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An analysis of water level dynamics in Esteros del Ibera wetland

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Abstract

There are several freshwater systems associated to large rivers in South America, being the inland wetlands one of substantial significance from an environmental and ecological point of view. Largely sub-valued and unknown, the permanent-temporary flooded ecosystems related to the Parana River in Argentina and Paraguay must be studied in view to their conservation. In the particular case of the Ibera wetlands, their extension (14,000 km^2), their inaccessibility, and the scarcity of available data need to be taken into account when attempting to study water dynamics. As a tool to understand the hydrology, main driving force of the ecosystem, a water balance was performed for analyzing the state of the system. As a result, a good agreement between measured water levels and calculated balance was encountered and the possibility of a non-previously considered ground-water inflow tested.

Keywords: Esteros del Ibera; Water balance model; Wetland

1. Introduction

Esteros del Ibera is a vast inland wetland located at the subtropical zone of Argentina between Latitudes 27°30′ and 29° S, and Longitudes 56°25′ and 58° W. Surficially, these wetlands contribute to the Parana River through the Corriente River. The great depression that conforms the sub-watershed lies on the paleolithic-river beds of the Parana River. The Ibera watershed, obtained using internal function of ERDAS IMAGE® 8.5 is shown in Fig. 1.

The major components of the hydrologic cycle in a wetland are precipitation, evapotranspiration, surface-water flow and groundwater flow. The relative importance of each component in maintaining wetlands varies both spatially and temporally, but all these components interact to create the hydrology of an individual wetland (Carter, 1997).

More than 50 m of permeable and semi-permeable fluvial sandy sediments rest over a geologic unit named Ituzaingo formation, constructed from numerous subsequent lava flows during the Cenozoic Era. The regional geology and hydrogeology underlying the Ibera system are completely unknown. The hydraulic properties have not been measured.

Nevertheless, it is relevant for understanding its water dynamics to have some knowledge of the general

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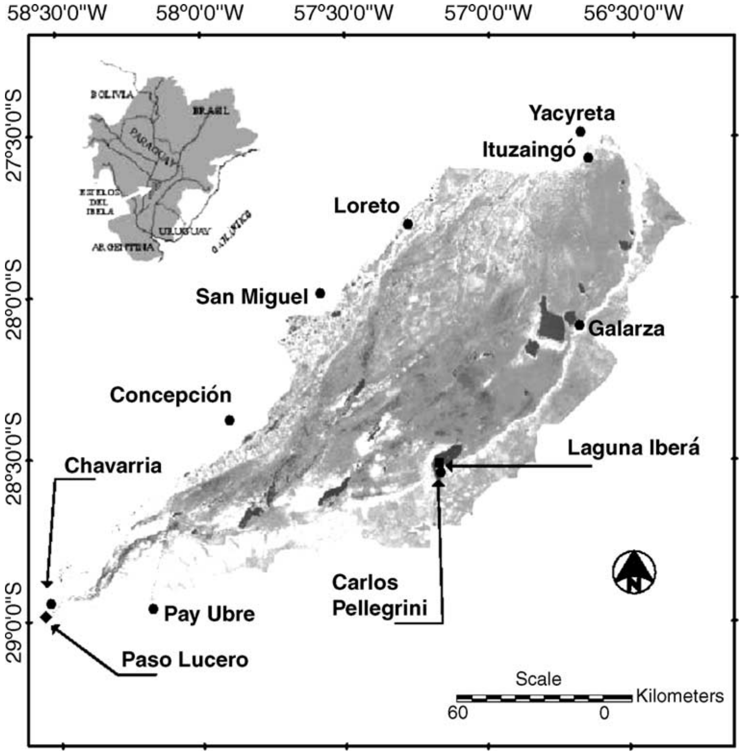

Fig. 1. Location of rain gauge stations (circles), graduated staff gauge station (squares) and water gauge station (diamonds) in the Ibera watershed.

behavior of the underlying basalt structure that is present in this region. Hydraulic properties of volcanic rocks are largely determined by the mode of extrusion and geologic controls on porosity development and fracturing. Volcanic rocks are inter-stratified with fluvial sediments deposited between eruptive events. These inter-flow deposits exhibit varying degrees of lateral continuity, and where they are really extensive and composed of coarse-grained material, they may be the most permeable units in the section. Basalt permeabilities are typically anisotropic with highest permeabilities in the direction that the basalt moved across the ground surface. Representative hydraulic conductivity values indicate that local values of permeability may differ by six or seven orders of magnitude within a sequence of basalt flows. The hydraulic conductivity for inter-beds in Cenozoic flood basalt varying between 10^{-3} and 10^{+3} m/day (Maidment, 1993).

