The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

2022-41

Workshop on Theoretical Ecology and Global Change

2 - 18 March 2009

Esteros del Ibera: hydrometeorological and hydrological characterization

CANZIANI Graciela Ana Ferati R. and Moreno D.R.

*Universidad Nacional del Centro de La Provincia de
Buenos Aires
Facultad de Ciencias Exactas Departamento de Matematica
Campus Paraje Arroyo Seco 7000 Tandil
ARGENTINA*

Available online at www.sciencedirect.com
SCIENCE DIRECT®
ELSEVIER
Ecological Modelling 186 (2005) 3–15
ECOLOGICAL MODELLING
www.elsevier.com/locate/ecolmodel

Esteros del Ibera: hydrometeorological and hydrological characterization

Rosana Ferrati *, Graciela Ana Canziani, Diego Ruiz Moreno

Mathematical Ecology Group, Facultad de Ciencias Exactas, Universidad Nacional del Centro de la Provincia de Buenos Aires, Campus Paraje Arroyo Seco, 7000 Tandil, Argentina

Available online 26 February 2005

Abstract

The objective of this work is to analyze at a regional scale the hydrometeorological and hydrological characteristics of the Esteros del Ibera, a vast freshwater wetland located in NE Argentina. Since water is the main driving force in the inland wetlands and variations in water level impose conditions on the behavior of vegetation and animal populations, the knowledge of the main hydrometeorological variables that affect the hydrology is essential. Data correlation analysis makes it possible to evaluate the observed changes in the wetland and to infer its response to regional climatic change. As a first approach, the construction of a topo-bathymetric map provides a basic tool for developing a digital elevation model (DEM) using a geographic information system (GIS) and models that are based on a spatial scale.
© 2005 Elsevier B.V. All rights reserved.

Keywords: Esteros del Ibera; Wetland; Hydrology; Hydrometeorology

1. Introduction

Esteros del Ibera is one of the largest isolated inland freshwater wetlands located in South America. It is quasi pristine as it has not suffered negative impacts from superficial inflow from water courses nor industrial activities in its borders.

Wetlands are broadly defined as a transitional ecosystem between aquatic and terrestrial environments characterized by permanent or temporary inundation. In other words, a wetland is a terrestrial ecosystem with water-saturated soils that hosts plants and animals adapted to live in such an environment (Lewis, 1995). Species that form wetland communities are adapted in varying degrees to live in a flooded environment. These phenomena show large spatial variability, and different species show varying degrees of susceptibility to them, so it is not surprising that wetland vegetation exhibits such a high degree of variation in species composition (Crawford, 1983).

Wetlands cover 6% of the world's land surface and contain about 12% of the global carbon pool, playing an important role in the global carbon cycle (Sahagian and Melack, 1998; IPCC, 1996). When coastal wetlands and peatlands are included, wetlands represent

* Corresponding author. Tel.: +54 2293 447104x415; fax: +54 2293 446317.
E-mail address: rferrati@exa.unicen.edu.ar (R. Ferrati).

0304-3800/$ – see front matter © 2005 Elsevier B.V. All rights reserved.
doi:10.1016/j.ecolmodel.2005.01.021

the largest component of the terrestrial biological carbon pool (Dixon and Krankina, 1995).

Pressures on wetlands are likely to be mediated through changes in hydrology, direct and indirect effects of changes in temperatures, as well as land-use change. There would be interactions among these pressures and subsequent impacts on services and goods from these ecosystems. Consequently, land-use and climate change impacts on these ecosystems can be expected to be mediated through changes in the hydrological regime (IPCC, 2001). From the ecological perspective, the changing wetland communities result largely from their occurrence in environments where a single extremely variable habitat factor – water supply – is predominant (Tallis, 1983).

Climate change will affect the hydrology of individual wetland ecosystems mostly through changes in precipitation and temperature regimes. From the perspective of assessment of climate variability and change of wetlands, these systems need to be viewed in the broader context of their hydrological setting (Woo et al., 1993). Because the hydrology of the surface layer of wetlands is dependent on atmospheric inputs (Ingram, 1983), changes in the ratio of precipitation to evapotranspiration may be expected to be the main factor in ecosystem change.

An important adaptation strategy is the prevention of additional stress that can reduce the ability of wetlands to respond to climate change. Reducing pollution, avoiding vegetation removal, and protecting wetland biological diversity and integrity are, therefore, viable activities to maintain and improve the resiliency of wetland ecosystems so that they continue to provide important services under changed climatic conditions (Kusler et al., 1999).

1.1. Location

Esteros del Ibera is one of the largest wetlands located in the south of Latin America. This wetland, together with the Pantanal in Brazil and the Ñeembucu in Paraguay, is part of the Del Plata basin, an extended watershed that covers more than 3.5 million km^2 within five countries of South America. The climatic and geomorphologic features of this basin are ideal for the formation of large inland wetlands.

The study site, Esteros del Ibera, covers approximately an area of 14,000 km^2, between latitudes 27°30′ and 29°S, and longitudes 56°25′ and 58°W and is located in the Province of Corrientes, in NE of Argentina. This wetland is associated to the Parana River. Its headwater is located close to the High Parana watercourse, and its natural drainage through the Corriente River flows into the Middle Parana watercourse.

The major components of the water 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). Due to the gradual slope that characterizes this flat system and as a consequence of the strong relationship between morphological, hydrological, climatic, and edaphic factors, the Ibera system is featured by a predominance of atmospheric vertical balance (precipitation–evapotranspiration) rather than overland flow and discharge.

1.2. Hydrology

The Ibera is a flat system with a very gradual general slope. The absolute altitudes between extremes are 72 m a.s.l. at the northeast and 50 m a.s.l. at Laguna Itati, to the southwest. More than 70% of its surface is permanent or temporarily flooded, yielding a fluctuant stage that oscillates up to 1 m in depth. This wetland is characterized by a deficient superficial drainage and a slow movement of masses of water, regulated by biotic effects.

The Esteros are a marshy depression located over the ancient bottom of the Parana River. In the Pliocene, the Parana River flowed towards the High Uruguay River. Later on, the water flow shifted towards the Uruguay River across of Aguapey River. Further on, divisions of the riverbed occurred and were maintained until the Pleistocene. When a geological uplifting of this region occurred, the Parana River shifted towards NW, finally forming the present river bed, and leaving NE–SW slopes with well marked lines of preferential flows, shallow lakes and '*esteros*' systems. These are divided by '*lomadas testigos*' (*elongated sandy hills*) in the NE and in the SW by collecting rivers (Santa Lucia, Corrientes, and others) that flow to the Middle Parana River.

