Partner Report -UNIVERSIDAD NACIONAL DEL CENTRO DE LA PROVINCIA DE BUENOS AIRES
Partner 3
Final report (1999-2001)

Scientific Coordinator: Dr. Graciela Ana Canziani

The group at UNCPBA is formed by:
Dr. Graciela Canziani, Professor, Mathematics and Mathematical Ecology,
Ing. Rosana Ferrati, Engineer in Water Resources and Graduate student in Mathematics,
Lic. Paula Federico, Graduate student in Mathematics,
Diego Ruiz Moreno, advanced student in Computer and Systems Engineering (joined this group in November, 1999),
Florencia Castets, Photographer and Graphics Processing technician (joined in January 2001),
Lic. Anibal Aubone, Graduate student in Mathematics (joined in May, 2001),
Ing. María del Carmen Romero, Graduate Teaching Assistant in Computer and Systems Engineering (joined in July, 2001).

And also by other Faculty members who have devoted part of their research time collaborating in the project:
M.Sc. M.V. Fernando Milano, Professor, Natural Resources and Sustainability, Facultad de Ciencias Veterinarias,
Dr. Marcelo Gandini, Professor, Ecology, Remote Sensors, Facultad de Agronomía,
Dr. Roberto Sanchez, Professor, Environmental Management, Facultad de Ciencias Humanas.

Professors Canziani, Milano and Sanchez, together with other researchers of the University, have presented a proposal for the creation of an interdisciplinary research group on Sustainability and Ecosystems, which is under study by the authorities. Hence, Dr. Canziani and her group do not participate in NUCOMPA´s activities since April, 2000..

As stated this group participates in the development of several different tools and models to be used by other project partners:

i. GIS to organize in systematic form data provided by previous and present studies on the region

ii. Hydrological models

iii. Dynamic vegetation maps

iv. Population models for several species of macrovertebrates that are particularly important relative to the management of resources.

STUDY DESIGN

Description of area

The freshwater wetland ecosystem under study is that of the Esteros del Ibera, in the Province of Corrientes, in NE Argentina. The region is located between latitudes 27°30' and 29° S, and longitudes 56° 25' and 58° W.

Wetlands are broadly defined as a variety of shallow water bodies and high ground water environments that are characterized by permanent or temporary inundation or, in other words, a terrestrial ecosystem which hydraulic condition is that of water saturated soils with plants and animals adapted to life in such an environment (Lewis, W.M., 1995). From a hydrological point of view, the Ibera wetland is located in the Del Plata Basin, which covers some 3.5 million square kilometers within five countries of South America: Brazil, Paraguay, Bolivia, Uruguay and Argentina. The main watercourses are the Parana, Paraguay, Pilcomayo, Bermejo, and Uruguay rivers. Many hydroelectric dams have been built along these rivers, being the Parana River the one with the largest numbers of dams, basically due to its 4,000 Km. and an average flow of 19,000 $m^3 s^{-1}$. The climatic and geomorphologic features of this basin are ideal for the formation of large inland wetlands, among which can be found the Pantanal in Brazil, Ñeembucu in Paraguay and the Esteros del Ibera in Argentina

The Ibera wetland region in Argentina is one of the largest and last remaining wetland regions of its kind in Latin America. It is mainly known for its remoteness and isolation, and for the presence of several unique animal species. An extensive study of the Ibera macrosystem was carried on during the seventies by Instituto Nacional de Ciencias y Tecnicas Hidricas (INCyTH) and Instituto Correntino del Agua (ICA) and was published in 1981.

Morphology

The Ibera is a great depression located over ancient beds of the Parana River. The system rests on top of more than fifty meters of permeable sediments, mainly deposited fluvial sand taking the form of a pool of superficial storage of pluvial water. These sediments rest over a bed of basalt. The ancient islands emerge as longitudinal hills or *"lomadas"* with a physiognomy of savanna. An outstanding longitudinal hill separates Ibera into to subsystems of distinct dynamical characteristics. The system shows a diversity of deposited materials, removed and deposited again by complex physical and chemical factors that changed both spatially and temporally. In general, sandy materials are dominant at the bottom of extended bodies of water and as elongated elevations. These sandy materials develop over an average depth of 50m and belong to the Ituzaingo formation that rests over the impermeable formation of Fray Bentos.

The catchment area has been estimated in 13,700 Km^2. It has a triangular shape some 250 Km long and between 20 and 140 Km wide. Roads and human settlements are to be found only on the surrounding areas, not within the wetlands. The isolation and the inaccessibility of the region have, up to now, helped its preservation.

Nowadays, 90% of its area is covered by permanent or temporary floods, depending on the balance of atmospheric input and output, the surface runoff, the underground water balance, as well as on the previous storage level. The weedlands (*malezal*) and marshlands (*esteros*) cover some 80% of the water surface. The deeper wetlands are for the most part covered by aquatic vegetation forming characteristic "*embalsados*" or dammedlands–floating vegetation islands as much as 4m. thick (Neiff, 1981).

The Eastern subsystem is characterized by a sheet-flow dynamics and a deeper topographic profile. 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 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 Ibera from the Batel-Batelito system to the West, permit the transfer of groundwater between the systems. At surface level, both hills hold pseudokarstic lagoons (INCyTH-ICA, 1981a).

The Ibera system is a great "natural reservoir" in which the only superficial input is precipitation. The main output is given both by evaporation and evapotranspiration, and by the superficial discharge through the Corriente River, at the Southern limits of the system. The long response delay of the system is due to its morphology, the soil types, and the presence of vegetation that conditions the flow. The water flows very slowly over a general slope of 1:10,000, from de NE to the SW. In general terms, as a consequence of the strong relationship between morphological, hydrological, climatic, and pedological (edafological) factors, the macrosystem may have a regulatory mechanism that corresponds to an ultrastabilized system that has a long response time and a tendency to reach a dynamic equilibrium with the environment (INCyTH-ICA, 1981a).

Vegetation

The behavior of the system is strongly conditioned by vegetation. The lagoons and the permanent channels are the only free water areas. The main lagoons have been measured and studied since 1910, as reflected in remarkable reports published in the Annals of the Sociedad Cientifica Argentina (1910-1914). Their boundaries have not changed substantially with time, even though the variations in water levels have been important. The reason for them remaining unchanged may be given by the fact that the borders are dammedlands (*embalsados*) rather than firm soil.

The dammedlands are formed by accumulation of interweaving aquatic plants that create floating platforms strong enough as to allow the growth of other plants and trees over them. These floating islands are generally 1 to 3 m. thick and can go up or down with the fluctuations of water level. They are the ideal habitat for birds and for large vertebrates, which have adapted to live on them, such as capybara (*Hydrochaeris hydrochaeris*), black caiman (*Caiman yacare*) and marsh deer (*Blastocerus dichotomus*). The relationship between the geomorphology and the dammedlands, and the reasons for floating vegetation not invading the lagoons and natural channels are not well understood yet.

Observed changes

This special system has recently suffered an important change in the average water level that is affecting the native populations of plants and animals, as well as the neighboring human activities. The hydrometric scale located in the Ibera Lagoon is the only station located inside the borders of the system that has been measuring water levels since its installation in 1968. The records show a very important and rapid increase in water levels over the period of few months between 1989 and 1990. These levels have been maintained until today, bringing the relative mean level from 1.24 m (62.29m a.s.l.) over the period 1970-1988, to 2.06 m (63.11m a.s.l.) over the period 1991-2000, as shown in Figure 43. Considering the topography and the characteristics of the system, such a change in the average water levels (0.82m) can be translated into a total increase in storage within the system of approximately 11,000 hm^3.

The observable consequences of this increase are significant loses in productive lands located besides the Western and Northern borders of the system. Within the system, there is an increase in the flux and the dragging of sediments, as well as changes in vegetation dynamics and habitat quality. It is difficult to assess the degrees of impact that these changes on environmental conditions may have on the persistence of native species, both plants and animals. On the one hand, the Ibera system has been able to maintain its equilibrium through hydro-biological regulation mechanisms favored by the hydraulic characteristics of the “*embalsados*” and the morphology of the submersed soils. On the other hand, geosystems such as the Ibera show a long response delay. Both features put together allow us to assume that the consequences of this sharp increase in water levels are not yet fully manifested by the ecosystem.

As a matter of fact, the Del Plata Basin, as a whole, has suffered changes due to both natural and anthropic processes. The natural causes for changes in the basin have been studied at basin level. Global climatic change since 1970 and the addition of climate variability, namely El Niño Southern Oscillation (ENSO) events have been considered as the main culprits. The consequences are the increase of rainfall and runoff, leading to a water excess in the area. The IPCC (1997) reports on these changes. It is generally agreed that the stage and extent of large reservoirs and lakes may serve as useful indicators of climate change, as they have a tendency to filter out short-term variability and respond to long-term change in the hydrological cycle (Kelly et al., 1994). In the case of the Esteros del Ibera, given the vastness and inaccessibility of the region, it seems very natural to turn to remote sensing as a tool for detection of changes. Nevertheless, it is difficult to use satellite images in a direct way for the determination of monthly or seasonal variations between flooded versus dry areas within the system because of particular characteristics of this system.

The anthropic changes introduced into the system are mainly the construction of more than forty dams on the rivers making the Del Plata Basin. Only a few Km. North of the Esteros del Ibera system, and separated by a thin saddle (*albardon*) of sand and clay sediments, sits the Yacyreta dam, on the Parana River.

There is a growing scientific agreement that environmental issues are closely interlinked, meaning that the development of any ecosystem requires an integrated approach, very particularly when aiming at its sustainability. Since climate a crucial factor in biodiversity issues, therefore, the sustainable management of wetlands can no longer be achieved without taking climate change into account. Increasing temperatures and changes in precipitation, and evapotranspiration are the main variables of climate change that will affect wetland distribution and function (Bergkamp & Orlando, 2000).

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TERRAIN ANALYSIS

One main objective was to develop several Hydrological Models to serve as a base for other modeling. All of these models require information about the watershed. Hence, all the available information that could be useful to the definition of the watershed of the Ibera system was compiled.

Topographic Map

One main source of information were cartographic maps of the "*Esteros del Iberá*" developed by the Military Geographic Institute (*IGM, Instituto Geográfico Militar*). Nineteen maps in the scale 1:100000 were required to cover the study area. The main information retrieved from the maps were the **Level Curves (LC)**. We decided to use the LC in order to define the limits of the watershed by using a Geographic Information System (GIS). Hence, our first step was to digitalize the LC and use the GIS functions to define the watershed.

During this process it was discovered that the LC in the maps were insufficient. In some places information, such as bathymetric data, (*Fig. 1*), was missing, and in others the LC presented some discontinuities (*Fig. 2*). As a way to solve the lack of information, we tried to complete the maps with data retrieved from other documents. We recovered data from phitogeographic maps, from soil maps developed by INTA (Instituto Nacional de Tecnología Agropecuaria), from geomorphological studies and flux analysis maps (Estudio del Macrosistema Iberá–ICA-1981), These were added to remote sensing data and the information provided by the bathymetric studies made by Laboratorio di Idrobiologia di Roma (*Fig. 3*). The results allowed us to infer the Topography in the areas where the topographic maps are incomplete. All the information was drawn by hand into a unique topographic map (*Fig. 4*). It is necessary to remark that this output could be further improved with more detailed studies in situ.

