HYDROLOGICAL MODELS

There is no doubt that the driving force in a wetland is the water, and the dynamics of water is what characterizes each particular wetland ecosystem. Hence, its was of outmost importance to understand the hydrology of the Ibera ecosystem before management strategies could be advanced or the sustainability of any activity could be assessed.

A hydrometeorological characterization of the main variables was undertaken with the purpose of understanding, from a hydrological point of view, the present conditions of the Ibera system and its response to climate variations. The quantification of the phenomena was done by performing both a water balance at regional level and yearly intervals and a balance at system level on monthly basis. In addition, the analysis of all available information after an appropriate quality control, a detailed survey of the present state of the system and its dynamics, together with the data obtained from the stations installed in 1999 and operated since then, were integrated to provide the basis for a mathematical model to be developed for the Ibera system.

Given the limitations of available historic data, an analysis at regional scale of the main variables affecting the water storage in the Ibera system was adopted. Then, for periods of time with non standardized data obtained at system level, specific results were derived by comparison. The objective was to obtain a scientifically founded deductions to answer the following questions, which are related to the possible causes of the increase in the storage capacity of the Ibera system:

- Could the increment in storage be explained by the increase of precipitations recorded on the Del Plata Basin during the last century (IPCC SRRICC) with a remarkable positive tendency since the seventies, as enhanced by the extraordinary precipitations due to ENSO events?
- Is it possible that an accumulation of vegetation may have obstructed the outflow through the Corriente river towards the Parana River? Or, is it that the floods recorded in the Middle Parana River may have reversed the flow of the Corriente River, then keeping back the natural outflow from the Ibera system?
- Is there a change in the groundwater flow system? If it is the case, could the change have been originated in the dammed water, after the construction and filling of the Yacyreta dam, given that the period when the increases were registered coincides with the closing of the main branch of the Parana River and the utilization of the derivation channel next to the Northern border of the Esteros del Ibera?

Hydrological Data

Variables and data description at local level

In order to estimate basic hydrological data for basins of water gauge stations, four entry data sets were processed: monthly precipitation depths at precipitation stations, P [mm]; mean monthly discharges, Q [m3 s-1]; mean monthly temperature, T [ºC] and mean daily level of water, h [m].

Precipitation

The precipitation depth is a volume of water from precipitation, that has fallen over a catchment in a given time interval, expressed by the depth of water layer uniformly distributed over the area.

A set of monthly precipitation depths, comprising data from 1968 at ten rain gauge stations was available from INCyTH-ICA (volumes III.4, III.5 and III.6 of “Macrosistema del Iberá “), SERNAH (Secretaría de Recursos Hídricos de la Nación), SMN (Servicio Meteorológico Nacional) and EEA INTA Mercedes, local measurement take in the Estancia San Juan Poriahu and the hydrological, meteorological and hydrometric stations belonging to this INCO project.

However, individual series differ considerably in length and period of observation. Many precipitation stations have gaps in their records and the spatial distribution is not regular inside the system . [*Fig. 28.a and b*]

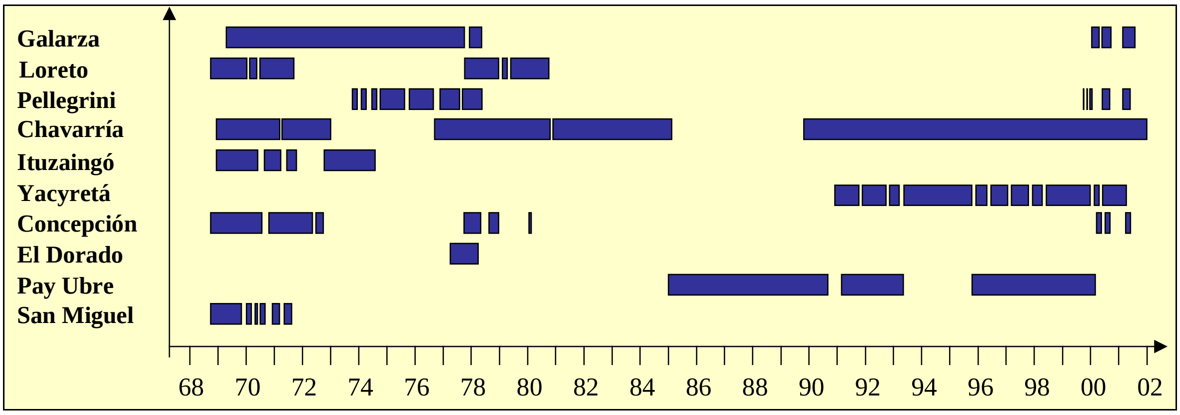


Figure 28.a: Series of Precipitation at the Pluviometric Stations

Figure. 28.b: Localization of Pluviometric Station in Ibera System

For this reason, a comparative study was proposed between Pay Ubre and Chavarría stations, both located at the South-West of the system, and between Ituzaingo and Yacyretá, at the North-East.

A **double-mass curve analysis** is a graphical method for identifying or adjusting inconsistencies in a station record by comparing its time trend with those of other relatively stable records of a station, or an average of several nearby surrounding stations. The results of a regression analysis and a double-mass curve analysis were checked in order to contrast both series and to use them alternatively when a segment of anyone of the series was missing. The first method showed a considerable close correlation with correlation coefficient 0.93 and the second one, 0.99. The points plotted in a double-mass curve fit closely without changes in slope. The slopes for the different time-series varies between 0.85 and 1.05 in the first case and between 0.98 and 1.03 in the second.

The temporal series of monthly precipitation depths registered at Ituzaingo-Yacyreta, Chavarría-Pay Ubre, Concepcion, Galarza and Pellegrini stations can be see in *Figures 29 to 33*.