As a tool to understand the hydrology, a water balance is performed for analyzing the state of the system. As a result, a good agreement between the pulses of the measured water levels with the calculated balance is encountered. The water balance model thus provides the means to analyze the possibility of a non-previously considered ground-water inflow.

2. Materials and methods

2.1. Data description

A set of monthly precipitation depths, comprising data from 10 rain gauge stations located close to the system in a non-homogenous distribution, were available for the study (Fig. 1). The data were obtained from EVAR S.A. (ex governmental organism) through the National Secretariat for Water Resources (Subsecretaria de Recursos Hidricos de la Nacion, SERNAH), from the National Meteorological Service (Servicio Meteorologico Nacional, SMN) through the free on-line NOAA web service, from the National Institute of Agricultural Technology (Instituto Nacional

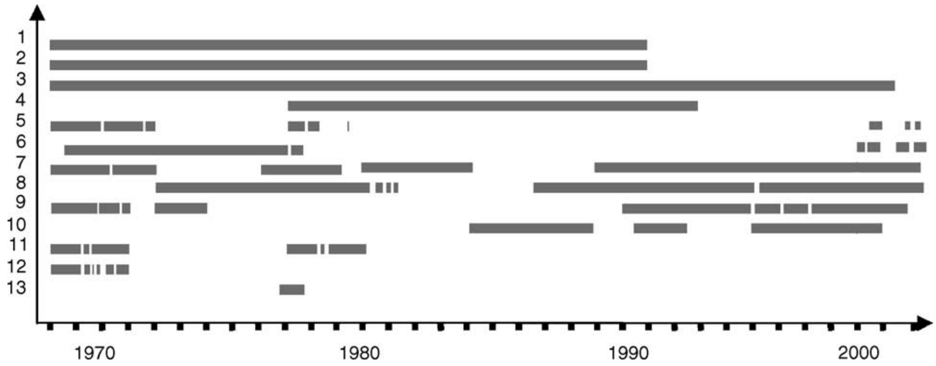

Fig. 2. Bar graph showing periods of records at rain stations: (1) Posadas; (2) Corrientes; (3) Mercedes; (4) S.J. Poriahu; (5) Concepción; (6) Galarza; (7) Chavarría; (8) Ituzaingo; (9) Yacyreta; (10) Pay Ubre; (11) Loreto; (12) San Miguel; (13) El Dorado.

de Tecnología Agropecuaria, INTA) and from local landowners.

However, individual series differ considerably in length and period of observation over the period 1968–2001 (Fig. 2).

As the majority of the stations had gaps in their records, appropriate techniques were applied in order to estimate missing data. A comparative study of double-mass curve analysis was proposed between data from Pay Ubre and Chavarria stations, both located at the southwest of the system, as well as between those from Ituzaingo and Yacyreta, at the northeast. A double-mass curve analysis is a graphical method used to identify or adjust inconsistencies in a given record by comparing its time trend with a relatively stable record of another station or an average of several nearby surrounding stations. A regression analysis and a double-mass curve analysis were performed with the purpose of comparing both series and the result allowed using both series alternatively. Both Pay Ubre-Chavarria and Ituzaingo-Yacyreta data sets showed a considerable high correlation, with the correlation coefficient being 0.93 in the first case and 0.99 in the second. The points plotted in a double-mass curve fit closely without changes in slope.

Due to the sparse, peripheral and non-uniform location of rain gauge stations, the method of Thiessen was used to calculate mean monthly precipitation depth over the basin. In this procedure, lines were drawn between adjacent stations on a map. The perpendicular bisectors of these lines form a pattern of polygons with one station in each polygon. The area that each station is taken to represent is the area of the corresponding polygon, and this area is used as a factor for weighting the station precipitation. The sum of the products of each station area and precipitation is divided by the total basin area to get the average precipitation (WMO, 1974).

The analysis was performed imposing as a restriction the availability of data series from at least three stations, so as to represent the gradient of rain distribution. This resulted in the study of the system dynamics over three periods: July 1968–December 1970, January 1977–October 1979 and August 1986–May 1999 (Table 1).

