The Increase in the Storage Capacity

With the aim of obtaining the possible causes of the increase in the storage capacity of the Iberá system, three questions needed to be answered with scientifically founded deductions:

- Could the increment in storage be explained by the increase of precipitation 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 precipitation 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 dykes (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 Iberá?

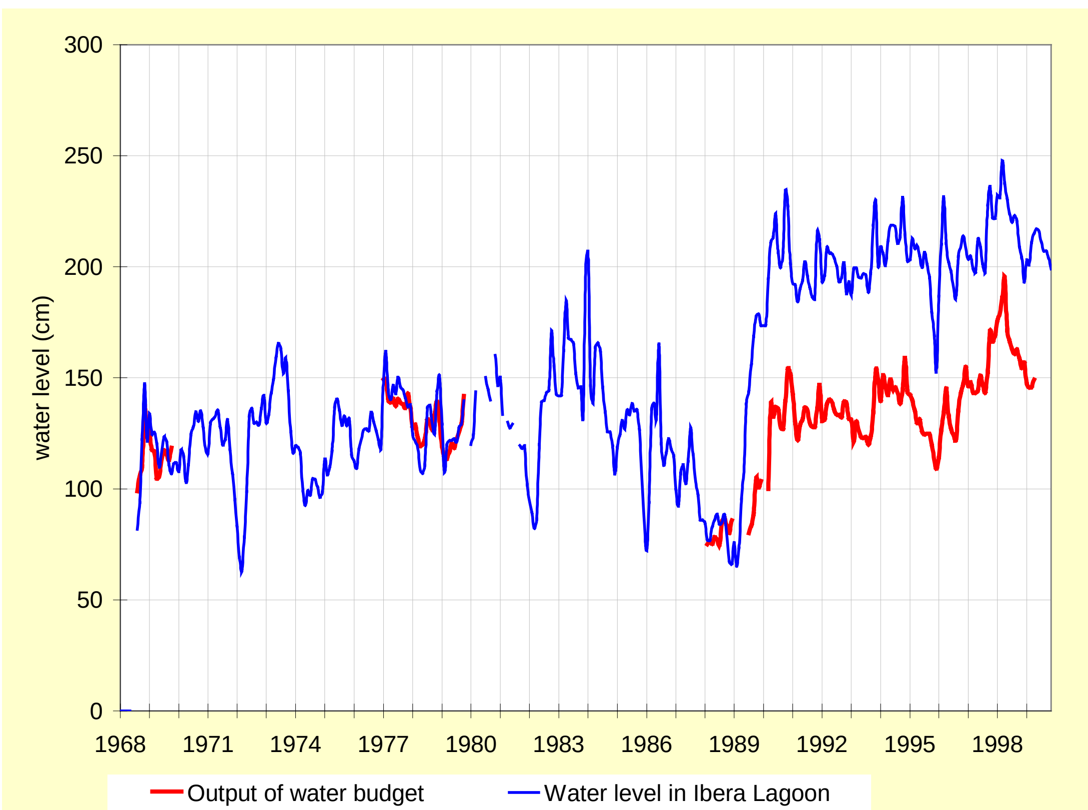


Figure 44: Water level variation in Ibera Lagoon and calculated values

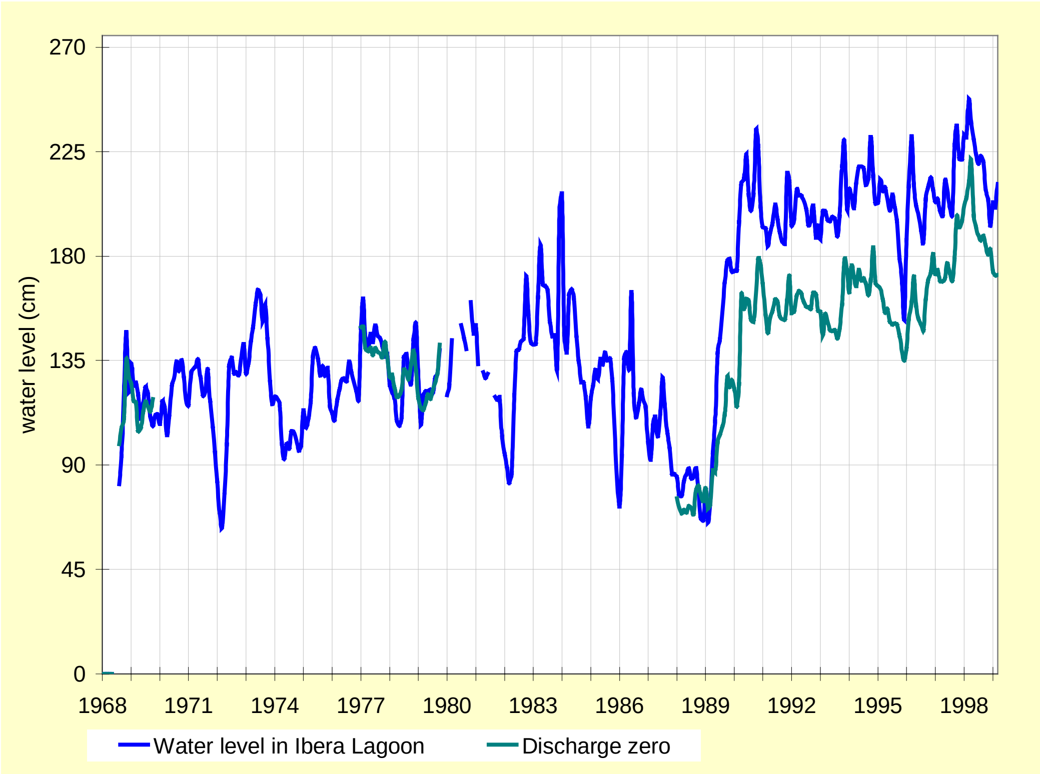


Figure 45: Water level variation in Ibera Lagoon and calculated values considering discharge zero in place of missing data

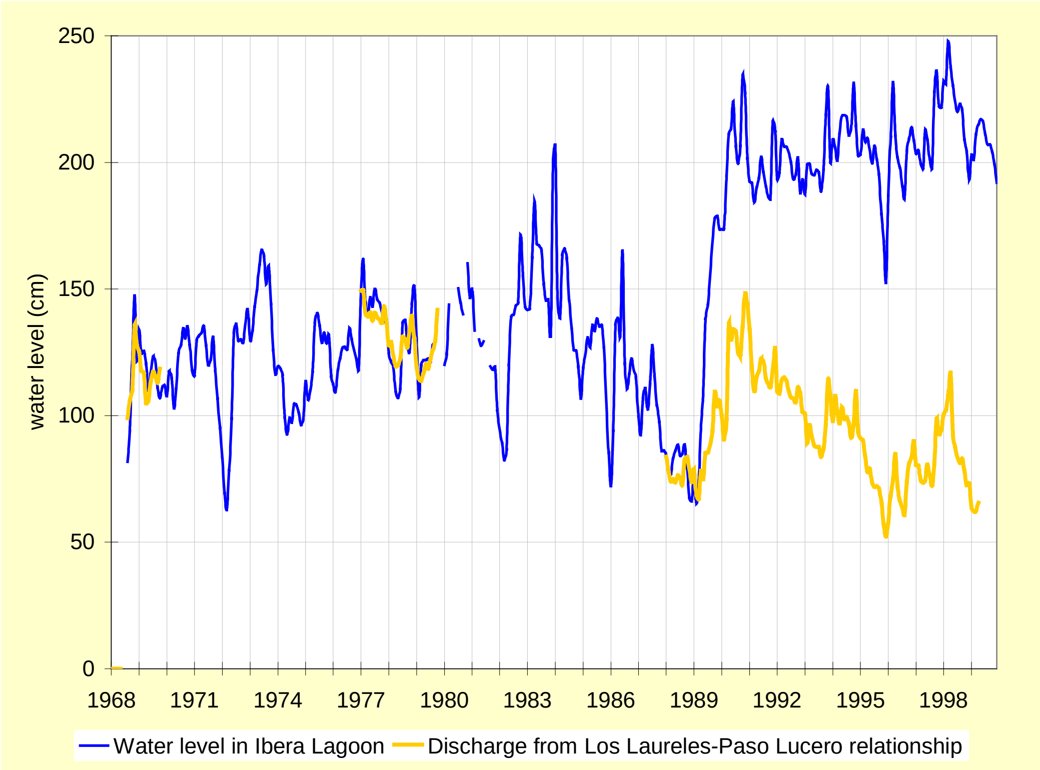


Figure 46: Water level variation in Ibera Lagoon and calculated values considering discharge interpolated from Los Laureles-Paso Lucero relationship in missing data

- ***Effects of Global Climate Change and ENSO***

From a precipitation depth and potential evapotranspiration calculated at Ibera system in a regional way utilizing data from the meteorological stations located at Posadas, Corrientes and Mercedes, ten years of previous excess and deficits have been considered to analyze this possible cause of the important and non explained increase in the water level that occurred in the period 1989-1990.