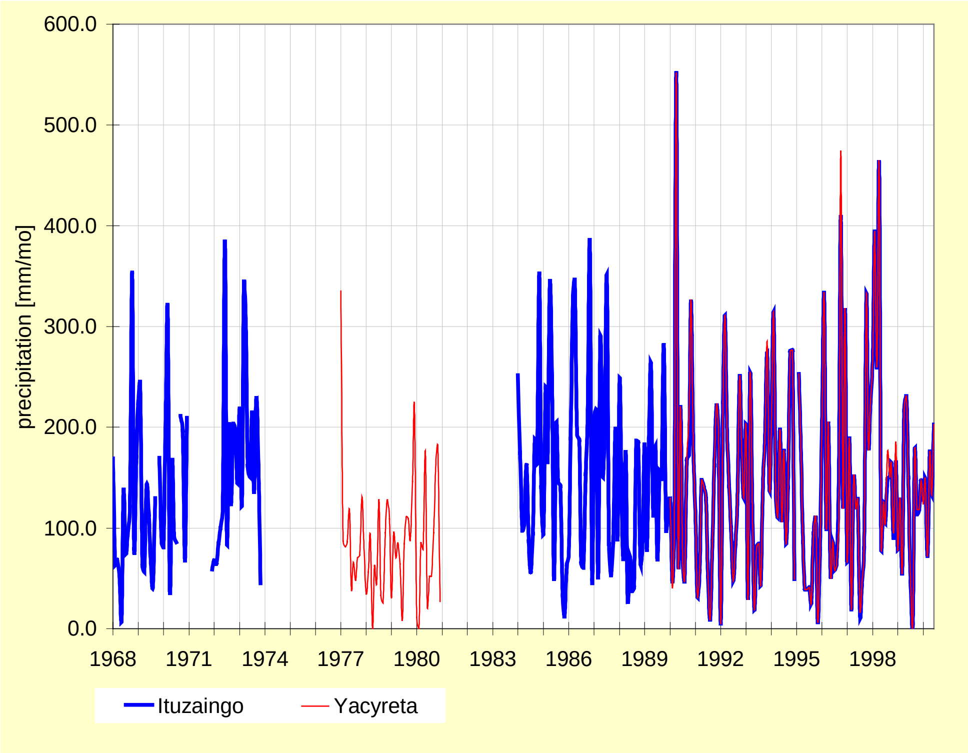


Figure 29: Monthly Precipitation in Ituzaingo and Yacyreta

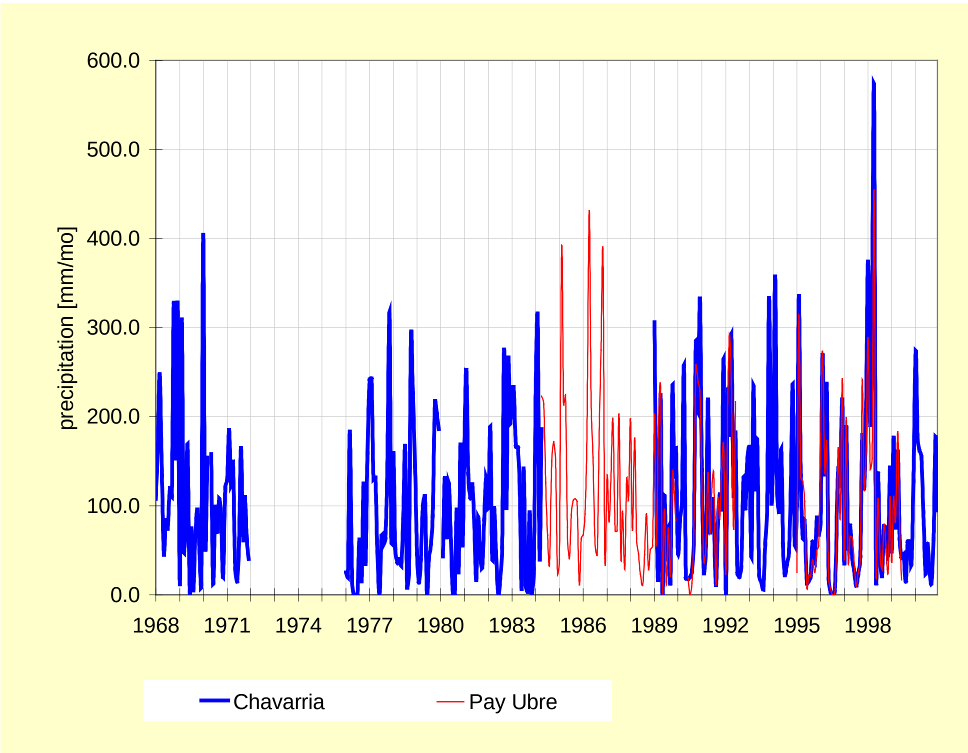


Figure 30: Monthly Precipitation in Chavarría and Pay Ubre

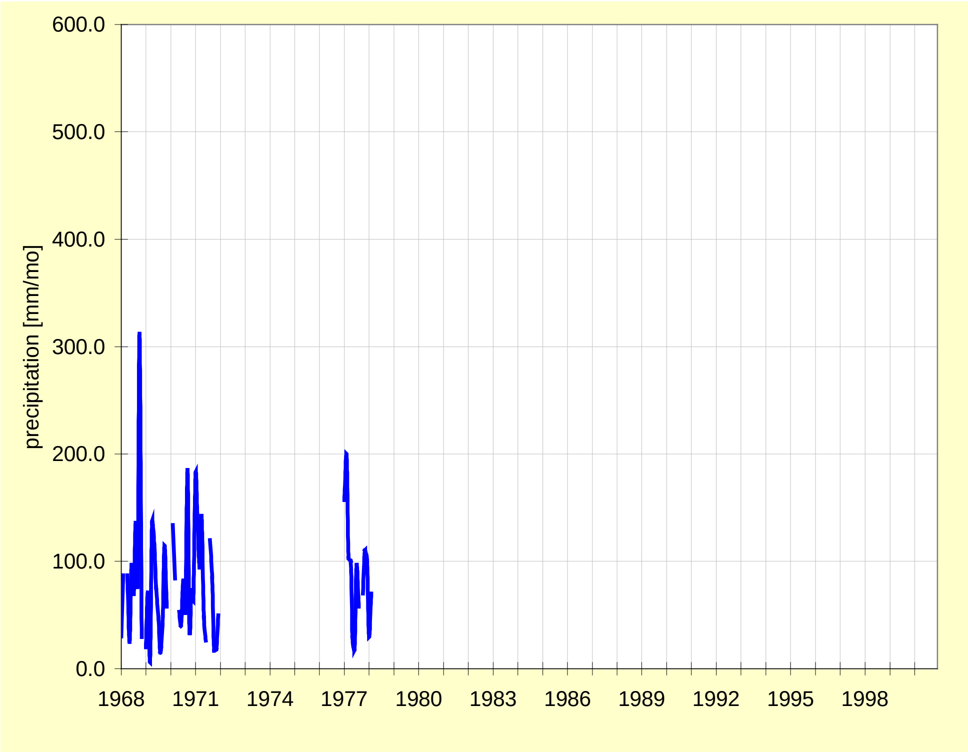


Figure 31: Monthly Precipitation in Concepcion

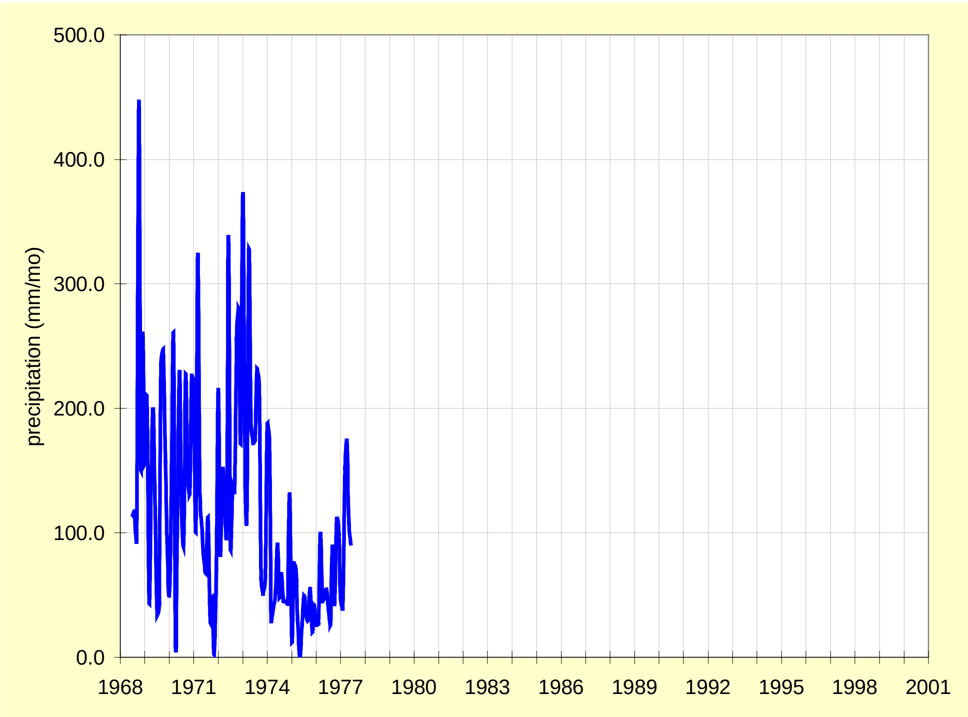


Figure 32: Monthly Precipitation in Galarza

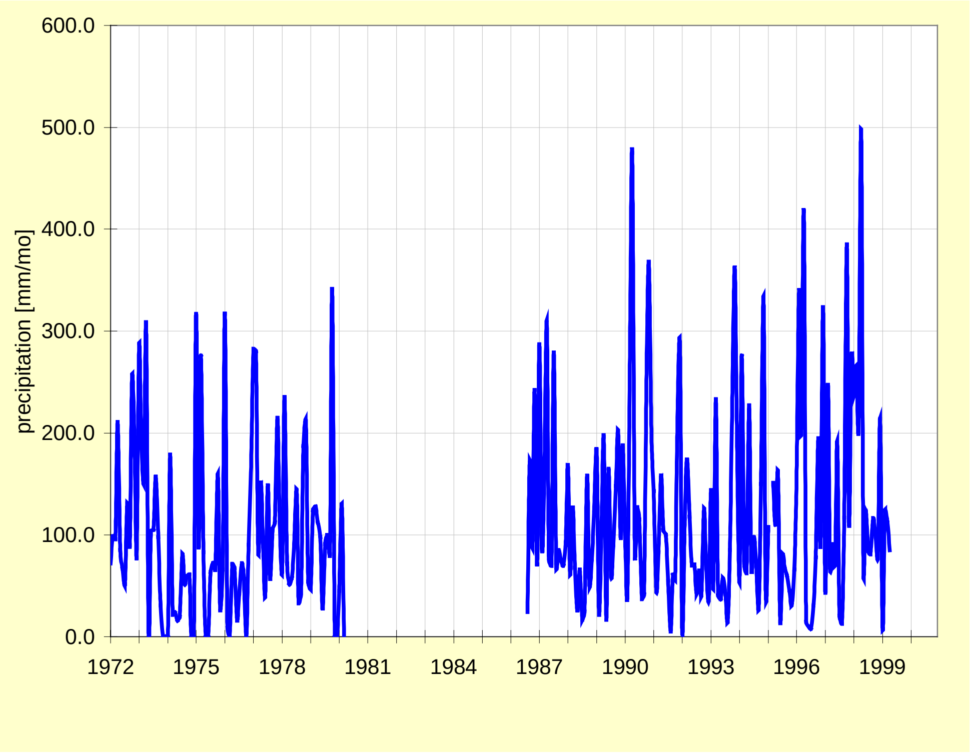
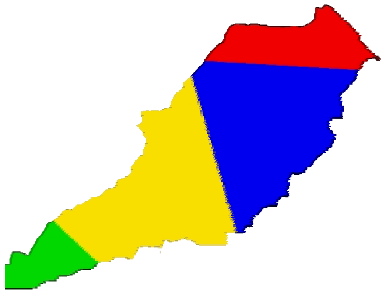
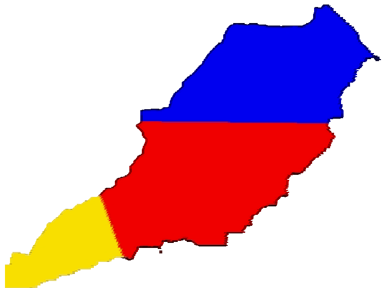
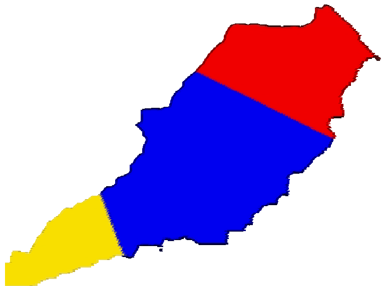


Figure 33: Monthly Precipitation in Pellegrini

RECORDS	RAIN STATIONS	THIESSEN DISTRIBUTION
July 1968 - September 1969	Concepcion (38%) Chavarria (8%) Ituzaingo (15%) Galarza (39%)	
January 1977 - October 1979	Pellegrini (48%) Chavarria (14%) San Juan Poriahu (38%)	
January 1988 - December 1997	Pellegrini (56%) Chavarria y Pay Ubre (14%) Yacyreta and Ituzaingo (30%)	

Due to the sparse, peripheral and non-uniform location of rain gauge stations, the method of Thiessen was utilized to calculate mean monthly precipitation depth at 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 which each station is taken to represent is the area of its 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. No 168).

As a result of this spatial-temporal analysis, three periods of time were selected to calculate the mean monthly precipitation at the basin.