The complete topographic map was scanned and afterwards all the LC were digitalized. The digitalization process involves redrawing all the LC using

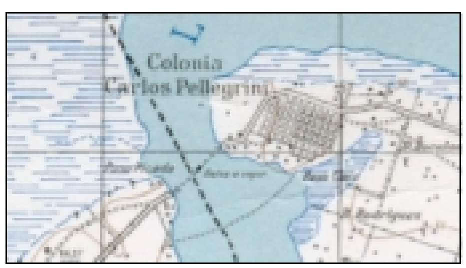


Figure 1. Sample of topographic map without bathymetric information

Figure 2. Sample of discontinuities in topographic maps

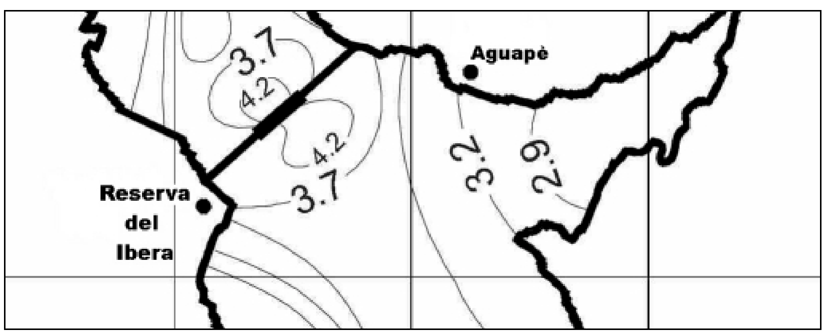


Figure 3. Sample of bathymetry performed by LabRoma.

an appropriate software tool. Each curve was assigned an identity number (related we the altitude a.s.l.), and all the LC were stored in a vector file format (DXF). The time of processing all the curves was considerable due to there are almost 13000 segments (*Fig 5 & 6*).

In order to incorporate the LC into the GIS it was necessary to georeference the file produced. As a first step, colleagues allowed us access to software that performed this process. Once we tested the performance, we begun to discuss which software to acquire. We exchanged experiences with UNISI, CONAE (Comisión Nacional de Actividades Espaciales), and colleagues from Geographic Research Centre (CIG, Centro de Investigaciones Geograficas) at our

University. Since UNISI and CONAE were using ERDAS software packages, CIG colleagues strongly recommended it, and because of the need for compatibility between partners, we decided acquire ERDAS 8.4 which, in Argentina, is packaged together with ARC-VIEW 3.1.

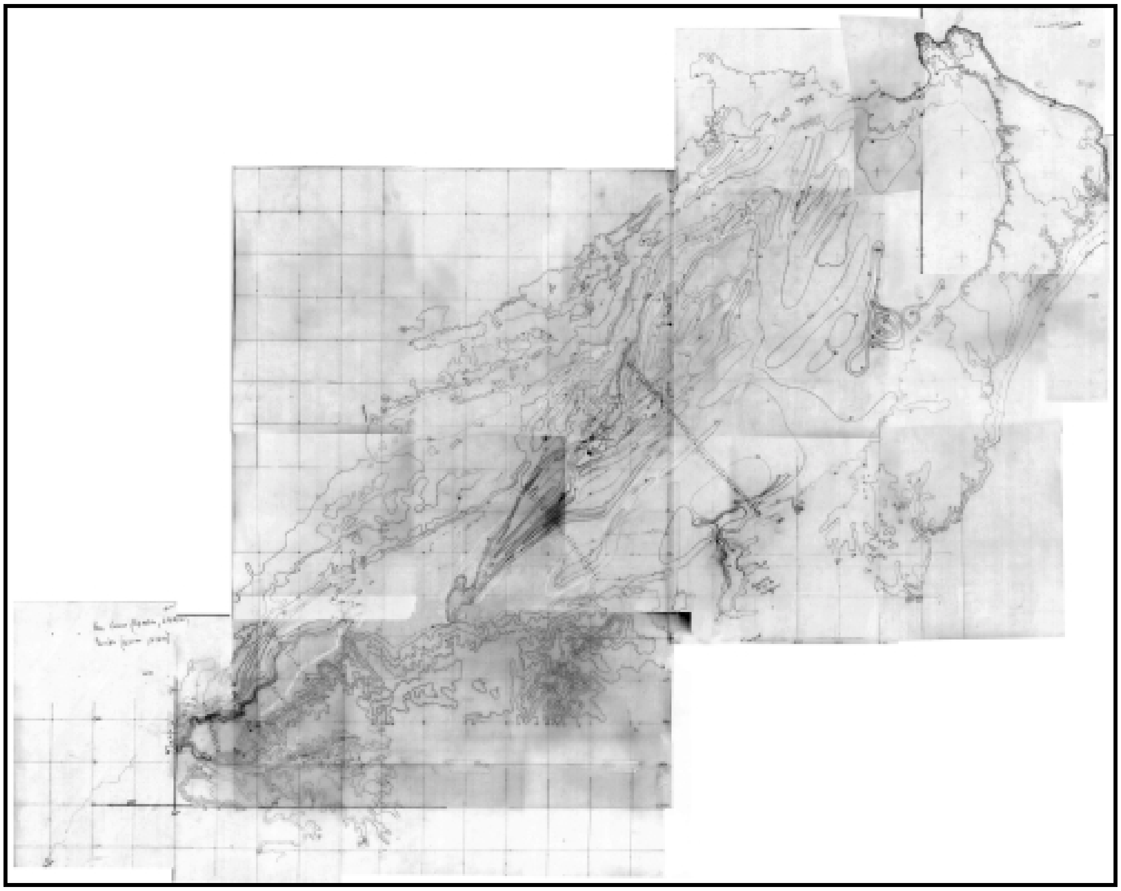


Figure 4. Hand-drawn topographic map with compiled information

At this point, the DXF file produced was imported to the GIS and georeferenced. The process of assigning coordinates in any system to a vector or image file, is known as **registration**. In Argentina all geographical information is expressed in the Gauss-Krüger Coordinate System. Hence, it was decided to use this same coordinate system. Vector and Image registration requires that a set of

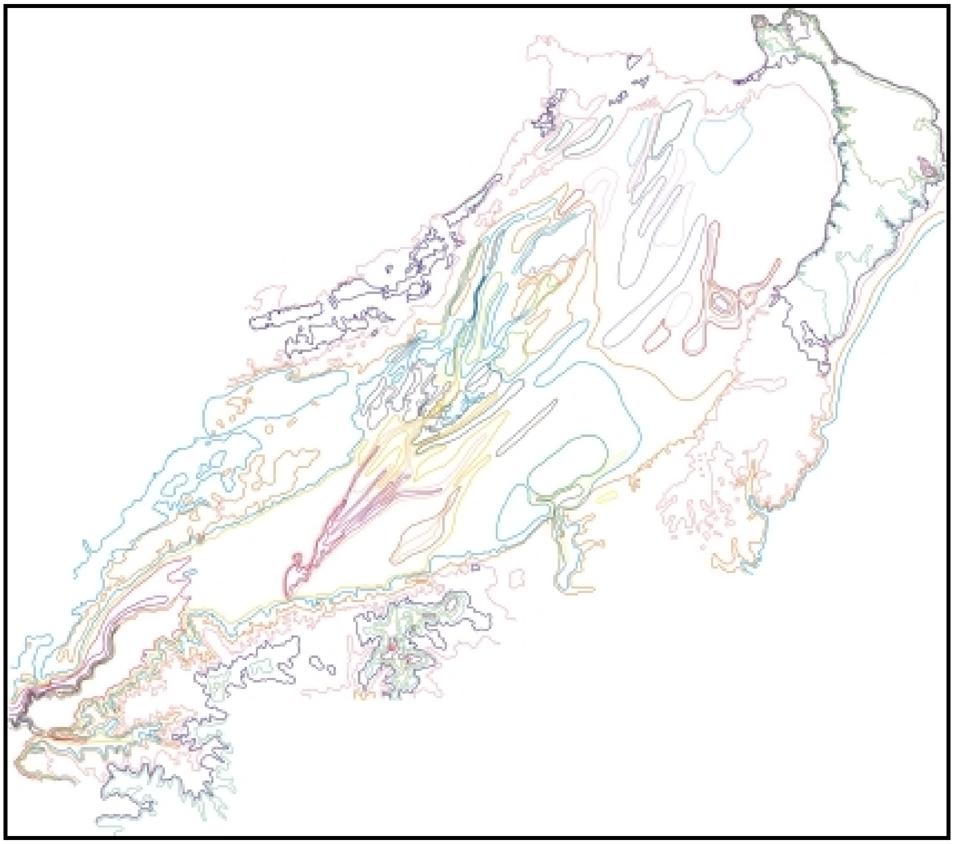


Figure 5. Digitalized topographic map.

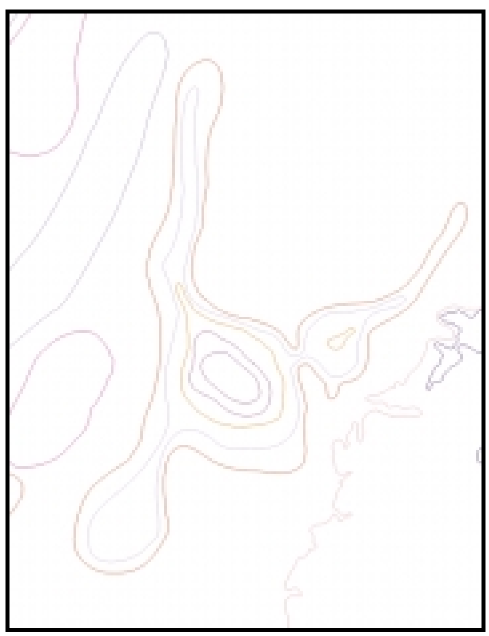


Figure 6. Detail of digitalized level curves.

Ground Control Points (GCP) are marked and map coordinates entered manually for each point. Once enough points have been picked, the definitionof a warp polynomial requires the execution of the **Warping** and **Resampling** processes. The warping process selected is known as RST (Rotation, Scaling and Translation). This is the simplest method and it is particularly efficient with flat coordinates. Due to the fact that the vector file is a flat map, we used a linear warp polynomial. The resampling process selected is know as Cubic Convolution. Cubic convolution to resample the vector or image file uses 16 pixels to approximate the sine function with cubic polynomials. Note that cubic convolution resampling is significantly slower than other methods. After all these processes a georeferenced vector file containing all the Level Curves was obtained.

Digital Elevation Model

A Digital Elevation Model (DEM) is an image file that records the corresponding altitude in each pixel of the map. To build a DEM from a set of LC it is necessary to perform a bidimensional interpolation.

The first step is transforming the previous vector file into an image file, a process known as **rasterizing**. It was decided to start with an image (or map sheet) with a spatial resolution of about 100 meters per cell size and rasterize the LC into it. It is particularly important that contours (vector lines) intersect the edge of the map sheet exactly, because the algorithm ignores all the lines that fall outside the image area. Any pixel not containing a curve segment was assigned a zero value. In addition, it was necessary to estimate manually the altitudes of the four corners of the study area based on the contours. After this was accomplished, the interpolation process was performed. The interpolation process requires a total of six passes over the image following different directions.

Later, the created DEM is resampled in order to obtain a DEM with a spatial resolution of 180 meters (*Fig. 7*). This is required for a later overlapping with SAC-C satellite images. After interpolation was finished, it became indispensable to run several times a mean filter operation in order to remove some of the angularities of the linear interpolation (*Fig. 8*).

With the newly created DEM we develop an **Aspect** image. In an aspect image we can see the direction in which a slope runs. This is determined as the direction facing downhill at the line of steepest descent (*Fig 9*).