The cumulative values in between the years 1981-1990 are: rainfall, 17127 mm, and potential evapotranspiration, 10659 mm (62% of rainfall) which yield an excess of 6468 mm in ten years. During this decade, two ENSO events occurred, the first in 1983 and the second in 1986. The two ENSO events are responsible for 25% of the total rainfall recorded in this period.

With the aims of calculating the annual balance, the outflow through the Corriente River is analyzed. In this period, some gaps are observed in the discharge series from 1983 to 1990. Two possible approaches are here proposed. Firstly, an annual average runoff was calculated from a precedent full decade, 1968-1977, with a total loss of approximately 3900 mm (23% of rainfall). Secondly, the months without measurements in the record 1981-1990 were completed using interpolating data from the Corriente River at Los Laureles water gauge station, yielding a total loss of 8835 mm (52% of rainfall). :

The annual distribution of the outflow, considering average annual runoff in the first case and annual runoff obtained by interpolation in the second one are shown in *Figure 47* and *Figure 48*.

A cumulative deficit of 56 mm between 1988-1989 and an excess of 263 mm between 1989-1990 were calculated when the conservative average runoff was utilized. The ENSO event effect, that can be seen in *Figure 47* due to the rainfall, is the driving force considered. Nevertheless, this excess volume cannot explain the jump observed in the storage.

A cumulative excess of 221 mm between 1988-1989 that maintained until 1990, with zero accumulation, was obtained when measurement and interpolating data were used. Curiously, a big deficit in between 1985-1987 can be seen in *Figure 48*. Obviously in this case, the rainfall is not the only driving force of the system and hence a non yet considered factor must be taken into account.

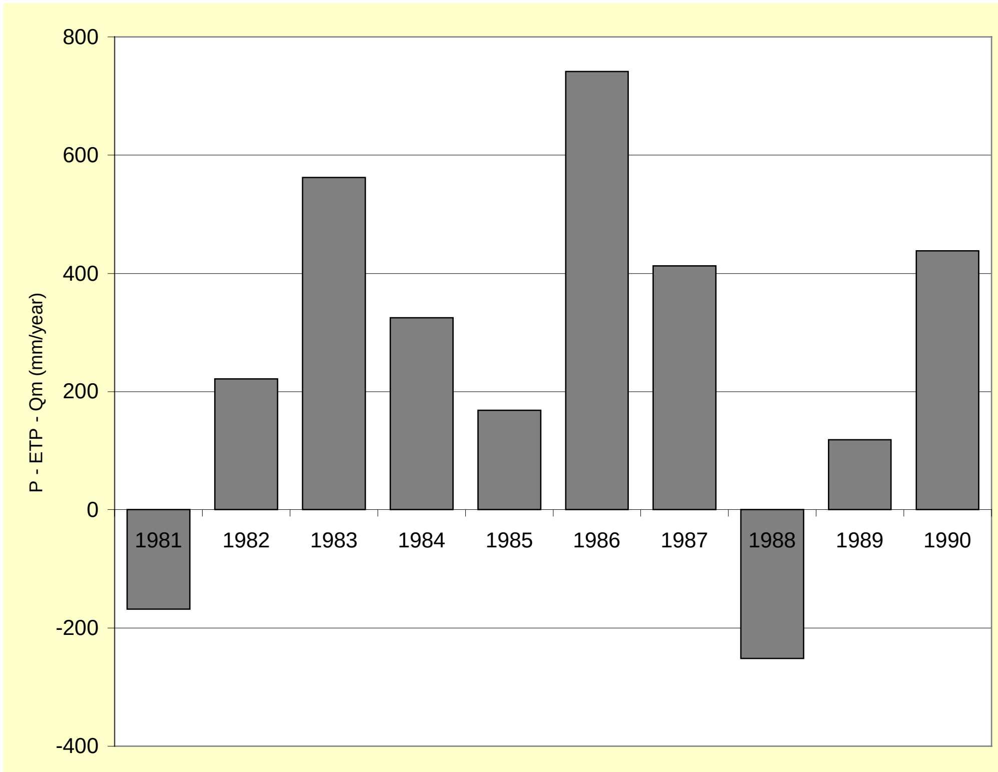


Figure 47. Annual balance considering average annual runoff calculated from series 1968-1977.

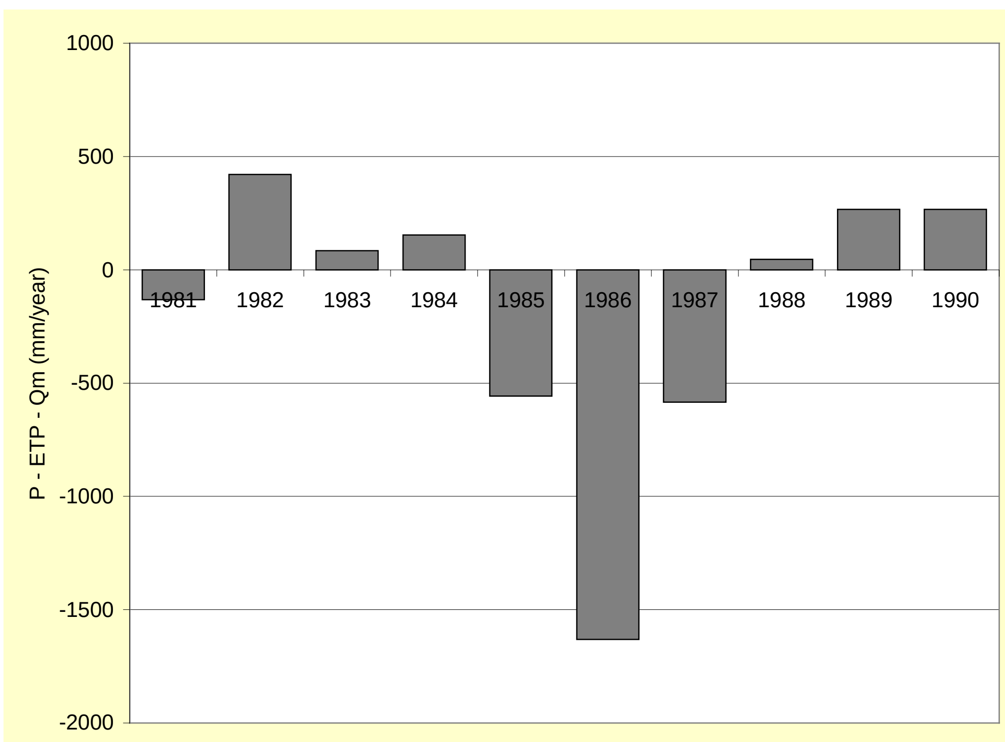


Figure 48. Annual balance considering interpolated annual runoff from Los Laureles station.

- ***Effects of an outflow obstruction***

A detailed study of runoff was carried on in order to analyze the changes observed in the dynamic of the system. A first hypothesis has been tested when discharge zero in lacking data was considered in the balance and a satisfactory response to explain the jump could not be obtained. Here again, the water balance equation including the assumption of a worst possible situation does not explain the sudden change in the behavior of the system. However, is evident that outflow and storage of the system have suffered considerable changes. In order to explain them, statistic tools have been utilized in analyzing the behavior of runoff in Paso Lucero, storage changes in the Ibera Lagoon and precipitation depth at the basin from regional and local scale variables put together.