The marshy formation started in the Holocene, beginning with the accumulation of *Lujanense* sediments that hinder the flow from the depression. The Esteros were affected by a steppes regime, with a negative water balance that slowly reduced the water lakes created by marine immersions and the Fourth Entrerriano Sea during the Tertiary Era, changing them into lentic and dystrophic environments, with formation of lake biotypes that acquire the '*esteros*' characteristics. The rigorous rough climate contributed to the formation of a calcareous crust (caused by capillary ascent from subsurface layers with a high saline content) close to the surface, giving it a high index of impermeability and water surface accumulation.

Presently, the superficial water divide of the Ibera system is:

- The northern border, formed by consolidated dunes some 4–15 km wide, composed by sandy fluvial sediments covered with natural vegetation that rests over basalt of different consistencies.
- The eastern border, well marked due to a geological discontinuity.
- The southern border, also well marked by ramifications of Cuchilla Grande hills.
- The western border, defined as permeable boundary (INCyTH-ICA, 1981). It is less defined, with "lomadas testigos" (elongated sandy hills) separating Ibera from the Batel-Batelito wetlands.

From a hydrological point of view, three subsystem have been identified (INCyTH-ICA, 1981):

- The oriental subsystem, characterized by a slow sheetflow which is regulated by biotic effects over predominant histosol soils. The highest depths are observed in the eastern border, on the ancient drainage bed Parana–Miriñay, where the biggest permanent shallow lakes are located: Conte, Luna, Galarza, Naranjito, and Ibera. Their surface areas are between 3 and 80 km^2. These shallow lakes are connected with the contiguous marshland, but maintain their form because they are deeper and are bordered by dammedlands (*embalsados*). Short permanent streams go in and out of the shallow lakes, but they do not interconnect them.
- The occidental subsystem, characterized by an irregular topography which tends to form a plain and semi-fluvial drainage network. The waters from the northern marshlands are collected by the Carambola–Carambolita streams. These streams are presently immersed in a complex interconnected system of marshlands and weedlands that hinder the formation of a definite drainage network. Both the sandy hills that separate this subsystem from the oriental subsystem and the characteristic predominantly entisolic soils – semi-permanently flooded – are highly permeable allowing an underground flow. The Parana, Medina and Trin shallow lakes collect and convey the flow towards the transitional subsystem.
- The transitional subsystem, located at the southwest end of the system. It receives the water from the oriental and occidental subsystems, showing a tendency to erosion and the formation of an incipient fluvial network.

While clearly defined landscape units can be observed within the ecosystem, no strict compartments can be considered, because the interfaces show mechanisms of dynamic equilibrium which maintain the system's stability.

1.3. Bathymetry

Topographic maps developed by the Military Geographic Institute (Instituto Geografico Militar, IGM) of Argentina were the primary data sources utilized to analyze the region. Nineteen maps (1:100,000) were required to cover the study area. Several ground control points (GCPs) were selected for further geometric rectification process of the satellite images. Gauss–Krüger coordinate reference system was used in this work.

In order to cover the flooded zones, which represent more than 80% of the total area, it was necessary to gather all precedent information: maps of soil classification (1:500,000, Instituto Nacional de Tecnologia Agropecuaria, INTA), geomorphologic, phytogeographic and predominant flow maps (1:33,333; Instituto Nacional de Ciencia y Técnica Hídricas, INCyTH,), topobathymetric profiles (Instituto Correntino del Agua, ICA), satellite images (SAC-C, Comision Nacional de Actividades Espaciales CONAE), and bathymetries of Ibera and Galarza shallow lakes performed during the development of our studies.

Moreover, the level curves (elevation data) of the maps were digitized and referenced, and later a digital elevation model (DEM) was built. This map was used to define of the limits of the watershed through the use of internal functions of a Geographic Information

System (ERDAS IMAGINE® 8.5) and to create a vectorial layer with the watershed itself.

Hence, the result of this work is a first approach of a digital inferred topo-bathymetric map, susceptible to be updated and corrected as new information is gathered.

2. Variables, data and method description

2.1. Precipitation

The climatic characteristics of the region in northeastern Argentina where the Ibera system is located, are defined by a longitudinal gradient relative to the precipitation pattern that decreases towards the W. The area is affected by air mass circulation from two main sources, namely the south Atlantic and the south Pacific semi-permanent anticyclones. The south Atlantic semi-permanent anticyclone dominates the atmospheric circulation in the area. It maintains a steady NE airflow of warm and humid air masses. This circulation pattern is broken by outbreaks of cold and drier air, from the S–SW, generated by the intrusion of the south Pacific semi-permanent anticyclone, which may reach up to latitude 10°S. Therefore, the precipitation over the Ibera wetland is caused by either air-mass instability or by the cold fronts reaching the area, producing storms and abundant torrential rains.

In subtropical Argentina, Paraguay, and Brazil, precipitation exhibits a long-term change, with a dry period along 1921–1955 followed by a sharp increase in the period 1956–1990 (Castañeda and Barros, 1996). Over Paraguay, southern Brazil, Uruguay and northeast Argentina, northeastern circulation associated to the subtropical Atlantic anticyclone increased after 1954 (Hoffman et al., 1987; Minetti and Sierra, 1989; Castañeda and Barros, 1996; Barros et al., 1999).

In order to observe the pattern of the spatial distribution and the temporal trend of precipitation in the Ibera system, data series from three meteorological stations of governmental organisms (Servicio Meteorologico Nacional SMN and INTA) located in the province of Corrientes and Misiones have been analyzed (Fig. 1).