The comparative analysis between calculated average monthly precipitation depth at basin level from available regional and local data has been done to compare the another temporal series recorded at Pellegrini, San Juan Poriahú and Concepcion rain stations. *Figures 34.a and 34.b* show a very similar behavior between temporal series of monthly precipitation depth at basins level from regional and local data from 1988 and the monthly distribution along the year. The differences over the total annual precipitation depth at the available periods could be observed in Table 1

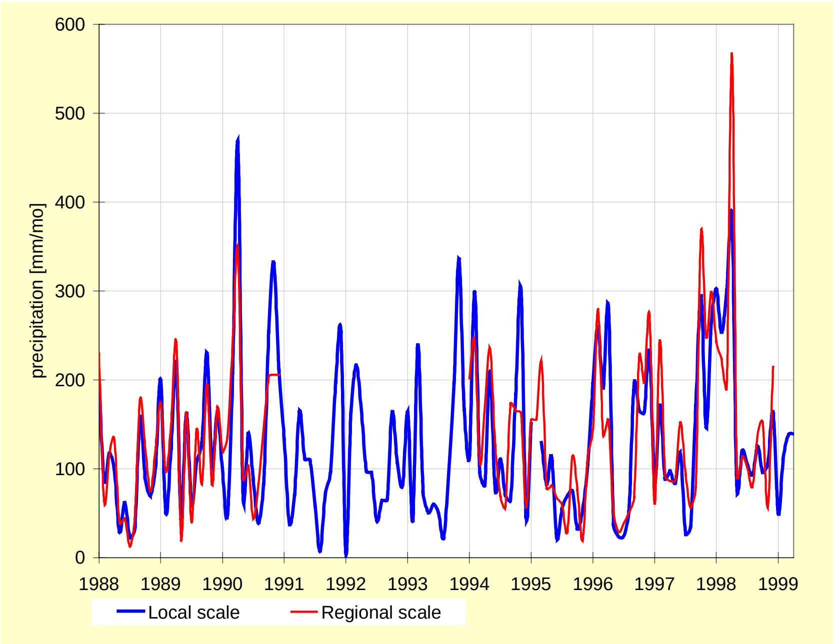


Figure 34.a: Comparative Distributions of Monthly Precipitation at Regional and Local Scale

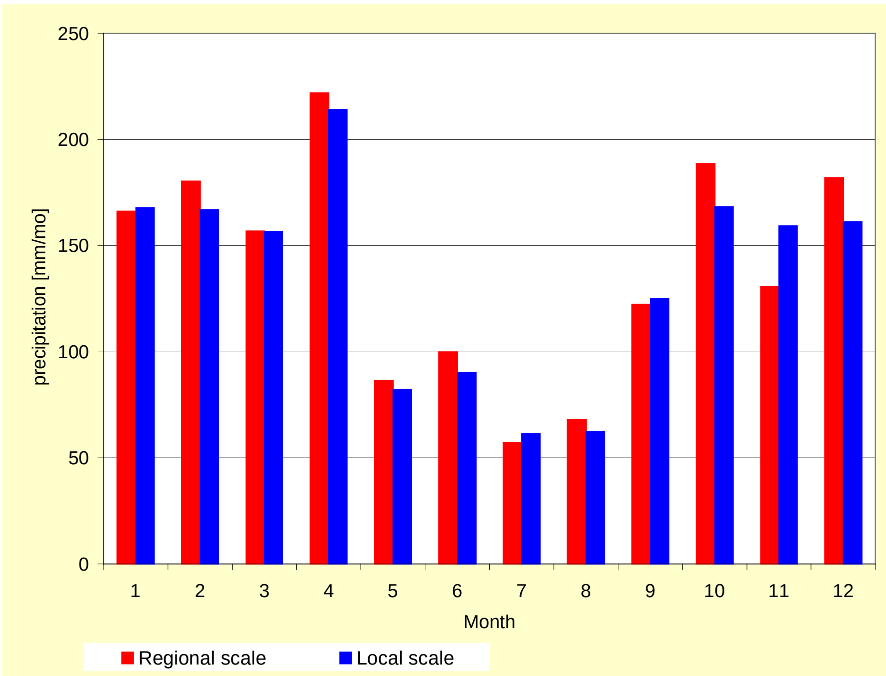


Figure 34.b: Mean Monthly Distribution of Precipitation at Regional and Local Scale

YEAR	Annual Precipitation at the Ibera System (mm/year)		Difference (%)
	Regional Scale	Local Scale	

1977	1633	1473	-9.8
1978	1210	1106	-8.6
1979	1521		
1988	1182	1067	9.7
1989	1560	1592	-2.0
1990	1922	2034	-5.9
1994	1767	1653	6.4
1996	1650	1822	-10.4
1997	1866	1582	-15.2
1998	2159	2124	2.3

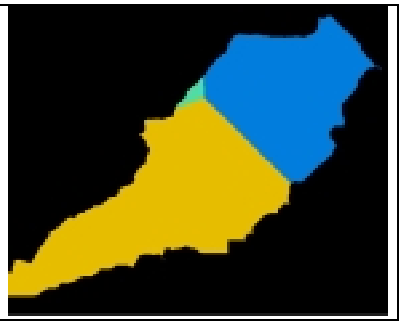
Table 1

Evapotranspiration

The loss of water to the atmosphere is an important component of the wetland water budget. 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 (Carter, 1997; http://water.usgs.gov/nwsum/WSP2425/hydrology.html).

In order to evaluate monthly losses by evaporation and evapotranspiration for the data series that have been considered so far, only monthly temperature data at Posadas, Corrientes and Mercedes during the period 1931-1990 have been considered. No records of temperature from within the system are available. Due to the lack of direct measurements and of systematic information of other variables that might allow the use of more accurate methods, the evapotranspiration (ET) was estimated by means of the empirical formulation proposed by Thornthwaithe (1948). The potential evapotranspiration, adjusted for temperatures above 26°C , is calculated from monthly mean values of temperature at Posadas, Mercedes, and Corrientes, and the annual series for the Ibera system is generated using Thiessen polygons.

RECORD	STATIONS	THIESSEN DISTRIBUTION

1931 - 1990	Posadas (45%) Mercedes (54%) Corrientes (1%)	

Discharge

The mean discharge is an arithmetic average of all discharges in a given stream site from a given period. It is determined as the total discharge volume of streamflow divided by the number of seconds in the considered period and express in $m^3 s^{-1}$. When the mean discharge is divided by basin's area, the average runoff expressed in m is obtained.

The series of mean daily discharges in a water gauged station were available from a database of the SERNAH (Secretaría de Recursos Hídricos de la Nación) at Paso Lucero in the Corriente river, with numerous gaps in their records (Figure 35). Mean monthly discharges were available at Paso Lucero and Los Laureles on the Corriente river and at Paso Cerrito on the Batel river.