Regional precipitation and mean monthly runoff

Annual precipitation depth at the Ibera system from regional scale (mm/year) and the mean monthly runoff across Paso Lucero stream gauge station (mm/mo) are shown in *Figure 49*. The statistics were calculated from mean monthly discharge for two available records, 1968 – 1983 and 1990 – 2000 and are described in Table 3. The months corresponding to ENSO events have been taken in account and removed.

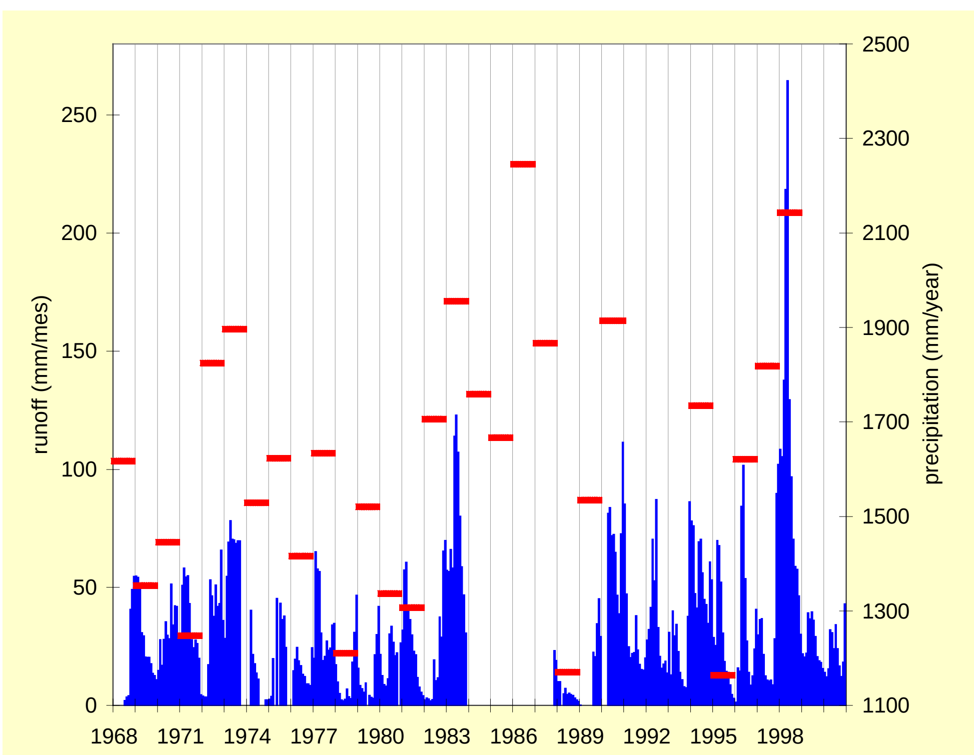


Figure 49. Annual precipitation depth (regional scale) in red and monthly mean runoff across Paso Lucero stream gauge station in blue.

Statistics	1968-1983		1990-2000	
	With ENSO	Without ENSO	With ENSO	Without ENSO
Mean	159 $m^3\ s^{-1}$	149 $m^3\ s^{-1}$	224 $m^3\ s^{-1}$	200 $m^3\ s^{-1}$
Standard deviation	123	127	200	140
Coefficient of variation	0.77	0.85	0.89	0.70
Skew Coefficient	1.12	0.55	2.74	1.03

Table 3

An increase in mean monthly discharge, in agreement with regional rainfall is observed. In the records corresponding to the periods 1968-1983 and 1990-2000, the annual mean runoff were 360 mm/year (23 % of rainfall in this period) and 506 mm/year (29 % of rainfall) respectively. The coefficients of variation and skew show an increase in dispersion which deepens the complex behavior of the Corriente River.

Local precipitation and monthly mean runoff

Tree periods have been considered for the water budget equation due to the availability of data at the local scale. For these, the rate runoff relative to antecedent precipitation was calculated, and very much different values were encountered. The results are shown in *Figure 50* and Table 4.

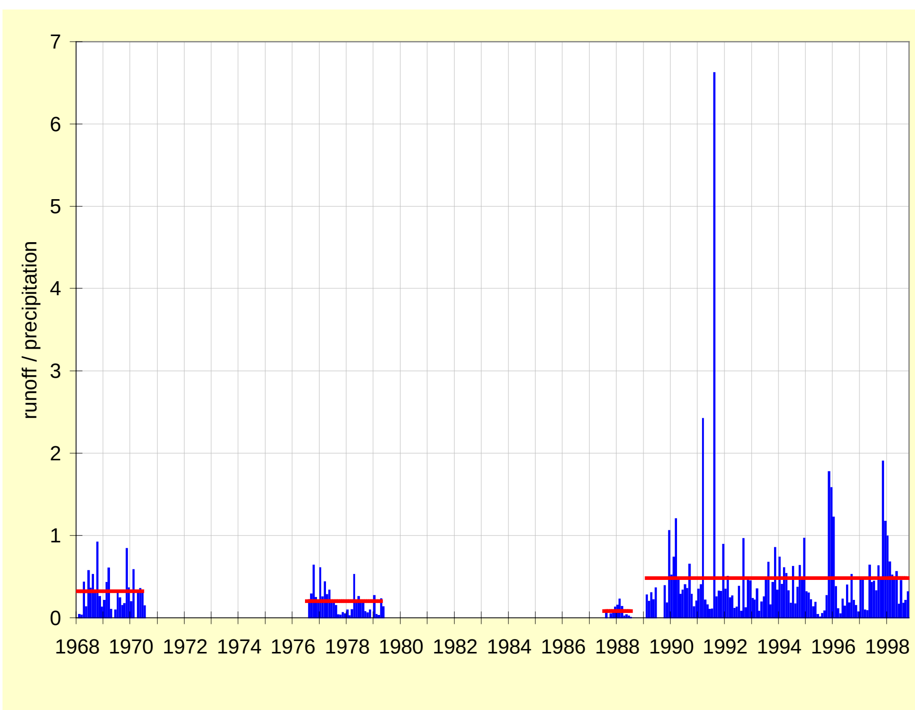


Figure 50. Runoff at Paso Lucero relative to antecedent precipitation.

Statistics	1968-1970	1977-1979	1988-1989	1990-1999
Mean	**0.32549738**	**0.20320689**	**0.08**	**0.48432586**
Standard deviation	**0.22499201**	**0.16070256**		**0.6952662**
Variation Coefficient	**0.69122524**	**0.79083222**		**1.43553392**
Skew Coefficient	**1.07841939**	**1.27543378**		**6.48954081**

Table 4

The analysis of the relationship discharge/precipitation indicates that, under the assumption of constant precipitation, the relative discharge has at least doubled compared to records on previous decades. Note that the analysis is not saying that there have been no obstructions, but rather that, even if there were, they could not explain the accumulation of water in the system.

Monthly mean runoff and water level at the Ibera Lagoon

An analysis of the relationship between the discharge at Paso Lucero and the water levels at Iberá Lagoon yields further insight into the dynamics of the system.