The characterization at a regional level was done using the records from the above-mentioned stations over 60 years (1931–1990) since complete data from the last decade was not available. Table 1 and Fig. 2a, b show the comparative studies of different variables taking periods of 30 years. The tendency has been

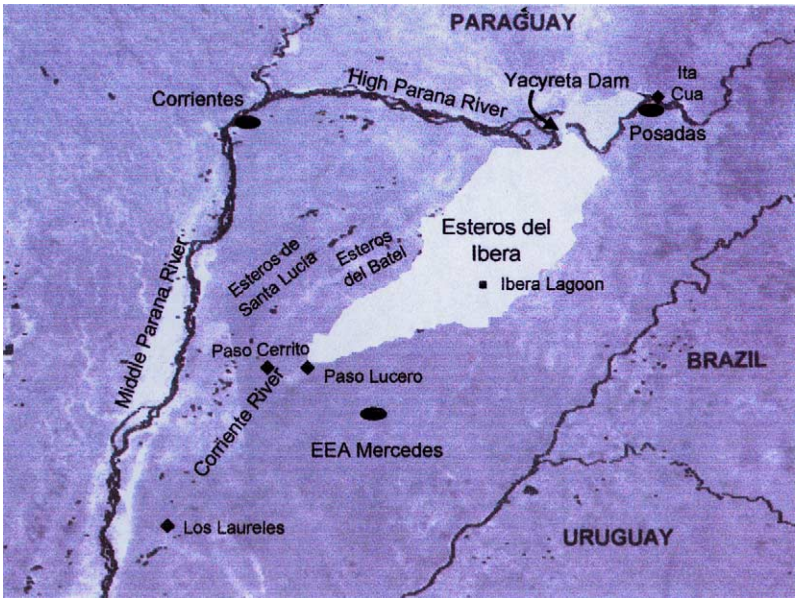

Fig. 1. Esteros del Ibera in the Province of Corrientes, Argentina. Meteorological stations (dark elipses: Corrientes, EEA Mercedes, and Posadas), water gauged stations (dark diamonds: Ita Cua, Paso Lucero, Los Laureles, and Paso Cerrito), and graduated staff gauge (dark square: Laguna Ibera).

Table 1
Annual values of precipitation, temperature, evapotranspiration and excess-deficits for each meteorological station

Variable	Period	Posadas	Mercedes	Corrientes
Mean annual temperature (°C)	1931–1960	21.2	19.8	21.1
	1961–1990	21.4	19.8	21.1
Mean annual precipitation (mm)	1931–1960	1695	1285	1266
	1961–1990	1722	1460	1408
Mean annual PET (mm)	1931–1960	1130 (67%)	1008 (78%)	1098 (87%)
	1961–1990	1130 (66%)	1026 (70%)	1111 (79%)
Excess and deficits (mm)	1931–1960	565	277	168
	1961–1990	592	434	297

analyzed in each station using the moving average method, taking into account 11 years, 5 years before and 5 years after any given year (Fig. 3a).

The precipitation depth is the volume of water from precipitation that has fallen over a catchment in a given time interval, expressed by the depth of the water layer uniformly distributed over the area. Preliminary studies have been done to characterize the areal distribution using the isohyetal method. From this information, values of annual precipitation were calculated for the system

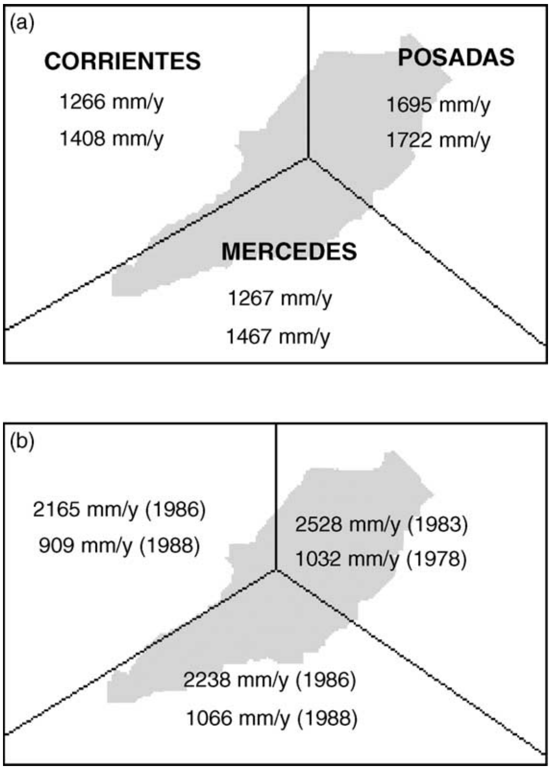

Fig. 2. (a) Mean annual precipitation for the series 1931–1960 and 1961–1990; (b) maximum and minimum values of annual precipitation for the series 1961–1990 (year of occurrence) recorded at Posadas, Corrientes and EEA Mercedes meteorological stations.

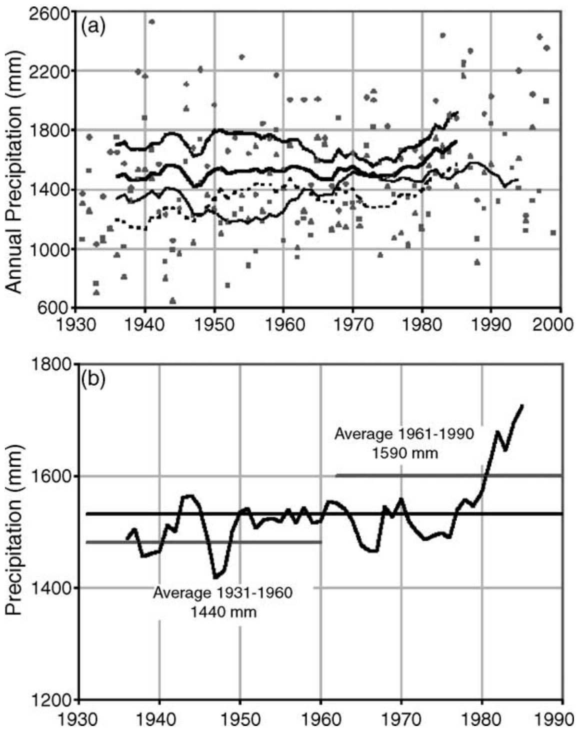

Fig. 3. (a) Annual precipitation (points) and moving average (lines) for Posadas (diamonds, thick gray line), EEA Mercedes (squares, thin gray line) and Corrientes (triangles, thick black line) stations; (b) mean annual precipitation for the periods 1931–1960 and 1961–1990 (gray lines) and moving average (bold line) for the Ibera system.

using the algorithm:

$$P_a = P_{p_a} \times 0.5 + P_{m_a} \times 0.3 + P_{c_a} \times 0.2 \quad (1)$$

where P_a is the annual precipitation at system level, P_{p_a}, P_{m_a} and P_{c_a} are the annual values of precipitation for Posadas, Mercedes and Corrientes, respectively. The synthetic output series was analyzed using the moving average method. The trend is shown in Fig. 3b.

2.2. Evapotranspiration

The loss of water to the atmosphere is an important component of the wetland hydrological cycle. Water is removed by evaporation from ground or surface water bodies and by transpiration by plants, i.e. evapotranspiration (ET). Solar radiation, wind speed and turbulence, relative humidity, available soil moisture, and vegetation type and density affect the rate of ET.