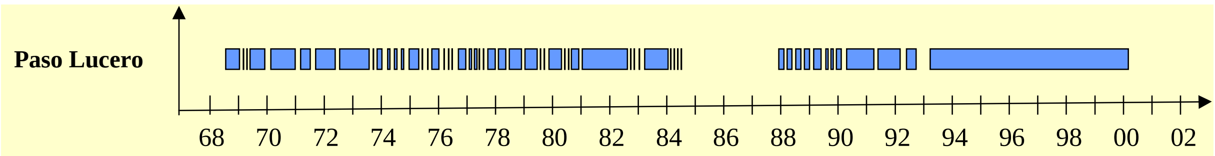


Figure 35. Series of mean daily discharges at Paso Lucero.

Paso Lucero (number 3803 in Figure 36) is located on the Corriente river, close to Ibera system. Los Laureles (number 3821) is also located on the Corriente river, downwater from the previous station and Paso Cerrito (number 3849) on the effluent Batel river.

The large depression that forms the Ibera wetland works in a way similar to 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.

Figure 36. Location of water gauged stations in the Province.

Source SERNAH - http://www.mecon.gov.ar/hidricos/mapashidricos/est_act_corr.jpg

The Ibera system has a very slow general slope of 1:10,000 from NE to the SW, from 72 m above sea level at the headwater area next to Parana river, to 50 m above sea level at Paso Lucero on the Corriente river. For this reason, the flow velocity is very slow and the vertical loss due to evaporation and evapotranspiration are very important when water level fluctuations are considered with monthly step. Then, the excess and deficits, defined as the difference between rainfall and vertical losses due to evaporation and evapotranspiration, are driving the hydrology of the Ibera wetland. The rainfall excess govern the fluctuations of water level inside the subsystems which later condition the complex regime observed in the Corriente and Batel rivers.

Nevertheless, it is not clear that there exists a direct excess-runoff relationship because rainfall that occurs over the last ten kilometers of stream channel, from Itati lagoon to Paso Lucero station, and the effluent stream Pay Ubre, located between both points, sum their volumes downwater of the actual wetland. The hydrologic behavior of a catchment includes some form of accounting the temporal distribution of runoff volume released into the stream channel in a given time period.

Figure 37 shows the monthly discharge hydrograph at all three stations. From this, the Corriente river and its effluent, Batel river, are perennial streams which flow continuously toward the Middle Parana river and is not possible to observe monthly or seasonal patterns along the year.

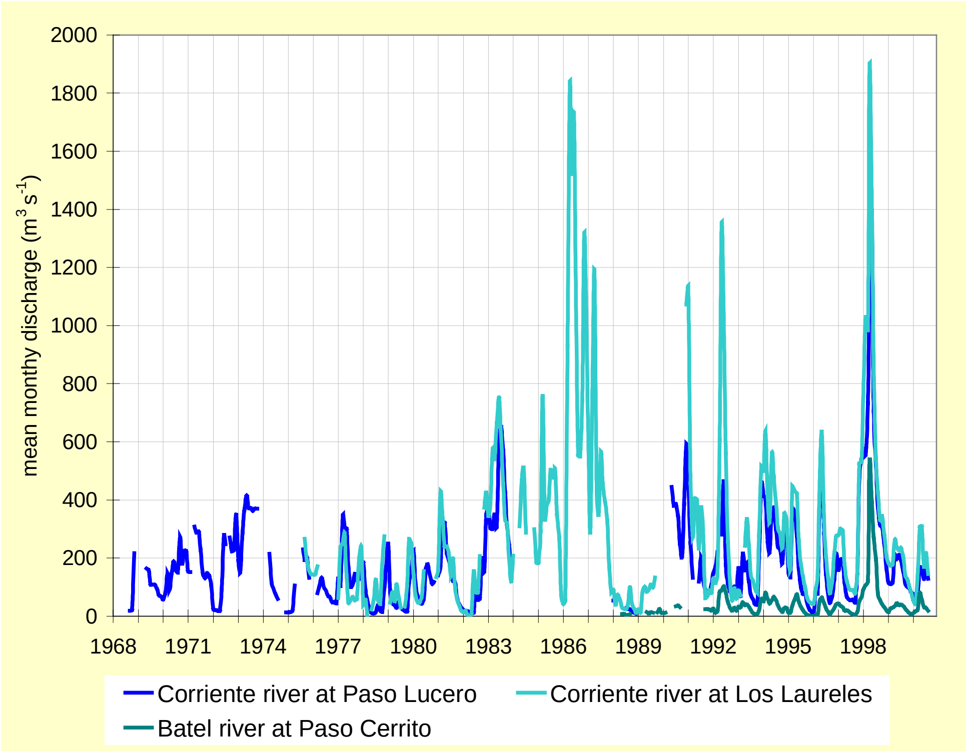


Figure 37. Monthly discharge hydrograph at Paso Lucero, Los Laureles (Corriente River) and Paso Cerrito (Batel River).

The variation coefficient of monthly precipitation in the system and monthly mean discharge at Paso Lucero, Los Laureles and Paso Cerrito have been calculated with available data and a strong dispersion was reflected in them (Table 2).

Month	Precipitation	Variation Coefficients		
		Paso Lucero	Los Laureles	Paso Cerrito
January	0.60	0.84	1.09	0.90
February	0.69	0.80	1.11	0.98
March	0.43	0.77	0.84	0.81
April	0.63	0.95	1.01	1.60
May	0.55	1.03	0.89	1.41
June	0.46	0.69	1.05	1.22
July	0.97	0.76	0.85	1.15
August	0.53	0.80	0.67	0.80
September	0.41	0.83	0.81	0.75
October	0.50	0.74	1.02	0.57
November	0.58	0.76	1.21	0.52
December	0.50	0.91	1.09	0.79

Table 2

When considering mean discharges for a certain period, the discharge at Los Laureles water gauge station, downstream of the confluence with the Batel river, could be contrasted with the sum of the discharges upstream (*Figure 38*). A regression analysis between both series has been done and a high coefficient of correlation (equal to 0.908) was encountered (*Figure 37*) which explains the very similar behaviour observed. In the average, a 75 % of the volume gauged at Los Laureles station flows from the Ibera macrosystem and a 14 % from the Batel system.