A temperature-based equation was used for estimating monthly losses by evapotranspiration from the data series. This choice was based in the fact that temperature is the only available state variable regularly being measured at Posadas, Corrientes and Mercedes during the period 1931–1990 and 1994–1999 (Ferrati et al., 2005). No records of temperature from within the system are available. Hence, the potential evapotranspiration (PET) was estimated by means of the empirical formulation proposed by Thornthwaithe and Holzman (1942). It should be taken into account that in the one hand this method underestimates the value of evapotranspiration with respect to the radiation-based method, while in the other, under certain conditions, potential evapotranspiration may be equal to free water evaporation.

The spatial distribution of PET from values calculated in each station was done taking into account the isothermal distribution (Ferrati et al., 2005) resulting in the algorithm

$$\mathrm{ETP_S} = 0.5\,\mathrm{ETP_P} + 0.2\,\mathrm{ETP_M} + 0.3\,\mathrm{ETP_C}$$

Table 1
Spatial distribution of data collection stations for each period following Thiessen's method

Records	Stations	Spatial distribution
July 1968–December 1970	Concepción (38%), Chavarria (8%), Ituzaingo (15%), Galarza (39%)	
January 1977–October 1979	Pellegrini (48%), Chavarria (14%), Ituzaingo (38%)	
August 1986–May 1999	Pellegrini (56%), Chavarria-Pay Ubre (14%), Ituzaingo-Yacyreta (30%)	

where ETP_S, ETP_P, ETP_M and ETP_C are the potential evapotranspiration values for the system, Posadas, Mercedes and Corrientes, respectively.

The series of mean monthly discharges at Paso Lucero and Los Laureles water gauged stations on the Corriente River and at Paso Cerrito water gauged station on the Batel River were available from SERNAH's database, with numerous gaps in their records.

In order to fill-in gaps in the series at Paso Lucero, a regression analysis between it and the series at Los Laureles has been done (correlation coefficient 0.93) and a least squares method was used to determine the equation parameters. In average, a 75% of volume gauged at Los Laureles station flows from the Ibera wetlands through the Corriente River.

Nevertheless, 22 months of data from the period 1968–1999 are missing as well as 5 months from the period of maximum importance (Fig. 3), from December 1989 to April 1990. The filling of data was done using three different algorithms:

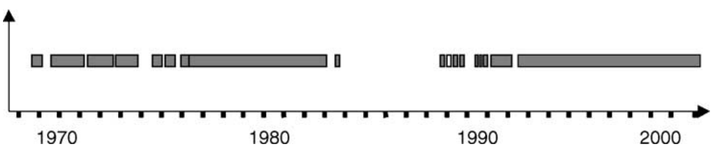

Fig. 3. Bar graph showing periods of records at Paso Lucero water gauged station on the Corriente River.

(i) monthly mean values of discharge for the period 1980–1989;
(ii) relationship between annual precipitation (P_a) and annual discharge (V_a), as given by the equation:

$$(V/P)_a = 0.078 + 3.10^{-5} V_a \,(\mathrm{hm}^3)$$

(correlation coefficient 0.97); and
(iii) relationship between monthly precipitation (P_m) and monthly discharge (V_m), given by the equation

$$V_m = 0.10 P_m \,(\mathrm{hm}^3)$$

This last algorithm is the one selected here to represent the monthly runoff-precipitation ratio, given that 10% is a conservative approach to normal ratios of 20% for typical years, that may exceed 100% during extreme events.

2.2. Water balance

The processes by which water is introduced, temporarily stored, and removed from a wetland are commonly known as the water budget or water balance. From a general perspective, water is introduced to a wetland through direct precipitation, overland flow or runoff, channel and overbank flow and groundwater discharge. Temporary storage includes channel, overbank, basin, and groundwater storage. Water is removed from the wetland through evaporation, plant transpiration, channel and overland, and groundwater recharge. Depressional wetlands, such as the Ibera system, which can have residence times ranging from weeks to seasons, have water budgets that depend mainly on direct precipitation, evaporation, transpiration and groundwater interaction (U.S. Army Engineers, 1993).