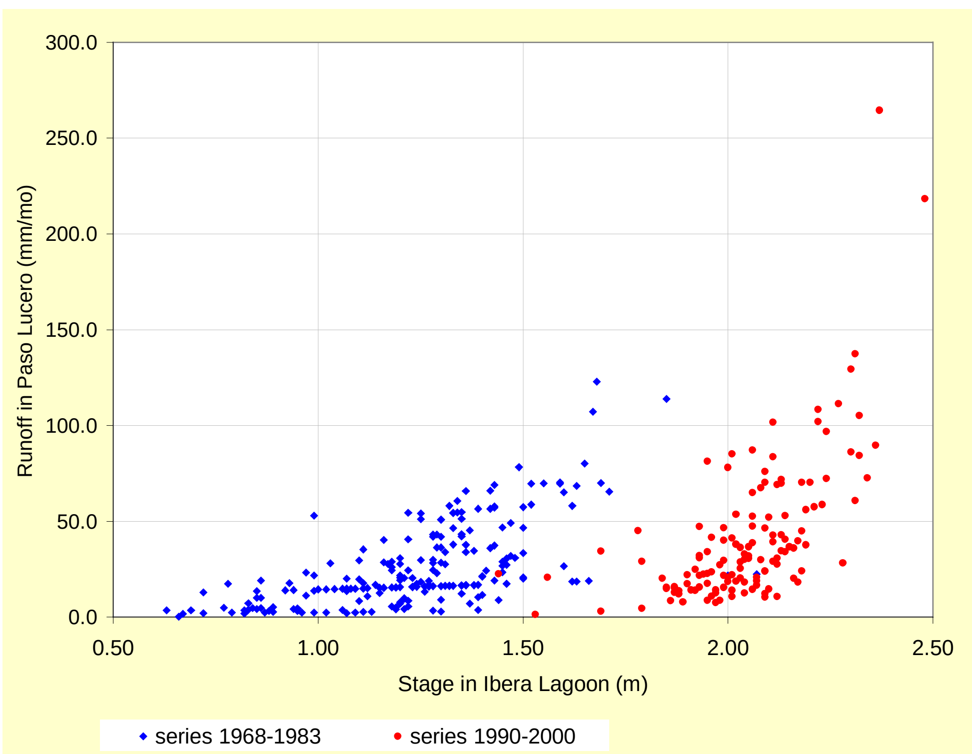


Figure 51. Discharge at Paso Lucero relative to water levels at Ibera Lagoon

In *Figure 51*, a remarkable change in the behavior of the system as a natural reservoir is made evident. By comparing the set of data recorded in 1968-1983 to that of 1990-2000, it can be observed that the system is retaining a much larger volume of water. An immediate interpretation of this would be that the system was moved from a previous equilibrium to a new steady state.

A new question emerges from this analysis: if the system has moved to much higher storage levels, how is it that the discharge remains within the same values? For one thing, the instant discharge values show a variation in frequency, which results in an increase in total volume of water removed from the system. But it is also reasonable to analyze the particular characteristics of the system. The topographic differences that separate the subsystems become blurred, undefined when the water levels rise, inducing a more homogeneous response. Besides, the vegetation, particularly the floating *"embalsados"*, might be playing different roles, retaining or releasing water, as their levels vary.

- ***Effects of groundwater flow***

It is clear that the water budget model shows a good fit in the fluctuations between observed and calculated variations in water level inside the system. It is also clear that neither of its variations can explain the important jump registered. For this reason, the hypothesis about the precipitation as main and only driving force of the system considered for the water budget equation must be revised and changed, and new information should be tested. Hence, the groundwater balance needs to be considered separately from the storage compartment.

The northernmost surface limit of the system is adjacent to the Parana River, the main watercourse of the Del Plata basin. The average discharge of the Parana River has increased from a historical 12,000 m^3 $s^{-1}$to 19,000 m^3 s^{-1}over the last tree decades as a consequence of climatic changes, and extreme records of more than 50,000 m^3 s^{-1} have been registered (1983), due to ENSO.

The Iberá system lays on the paleolithic-river beds of the Parana River which shifted to its present position as result of cataclysms occurring from the late Pliocene to the middle Pleistocene periods. In following one ancient course, the Parana River carved a canyon of 400 m width per 50 m deep on the thin erosion front (4 Km wide) that separates it from the Ibera system, which was subsequently filled with sandy sediments of various degrees of coarseness of grain. Moreover, the Apipe rapids signal one of the fractures on the basalt layer in the vicinity of the Yacyreta Island. Besides the large fractures, the basalt bed presents many fragmentations or diaclasae, into which water can flow.

The water level at the headwater of the Esteros del Iberá system has been 12m above the level of the Parana River. Because of this, the Iberá system contributed with groundwater to the Parana River. Nowadays, the lake created by the Yacyreta dam rises some 4m. above the previous water levels of the Iberá system.

The Dam is anchored on the Yacyreta Island, taking advantage of the gap created by the Apipe rapids and the possibility of using the two branches of the Parana, the Main branch and the Aña-Cuá branch *(Figure 52).* The civil works of the dam started in 1983 with the construction of the dams that delimit the reservoir. On the Northern or right margin of the river, on Paraguayan territory, was built the Right Lateral Dam (25.7 Km long). This dam, as well as the Yacyreta Island Lateral Dam (18.7 Km long), is constructed with zoned section, clay central core and sand shoulders, and including a watertight cutoff wall of bentonite cement which runs from the core to the rock (EBY, undated). Curiously, the Left Lateral Dam (12 Km long), with homogeneous section, built with watertight soils, and the Main Left Dam 1.8 Km long), with zoned sections with central clay core and sand shoulders, were not provided with a cutoff wall of bentonite as the Northern dams were.

Figure 52. Map of the Yacyreta Dam construction site.

The construction was initiated on firm soil and much of the structure was built before it was necessary to deviate the river. The 27m wide navigation lock and the 15m wide Main spillway were built against the Southern or left margin, on Argentine territory. Even the construction of the Main Branch powerhouse on the Yacyreta Island could be undertaken before the river was deviated. The Main Branch Closing Dam, consisting of a clay core directly seated on the rock beds, sand shoulders and rip-rap protection, and the Aña-Cuá Branch Closing Dam (3,6 Km long), bearing the same bentonite cutoff wall as the Yacyreta Island Dam, were the last sections undertaken.

In order to build the Main Branch Closing Dam, the Main branch of the Parana River was deviated towards the navigation channel on the Southern margin and the Main spillway. The models that permitted the choice of the

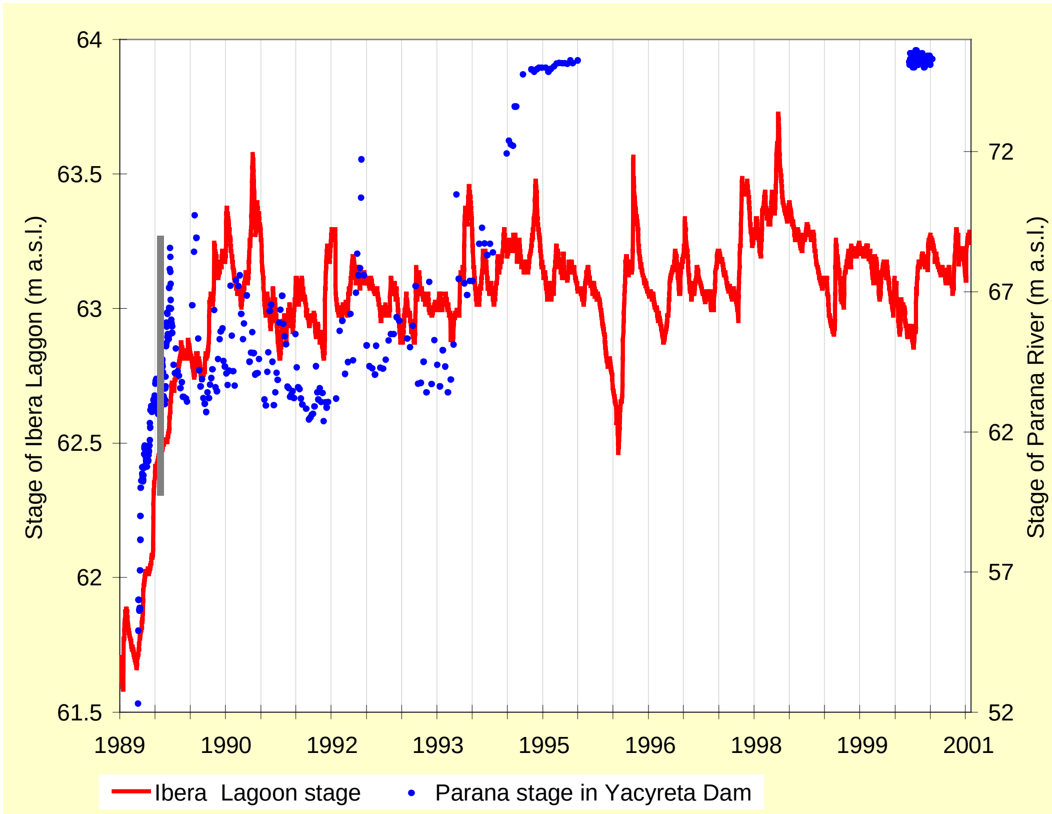


Figure 53. Comparison betwen water levels at Paraná River and Ibera Lagoon.

method (a combination of frontal advance and horizontal increase) to be used for the deviation of the river were done by INCyTH. The deviation work was executed during the period April-June 1989 (Clarin, May 12,1989) . The construction work was completed and the reservoir filled to its current level in 1994.