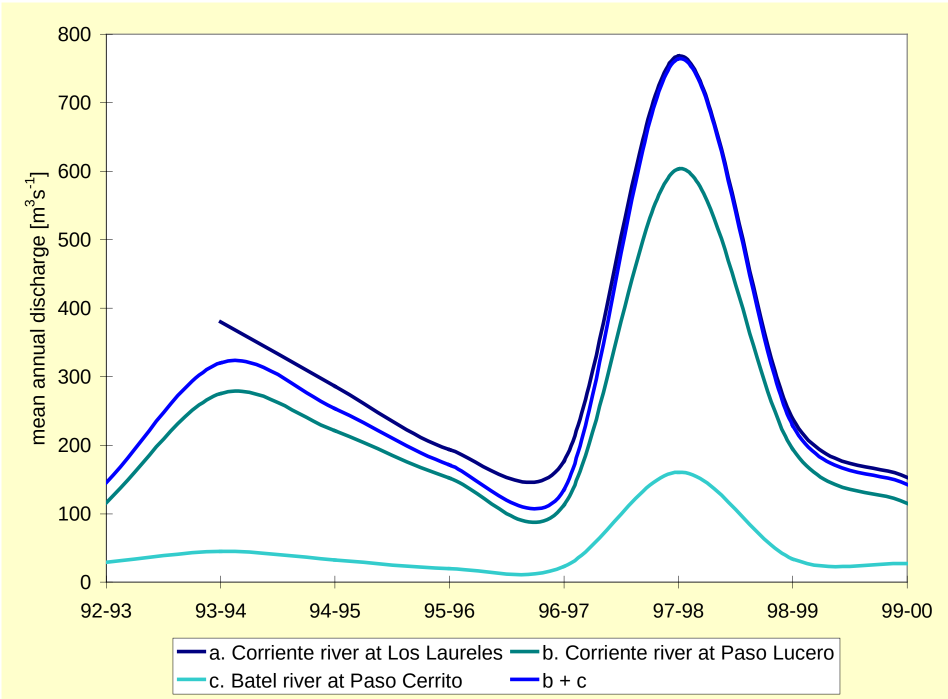


Figure 38. Mean annual discharge at the three gauge stations.

Other observations could be extracted from *Figures 37 and 38*, and that is the good fit between the mean monthly discharges gauged at Paso Lucero and at Paso Cerrito stations since 1990 until today (coefficient of correlation equal to 0.869), and the possibility to complete Paso Lucero series with Los Laureles series using a regression line equation (coefficient of correlation equal to 0.926) (*Figures 39 and 40*).

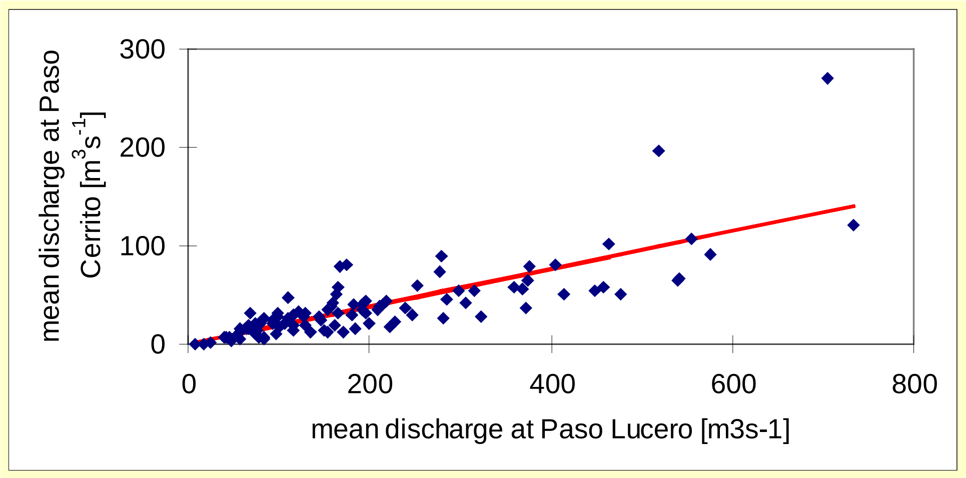


Figure 39. Linear regression of discharge data at Paso Lucero/Paso Cerrito

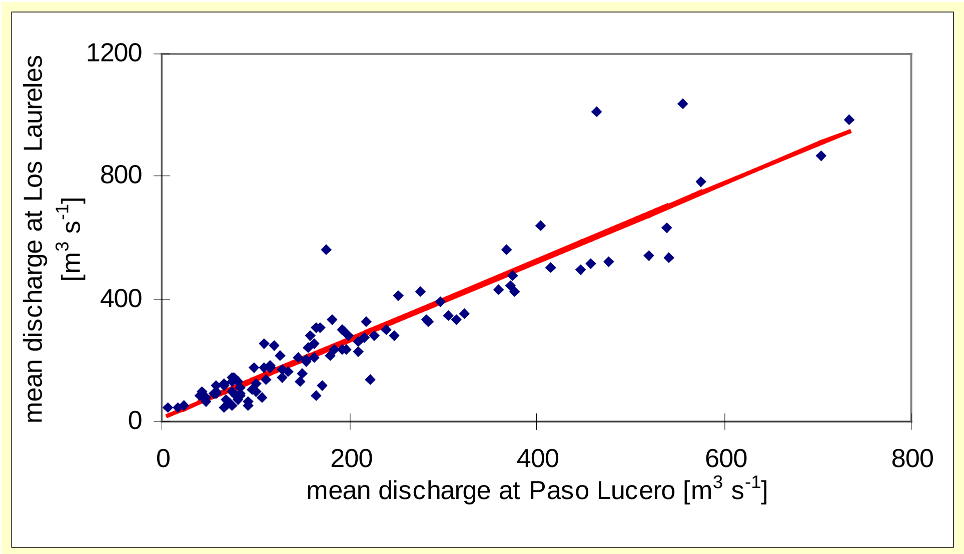


Figure 40. Linear regression of discharge data at Paso Lucero/Los Laureles

Water level

Stage or water level is the elevation of the water surface of a water body relative to a fixed datum.

In the Ibera system, seven graduated staff gauges were installed by INCyTH-ICA in 1968 *(Figures 41 and 42)*. At these sites, local observer were available to report daily the water level observed from manual gauges. The readings were done once a day. Daily measurements of stage in a natural reservoir like the Ibera system are usually sufficient for the purpose of computing changes in storage.

Due to the long-term record obtained from water levels station located at Ibera Lagoon, their stages have been used to correlate changes in storage volume in Ibera system *(Figure 43)*.