As mentioned earlier, the Ibera system is an inland wetland located in a depression and it conforms a physiographic unit in which surficial waters flow towards a common outlet: the Corriente river. The surficial water divide that defines the basin was obtained from a digital elevation model (DEM, Fig. 4) constructed through the use of internal functions of a Geographic Information System (ERDAS IMAGINE® 8.5) (Ferrati et al., 2005).

The mass conservation equation for an inland wetland is:

$$P + \mathrm{SWI} + \mathrm{GWI} = \mathrm{ET} + \mathrm{SWO} + \mathrm{GWO} + \Delta S \,(\mathrm{hm}^3) \quad (1)$$

where P is the volume of net precipitation input, SWI the surface-water inflow, SWO the volume of surface-water outflow, GWI the volume of ground-water inflow, GWO the volume of ground-water outflow, ET the volume of evaporation and evapotranspiration loss, and ΔS the variations of water volume in the storage compartment. The relative importance of each component in maintaining wetlands varies both spatially and temporally, it is important to note that all these components interact to create the particular hydrology of a wetland.

The hypothesis is that the Ibera system, as a whole, behaves as a response function whose main characteristic could be analyzed in the variable water storage compartment. The main input variable is precipitation P, while SWI is considered to be null. The main surficial outputs are the outgoing flow SWO of the Corriente River and the evaporation and evapotranspiration demand ET. The behavior of groundwater flows GWI and GWO is unknown, as they could be inputs or outputs of the system at different times and places. Hence, the balance (GWI–GWO) is here considered to be contained in the storage compartment ΔS.

Under the above hypothesis, the mass balance equation applied over a particular time interval of 1 month is

$$P - \mathrm{ET} - \mathrm{SWO} = \Delta S \,(\mathrm{hm}^3) \quad (2)$$

The available data permitted to calculate the water balance in the periods July 1968–December 1970; January 1977–October 1979; August 1986–September 1989, and May 1990–May 1999.

The only hydrometric data recorded in the Ibera system corresponds to the graduated staff gauge station located in the Ibera Lagoon. Data has been taken daily since 1969 (Fig. 5). The main observable feature in the hydrometric curve is the shift from one average water level (steady-state) over two decades (1970–1989) to a higher average over the last decade (1990–1999). The gap in the calculated balance between October 1989 and April 1990, due to incomplete series of discharge,

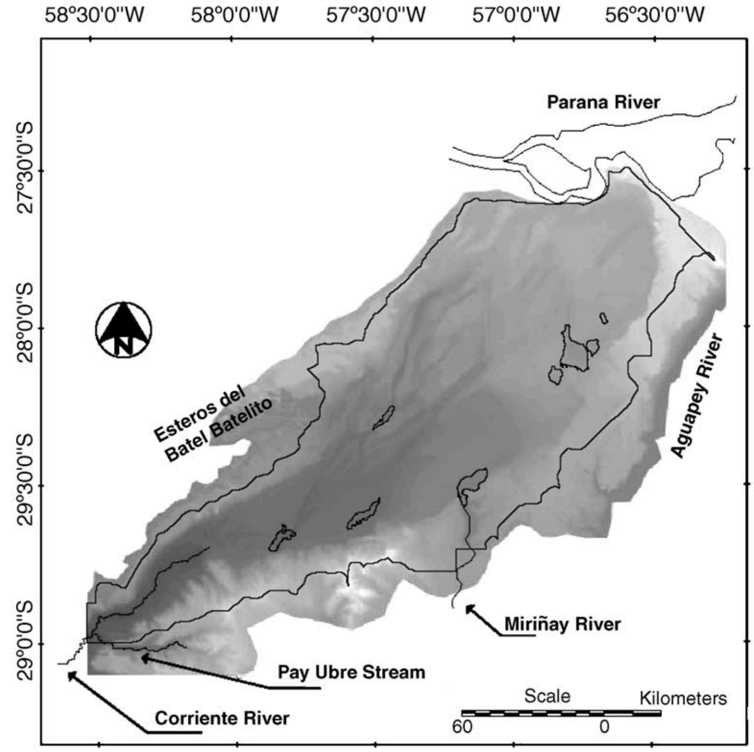

Fig. 4. Digital elevation model (DEM) of the Ibera system.

coincides with the observed jump in water level. A first approach was proposed by completing the missing values with a monthly runoff-precipitation ratio of 10%, algorithm iii, Section 2.1. This ratio was selected taking into account a conservative percentage relative to the current values of 20% for typical years (Ferrati et al., 2005).

