over the 1998–2006 time period indicated a slight underestimation for the last 5 years (Fig. 5). These results came from the high proportion of missing data which induced a poor representation of high flood events that occurred during this period (gaps filled by the monthly average). Nevertheless, general lake level trends were roughly represented.

7. Lake water balance variability and sensitivity analyses

The model allowed us to quantify the lake water balance and the distribution of lake water inflows between local influences (i.e. direct precipitation), and remote influences (i.e. catchment contribution) mainly due to upstream river flows. We determined that the catchment contributed, on average, 33% to total inflows during the simulation period, and its proportion was highly variable, from a zero value (e.g. dry years of 1972 or 1989) to almost 71%.

Sensitivity analyses were performed in order to compare the potential impact of each water balance component on lake level variations and to identify the main factors responsible for the high lake level stage observed since the 1970s. One important issue was to identify (inside the large lake basin) whether or not there was a predominant geographical zone with a main influence on lake behaviour.

Thanks to the range of hydroclimatic conditions covered by the study period and based on the variations in precipitation and river discharge (Fig. 3a and b), two constrated climatic situations were extracted and defined – dry (1967–1972 average) and wet (1976–1985 average). A one-year mean monthly data set was created for the two periods.

7.1. Wet and dry equilibrium conditions of Laguna Mar Chiquita

We ran the water balance model by iterating the same one-year mean monthly data over a 50 year time span to determine the equilibrium conditions of Laguna Mar Chiquita for the dry and wet climate scenarios, starting from different initial lake level values. The results indicated that both the response time and the equilibrium levels did not depend on initial conditions. For the dry scenario, the response time was approximately 20 years, and the equilibrium lake level (63.3 a.m.s.l.) corresponded to the average lake level observed during dry events (Fig. 6). A shorter response time was evidenced for the wet scenario (Fig. 6), with an equilibrium lake level of 71.9 a.m.s.l., close to the lake level observed in April 2003 (Fig. 1b).

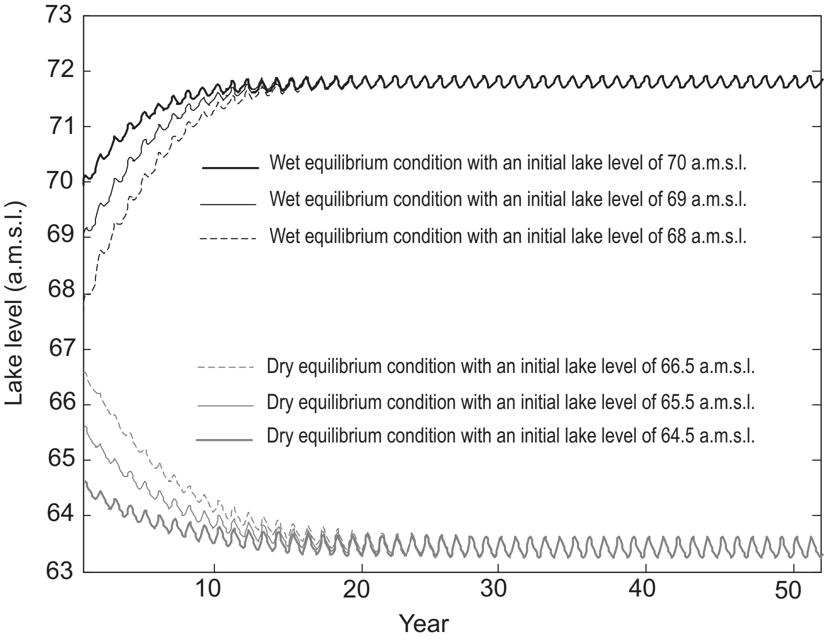

Fig. 6. Lake level simulations under wet and dry scenarios, starting from different initial conditions. The dry and wet equilibrium levels are found to be 63.3 and 71.9 a.m.s.l., respectively.