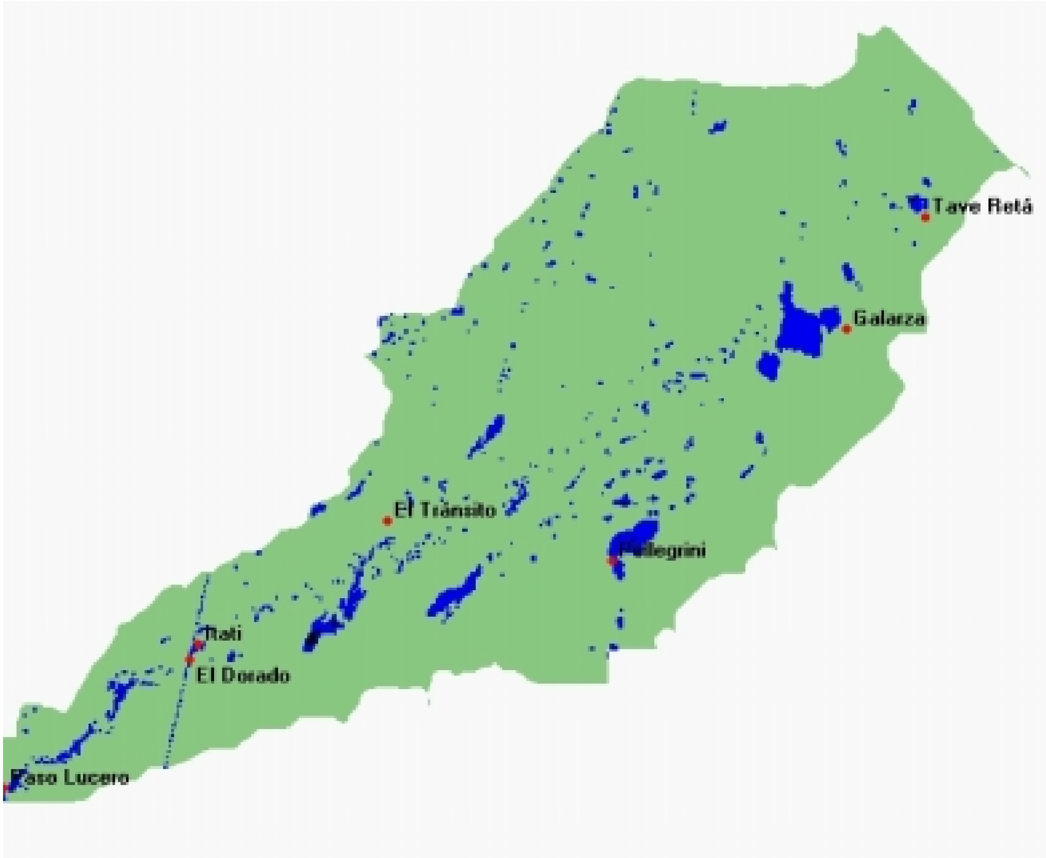


Figure 41. Location of hydrometric stations

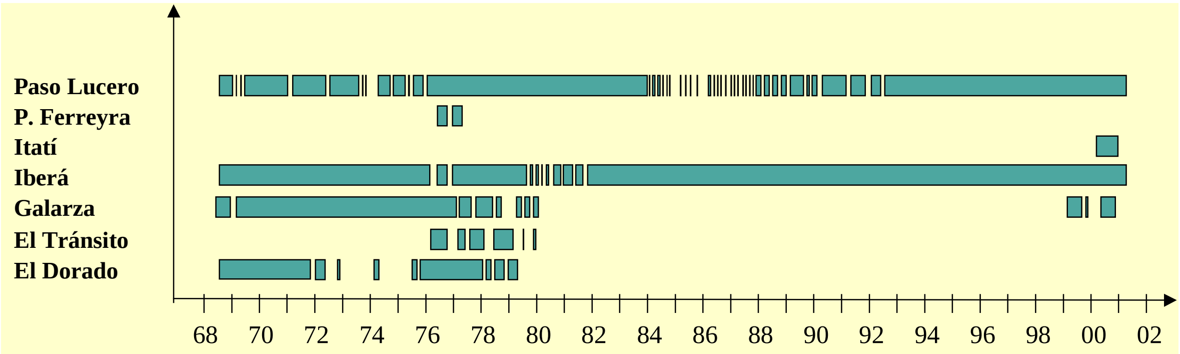


Figure 42. Series of hydrometric data.