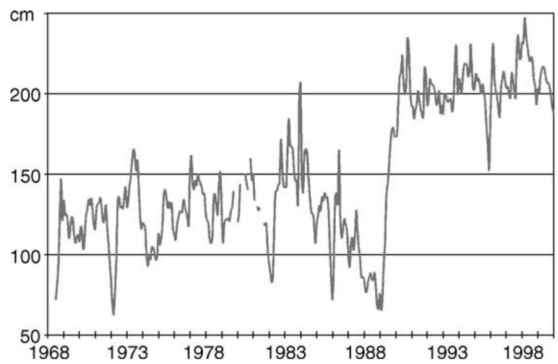

Fig. 5. Relative hydrometric levels measured at Ibera Lagoon.

3. Results and discussion of hypothesis

The result of the balance was compared to water levels (Fig. 6, thin gray line) measured in the Ibera Lagoon, the only stage station located inside the system. The thick gray line in Fig. 6, shows the result of the water balance computed over the periods where data is available, while the thick black line shows the result of the water balance in which the data series was filled using algorithm (iii). The curves show similar behavior in the pulses.

The balance model can be considered in terms of depth of water layers of precipitation, evapotranspiration and runoff, uniformly distributed over the surface. The qualitative results can show the response of the system in a better way when a comparative analysis on the basis of hydrometric data is displayed. Due to the vastness of the watershed, satellite images are a suitable tool for analyzing the flooded area. Nevertheless, it is well known that the non-existence of reliable algorithms to distinguish water

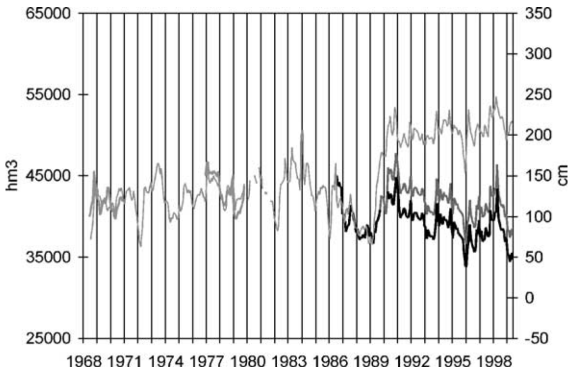

Fig. 6. Thick gray line represents calculated monthly stored volumes of water (main axis, hm^3), thick black line represents calculated monthly balance filling series using algorithm (iii) (main axis, hm^3), and thin gray line represents mean monthly relative water levels recorded at Ibera Lagoon (secondary axis, cm).

from firm soil in wetlands like Ibera, due to the presence of floating and emergent vegetation (INCyTH–ICA, 1981) that exhibit a misleading continuity in the landscape.

The output of the balance, expressed in units of length, has been analyzed in Canziani et al. (in press). It permitted to identify in a qualitative way, four periods corresponding to different responses in the hydrometic levels at the Ibera lagoon. The gap between measured water level and continuous water balance output requires a closer look into the processes taking place in a wider frame of reference. The rapid increase in water levels in 1989–1990 cannot be caused exclusively by hydrometeorological variables, but may be correlated to the water level of the Parana River, during the construction and filling of the Yacyreta Dam. The fact that the increase in the hydrometric level cannot be totally explained by precipitation, evapotranspiration, and discharge variables imposes the modification of the hypothesis of an isolated ground-water basin. Moreover, when the water levels of Ibera Lagoon are compared in a larger time-frame to the cycles of discharge of the Parana River, a correlation between pulses is observed until 1989 (Ferrati et al., 2005). The pulses of the Ibera system respond to local processes, while the Parana River accumulates at this point water flows from an upper basin that covers some 1,925,000 km^2. Hence, the correlation between pulses makes plausible the hypothesis of a ground water connection.

This first approach permitted to analyze jointly the calculated balance in units of depth layer and the water level records. Due to the lack of information on the relationship between the flooded area and the volume storage in Ibera system, the depth layer cannot be computed in a reliable manner.

3.1. Simulations for volume analyses

In order to improve this rough simplification, a new analysis of the water balance was performed taking into account volumes of water instead of depths. For this purpose, a water balance model in which the simulations concentrate on the storage compartment was developed. In this new approach, two conditions are taken to be true in order to calibrate the model: (a) an equal water level in Ibera lagoon corresponds to an equal volume in the system; and (b) the flooded area increases linearly in time over the period 1989–1990.