In order to evaluate monthly losses by evaporation and evapotranspiration, monthly temperature data at Posadas, Corrientes and Mercedes meteorological stations have been considered. Available data cover the periods 1931–1990 and 1994–1999.

At a regional scale, temperature and radiation conditions exhibit a latitudinal gradient. The mean annual temperature ranges between 20 and 22 °C (series 1931–1990), with minimum values in June–July of 14–15 °C and maximum values in January–February of 26–27 °C. The range varies between −2 and 44 °C. No evidence of significant differences were encountered (<0.2 °C, $p = 0.50$) between mean annual temperature values recorded over the period 1961–1990 relative to the previous period 1931–1960.

Potential evapotranspiration (PET) was estimated by means of the empirical formulation proposed by Thornthwaithe which defines potential evapotranspiration as the water loss, which will occur if at no time there is a deficiency of water in the soil for the use of vegetation (Thornthwaithe and Holzman, 1942).

In concordance with temperature, a slight increase of less than 2% in mean annual values of evapotranspiration has been observed in 1961–1990 relative to the series 1931–1960 (Table 1).

In order to obtain an areal distribution of the annual evapotranspiration at system level, the following algorithm was used

$$ET_a = ET_{p_a} \times 0.5 + ET_{m_a} \times 0.2 + ET_{c_a} \times 0.3 \quad (2)$$

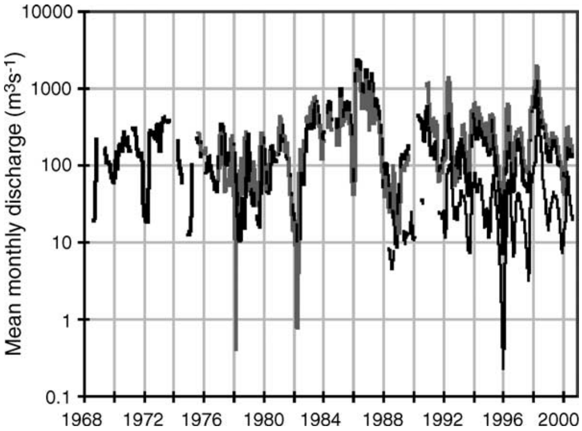

Fig. 4. Mean monthly discharge (logarithmic scale) measured at Paso Lucero (thick black line) and Los Laureles (thick gray line) water gauge stations on the Corriente River and at Paso Cerrito (thin black line) water gauge station on the Batel River.

where ET_a is the annual potential evapotranspiration at system level, ET_{p_a}, ET_{m_a} and ET_{c_a} are the annual values of potential evapotranspiration for Posadas, Mercedes and Corrientes, respectively and the coefficients calculated by taking into account the isothermal distribution.

Note that the algorithms are different because precipitation show a longitudinal gradient while temperature exhibit a latitudinal one.

Consequently, a strong predominance of vertical balance is observed in the system, the evapotranspiration representing a 74% and 70% of the precipitation measured in the series 1931–1960 and 1961–1990, respectively.

2.3. Discharge

The series of mean daily discharges over the period 1968–2000 were available from a database of Subsecretaría de Recursos Hídricos de la Nación (SERNAH) at Paso Lucero water gauge station (Fig. 1) located in the Corriente River, with numerous gaps in their records. Mean monthly discharges were available at Los Laureles water gauge station in the Corriente River (1975–2000), at Paso Cerrito water gauge station in the Batel River (1991–2000) and also at Ita Cua station in the Parana River, nearby Posadas, some 60 km upriver from the Ibera headwaters (1900–2000).

Fig. 4 shows the monthly discharge hydrograph at the three stations located on Corriente and Batel Rivers.

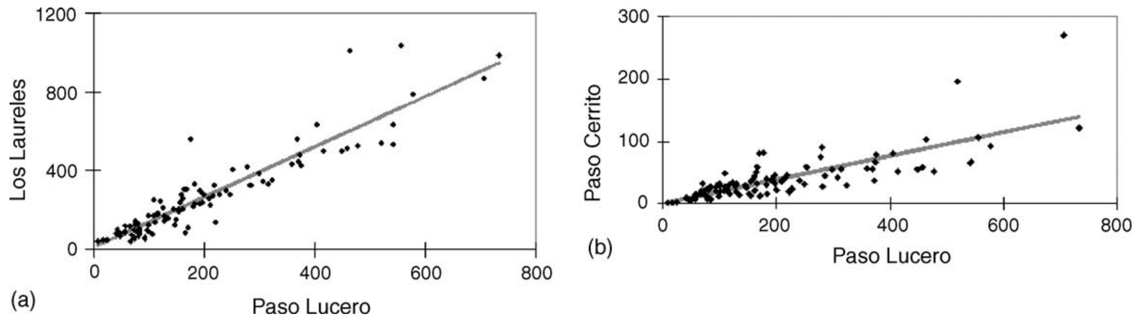

Fig. 5. (a) Regression line of mean monthly discharges (m^3/s) measured at Paso Lucero and Los Laureles gauge stations in the Corriente River; (b) regression line of mean monthly discharges (m^3/s) measured at Paso Lucero and Paso Cerrito (Batel River) gauge stations.

As shown in the graph, the Corriente River and its effluent, the Batel River, are perennial streams that flow continuously towards the Middle Parana River. It is not possible to observe monthly or seasonal patterns along the year. The excess of rainfall governs the fluctuations of the water level inside the subsystems which condition the complex regime observed in the Corriente and Batel Rivers.

With the aim of analyzing the contribution of the Ibera system to the total discharge of the Corriente River measured at Los Laureles water gauge station and to be able to complete the gaps in the Paso Lucero series, a regression analysis between both has been performed and a correlation coefficient equal to 0.93 was computed (Fig. 5a). In the average, some 75% of the volume gauged at Los Laureles station flows from the Ibera wetland and some 14% from the Batel system. Similarly, there is a good correlation between mean monthly discharge gauged at Paso Lucero and Paso Cerrito stations from 1990 until today (coefficient of correlation equal to 0.83) (Fig. 5b).

The mean value of cumulative annual volume measured at Paso Lucero – and completed whenever needed using the data values gauged at Los Laureles station—over the period 1969–1988 was 6300 hm^3/yr which yield a runoff of 453 mm/yr when the watershed area is considered. The maximum value, 20,574 hm^3 was recorded in 1986 and the minimum was 964 hm^3 in 1988, in correspondence with the maximum and minimum annual precipitation registered in the region.

Over the period 1969–1988, the response of the system to precipitation was highly predictive. The ratio between annual discharged volume and annual precipitation was correlated with annual discharged volume, and the result was a coefficient of correlation of 0.97.