Once the Aspect image was developed, the Corriente river was marked as an output point of the region (at coordinates X=6350000 and Y=6794840 in the Gauss-Krüger reference system, or –58° 32’ 19.9742” Longitude and –28° 58’ 27.6618” Latitude). At this point it was possible to run the watershed definition process. The watershed definition process returns a binary image where 0 values are sites located out of the watershed, and 1 values are pixels contained in the watershed (*Fig. 10*). This process combs the region following the slope faces, and for this reason it is very important to run a mean filter operation previously. Otherwise the process can suffer an unwelcome interruption.

After the watershed process was finished, the GIS internal functions could create a vector file that delimits the watershed image obtained (*Fig. 11*).

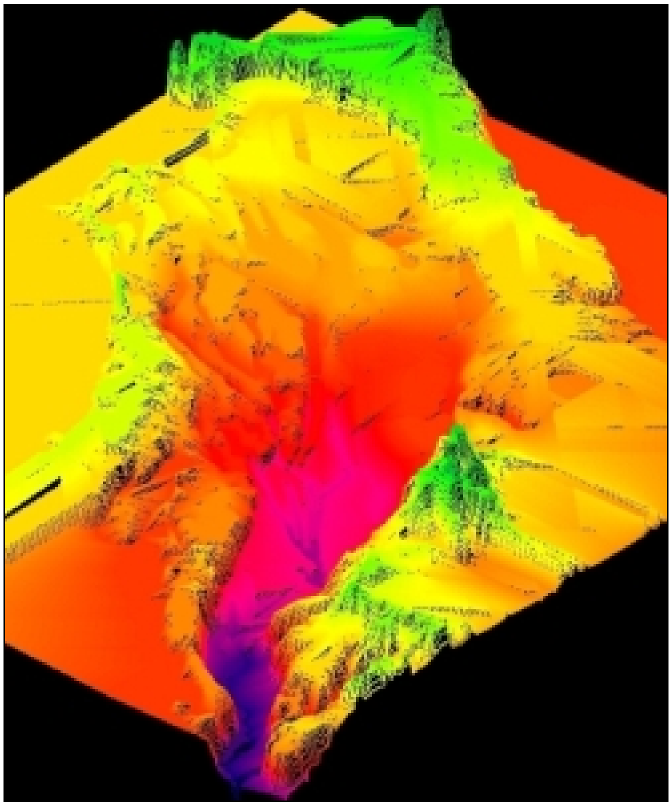


Figure 7. Initial Digital Elevation Model (DEM)

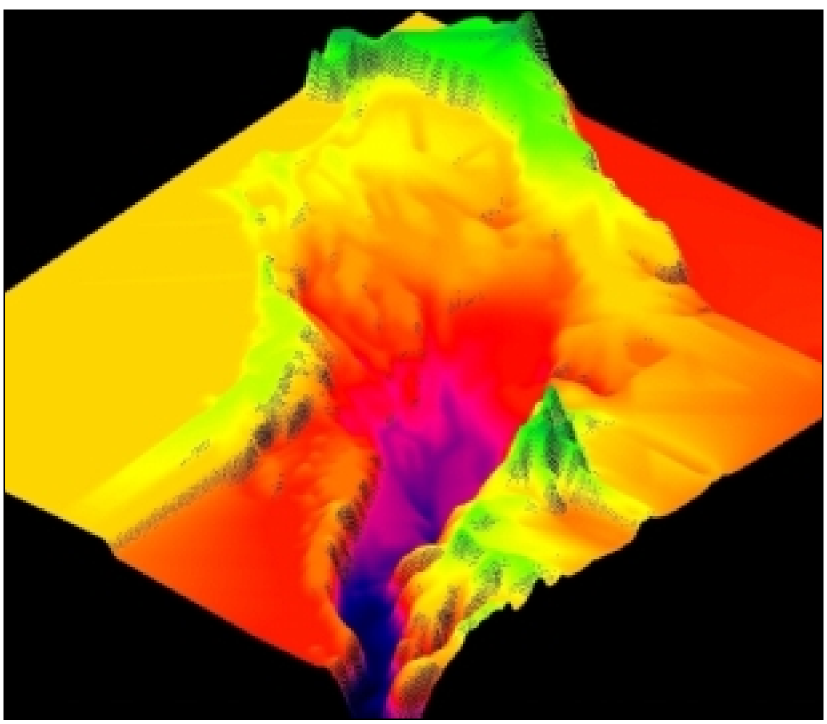


Figure 8. Smoothed Digital Elevation Model (DEM)

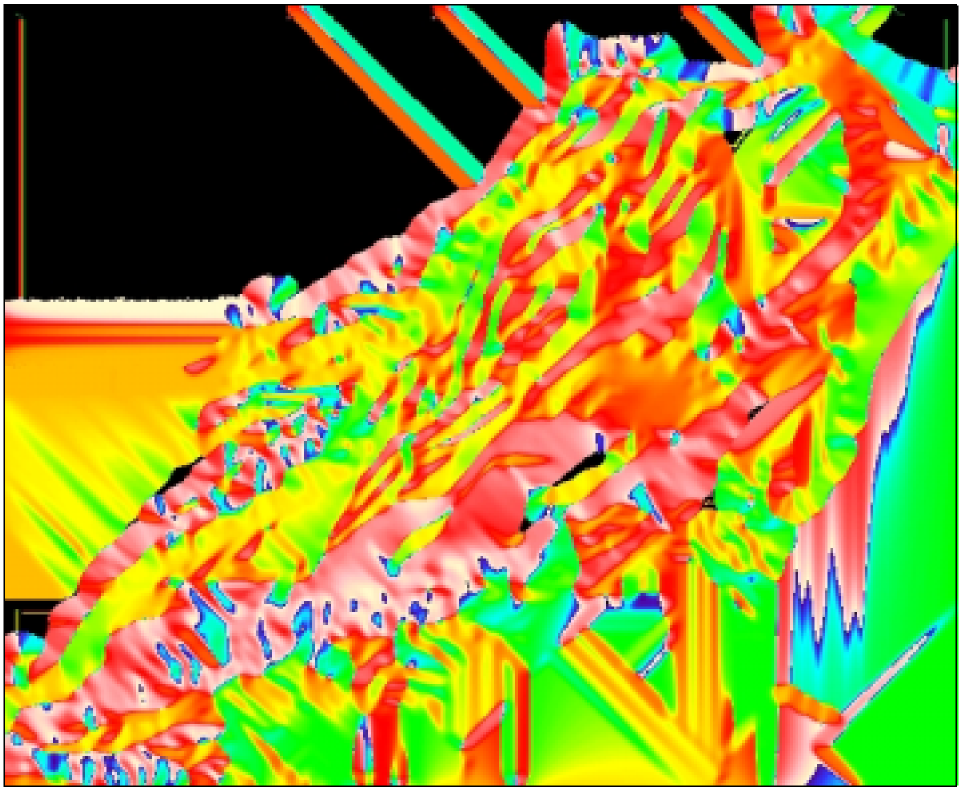


Figure 9. Aspect image (steepest descent) of the Digital Elevation Model

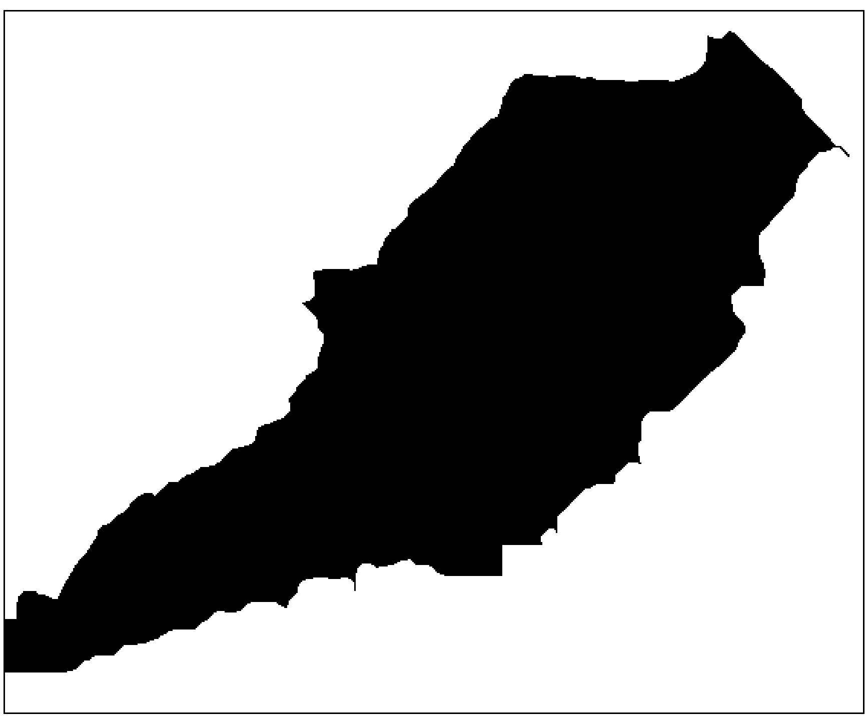


Figure 10. Definition of the watershed using the Aspect image.

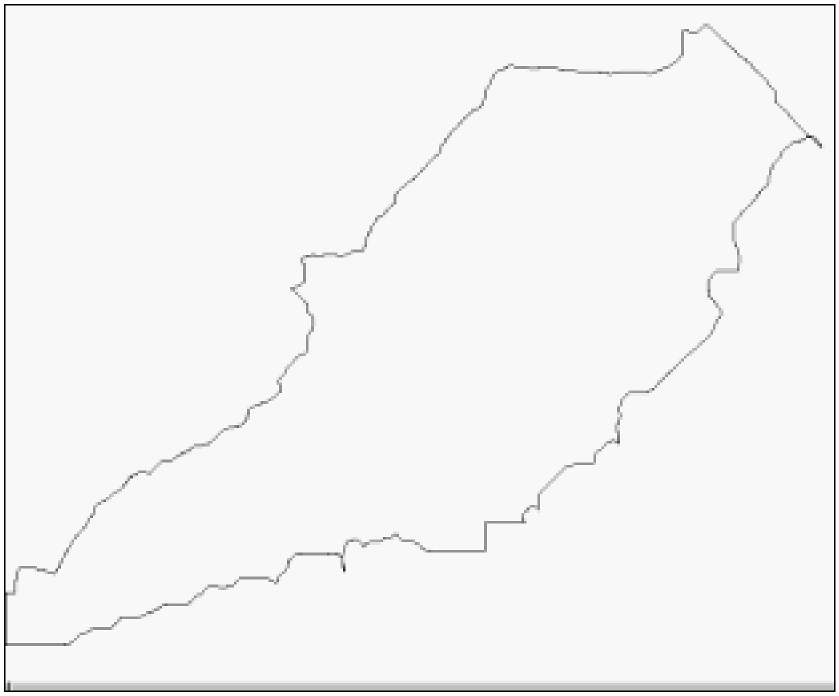


Figure 11. Vector file of watershed borders.

Satelital Images

Since this Project was approved to be part of the SAC-C Mission, CONAE provided us with all necessary satelital images. Because of the SAC-C launching was delayed until November 18, 2000, we received LANDSAT 5 images instead. Some LANDSAT 5 images were preprocessed at CONAE making their resolution similar to that of SAC-C images. A "*historical*" LANDSAT 5 mosaic image composed by different images from several dates between June and July 1986 was also provided.

The registration process applied to the Level Curves vector file was also applied to all the satelital images received from CONAE. Once the file is displayed, image registration requires that a set of Ground Control Points (GCP) be marked and map coordinates be entered manually for each point. Once enough points have been picked, it is necessary to define a warp polynomial in order to execute the Warping and Resampling processes.