As a consequence of the deviation of the flow of the Parana River into the much narrower section of the channels, the level of the waters increased, as seen on the river level measurement taken *in situ* during the period April 1989-December 1990 (A. Fulquet, pers. comm., Eriday data). Since this period coincides with the period where the remarkable increase in water levels at the Iberá Lagoon was recorded, it is natural to compare the two time series and try to analyze the correspondence *(Fig. 53).*

The comparison of the two crude data sets shows a clear response --exhibiting a very short delay-- of the level at the Ibera lagoon to the increase in the level of the Parana River. This would imply that the transfer process was so important that it blurred the effect of other possible factors during this few months between April and November 1989. In *Figure 54*, it is easy to observe that the level at Iberá lagoon continuously increased as the level of the Parana River moved upwards, but did not decrease as it moved downwards. From then on, the Iberá system reached a new equilibrium and maintained a pattern where the oscillations are tied to atmospheric processes.

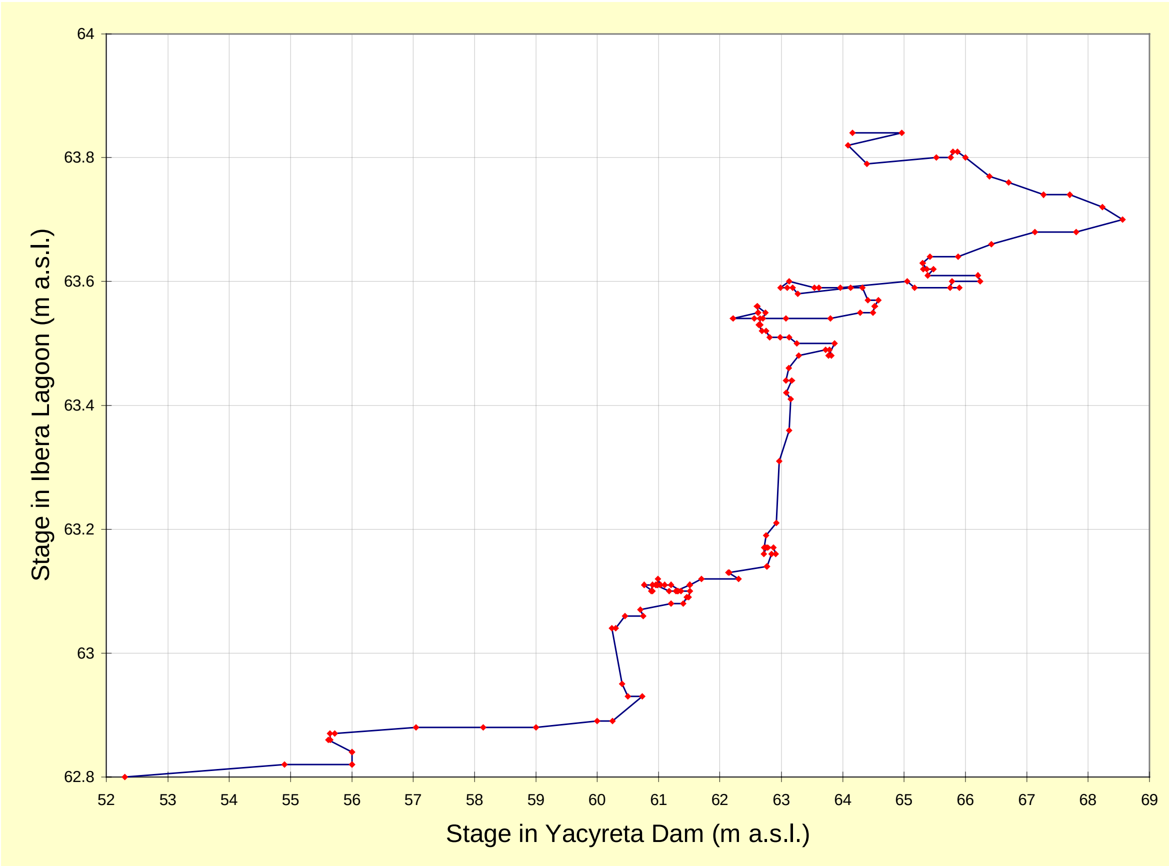


Figure 54. Water level at Ibera Lagoon relative to water level of the Paraná River at Yacyreta Dam.

Successive groundwater inflows have been considered in order to obtain a close agreement between the balance model output *(Figure 55, gold line).* and the historical stage data at Ibera Lagoon. Firstly, a theoretical effluent volume that increased the water level by 10 cm/mo was incorporated in the groundwater balance along a period of eight months, from April to November of 1989, when the water level in Parana River reached successively 60.5 m and 63 m above sea level *(Fig. 55, orange line).* If we consider the volume of water required to increase the water level in 10 cm/mo. over an extension of thousands of Km^2, it becomes very difficult accept that the water is entering the system through the sandy erosion front that separates it from the Parana River. It is necessary to add that the response is extremely rapid and that in 1989 the Parana River was still bellow the level of 72 m at the headwater of Ibera. Nevertheless, the Parana River was indeed above the level of the Ibera lagoon. This observation seems to support the hypothesis of a groundwater inflow through the fractures and diaclasae in the basaltic beds. If this is the case, the main inflow could be entering the Ibera system at its heart and not at the headwater.

Afterwards, a monthly theoretical effluent volume that increased the Ibera system in 2 cm/mo was added *(Fig. 55, red line)* during the months when the water level in Parana River at Yacyreta Dam rose to 65 m above sea level

(Figure 56). These months are April and June of 1991, February, April, May, June, August, October, November and December of 1992, March of 1993 and February and June of 1994. This extraordinary fit of the corrected model with the measurements recorded at Ibera Lagoon seems to be in agreement with the hypothesis of a rapid inflow of enormous magnitude through fractures and diaclasae in the basatic bed.