The coincident minimum values of water level recorded in Ibera lagoon in the years 1986 and 1995 were used to calibrate the water balance model. A relative minimum value of 1.50 m, recorded in August 1986, is assumed to correspond to a volume of 20,000 hm^3 proposed as an arbitrary initial condition of the balance. That water level value is reached again only in December 1995. The calculated volume for this month, obtained through a continuous balance using algorithm (iii) for estimating conservatively the discharge when the data is missing, was 11,330 hm^3, which yields a lack of 8670 hm^3. This is an enormous volume, even for a system of 14,000 km^2, and cannot be explained by processes at the surficial level, even if condition (a) is a rough simplification (Table 2).

The jump that changed the equilibrium of the system began in April 1989, coinciding with the derivation of the water of the Parana River through the channel located in the left margin of the river (Argentina), which was maintained until November 1989. In order to quantify the volume of water required to bring the water balance to agree with the measured levels, monthly additional inputs to the water balance were included in the model. During this initial period additional inputs of 500 hm^3/mo were added in the model in response to the rise in the water levels of the Parana River at the Yacyreta construction site (above 60 and 63 m a.s.l.). This input was considered as a ground-water inflow in this first step (Canziani et al., in press).

Table 2
Comparative analysis between water level and accumulated volumes calculated with the balance equation

	Date	Water level reached (Ibera lagoon) (cm)	Accumulated volume [hm^3]	
Low values in Ibera	July 1986	150	20000	20000
	December 1995	150	11330	11330
High values in Ibera	October 1990	230	21860*	21860*
	November 1993	230	20520*	21570**
	October 1994	230	18140*	21360**
	March 1996	230	15743*	20070**

Considers correction from first step (*), and corrections in all steps (**).

A second step in this analysis was done by considering the highest values of water level at Ibera lagoon once that the monthly additional inputs of step one are included in the balance. Stage measurements reached 2.3 m in October 1990, November 1993, October 1994, and March 1996. In order to maintain the hypothesis of "equal stage corresponds to equal volume", monthly input values of 300 hm^3/mo were added in the model over the period 1991–1994, every time that the water level of the Parana River reached a threshold of 65 m a.s.l. at the Yacyreta construction site. This situation was observed to occur in 12 out of 36 months over the above-mentioned period. Finally, additional input of 25 hm^3/mo were supplied to the model every time that the Parana River reached and exceeded 72 m a.s.l. head water level of the Ibera system. This situation was observed after 1994, when the Yacyreta reservoir was filled. Currently, the level of the Parana River at the Yacyreta Lake has reached values above 76 m a.s.l. (Fig. 7).

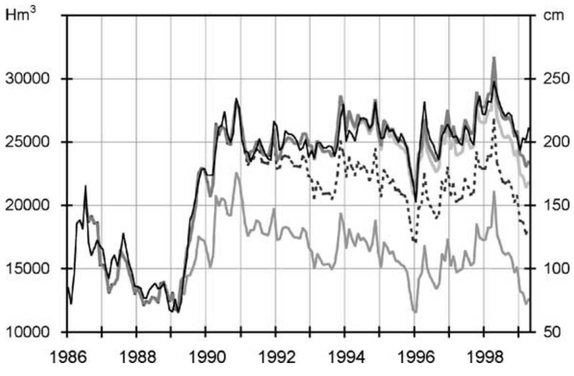

Fig. 7. Water levels at Ibera Lagoon (thin black line, cm), balance output (thin gray line, hm^3); balance in first step (dashed gray line, hm^3); balance in second step (light gray line, hm^3); balance in third step (thick gray line, hm^3).

After these additions were completed an adequate fit of the model output to the water level data could be observed.

3.2. Simulations for flood area analysis

From the results of the water balance model, and under the assumption of a linear change of flooded area in time due to the steady increase of the stage records over the 1-year period between May 1989 and April 1990, the answers to two questions have been attempted:

- Which has been the change in the flooded area during the jump, considering that the volume increased in more than 8000 hm^3 and the water level in Ibera lagoon increased in more than one meter?; and
- How many millimeters should have rained in this period to justify such a jump?