During the resampling process for LANDSAT 5 images, it was necessary to redefine the spatial resolution. Originally, LANDSAT 5 images have a spatial resolution of 30 meters, but in order to use them together with the SAC-C images, the spatial resolution of LANDSAT 5 was reduced to 180 meters (*Fig. 12*).

In the case of images, the GCP were selected from both satelital images and topographic maps. It was necessary to chose points, such as roads intersections, that are easily detected in the images and, moreover, which coordinates are easy to retrieve from the maps. In some cases, it became convenient to display the image using a False Color combination that enhanced the contrast of the GPC searched. Due to variations in contrast between images,

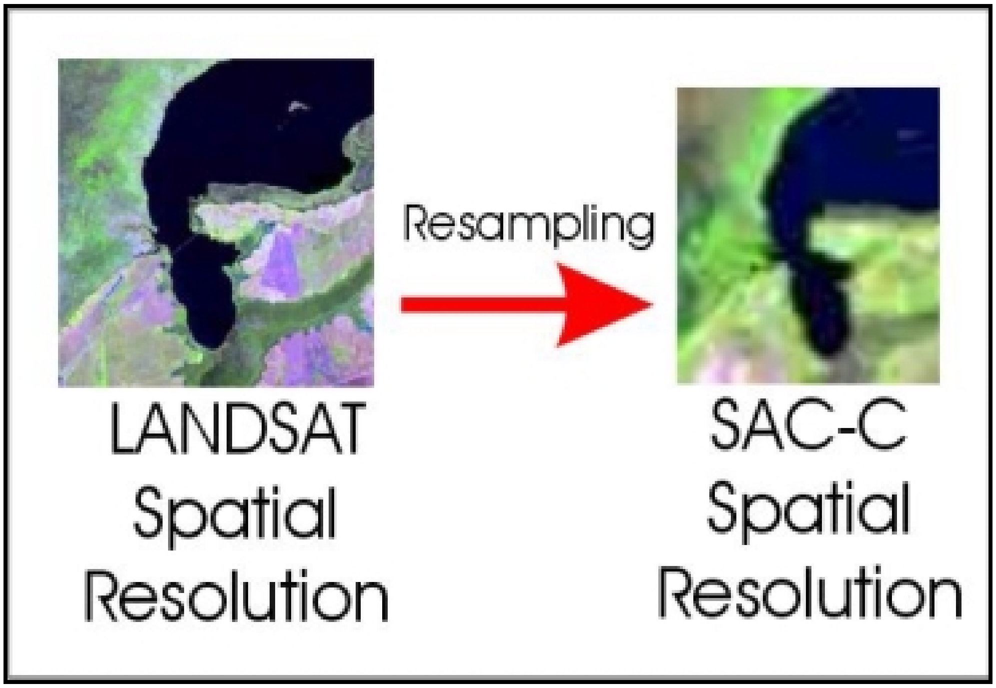


Figure 12. Comparison of resolutions between LANDSAT and SAC-C images.

different GCP were taken for different images. Both processes (the localization in the image and the localization in the map) incorporate measurement errors. In order to quantify these errors, a vector file was created containing the Iberá Lagoon for each georeferenced image. With an overlay comparison process, it was possible to assess that files differ in three pixels at most. The warping process selected was RST, and the resampling process selected was Cubic Convolution.

Georeferenced Image Files

After these processes, the georreferenced image files were obtained. Once the georreferenced images were ready, it was possible to merge the images form different Paths and Rows, creating “mosaic” images of the whole region of study.

At this point the watershed and the images had been georreferenced. Hence it was possible to use the GIS function to overlay the watershed boundaries into the satelital images (*Fig. 13 & 14*).

Classification

There are numerous methods available for enhancing spectral information content of LANDSAT data. In fact, many enhancements are specifically designed to feature vegetation, such as NDVI, DVI, Tassel Cap, etc.

The goals of the utilization of satelital images in this project were:

- To develop some kind of index to evaluate Habitat Quality that could be incorporated into the species population models.

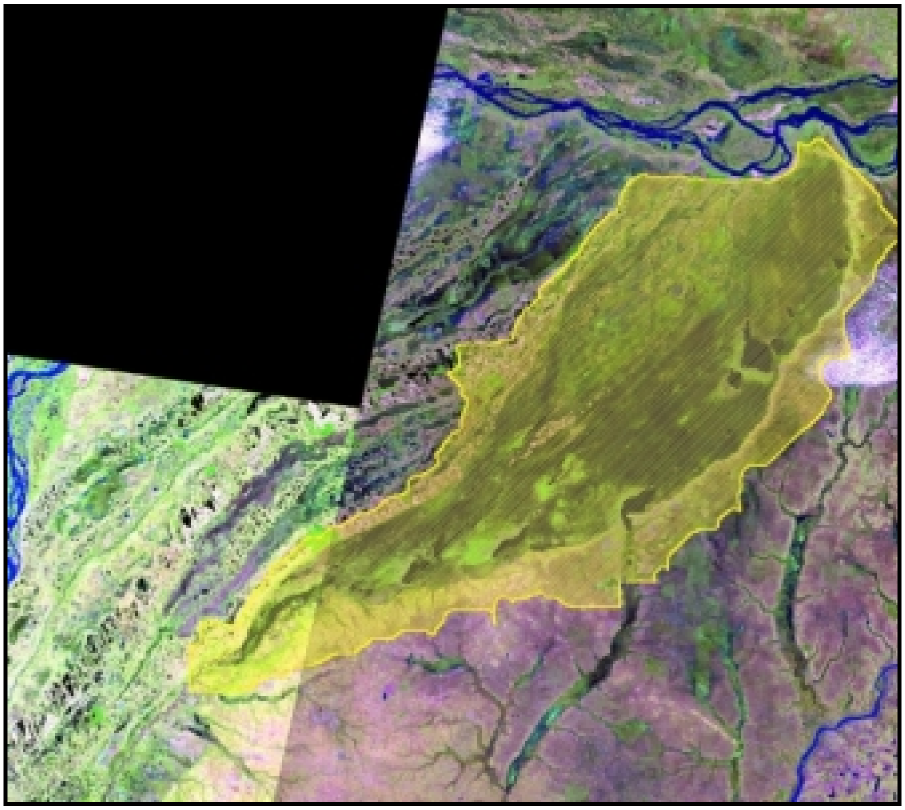


Figure 13. Watershed overlapped on a LANDSAT 5 image from 1986.

- To develop some kind of index to evaluate the vegetation roughness parameters that conditions the surface flow in the Hydrological Models.

The **Tasseled Cap (TC)** transformation was originally designed for LANDSAT TM images. The TC indices relate six TM bands (1-5 & 7) to measures of vegetation (greenness), soil (brightness) and the interrelationship of soil and canopy moisture. Each index corresponds to a linear transformation of six TM bands using a set of empirically derived coefficients. Afterwards, the information present in the 6 original bands is compressed into 3 TC transform bands.

In order to develop some kind of index for habitat quality following the philosophy of HEP (Habitat Evaluation Procedures) the variables under consideration are vegetation, water (or distance to water bodies), and some evaluation about the usefulness of the terrain (protection, etc). TC was especially interesting because it allows to extract almost all the information needed to define HEP indexes from satelital images.

The original TC transformation can only be applied to LANDSAT images. It can not to be applied to SAC-C images due to the absence of the 7th TM band. For this reason we use the **Modified Tasseled Cap (MTC)** transformation, developed by our colleagues at UNISI, that can be used with the five SAC-C bands. Hence it was possible to apply the MTC transformation to all

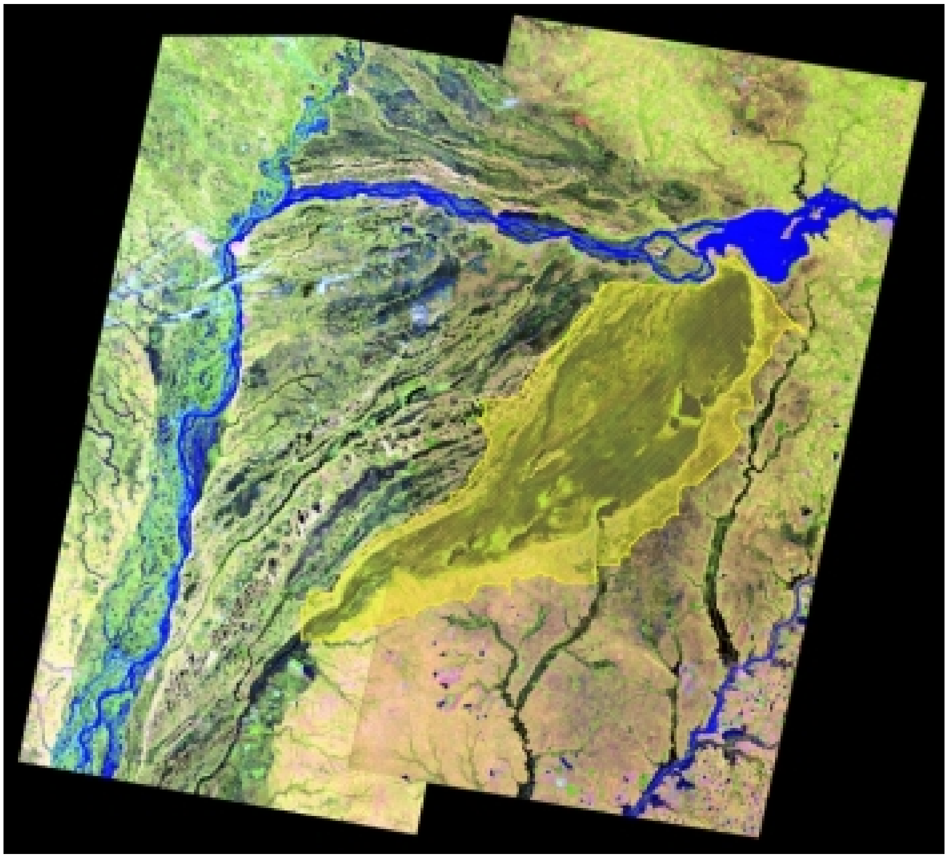


Figure 14. (Watershed & LANDSAT from 1998)

the available images, as the example shows *(Figs. 15 (brightness), 16 (greenness) & 17 (wetness))*.

When the MTC transformations are combined using Brigthness band as red, Greenness band as green and Wetness band as blue, a so called **Synthetic Map** (*Fig. 18*) is obtained. This kind of maps can be used as a base for an unsupervised classification, due to the amount of information they contain.

At this point, it is clear that the information contained in the synthetic maps exceeds the boundaries of the Esteros. The information beyond the watershed is not needed because its variability could incorporate noise in our future use of these maps. In order to eliminate those extra-watershed pixels we used a binary image of the watershed overlapping the synthetic maps in order to remove the unwanted sectors (*Fig. 19*).

Habitat Quality Index and Vegetation Roughness

However, the information present in the cut-out-synthetic maps is still too detailed. One way to reduce the amount of information is through **a multispectral classification process**. A multispectral classification is a process that organizes pixels onto a finite number of classes or data categories, based on the data value of each pixel. One pixel is assigned to a given class when a set of criteria is verified.

Figure 15. Modified Tasselled Cap transformation: brightness index.