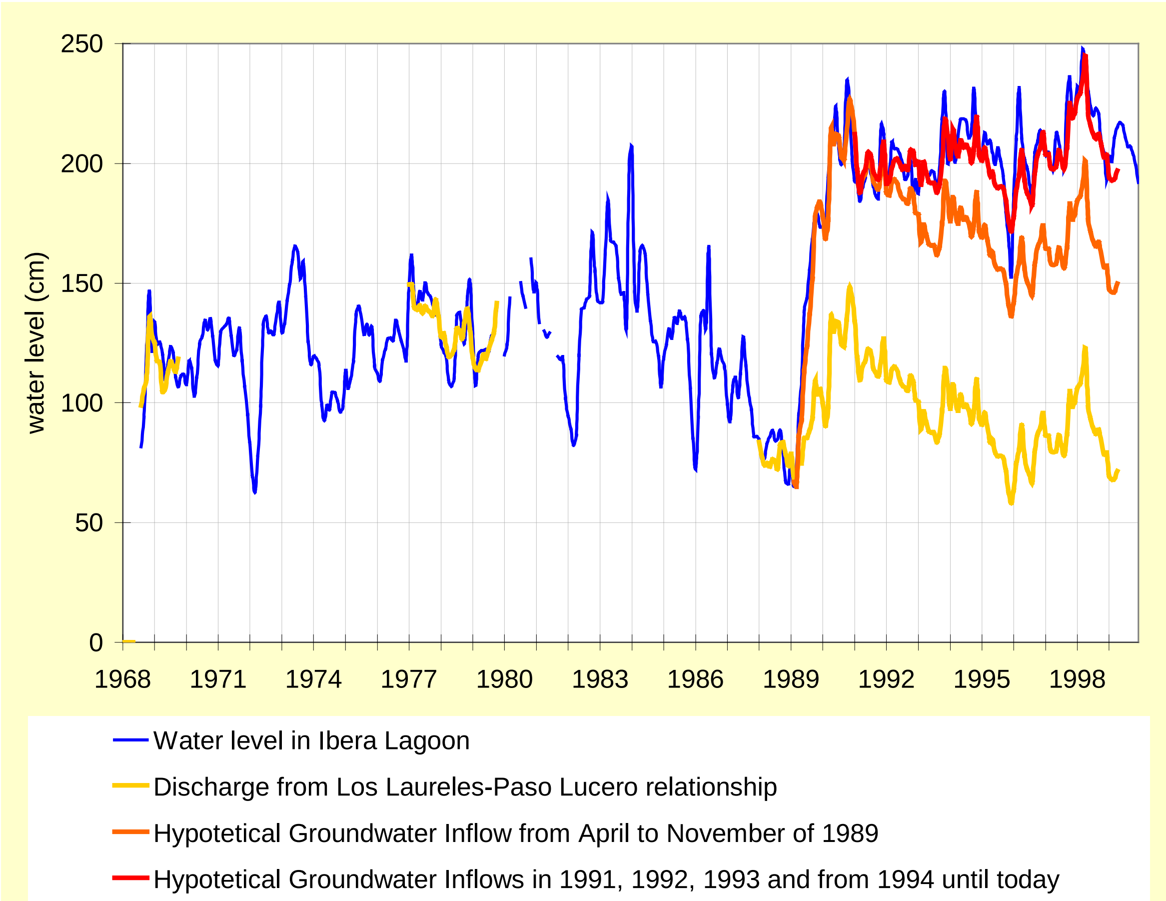


Figure 55. Corrected water balance model

Finally, a groundwater inflow that increased the stage in the Ibera system in 0.25 cm/mo was added, when the level of water at the Yacyreta reservoir exceeded 72 m above sea level (altitude at the headwater of the Ibera system). This last correction *(Fig.55, red line)* seems to be in agreement with the estimations of 12 m^3s^{-1} calculated by Lotti e Associatti (2000)

It is possible then to identify four different stages from the hydrometric data recorded at Ibera Lagoon. A first stage where the system is regulated by processes taking place at a surface level, such as precipitation, evapotranspiration and discharge through the Corriente River. A second stage, during the interval 1989-1990, where the system is taken to a new equilibrium by the contribution of an important groundwater inflow. Then, a third stage, from

1991 until 1994, with intermittent pulses, before the reservoir was filled. Finally, the fourth stage, when the reservoir reached a level above 72 m a.s.l., which is the headwater level of the Ibera system.

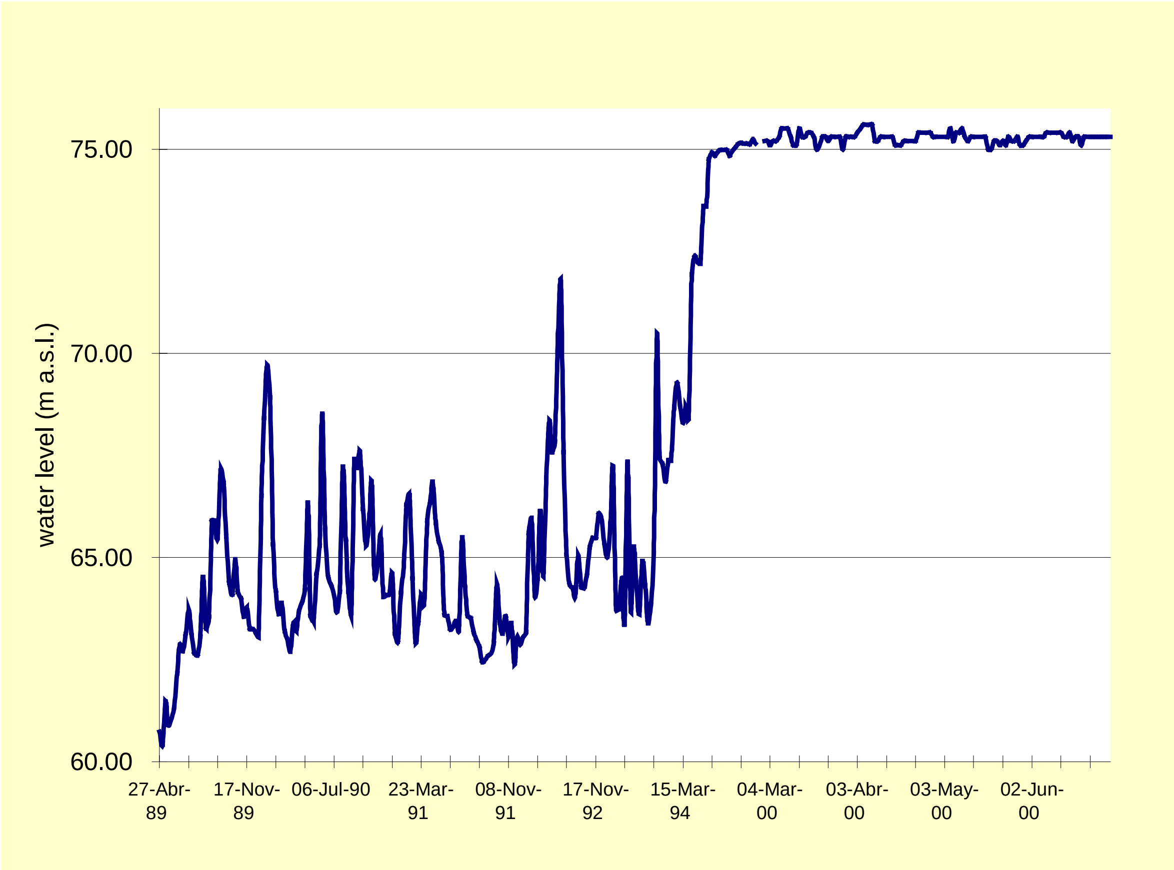


Figure 56. Water level at the Yacyreta Dam reservoir.

Putting together all that has been mentioned here, it is interesting to return to previous paragraphs and note the contrast between *Figures 47* and *48*. Historical data shows that during extreme events affecting the Del Plata basin, the dominant driving force is not rainfall *(Fig. 47)* but rather the levels of the Parana River as can be seen in the data from Los Laureles stream gauge station, downstream of the Corriente River *(Fig.48)*. The strong relationship between water levels at the Parana River and at the Ibera Lagoon attained during extreme events is confirmed in the graph of minima and maxima as provided by EVARSA data (*Figure 57*, A. Fulquet, pers. comm.) Moreover, the data from the Batel-Batelito basin *(Figure 37)* confirms the underground hydraulic connection between the three systems.