The regression function obtained was

$$\left(\frac{V}{P}\right)_{\mathrm{a}} = 0.078 + 3 \times 10^{-5}\,\mathrm{V_a} \qquad (3)$$

where V is the annual discharged volume and P is the annual precipitation. Taking into account the calculated volumes, this means that the annual mean evacuated volume in normal conditions is approximately 26% of the annual precipitation. In extreme events, this ratio reaches a value of 66% for maximum volumes (1986) and as low as 6% for minimum volumes (1988).

The climatic variation and increasing human activities developed in the Del Plata basin can be reflected in the discharge of its main watercourses. The discharge of the Parana River, measured at Ita Cua gauge station close to Posadas, shows a new tendency starting in 1970. The mean discharge over the period 1975–2000 is approximately of 14.800 m^3/s. The area of the Parana watershed at Ita Cua section is 975,375 km^2 (SERNAH, 2000).

In addition to the above-mentioned regional variations, ENSO events that occurred in 1982–1983, 1989, 1992 and 1998 show extreme values of discharge (Nuñez and Vargas, 1998). During the ENSO of 1982–1983, the floods were produced mainly in the Parana and Paraguay Rivers in Brazil and Paraguay. In a different way, the floods that occurred in 1998 were due to the extraordinary rainfall in Argentina. In this year, the Parana River reached the maximum historical level with extraordinary local permanency and completely covering its entire expansion plane (Goniadzki et al., 2002).

2.4. Water level

The continuous hydrometric data registered at the Laguna Ibera are the only ones available since 1968. The series shows a jump in 1989 that induces to calculate two mean values of water level, the first for the period 1968–1988 with a value of 61.87 m a.s.l. and the second corresponding to the period 1991–2000, with a value of 62.68 m a.s.l., some 80 cm above the previous value (SERNAH, 2000).

3. Results

3.1. Precipitation and evapotranspiration

The Ibera wetland is a large depression, which behaves like a dam. The special morphology and floating vegetation are the natural spillways that retain the sheetflow and release it slowly towards the Corriente River, which is the natural channel of evacuation.

The Ibera system has a very gradual general slope of 1:10,000 from NE to the SW, from 72 m a.s.l. at the headwater next to the Parana River, to 50 m a.s.l. at Laguna Itati, at the source of the Corriente River. For this reason, the flow velocity is very slow and the vertical loss due to evaporation and evapotranspiration is very important. A vertical balance is proposed to analyze the atmospheric excess and deficit together with the observed fluctuations in the accumulated volume in the system.

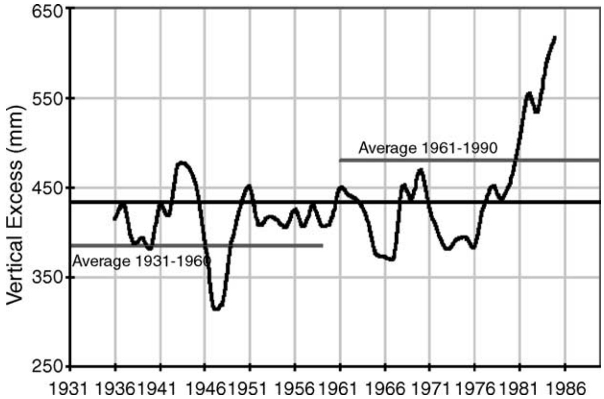

Fig. 6. Moving average of atmospheric excess (*P*–ET).

To determine the periods of excess and deficit, annual values of precipitation (*P*) and evapotranspiration (ET) were calculated for the system, for the first [FTP] and the second [STP] 30-year period of the data series (1931–1990). The tendency and memory of the system were evaluated using moving averages of the new series (*P*–ET). Fig. 6 shows the increase in the average value between series, the average being 385 mm/yr. for the series 1931–1960 and 480 mm/yr. for the series 1961–1990. Also in Fig. 6, it is possible to observe the sudden increase since 1970, influenced by ENSO events which took place in the 1980s. These average sheets of water are equivalent to a yield volume of 5351.5 and 6672 hm^3/yr, respectively.

The comparative monthly distribution calculated for the system in both series show for the second 30-year period a reduced seasonal variation and a deficit

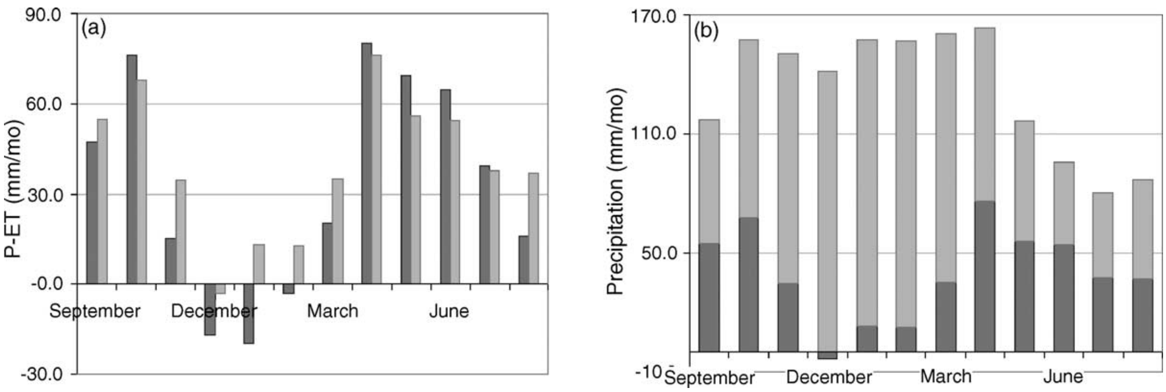

Fig. 7. (a) Mean monthly distribution of excess and deficits for the series 1931–1960 (dark gray) and 1961–1990 (light gray); (b) mean monthly distribution of precipitation into evapotranspiration (light gray) and excess-deficits (dark gray) for the Ibera system.