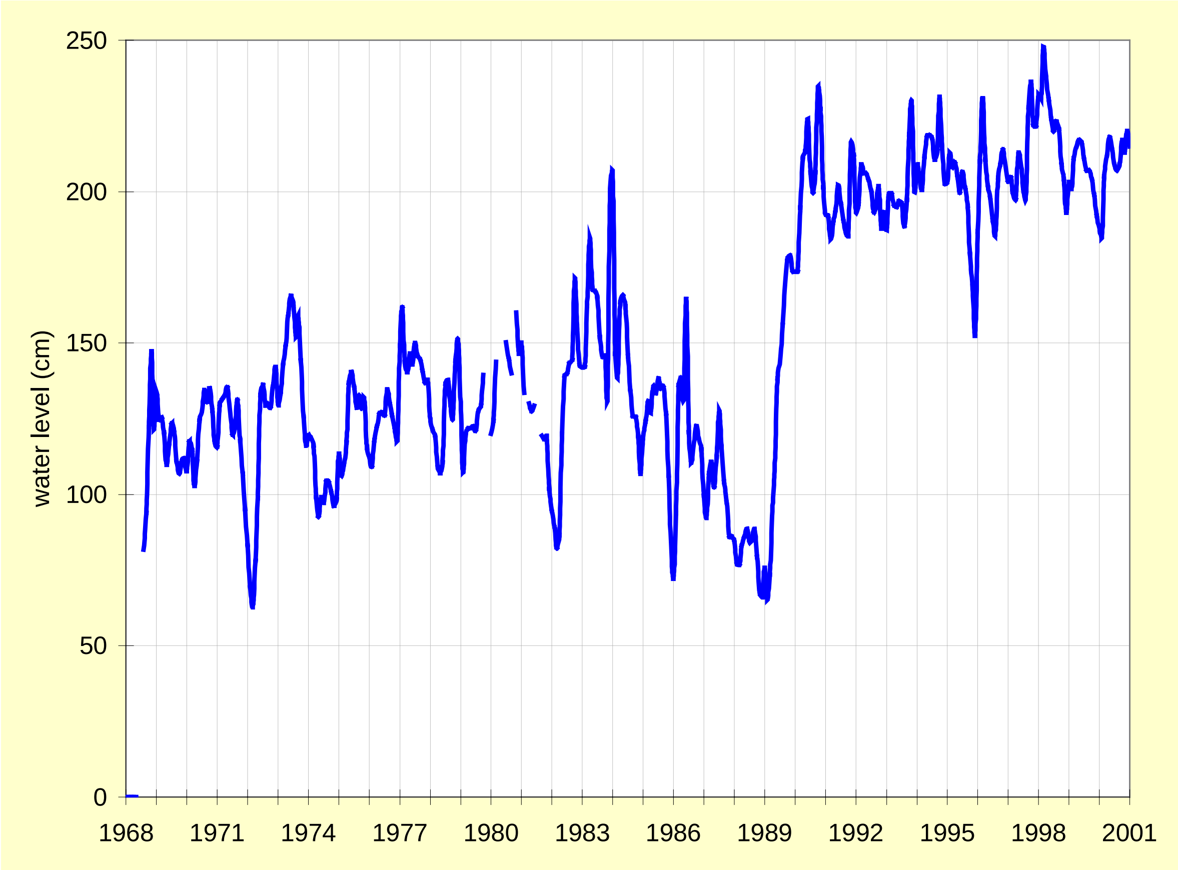


Figure 43. Water level records at Ibera Lagoon (Pellegrini).

Based in geomorphologic, phytogeographical and bathymetric profiles analyzed in the volumes of *"El Macrosistema del Ibera"* (INCyTH-ICA, 1981), the Ibera macrosystem could be separated in three subsystems of distinct dynamical characteristics: from the Medina-Trin lagoons towards the North, it is possible to identify two subsystems separated by a longitudinal sandy hill that meet at these lagoons, and then a third subsystem from Medina-Trin lagoons to Itati lagoon towards the South.

The North-Eastern subsystem is characterized by a sheet-flow dynamics. The open, vegetation free areas, delimited by floating "*embalsados*", generate lagoons which are, in some cases, interconnected by deep channels, and which follow the trace of the paleolithic-river bed of the Parana. The North-Western subsystem shows a more rugged topography with marked lines of drainage that converge towards the Medina lagoon at the SW end of the system. Both the central longitudinal hill that separates the two subsystems, and the longitudinal hill that separates the Iberá from the Batel-Batelito system to the West, permit the transfer of groundwater between the systems. The topographic differences that separate the subsystems become blurred, undefined when the water levels rise, inducing a more homogeneous response. At surface level, both hills hold pseudokarstic lagoons (INCyTH-ICA, 1981 a).

Nevertheless, a correlation analysis between the respective available data allows to detect a new differentiation in the North-Eastern subsystem. Ibera and Galarza lagoons seem to be correlated with a high coefficient and hence the Ibera lagoon will be used to correlate changes in storage volume due to the good fit of its data with that of Paso Lucero stream-gauging station –in spite of the fact that multiple regression must be done considering rainfall between Itati Lagoon and Paso Lucero and the discharge from the Pay Ubre stream- and because of the long-term record available.

In addition, a strong correlation occurs between the series at Tave Reta on the NE extreme of the Eastern subsystem, and El Transito on the southern half of the Western subsystem, close to the Batel-Batelito catchment, while no correlation exists between Tave Reta and the Ibera and Galarza time-series.

Stations	Period	Coefficient of correlation
Ibera- Galarza	7/1968 – 12/1968	0.88
	2/1969 – 2/1972	0.77
	10/1977 – 5/1978	0.91
Tave Reta - Ibera	6/1978 – 12/1979	0.553
Tave Reta – El Transito	6/1978 – 12/1979	0.91
	4/1976 – 10/1976	0.88
Ibera - Lucero	7/1968 – 11/1983	0.70
	4/1990 – 12/2000	0.76

Two possible hypotheses are being advanced in order to explain this phenomenon. Geologists suspect that some sort of bottom morphology located downwater of Luna-Galarza lagoons could be conditioning this change in the general flow direction inside the upper portion of the North-Eastern subsystem, deriving the water toward the North-Western subsystem, but no studies have been carried in this direction.

The second hypothesis is that of a natural ground water inflow between Conte and Rodeito lagoons (Tave Reta) at the top of the North-Eastern subsystem, where a potential end of a fracture in the basalt bed could be located (A. Fulquet, pers. comm.). Both hypotheses require of complete hydrogeological studies.

Water-budget method

The wetland water budget is the total of inflows and outflows of water from a wetland. Water budgets provide a basis for understanding hydrologic processes of a wetland.

The components of a budget are shown in the equation:

$$P + SWI + GWI = ET + SWO + GWO + \Delta S,$$

where P is precipitation, SWI is surface-water inflow, SWO is surface-water outflow, GWI is groundwater inflow, GWO is groundwater outflow, ET is evapotranspiration, and ΔS is change in storage. 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).

The hypothesis is that the Iberá system as a whole behaves as a response function whose main characteristic is storage. The main input variable is precipitation P, while SWI is considered to be null. The main surface output are the outgoing flow SWO of the Corriente River and the evapotranspiration demand ET. The behavior of groundwater flows GWI and GWO is unknown given that they could be inputs or outputs of the system at different times and places. Hence, the balance (GWI-GWO) is considered to be contained in the storage. As a first approximation, for a time step Δt equal to one month, the storage ΔS is taken as the state variable of the system, calculated as

$$\Delta S = P - ET - SWO$$

The surface water balance with monthly time step was calculated from precipitation data obtained at the stations in San Juan Poriahu, Ituzaingo, Yacyreta, Chavarria, Pay Ubre, Concepción, Galarza and Colonia Carlos Pellegrini (*see description in Variables*) and weighed using Thiessen polygons, while the evapotranspiration was computed taking monthly mean temperature data measured at Posadas, Mercedes and Corrientes meteorological stations, and monthly mean discharge for the Corrientes River was calculated from data at Paso Lucero.

The hydrometric data registered at the Ibera Lagoon are the only ones that correspond to the period of the time series used above. When plotted together with ΔS from the water balance equation, we can observe a clear fit in the fluctuations, as seen in *Figure 44*. This allows us to conclude that the water balance equation is a good first approximation to the behavior of the system.

Nevertheless, there are gaps in the data over the most interesting period, that is: March of 1988, February, March, April, May, June, July, October and December of 1989 and January, February, March and April of 1990, when an important jump in water levels was detected. These gaps brought the need to search for alternative options and two approaches have been tested: firstly, a discharge zero was considered in place of the lacking data and the result is shown in *Figure 45*. On the other hand, mean monthly discharge calculated by interpolation from Los Laureles-Paso Lucero relationship was took into account and is shown in *Figure 46*. It is evident that the observed jump can not be explained satisfactorily with any of the proposed approaches.