Due to the non-decreasing behavior of the water level at Ibera Lagoon and because the stage values corresponding to the two steady states (1.24 m for the series 1968–1988 and 2.05 m for the series 1991–2000) are reached within the proposed time interval, the period May 1989 to April 1990 was taken into account for responding to the first question. For the given period, the increment of stored volume and water level were about 8200 hm^3 and 102 m, respectively.

The process taking place over these 12 months can be modeled by expressing the monthly linear increase in flooded area by calculating

$$A_k = A_i + k\frac{(A_f - A_i)}{11}, \quad 1 \leq k \leq 12 \tag{3}$$

were A_i, A_f, and A_k are the flooded areas in April 1990, in May 1989 and in month k, respectively, expressed in km^2.

Table 3
Tests 1–6: simulated storage in cm for different initial and final conditions of flooded area (% watershed area); tests 7 and 8: simulated initial flooded area for fixed final area and stage

	Initial condition flooded area at 5/1989 (km^2)	Final condition flooded area at 4/1990 (km^2)	Storage in the period 5/1989–4/1990 (cm)	Difference (cm)	Precipitation depth necessary to justify $\Delta h = 102$ cm (mm/year)
Test 1	13900 (100%)	13900 (100%)	109 → **166**	**45**	2270
Test 2	10000 (72%)	13000 (94%)	109 → **176**	**35**	2167
Test 3	10000 (72%)	12500 (90%)	109 → **178**	**33**	2150
Test 4	10000 (79%)	12000 (90%)	109 → **180**	**31**	2133
Test 5	9000 (65%)	12500 (90%)	109 → **181**	**30**	2122
Test 6	7000 (50%)	12500 (90%)	109 → **188**	**23**	2050
Test 7	**4100 (30%)**	11500 (83%)	109 → 211		
Test 8	**3200 (23%)**	10000 (72%)	109 → 211		

Model output values are in bold type.

Since the variation of water volume in the storage compartment is given by Eq. (2), the water level attained during month k is computed using the equation:

$$h_k = h_{k-1} + 100\frac{(\mathrm{P}_k - \mathrm{ET}_k - \mathrm{SWO}_k)}{A_k} \quad (4)$$

where P_{k_k}, ET_{k_k} and SWO_{k_k} are the monthly precipitation, evapotranspiration and discharge calculated from data for month k for the watershed and expressed in hm^3; and h_k the simulated stage for month k expressed in cm (see Fig. 8).

Simulations with different initial and final conditions for the flooded area were considered in order to calculate the monthly stages and to compare with measured stages at the staff gauge installed in Ibera Lagoon. The results of some of these simulations are illustrated in Table 3. A final flooded area between 13,000 hm^3 (94% of the total area) and 11,500 hm^3 (83%) was considered reasonable in order to reflect the present condition of loss of emergent lands. When plausible initial conditions (above 7000 km^2 or 50% of the watershed) for the year 1989 were considered, the increase in water level remained insufficient in comparison to actual measurements: 188–176 cm as compared to 211 cm.

When a final flooded area and total stage increase are fixed and the simulation searches for the initial flooded area, the output is too small to be plausible. For example, taking a final area between 11,500 and 13,000 km^2, yields initial flooded areas between 3200 hm^3 (23% of the watershed area) and 4100 hm^3 (30%), a non-feasible value for the Ibera system (Table 3).

Regarding the second question, the accumulated precipitation and evapotranspiration were calculated for the same period. The accumulated precipitation depth was 25,286 hm^3 (1819 mm), the evapotranspiration depth was 14,138 hm^3 (1017 mm, 56% of precipitation) and the discharge was 3218 hm^3 (13% of precipitation). Hence, the difference in storage was 7930 hm^3.

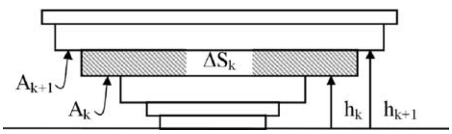

Fig. 8. Geometry of the storage compartment relative to flooded area and stage.