7.2. Lake level sensitivity to each water balance component

We tested the impact of variations in river discharge, on-lake precipitation, and on lake evaporation by varying values by ±10%. Sensitivity experiments were performed starting from dry (Fig. 7a) and wet (Fig. 7b) climate conditions. In each test, only one parameter was modified and the model was run until a new equilibrium level was established.

The evaporation component was the most sensitive parameter (Fig. 7). According to the model, if we maintained a 10% evaporation increase during the dry climatic scenario we simulated an equilibrium level of 62.7 a.m.s.l., close the total lake drying. A 10% reduction in the evaporation rate during the wet climate scenario induced a lake level increase of 0.75 m (Fig. 7b). The high lake level sensitivity to evaporation was related to its importance in the water balance. However, evaporation influence was lower than the combined impact of precipitation and river discharge. Laguna Mar Chiquita significantly reacts to a variation in input parameters with a predominant influence of runoff during the dry scenario and the complete lake drying was attained with only 5% river discharge decrease (Fig. 7a).

7.3. Factors responsible for the 1970s lake level rise

In order to identify which parameter supplied the lake level rise at the early 1970s, we analyzed the transition between the dry and wet scenarios, and tested the influence of isolated water balance components extracted from the wet scenario. The results indicated that a variation in precipitation or southern inflows alone was insufficient to produce the observed high lake level phase (Fig. 8b and d). On the other hand, the introduction of northern inflows during 20 years induced a high lake level stand (71.2 a.m.s.l.), very close to the wet equilibrium level (Fig. 8a and c). The change caused by northern runoff alone represented 92% of the maximum lake level variation obtained in response to the full wet scenario. Therefore, although the northern sub-basin only covers 19% of the catchment area, the high lake level rise observed in the early 1970s was mainly attributed to runoff increases in this region, which suggests a tropical climatic influence.

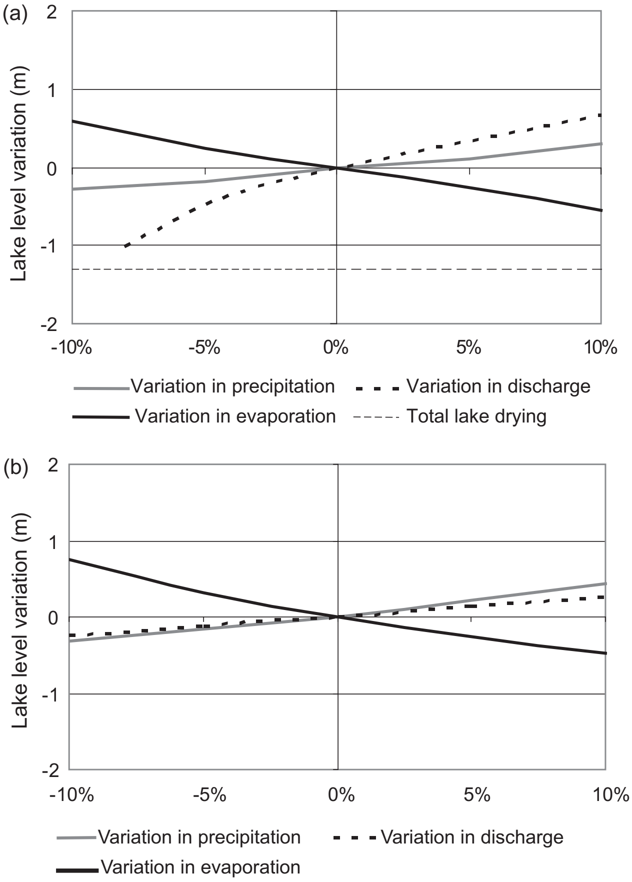

Fig. 7. Changes in the lake level equilibrium state in response to changes in each water balance component, under: (a) dry and (b) wet equilibrium conditions. Simulation were performed by individually varying mean monthly precipitation, discharge, and evaporation while holding all other parameters constant and computing equilibrium lake level in response to each new parameterization.