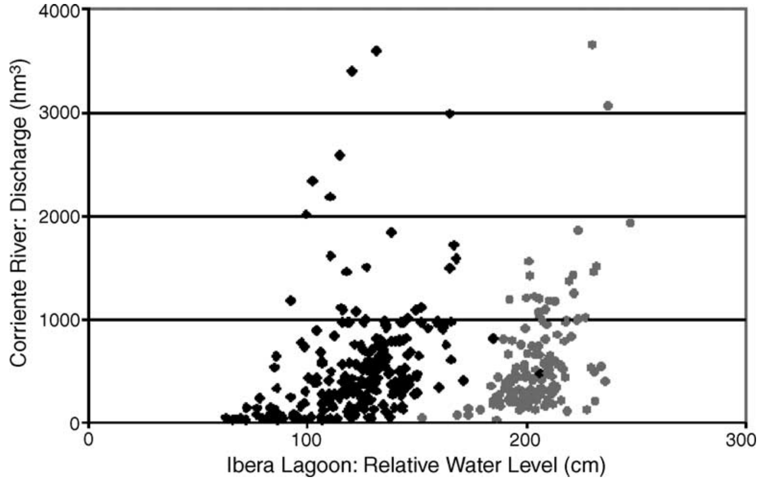

Fig. 8. Relationship between relative water levels at Laguna Ibera and discharge in Corriente River (hm^3) for the series 1969–1988 (black dots) and 1990–2000 (gray dots) showing a change in response to hydrometric levels.

only in December (Fig. 7). On the other hand, the seasonal pattern of the vertical balance for the series 1961–1990, shows higher values in spring (33%) and autumn (35%), unchanged in summer (27%) and much lower values in winter (5%). They are very different from the distributions of seasonal precipitation (Fig. 7b).

3.2. Discharge and system water level

The previous analysis on the Corriente River at Los Laureles gauge station showed that more than 70% of its discharge comes from the Ibera system. A relationship between hydrometric levels gauged at Ibera Laguna and the discharge measured at Paso Lucero

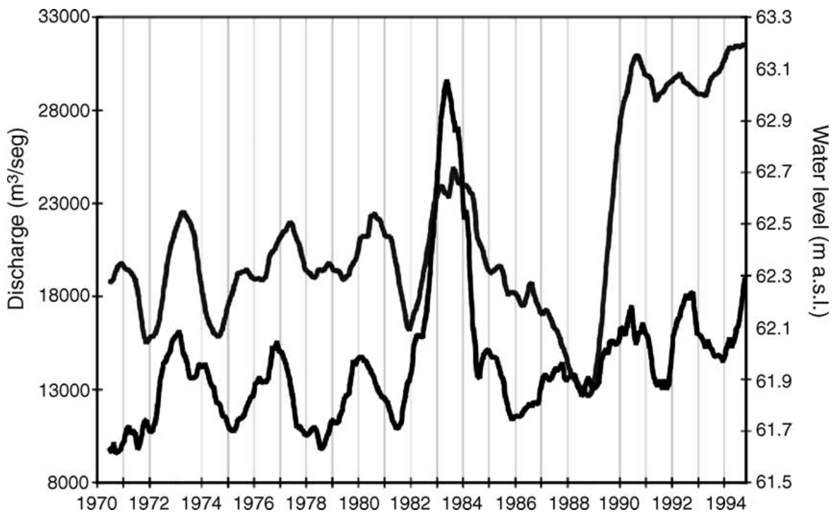

Fig. 9. Discharge in Parana River recorded at Ita Cua station (black) and water levels in Laguna Ibera (gray) for the series 1970–1995. The coupling of pulses suggests an underground connection.

Table 2
Response of the system in the considered period (20th percentile highlighted in gray, 80th percentile in bold)

Year	Precipitation (mm)	*P*–PET (mm)	Discharge Corriente River (hm^3)	Calculated storage (hm^3)	Water level Laguna Ibera (cm)	Discharge Parana River (m^3/s)
1970	1471	443	5301	859.30	122	9795.0
1971	1250	251	**5868**	−2377.83	120	10524.6
1972	1843	836	5624	**5993**.**78**	115	14138.3
1973	**1959**	**966**	**10994**	2435.64	**144**	14045.0
1974	1403	369	4727	405.78	103	12924.6
1975	1642	645	4422	4548.73	125	11813.2
1976	1373	382	2675	2632.17	127	13734.2
1977	1523	403	5776	−173.92	143	12870.4
1978	1122	60	2078	−1249.48	127	10327.0
1979	1508	502	2232	**4751**.**07**	123	12698.6
1980	1378	338	3454	1245.81		13930.2
1981	1386	341	4622	122.70	126	11671.5
1982	1798	743	3572	**6749**.**36**	126	**16917**.**4**
1983	**2043**	**1030**	**11389**	2931.12	**159**	**28283**.**8**
1984	1828	782	7357	3512.82	**145**	**15365**.**3**
1985	1681	558	**9156**	−1396.95	125	13458.1
1986	**2233**	**1126**	**20574**	−4926.21	117	12019.6
1987	**1954**	**934**	**13012**	−24.23	103	13806.8
1988	1164	139	964	967.54	81	12741.8
1989	1639	627	2339	**6382**.**47**	130	**14932**.**1**
1990	**1880**	**992**	8995	**4792**.**88**	**205**	**17130**.**5**

in the Corriente River was analyzed over the period 1969–2000. In spite of the fact that the average water level for the series 1969–1988 is quite lower than the level for the series 1990–2000, the monthly discharges recorded at Paso Lucero station remained within the same values (Fig. 8) although the distribution changed. Therefore, this shows a higher water volume stored in the system for the second period.

A similar pattern in the periodic fluctuations is observed when the water level at Laguna Ibera and the discharge of the Parana River recorded at Ita Cua station are compared (Fig. 9). The climatic conditions and the area of influence that governs the discharge distribution in each one of the sites are very different. The Parana River collects rainfall from an extended area in southern Brazil and Paraguay (1,925,250 km^2), while the Ibera receives only the contribution from local rainfall (14,560 km^2) (Ferrati et al., 2000). Hence, the similarity of behavior could be explained by an unknown interconnection between both systems, a variable not discriminated in the balance and considered in the general storage.

3.3. Water balance

An annual mass balance has been proposed to analyze the variation in the storage of the system and the absolute values per year at system level. The period 1969–1990 was analyzed, taking into account the intersection between available series of precipitation, evapotranspiration and discharge. The missing values of discharged volumes from November 1989 to April 1990 at Paso Lucero gauge station, were filled using Eq. (1).

Considering an annual scale, the excess and deficits, discharge and storage volume were compared with variations in water levels recorded at Laguna Ibera. The annual values are shown in Table 2. The annual storage volumes are shown in Fig. 10.