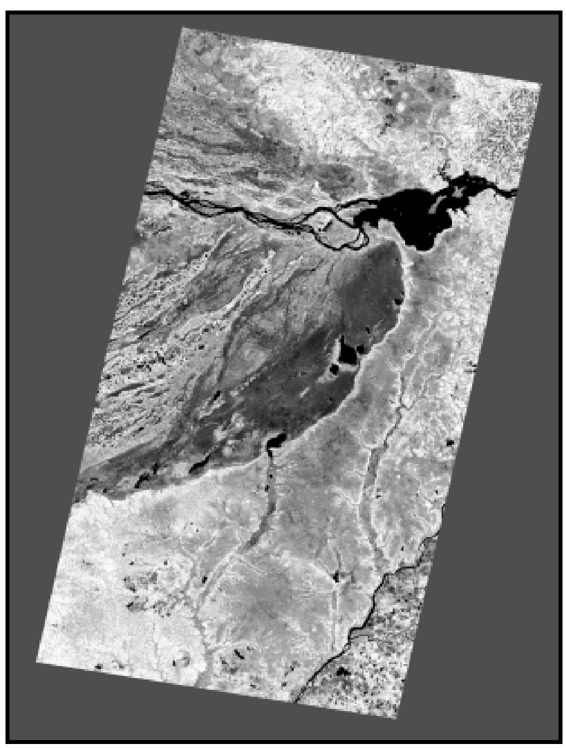


Figure 16. Modified Tasselled Cap transformation: greenness index.

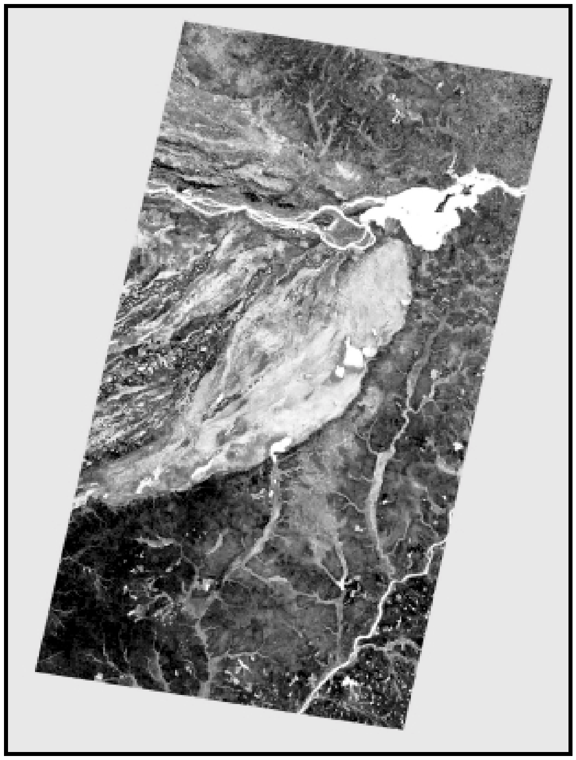


Figure 17. Modified Tasselled Cap transformation: wetness index.

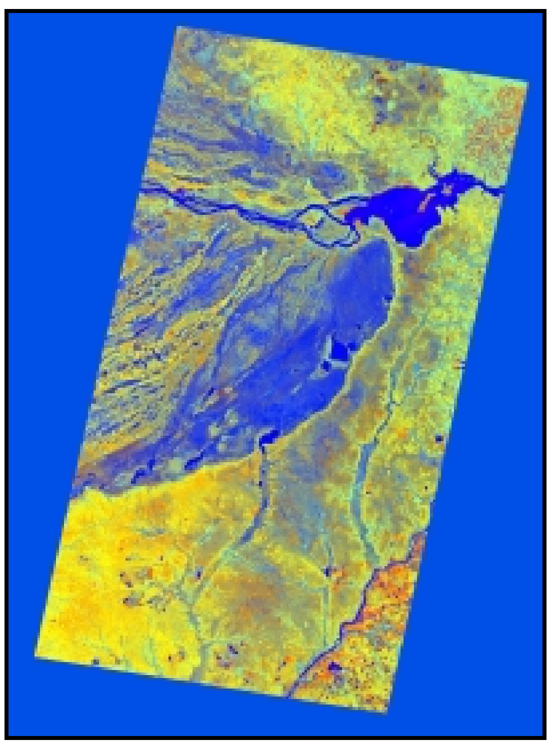


Figure 18. MTC transformations combined into a Synthetic Map.

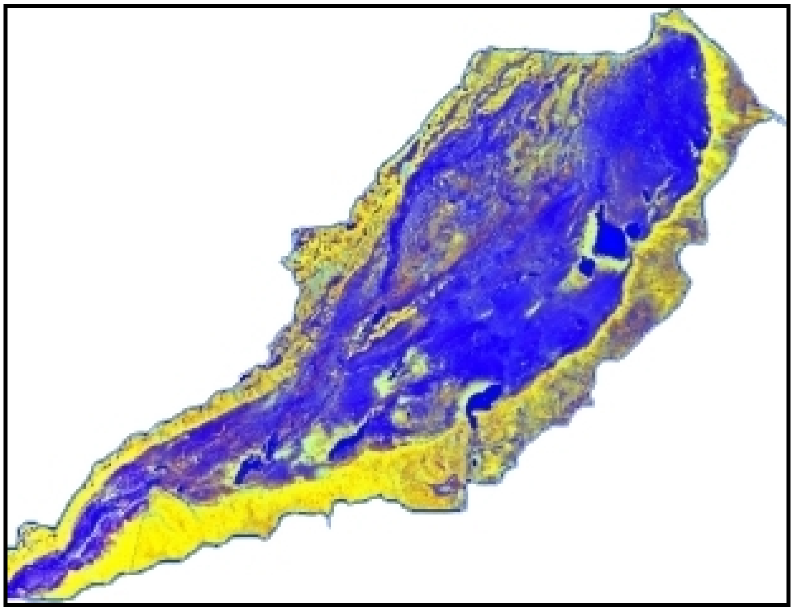


Figure 19. Synthetic Map of the Ibera Watershed.

Classification process is divided in two groups: **supervised** and **unsupervised classification**. A supervised classification process needs a description (kwon as Spectral Signatures) of some key spots in the image. An unsupervised classification does not need any information about the field. It was decided to run an unsupervised classification process due to the lack of sufficient field data to develop particular signatures.

Unsupervised classification is also known as **Clustering** because it is based in the natural clustering of pixels in the images. One clustering technique known as **ISODATA clustering** (**Iterative Self-Organizing Data Analysis Technique clustering**) was selected to make the unsupervised classification of all the images of the Iberá watershed. The classification of **MTC images** was done choosing **10-Classes images** (*Fig. 20*). The 10-Classes images must be evaluated later, before using them in any model. Also, a false color definition was used so that the classes could be differentiated easily (*Fig. 21*).

One of the objectives was to develop some kind of index appropriate for evaluating **Habitat Quality** that could be incorporated into the species models. For each one of the 10 classes, the information that corresponds to Brightness, Greenness, and Wetness can be recovered, so that by combining this information with given species preferences, it is possible to assign an index of Habitat Quality to each class.

Another objective was to develop some kind of index to evaluate the **vegetation roughness parameters** that conditions the surface flow in the Hydrological Modelling. First of all, we separate the inner watershed from the images (*Fig. 22*). The inner watershed was defined from wetness index (from MTC) taking into account a threshold value that represent areas with permanent water. The inner watershed map was classified with ISODATA clustering technique obtaining 8 classes of terrain with different roughness (*Fig. 23*).

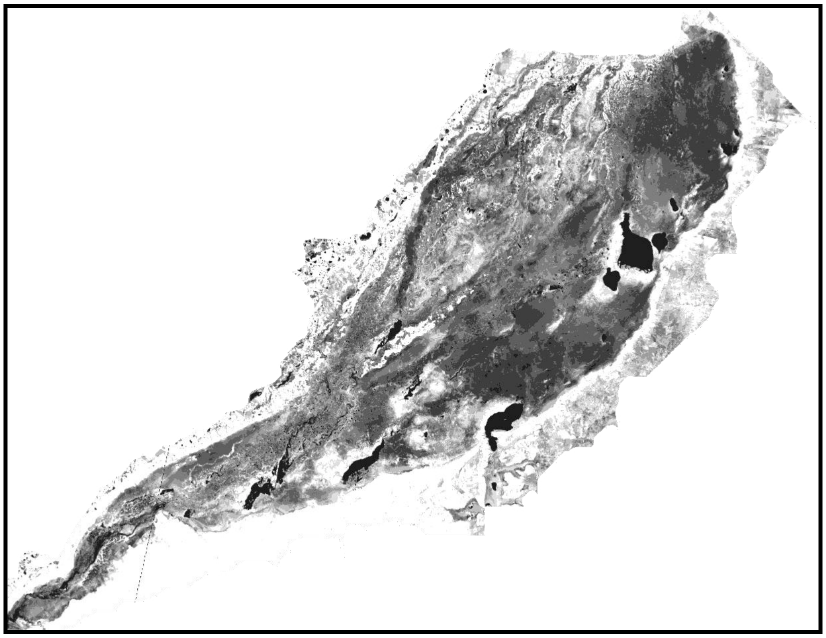


Figure 20. Synthetic map (MTC) classified into 10-Classes

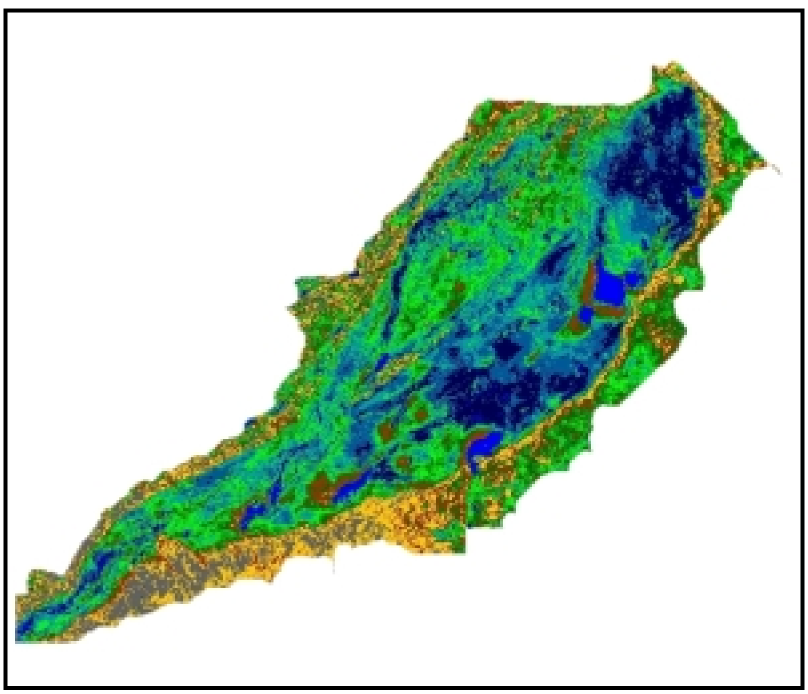


Figure 21. Classified synthetic map shown in false colors.