8. Extrapolated lake level simulation: 1926–2006

Using the available precipitation and river discharge data, we were able to begin the simulation in 1926, i.e. prior to the lake level monitoring. As in Section 6.2, we used the correlation established between R3a and R3b as an input in the lake model.

The correlation determined between water level and TDS ($H = 82.3 * TDS^{-0.0446}$; $r^2 = 0.95$) can be used to provide an indication of past lake levels. We tested different initial lake levels (±1 m) based on the value determined using the 1926 TDS measurement. Our results showed that, whatever the initial conditions, different simulated curves converged towards the same value after approximately 20 years (Fig. 9). The simulation is consistent with the low levels reconstructed in the early 1950s, which are similar to observed and simulated lake levels at the beginning of 1970s (Fig. 9).

Our simulated lake level variations (Fig. 9) are consistent with those semi-quantitative (Fig. 1b) proposed by Piovano et al. (2002). The trends are synchronous with lowstands during the first three-quarters of the 20th century, interrupted by two short wet pulses and followed by the most important highstand starting in 1977.

9. Conclusion

A monthly water balance model was built in order to investigate the link between climate and lake level variations. First, the lake model calibration showed a significant water loss, which was not induced by groundwater seepage, as indicated by the chloride balance. This water loss was attributed to evapotranspiration in the un-gauged part of the catchment. Second, no model dependence on hydroclimatic conditions was evidenced, supporting use of the model under contrasting climatic conditions with a constant calibration parameter. Despite the large size of the catchment, we determined that the lake was mainly fed by local precipitation, while its variations were controlled by remote runoff. The contribution of the catchment to total inflows represented on average 33% with high variation from 0% to 70%. Sensitivity analyses indicated a response time of approximately 15 years for a wet change and 20 years for a dry change. Recent dramatic rise in the level of Laguna Mar Chiquita at the early 1970s was fully explained by the hydroclimatic records. The results pointed to a dominant contribution from the northern sub-basin in lake level rise suggesting a tropical climatic influence. We evidenced that 92% of lake level variations were attributed to a runoff increase in the upper Rio Dulce catchment.

These results illustrate the importance of considering climate change impacts on hydrologic system, and demonstrate the usefulness of the lake model. The proposed lake level simulation curve, spanning 80 years, when compared to lacustrine archives would help to constrain the paleohydrological reconstructions from sedimentary proxies in Laguna Mar Chiquita.