Table 4
Annual rainfall over the Ibera system

Year	Annual precipitation (mm)	Year	Annual precipitation (mm)
1961	1851.0	1981	1386.5
1962	1071.6	1982	1797.6
1963	1614.2	1983	2042.8
1964	1277.0	1984	1828.0
1965	1832.5	1985	1681.1
1966	1722.7	1986	2232.9
1967	1274.2	1987	1954.4
1968	1426.0	1988	1164.5
1969	1337.4	1989	1638.9
1970	1470.5	1990	1880.0
1971	1250.3	1991	1475.2
1972	1842.8	1992	1789.6
1973	1959.2	1993	1477.0
1974	1402.7	1994	1792.0
1975	1641.9	1995	1207.6
1976	1373.1	1996	1894.0
1977	1523.0	1997	1888.7
1978	1122.0	1998	2175.1
1979	1508.0	1999	1412.2
1980	1377.8		

Considering the monthly storage calculated from Eq. (2) and the different initial and final flooded areas in the above mentioned ranges, an extra annual amount of rainfall is needed to explain the observed jump of 102 cm. The calculated values are shown in Table 3.

The rainfall needed to explain such a jump should have been close to the range of 2050–2276 mm, similar to the maximum accumulated precipitation for twelve months recorded in 1997–1998, the most devastating ENSO event ever observed in the region. Table 4 shows the computed annual rainfall over Ibera for the years 1961–1999.

4. Conclusions

In developing countries, large isolated inland wetlands such as Esteros del Ibera are rarely monitored. Until recently, they were considered wastelands. Their role as carbon sinks, freshwater purifiers and reservoirs, climate regulators, and wildlife refuges was unknown or ignored. Hence, there was little interest in understanding their dynamics.

The scarcity of hydrometeorological stations in these wetland regions forces the use of simple models that do not require a wealth of data. A water balance is a first approach to understanding the driving factors of the Ibera system and a basis for the population models to be developed in the framework of this INCO project as tools for wildlife management.

The water balance exhibits a good agreement with the fluctuations or pulses observed in the stage measurements recorded in the last three decades. This reflects the dependence of the system on precipitation. But from May 1989 on, it does not adjust to the water level data. A totally unprecedented increase over a period of 18 months is difficult to justify, particularly when the extreme ENSO events of 1983, 1986, 1992, and 1998 were unable to produce such a steady increase resulting in a 191 cm difference in water level at Ibera Lagoon.

Moreover, since that date and over the decade, the system exhibits an average level some 80 cm above the one maintained earlier. This means a sudden break in the dynamics of the system. It is important to note that during the 1983 ENSO event the system recovered very rapidly, starting a period of decrease in water levels. The trend was maintained even after the 1986 extreme precipitation event. On the contrary, during the 1992 and 1998 ENSO events, in spite of extreme precipitation, the response pulses of the system were dampened and the recovery was not as pronounced as before.

Although global climate change is ordinarily blamed for the floods caused by the increase in water levels in the Ibera region, meteorological data do not show an increment that could justify such an alteration in the storage of the system.

A water balance model was developed for analyzing possible hypotheses and for testing various scenarios. It is well known that the calculation of a water balance suffers from errors originated in measurements and as well as those inherent to the algorithms used to estimate the variables. Although the recommendations of the WMO were followed, the real distributions of precipitation and temperature ignore local phenomena common in a vast ecosystem.

One difficult point in the analysis has been the transformation of volumes into layer depth and viceversa. Here, different approaches were taken in order to reduce the errors inherent to the lack of knowledge on the variation in time of the flood area. Even if the model is a rough approximation, the outputs of the simulations point to the existence of a large unjustified volume of water in the system.

Since precipitation, temperature and discharge are variables that can be accounted for, only a groundwater input can explain the sudden variation in the storage compartment. Here the balance (GWI–GWO), assumed to be contained in the storage compartment ΔS, needs to be positive. Even if the underlying geology is partially known, the existence of paleolithic riverbeds carved in basalt, fractures, and diaclasae in the surrounding region, allows the hypothesis of a positive groundwater contribution. Also, the variations of water level at Ibera Lagoon coupled to the discharge pulses recorded in the Parana River to before 1989 seem to corroborate the existence of such a connection.

Further exploration of the possible underground connections between the Ibera system and the Parana River are needed in order to elucidate the origin of the changes observed in the dynamics of the system and, particularly, to quantify the groundwater input and output, which may be variable in space and in time depending on border conditions. It is important to understand the mechanisms that drive the water levels in the Ibera system because this knowledge is necessary for a rational management of the wetland's resources. If the variation in water levels can be predicted, and the effects on the habitat of native species, some of which are endangered, can be estimated, then it will be possible to envision conservation plans and a sustainable exploitation of resources. If the variation in water levels remains unpredictable, it will be unreasonable to attempt any management plans.

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