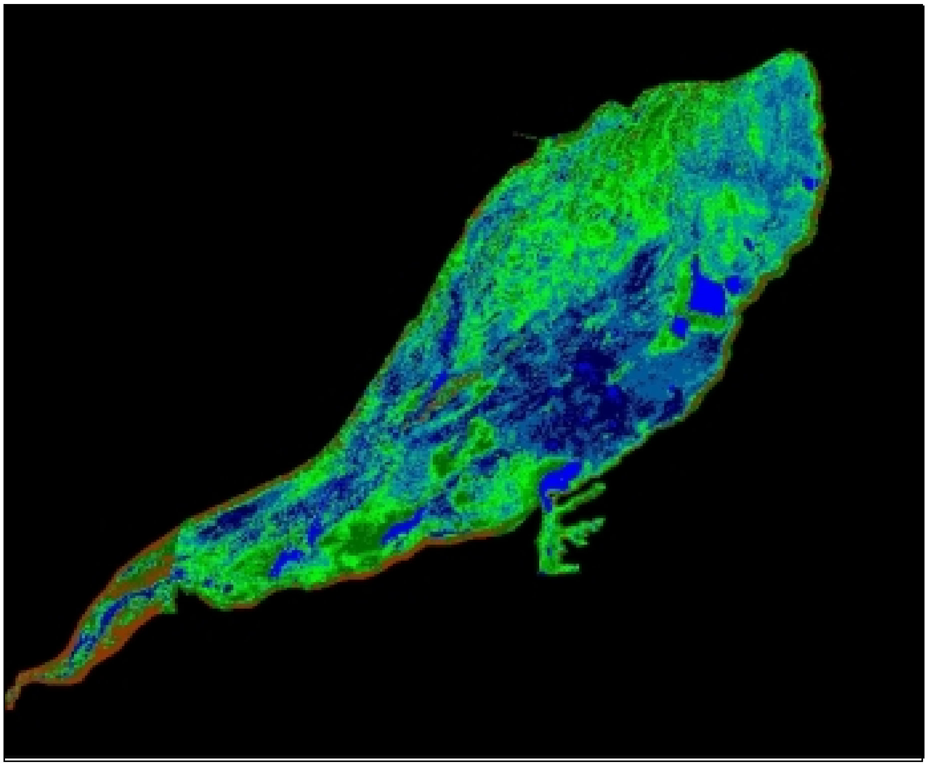


Figure 22. Classified Inner Watershed.

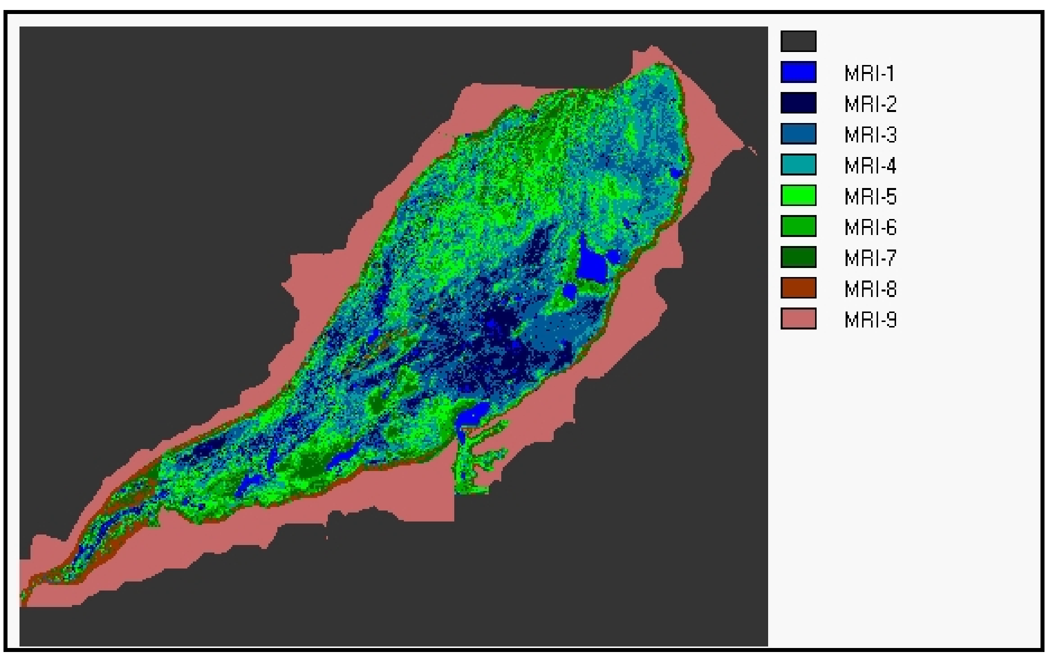


Fig. 23 Manning Roughness Index (used to define vegetation roughness parameters)

Uses of Classified Maps

At this point it is possible to select any region in the "*Esteros*" and create a series of classified synthetic maps that permit to study the dynamics of the habitat quality for any given species, or to analyze the variations in vegetation dynamically (*Fig. 24 & 25*).

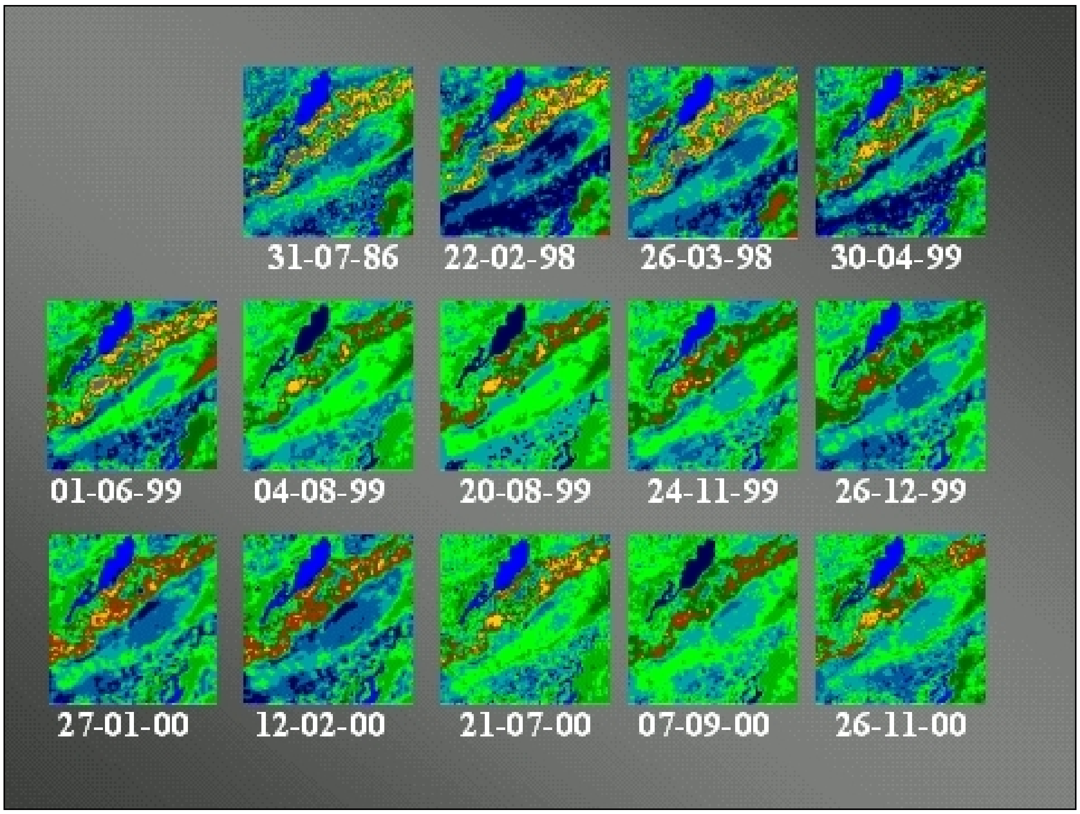


Figure 24. Dynamics of Habitat conditions near Parana Lagoon.

Also, it is possible to filter the classified images and isolate some particular class, i.e. "class-water". The "class-water" can be obtained from images by selecting the classes belong to the set of the water-covered classes. Using the appropriate GIS function, it is possible to create maps that show the distance to water bodies or **Water Distance Maps** (*Fig. 26 & 27*), that can be useful for evaluating habitat quality for some of the species that inhabit the "*Esteros*".

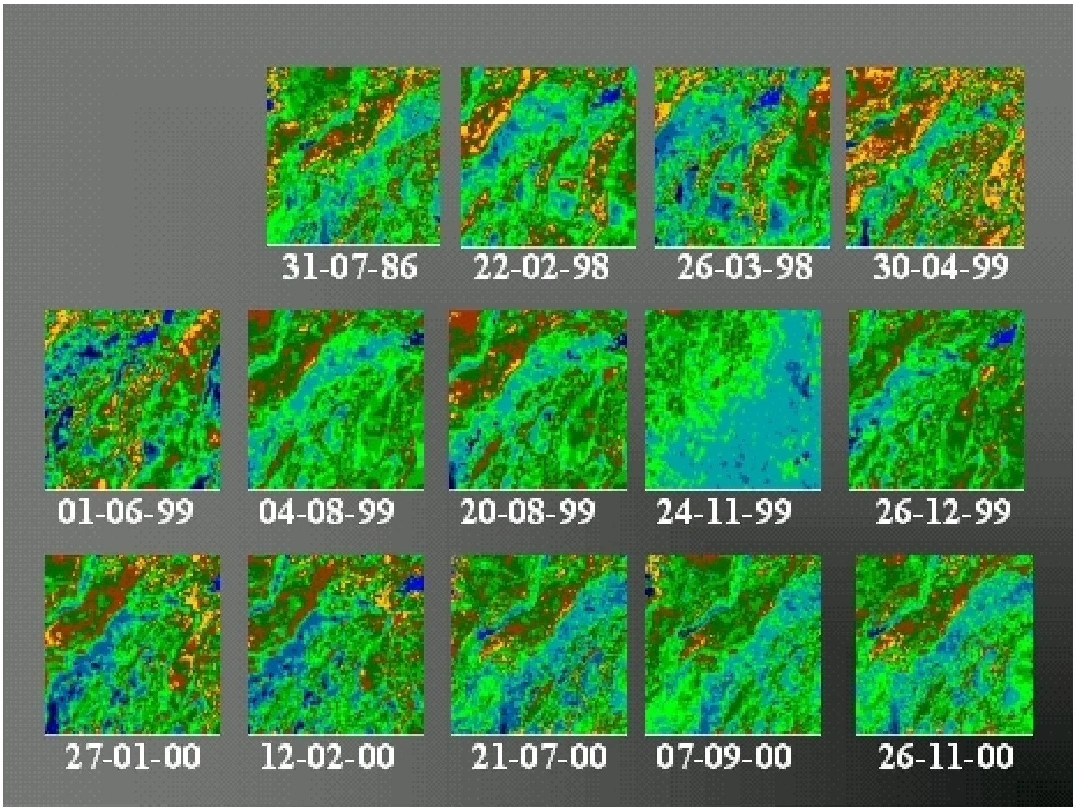


Figure 25. Dynamics of Habitat conditions near San Juan Poriahú.

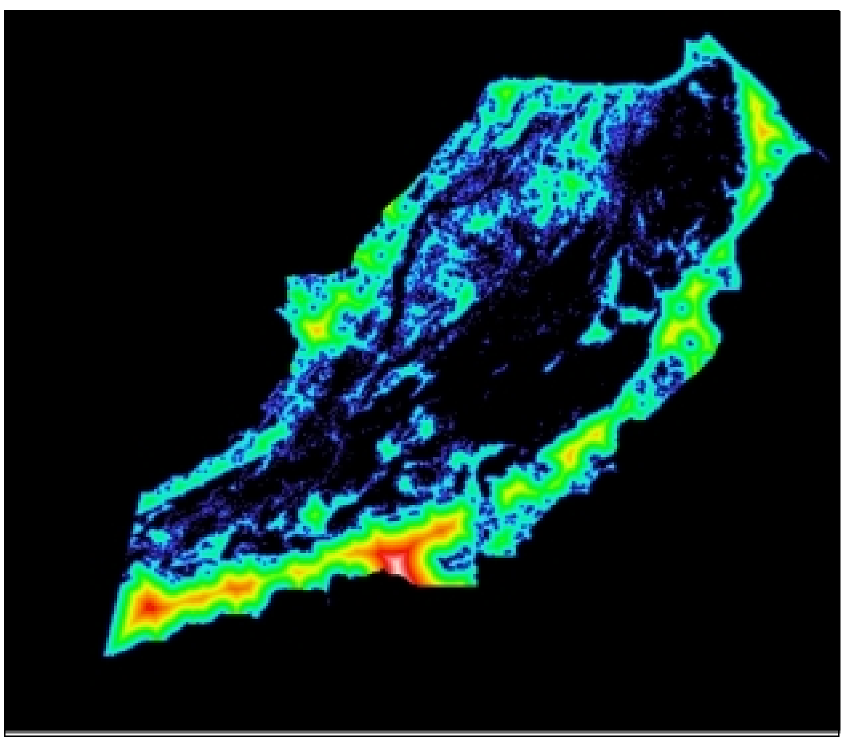


Fig. 26 Distance to Water map.