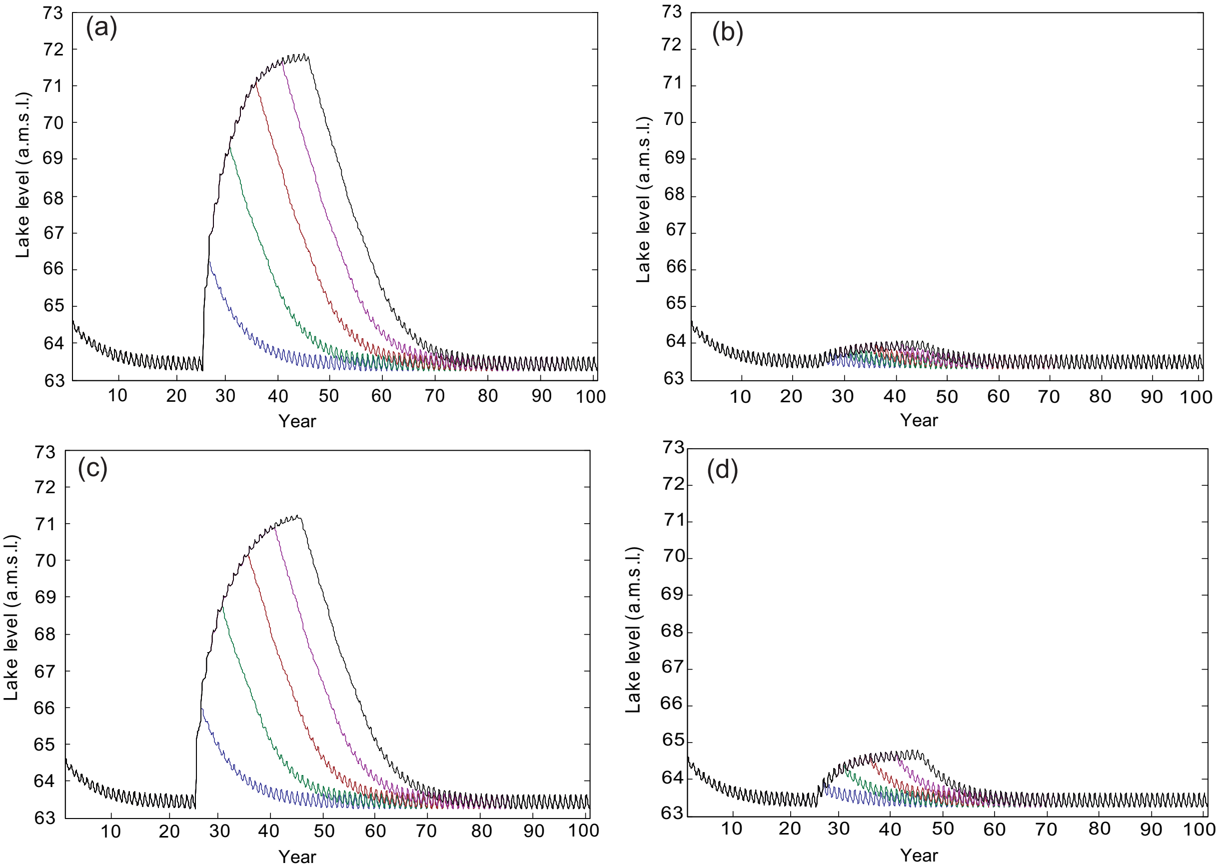

Fig. 8. Impact of a short-lived wet interval on steady-state dry equilibrium conditions. The wet intervals were defined using the hydroclimatic data of the wet scenario, with (a) full wet conditions (precipitation and discharge), (b) precipitation data for the wet scenario alone, (c) northern river data for the wet scenario alone (R3a) and (d) southern rivers data for the wet scenario alone (R1 + R2). The wet interval was applied for 1 (blue line), 5 (green line), 10 (red line), 15 (purple line), and 20 (dark line) years.

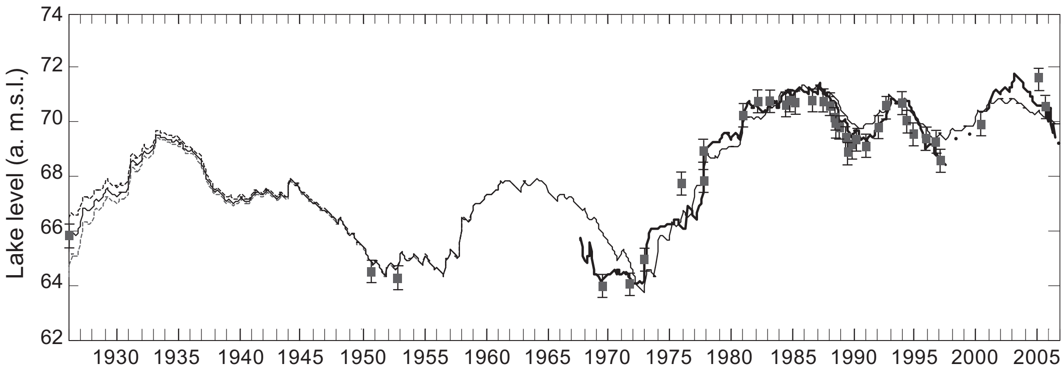

Fig. 9. Simulated lake level during the 1926–2006 time period (black line) and values of lake level reconstructed from the relation with TDS (grey squares). Uncertainties in reconstructed lake level represented by error bars are calculated from the least-squares fitting method. Different initial lake level values were tested, around the value based on the 1926 TDS data (65.3 a.m.s.l.). The observed lake level is plotted as the bold line.

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