A water balance model in which precipitation, evapotranspiration, discharge and storage are taken into account was constructed and used to assess deficits and excesses in storage by comparison with the water level recorded at Laguna Ibera. The water balance model was used to attempt the quantification of unknown variables

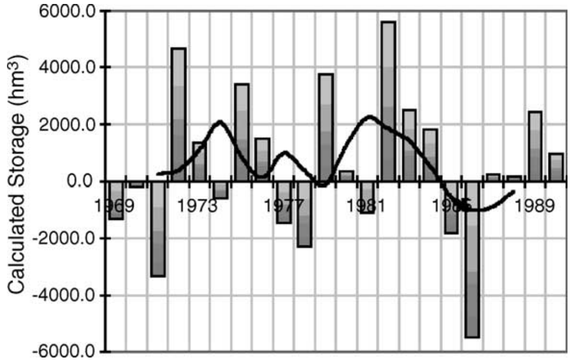

Fig. 10. Excess and deficits (hm^3/yr) calculated in the storage compartment and corresponding moving average.

and to examine the possible effects of the presence of the neighboring power plant on the Parana River. The results of this analysis are reported separately (Ferrati and Canziani, 2005).

3.4. Digital elevation model (DEM)

The digital elevation model (DEM) was built by using an algorithm for two-dimensional interpolation with the previous digitized topographic maps taken as input. The digital elevation model (DEM) was then resampled in order to obtain a spatial resolution of 180 meters. This was required for a later overlapping with SAC-C satellite images. In order to run the watershed definition process, it was necessary to smooth the DEM using a mean filter to remove some of the angularities created by the linear interpolation. A vectorial layer was built with the resulting watershed region. This allowed focusing all the analyses in the areas that have a real influence over the Esteros del Ibera without incorporating noises from the adjacent zones (Fig. 11).

The DEM was useful in understanding the general dynamics of the system. In particular, it helped in the computation of the area of influence of each of the meteorological stations for the definitions of the coefficients of the algorithms.

4. Discussion and conclusions

The hydrometeorological variables analyzed in the present study confirm a slight change in the trend observed in the annual precipitation and discharge for this region since the 1970s. In addition, the extraordinary rainfall occurred in the 1980s, brought about extreme situations of excess in the region. Due to the limited records of discharge registered at the Corriente River, the analysis of the relationship between hydrometeorological variables was essential in permitting the extrapolation of results.

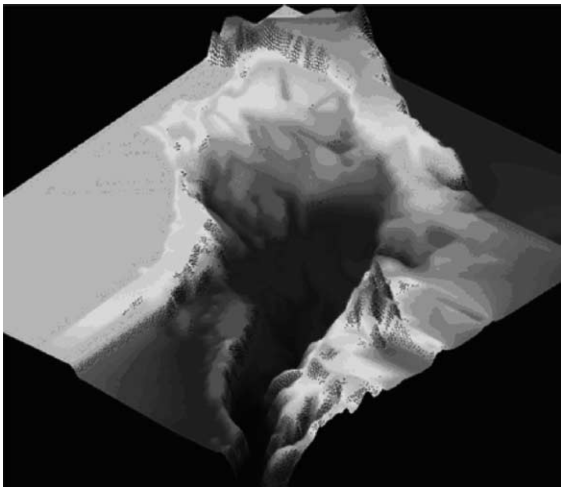

Fig. 11. Smoothed DEM of the Ibera system.

During the decades 1970–1990, the maximum rainfall (80th percentile) on the Ibera system occurred in 1973, 1983, 1986, 1987 and 1990 (Table 2). The mean annual discharge of the Parana River recorded at Posadas station exhibits relative maximum levels (above 14,500 m^3/s) in 1982, 1983, 1984, 1989 and 1990. The maximum annual outflow volumes of the Corriente River occurred in 1973, 1983, 1985, 1986 and 1987.

It is clearly seen that the system responded very differently to similar situations of extreme inputs and outputs. During the years 1973 and 1983, high precipitation and discharge values of the Corriente River were recorded. The balance resulted in a subsequent storage of water in the system and a considerable increase of the water level in Laguna Ibera. On the contrary, during the year 1986, with a similar high value of annual precipitation, the annual discharge of the Corriente River doubled, contributing to the decrease in the water levels in the Laguna Ibera. When the annual discharge variable of the Parana River is also considered, this dissimilar response can be explained by observing that in 1983 the Parana River attained maximal values of discharge, while 1986 data exhibits average values.

In the years 1987 and 1990, high values of precipitation and discharge were recorded (as in 1973 and 1983). But, while in 1987 the water level in Laguna Ibera descended, in 1990 it increased considerably reaching values some 30% higher than those of 1983 did and 60% higher than the average in the 1971–1990 series.

After analyzing the previous variables and considering the observed changes in the water levels in the Ibera wetland, it is possible to infer that the recorded maximum levels in Ibera system depend not only on the local conditions but also on the variations of the water level in the Parana River. This may indicate a possible underground interconnection between both systems. Hence, this connection would explain the anomalous increase of the water level in the Laguna Ibera observed during the years 1989 and 1990, and the unreasonable decrease observed during the years 1986 and 1987, during which the Parana River remained below its mean level.

During the year 1983, three extreme events took place simultaneously: very high precipitation over the system, maximum *maximorum* discharge in the Parana River, and a precedent high water storage inside the system. Under these extreme conditions, the Ibera wetland system reacted delaying and storing the surplus and causing an increase in the water level that persisted till the year 1984.

The minimum values of precipitation (20th percentile) were recorded in 1971, 1976, 1978, 1980 and in 1988. In these years, the discharge values remained below the mean value and, except for the records of the years 1971 and 1980, all the values are in the 20th percentile. The system responded with a moderate decrease in its water levels.

Clearly, the Ibera wetland in northeast Argentina has shown the resiliency of this type of ecosystems as they respond to extreme events. The Ibera system reacted by retarding and equilibrating the negative effects of wet and dry periods.

The analysis performed allowed the understanding of the hydrometeorological behavior of the system in the temporal scale (annual, seasonal, and monthly scales). A topo-bathymetric map and the digital elevation model (DEM) that was constructed from it provided the domain at an adequate spatial resolution. Nevertheless, and with the aim of having a tool that might help answering a variety of questions related to the impact of human actions (i.e. construction of megadams) and activities (i.e. extraction of water for agriculture) developed in the periphery of the system, the hydrological dynamics of the system needs to be studied.

A distributed model using Saint–Venant equations was proposed to model the flow and the water level in each point of the system. The development and construction of such a model, designed to simulate discharge and water levels as a function of space and time, depends strongly on the knowledge of the vegetational, edafological and topobathymetric aspects of the physical system under study. Based on the study carried on by INCyTH-ICA in 1980. Ferrati et al. (2002) propose in the one hand an updating of information through the use of satellite images that allows the inference of the submersed bathymetry in the digital elevation model (DEM). On the other hand, the processed satellite information using habitat classification techniques allows the fitting of Manning's roughness parameters that condition the surface flow. Both techniques converge in the formulation of the physical foundation of the hydrodynamic model for the Esteros del Ibera. This will provide not only a better knowledge of the dynamics of the wetlands but also an adequate tool for management decisions and for a sustainable use of the Ibera.