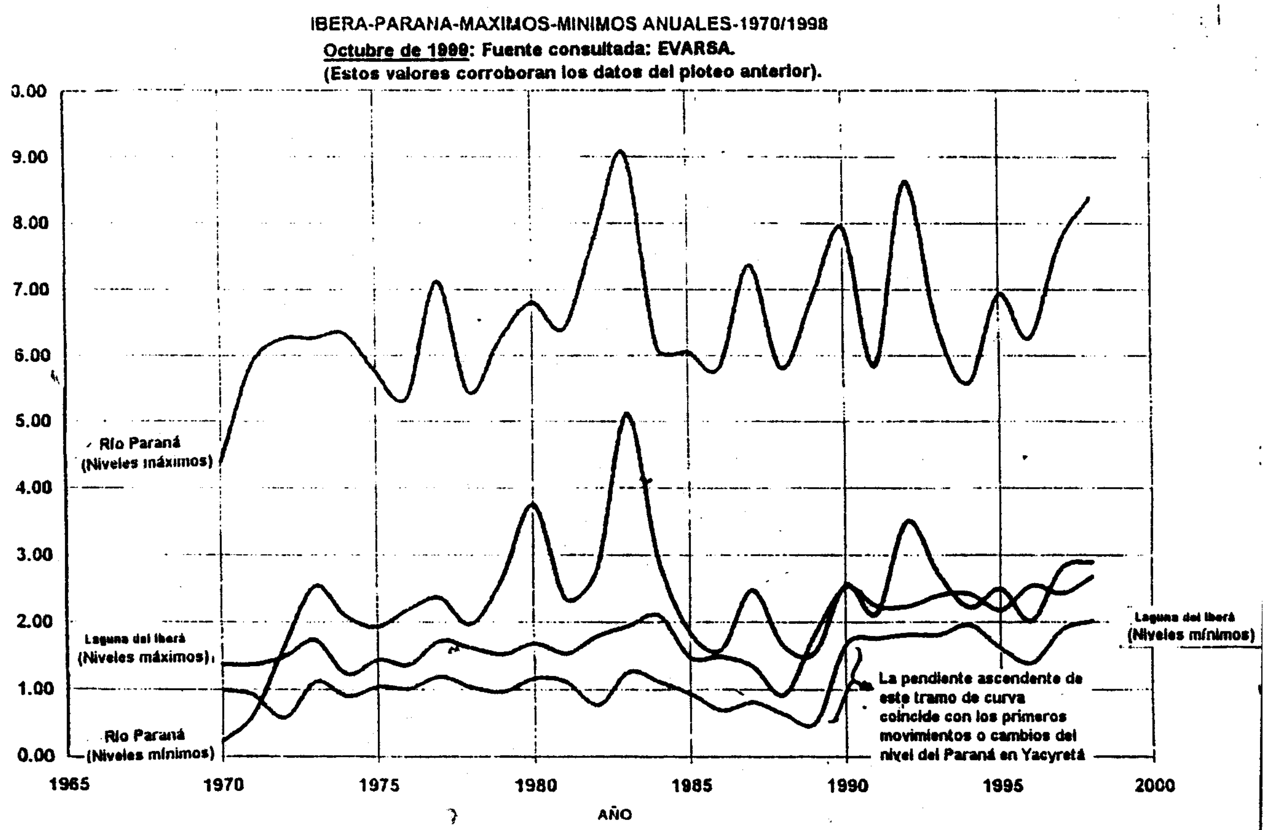


Figure 57. Annual minima and maxima stages of Ibera lagoon and Parana River (source EVARSA)

Distributed Hydrological Model

The Ibera wetlands are composed by a mosaic of open water, permanent shallow water covered totally or partially by fixed and floating aquatic vegetation, temporary inundated lands with alternative and successional patterns of vegetation and permanent emergent land, mainly the central sandy hills and its borders. For this reason, the knowledge of the water level at each point of the system is essential to develop any other model of species population because of the strong relationship between animal and vegetal species with water. Temporal and spatial variations in the storage water cause changes in vegetation patterns and, consequently, movements and changes in the population structure of animals living inside the wetland. For this reason, the construction of a hydrological distributed model at landscape scale is necessary, but the large and variable area that conforms the Ibera ecosystem and the lack of knowledge of the hydrogeological characteristics create several and great difficulties.

In wetland systems, there is a strong and variable relationship between surface, subsurface and groundwater storages, but no study was carried on in Ibera in order to quantify the variables involved that link them, such as seepage and percolation. The full geology and hydrology of the system is unknown and, additionally, there is no measure of ground inflows and outflows.

However, we have seen that, under normal conditions, the ultra-stable Ibera ecosystem responds tightly to atmospheric processes. For this reason, a closed and coincident superficial and subterranean theoretical watershed was considered and a first approach to a surface flow model was built searching to adjust it to stage data available in open water sites inside the system.

Being unable to use classic hydrologic methods developed for small scales in controlled systems, the challenge here is to construct a simple model with a appropriate spatial and temporal resolution that reflect the state of each portion of the system for each time step.

Model Characteristics

A spatially distributed water balance model applies the Mass Conservation Law to describe the mass balance within each spatial unit, and couples a momentum equation which defines the water movement between cells.

When a large temporal and spatial scale are used, discrete approximations of the essentially continuous hydrologic processes become a source of potential problems. In place of continuous movements of water and constituents over the area, we need to deal with essentially discrete motions, when large volumes of material are moved over large distances on relatively rare occasions (Voinov et al., 1998).

The simplified approaches to surface water fluxing more commonly used in 2-dimensional overland flow are based on the kinematics wave approximation of the Saint Venant's equations (Beven and Wood, 1993).

The complete Saint Venant equations of the mass conservation equation (1) and the momentum equation (2) are:

$$\frac{\partial A}{\partial t} = -\frac{\partial F}{\partial x} + q \quad (1)$$

$$\frac{1}{A}\frac{\partial F}{\partial t} + \frac{1}{A}\frac{\partial(\beta F^2/A)}{\partial x} + g\left(\frac{\partial h}{\partial x} + S_f\right) = 0 \quad (2)$$

where F is the flux of water between cells, A is the cross-sectional area of water flux, q is the lateral inflow or outflow, h is the surface water elevation above sea level, and S_f is the friction slope.

In this case, the horizontal flow between cells is simulated using slope-area method, which evaluate the friction slope using a uniform, steady-flow empirical resistance equation such as Manning equation (3).

$$F = AR^{2/3}G^{1/2}/M \quad (3)$$

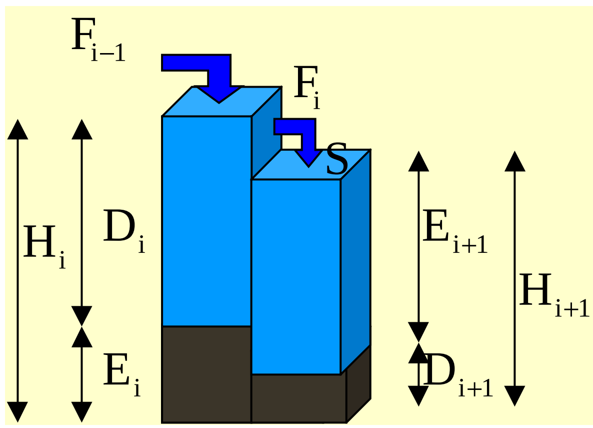
were R is the hydraulic radius, G is the slope of the energy gradient and M is the coefficient of Manning of surface roughness.

The equation~~s~~ of conservation (1) and equation of approximation of moment (3) in their discrete forms are

$$D_i(t+\Delta t) = D_i(t) + (F_{i-1}(t) - F_i(t))\,\Delta t / S \quad (4)$$

$$F = \mathrm{sgn}(H_i - H_{i+1})\sqrt{|H_i - H_{i+1}|}\,D^{5/3}\sqrt[4]{S} / M \quad (5)$$

where S is the area of square cell, H is the hydraulic heads (m) of the cell, E is the cell elevation above sea level, and the subscript describe the link between neighbor cells as can be see in the next graph (Voinov et al, 1998).



Two computational schemes can be used to model 2-dimensional overland flow: implicit or explicit. The resolution of implicit method uses the boundary conditions inside the scheme which are complex and non clearly delimitated in the flat wetlands. For this reason, a computational simple explicit method was used. The necessary but not sufficient condition of Courant $\frac{\Delta x}{\Delta t} \geq \frac{F}{S}$ is proposed to be verified due to instability of explicit scheme. From this, a short time step must be considered, which is a problem at moment of to evaluate the computational effort.

The model assumes homogeneity in physical and hydrologic characteristic and simulates hydrological processes within each grid cell. The hydrological processes within the cells are rainfall, evapotranspiration and seepage.

Data input

- ***Spatial data***

Land elevation data has been required to describe the physical features of the modeling domain. The construction of **DEM** (Fig. 8) was explained early and it permits to know the altitude in each cell of the grid utilized. The domain is comprised of 0.0324 meters square grid cells which cover the 14,000 km² that conforms the surface system, in concordance with the pixels (180 x 180 m) of satellital images utilized. The total number of cells in the rectangle that contains the basin are 1245 x 1025.

The **watershed image** (Fig. 11) (matrix of zeros and ones) is utilized to cut this rectangle and to obtain the modeling domain where the processes are simulated.