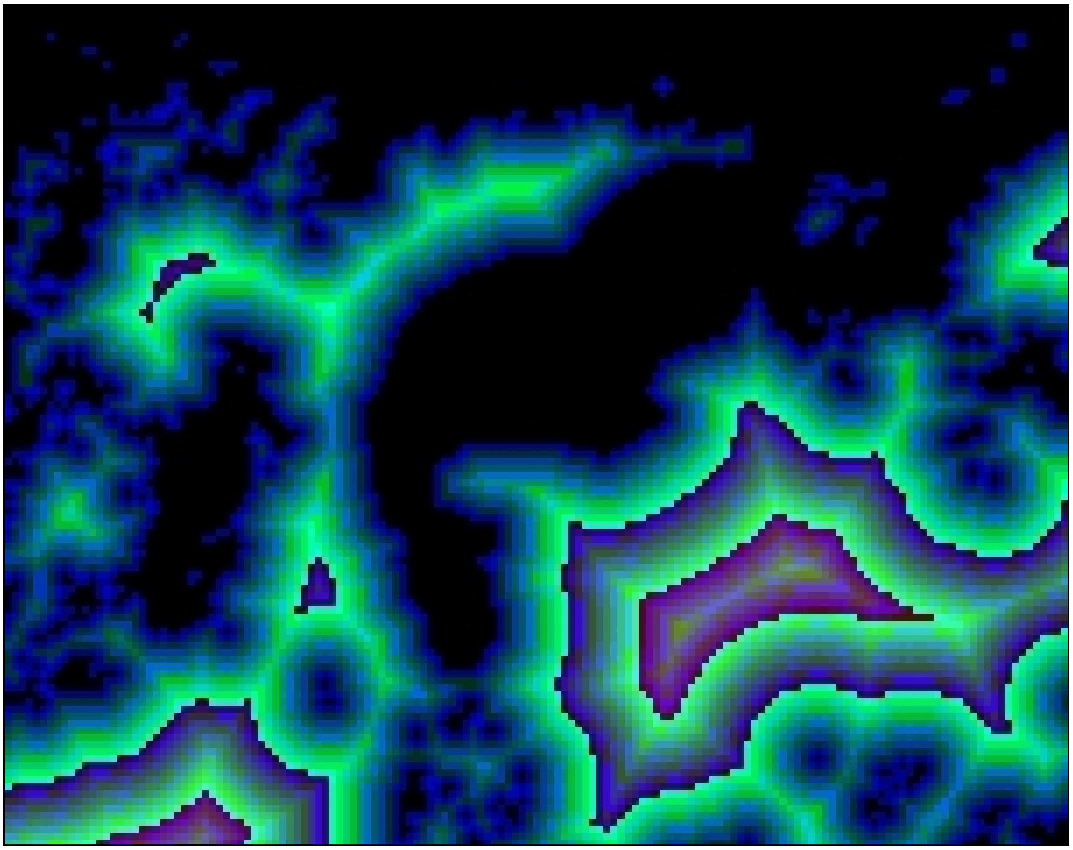


Fig. 27. Detail of distance to water map at the Ibera Lagoon.

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*]

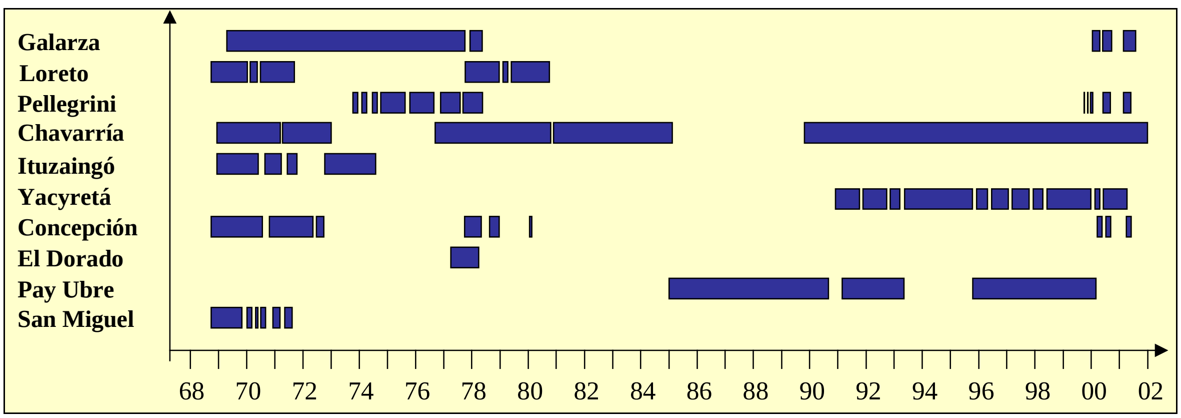


Figure 28.a: Series of Precipitation at the Pluviometric Stations

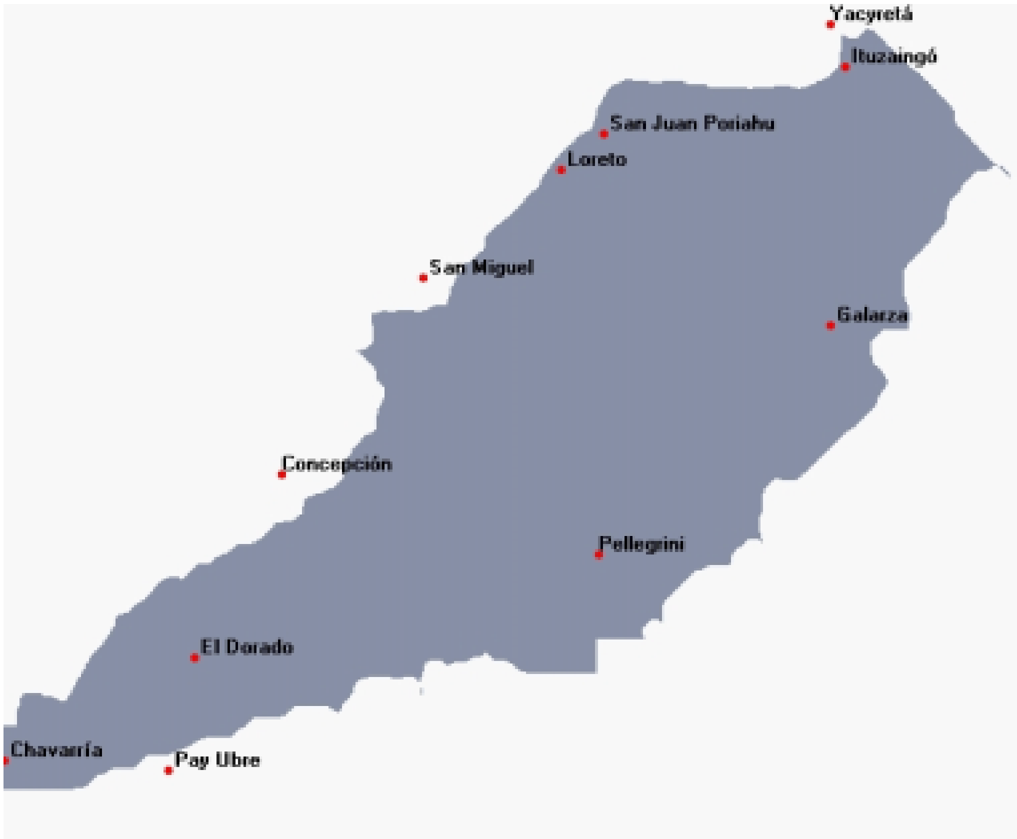


Figure. 28.b: Localization of Pluviometric Station in Ibera System

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*.