Acknowledgements

We thank SERNAH, EEA INTA Mercedes, CRL-INA, NOAA, María Josefa Fioriti, Daniel Cielak, Marcos Garcia Rams (San Juan Poriahú), and Luis Lenzi for allowing us access to hydrological and meteorological data. We are indebted to Instituto Correntino del Agua for permitting us to consult the many volumes of "Estudio del Macrosistema Ibera". We thank CONAE and NOAA for providing satellite images. Special thanks to Florencia Castets (Personal de Apoyo CIC) for her collaboration in digitalization and cartography, to Helena Vayo who helped us polish the text, and to Claudia Marinelli for her advise on statistics. This study, part of an INCO DC project, was possible thanks to funding from the European Commission'(Contract ERBIC18CT980262) and to the equipment provided through a special grant from UNCPBA.

References

Barros, V., Castañeda, M.E., Doyle, M., 1999. Recent precipitation trends in South America to the east of the Andes: an indication of climatic variability. In: Volheimer, W., Smolka, P. (Eds.), Southern Hemisphere Paleo and Neoclimates: Concepts and Problems. Springer-Verlag, Germany.

Carter, V., 1997. Wetland hydrology, water quality, and associated functions. National Water Summary on Wetland Resources. U.S. Geological Survey.

Castañeda, M.E., Barros, V., 1996. Sobre las causas de las tendencias de precipitación en el cono sur al este de los Andes. Reporte 26. Center for Ocean and Atmospheric Studies (in Spanish).

Crawford, H.S., 1983. Root survival in flooded soils. In: Gore, A.J.P. (Ed.), Ecosystems of the World, Mires: Swamp, Bog, Fen and Moor. General Studies. Elsevier Scientific Publishing Company, Amsterdan, The Netherlands, pp. 257–283.

Dixon, R.K.; Krankina, O.N., 1995. Can the terrestrial biosphere be managed to conserve and sequester carbon? Carbon sequestration in the biosphere: processes and products. NATO ASI Series. Series I. Global Environmental Change, pp. 33.

Ferrati, R., Canziani, G.A., 2005. An analysis of water level dynamics in Esteros del Ibera wetland. Ecol. Mod. 186, 17–27.

Ferrati, R.M., Ruiz Moreno, D., Canziani, G.A., 2000. Modelos de Balance Hídrico para analizar el cambio de régimen en un Humedal sujeto a perturbaciones antrópicas y climáticas. Edición Electrónica de la 6ª Conferencia Internaiconal del Seminario Permanente Ciencia y Tecnología del Agua. Madrid, España. http://agua.rediris.es/conferencia_iberdrola_2000.

Ferrati, R., Ruiz Moreno, D., Aubone, A., Canziani, G., 2002. Satellite images as a tool for hydrodynamic modelling. In: Proceedings of the International Symposium on Remote Sensing of Environment, XXIX ISRSE, Buenos Aires (Ref. 4.11 in CD).

Goniadzki, D., Carballo, S.M., Hartmann, T., 2002. Uso de la información espacial para la confección de cartografía de vulnerabilidad por inundaciones en la Cuenca del Plata. http://hosting.cricyt.edu.ar/INA/CARIS/PDF/9_2002.pdf/.

Hoffman, J.A.J., Gomez, T.A., Nuñez, S.E., 1987. Los campos medios anuales de algunos fenómenos meteorológicos. II Congreso de Meteorología. CAM, AMS, SBM, OMMAC, and SOCOLMET. Buenos Aires, Argentina (in Spanish).

INCyTH-ICA, 1981. Estudio del Macrosistema Iberá. Ministerio de Economía, Gobierno de la Provincia de Corrientes. INCyTH, Secretaría de Estado de Transporte y Obras Públicas de la Nación.

Ingram, H.A.P., 1983. Hydrology. In: Gore, A.J.P. (Ed.), Ecosystems of the World, Mires: Swamp, Bog, Fen and Moor. General Studies. Elsevier Scientific Publishing Company, Amsterdan, The Netherlands, pp. 67–158.

IPCC, 1996. Climate Change 1995 – impacts, adaptations and mitigation of climate change: scientific technical analysis. Contribution of Working Group II to the second Assessment Report of the IPCC. Cambridge University Press, Cambridge.

IPCC, 2001. Climate Change 2001 – impacts, adaptations and vulnerability. Contribution of Working Group II to the Third Assessment Report of the IPCC. Cambridge University Press, Cambridge.

Kusler, J., Brinson, M., Niering, W., Patterson, J., Burkett, V., Willard, D., 1999. Wetlands and climate change: scientific knowledge and management options. In: Institute for Wetland Science and Public Policy. Association of Wetland Managers, Berne, NY, USA.

Lewis, W.M., 1995. Wetlands Characteristics and Boundaries. National Academy Press, Washington, pp. 307.

Minetti, J.L., Sierra, E.M., 1989. The influence of general circulation patterns on humid and dry years in the Cuyo Andean region of Argentina. Int. J. Climatol. 9, 55–69.

Nuñez, M.N., Vargas, W.M., 1998. El Niño 1997–1998: un factor económico y social. Techint, Technical Paper 295.

Sahagian, D., Melack, J., 1998. Global wetland distribution and functional characterization: trace gases and the hydrologic cycle. IGBP Report 46.

SERNAH, 2000. Estadística Hidrológica del Siglo XX. República Argentina. Ministerio de Infraestructura y Vivienda. Subsecretaría de Recursos Hídricos.

Tallis, J.H., 1983. Changes in wetland communities. In: Gore, A.J.P. (Ed.), Ecosystems of the World, Mires: Swamp, Bog, Fen and Moor. General Studies. Elsevier Scientific Publishing Company, Amsterdan, The Netherlands, pp. 311–347.

Thornthwaithe, C., Holzman, B., 1942. Measurement of evaporation from land and water surfaces. U.S. Dept. Agr. Tech. Bull., 817.

Woo, M.K., Rowsell, R.D., Clark, R.G., 1993. Hydrological classification of Canadian prairie wetlands and prediction of wetland inundation in response to climatic variability. Canadian Wildlife Service, Environment Canada, Ottawa, Ont., Canada.