Over it, initial parameters are assigned in each cell using the **image of roughness parameters** (Fig. 23) obtained with Modified Tasseled Cap Transform method applied on wetness index image.

Temporal data

The available historical record of daily precipitation, discharge and stage and monthly evapotranspiraton data by stations are summarized in Figures 58 and 59

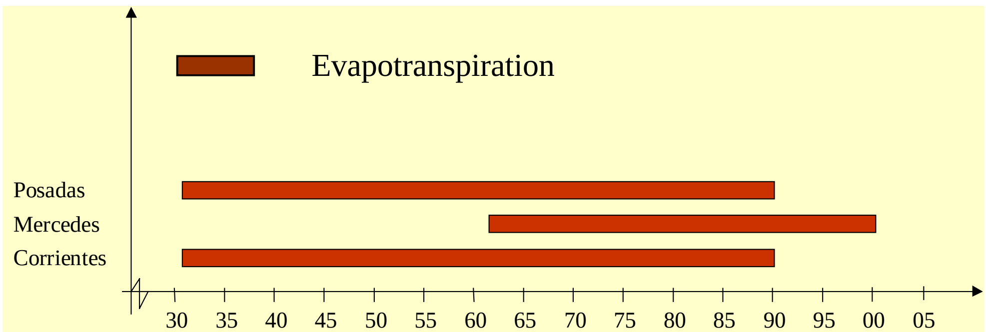


Figure 58: Records of available data

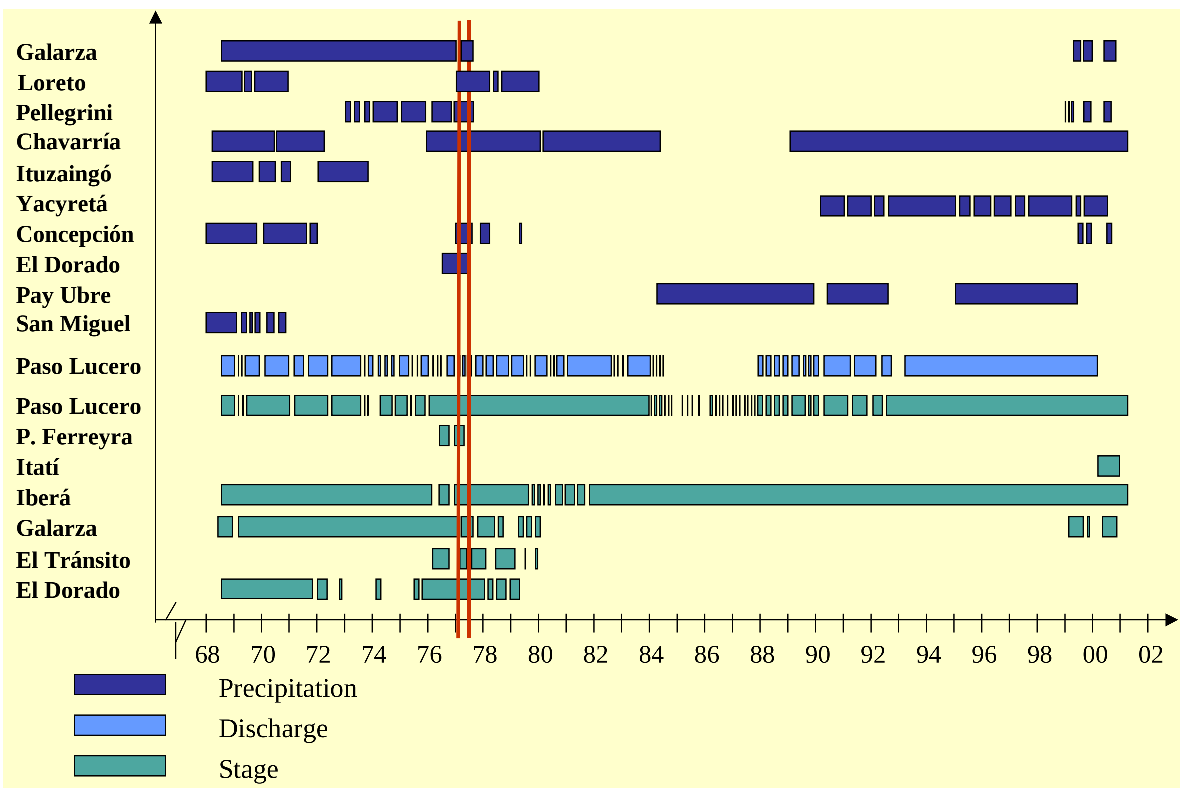


Figure 59: Records of available data

In the Figure 59, a period with an optimal number of stations with the longest record possible was marked. For this period, daily time series of precipitation depth was available from Pellegrini, Galarza, Concepcion, Chavarria, Loreto and El Dorado rain stations. Thiessen distribution by these stations is shown in Figure 60. Due to the unavailable local measurements that could make possible to calculate evaporation and evapotranspiration within the system, average daily potential evapotranspiration was calculated from regional data of mean monthly temperature a regional level for this period.

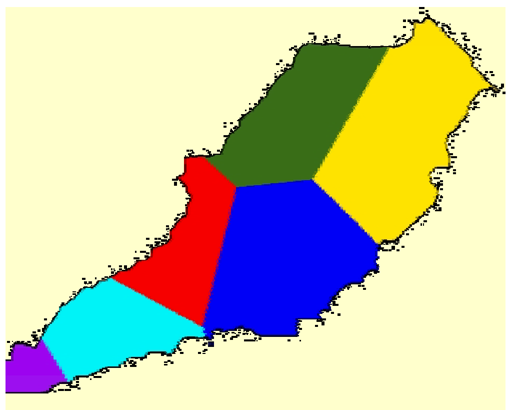


Figure 60: Spatial distribution of rain stations

The historical available data of rainfall and potential evapotranspiration, the primary atmospheric driving processes of the wetland Ibera system, were assigned in each cell in function of its corresponding Thiessen polygon. The difference between both series was taken as input for a period of six months between January and August of 1977 for each cell.

Daily runoff at Paso Lucero stream gauge station and daily stages in Galarza, Ibera, El Tránsito & El dorado hydrometric stations were available as initial condition the former and for calibration the latter.

A fixed time step of one day is used in the model, due to the available time step of the hydrological data. All the hydrologic processes are modeled within one time step.

Initial and boundary conditions

Boundary conditions refer to the time series of flows at the peripheral cells of the model domain. The external borders of all peripheral cells, except the cell~~s~~ of the Corriente River, were identified and no-flow boundary condition was imposed on them. The boundary condition at the Corriente River was defined in terms of mean historical discharge during the first stage (“filling” of the watershed) and with mean daily discharge series correspond to considered period after the “filling”.

At grid cells where the four hydrometric stations were located, a monthly value was considered for each one and a series was generated with them. The model adjusts a plane to the known altitude at each station, in each time step during six month, using multiple linear regression with the purpose of minimizing the difference between observed and calculated altitude. This plane is then used to estimate the altitude and stage in each pixel.

Calibration

The physical parameter used to calibrate the distributed model is the overland flow roughness coefficient in each cell. Initial values are taken from the literature and the purpose of this first approach, in spite of the limitations and strong simplifications, is to improve the adjustment of the calibration of parameters by incorporating as much available data as possible and to obtain a close agreement between the model output and the historical stage data at Ibera Lagoon. Model calibration aims at the fact that a well calibrated model enhances its predictive capability.

In this moment, the first stage, the "filling" of the watershed is being tested and a preliminary adjustment of the parameters is obtained. Average constant values taken from the balance are being considered as inputs, and average constant discharge is considered as boundary condition. Numerical oscillations occur due to the spatial and temporal scales elected, and hence must be corrected.

In a second stage, with new and more realistic initial conditions and coefficients obtained from the "filling" process, the model will be run with the purpose of adjusting the parameters until the initial water levels in the cells at day one is obtained.

Finally, the simulation will be initialized at day one with real inputs and boundary conditions and the output will be compared with stage in the lagoons.

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