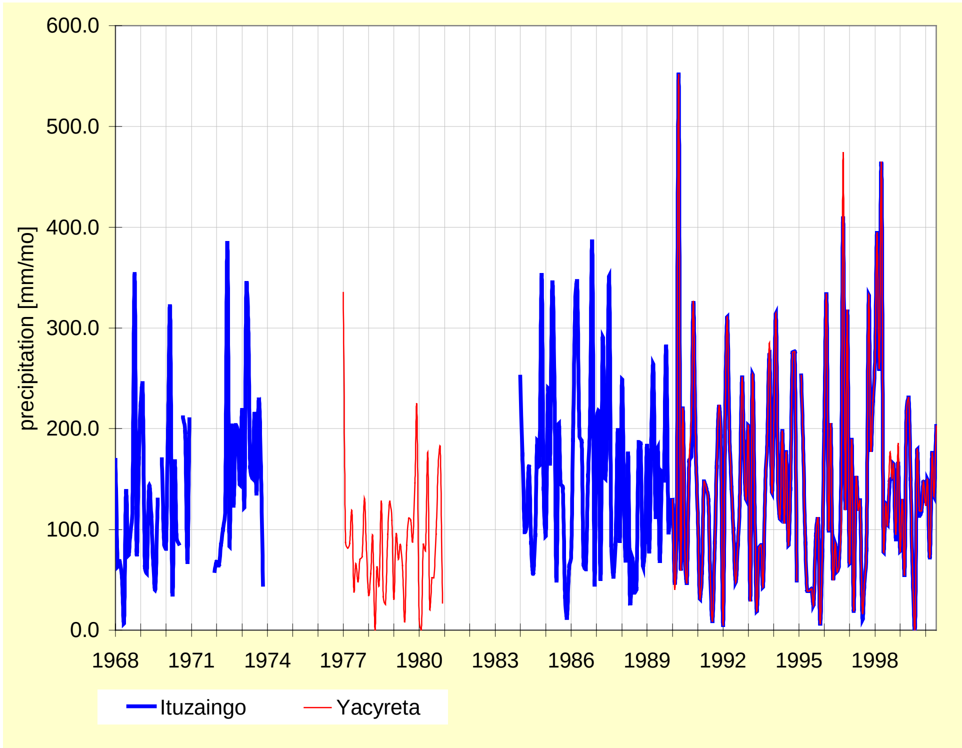


Figure 29: Monthly Precipitation in Ituzaingo and Yacyreta

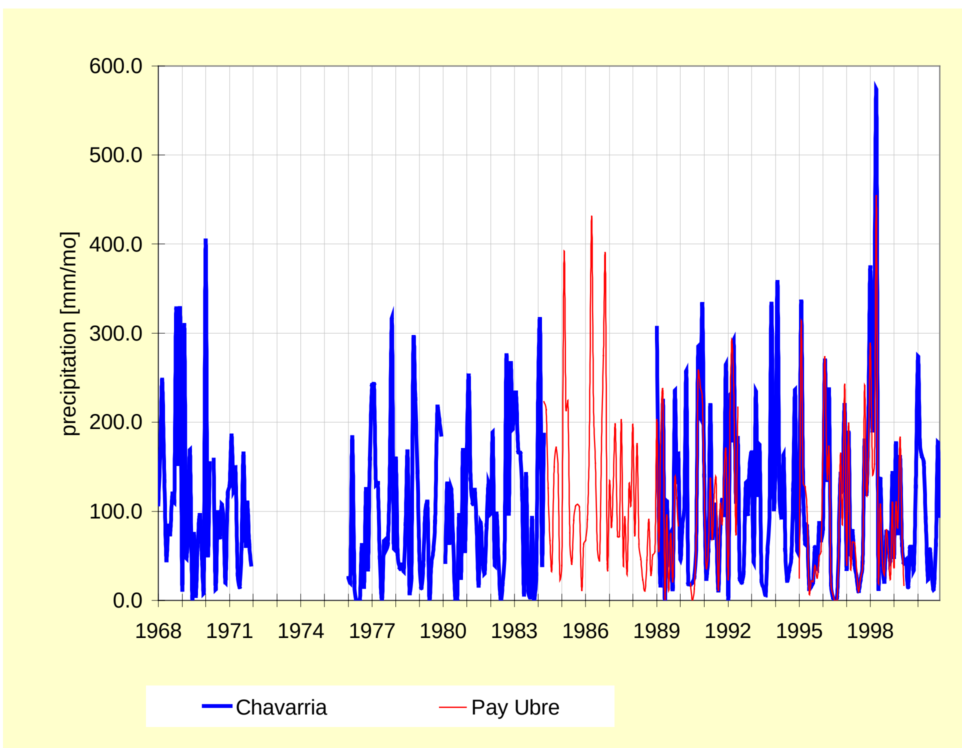


Figure 30: Monthly Precipitation in Chavarría and Pay Ubre

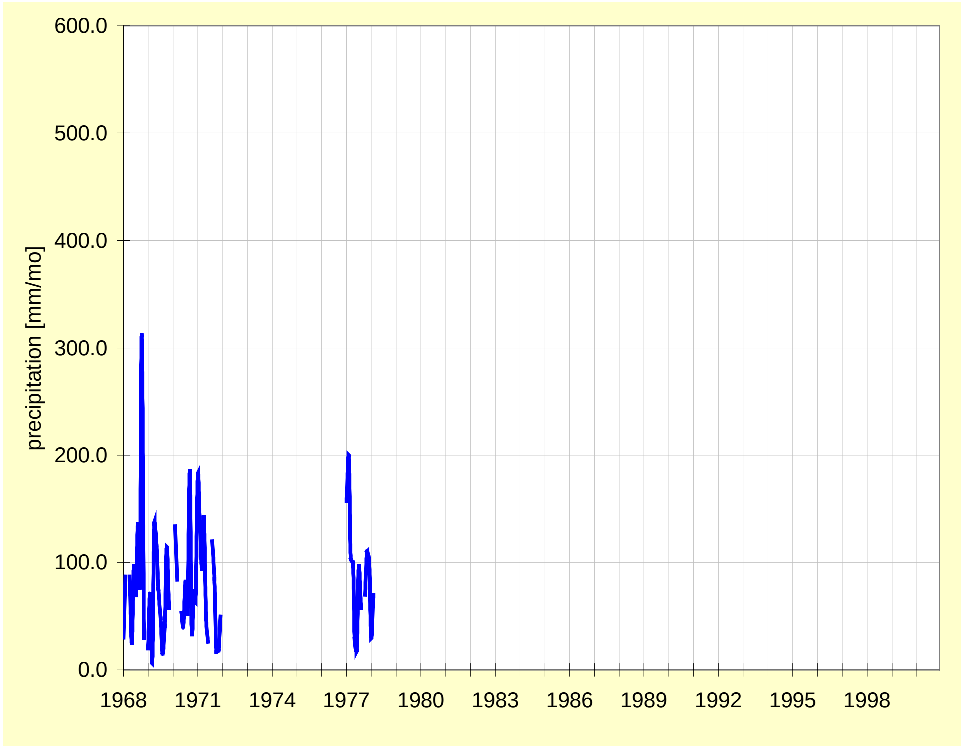


Figure 31: Monthly Precipitation in Concepcion

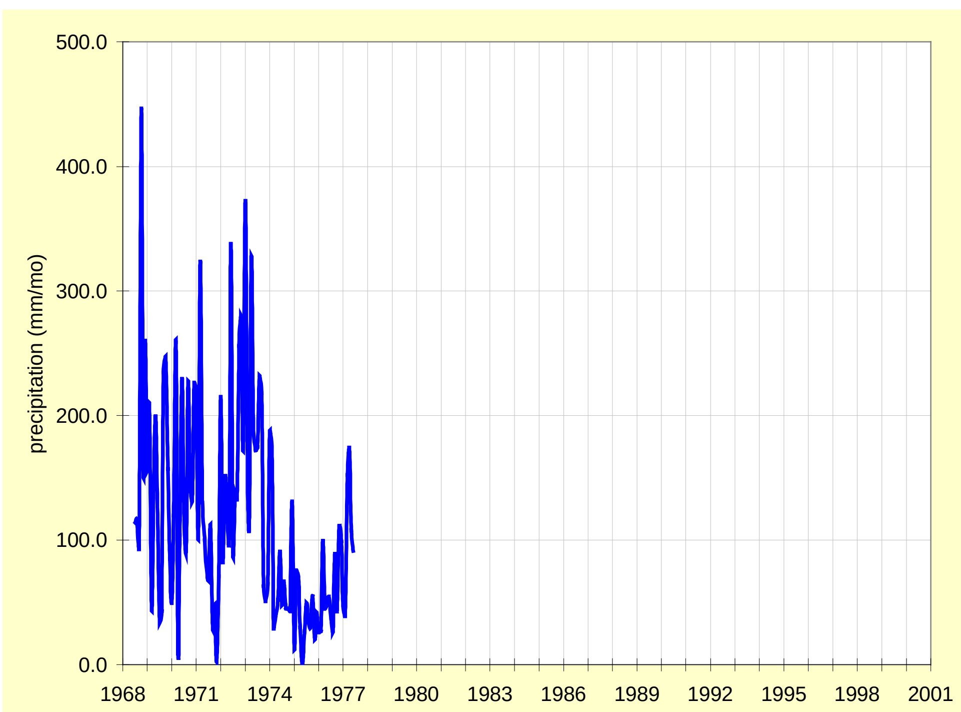


Figure 32: Monthly Precipitation in Galarza

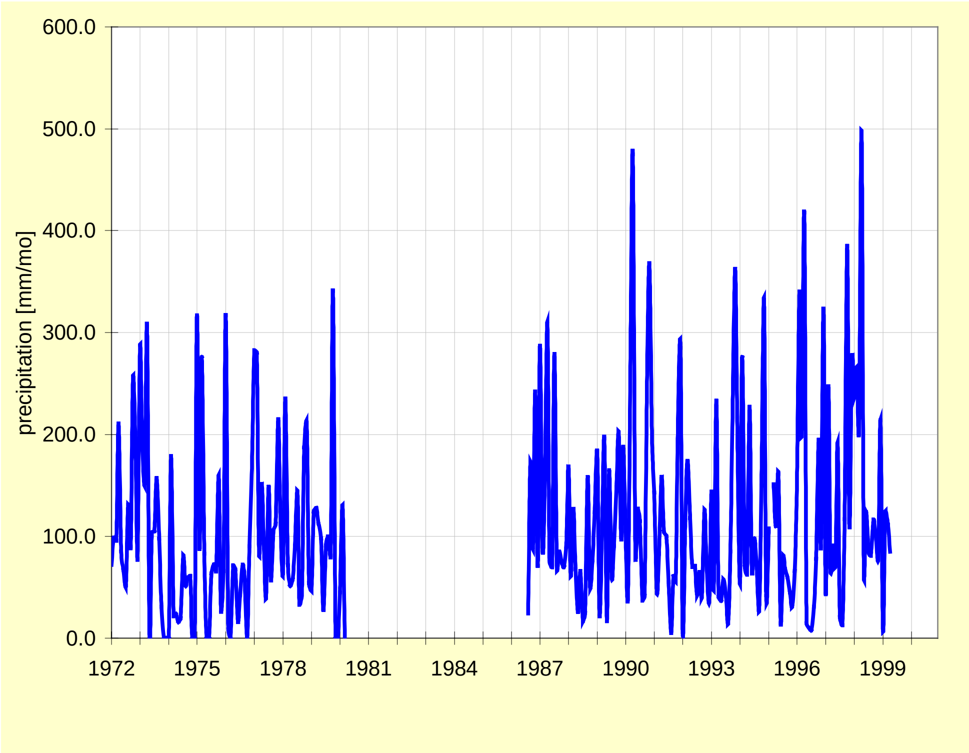
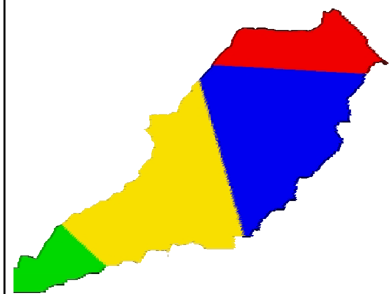
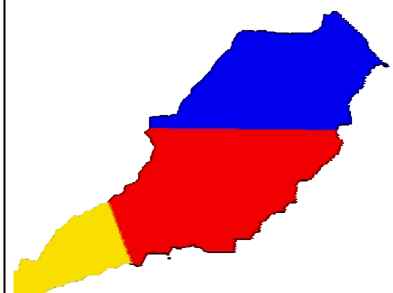
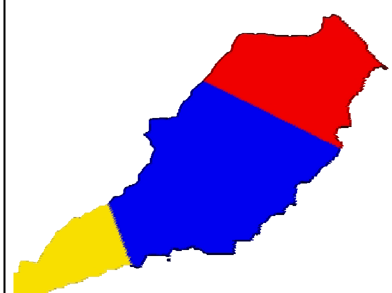


Figure 33: Monthly Precipitation in Pellegrini

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

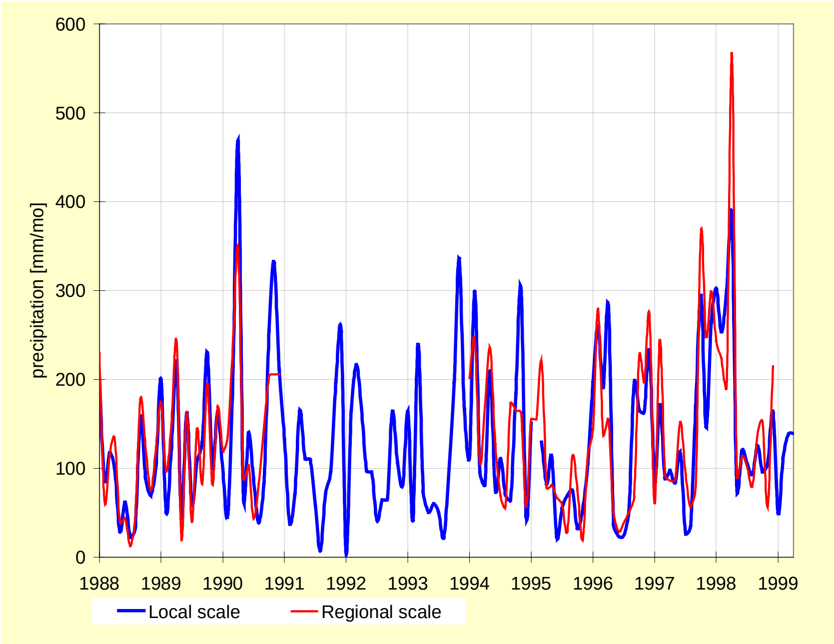


Figure 34.a: Comparative Distributions of Monthly Precipitation at Regional and Local Scale

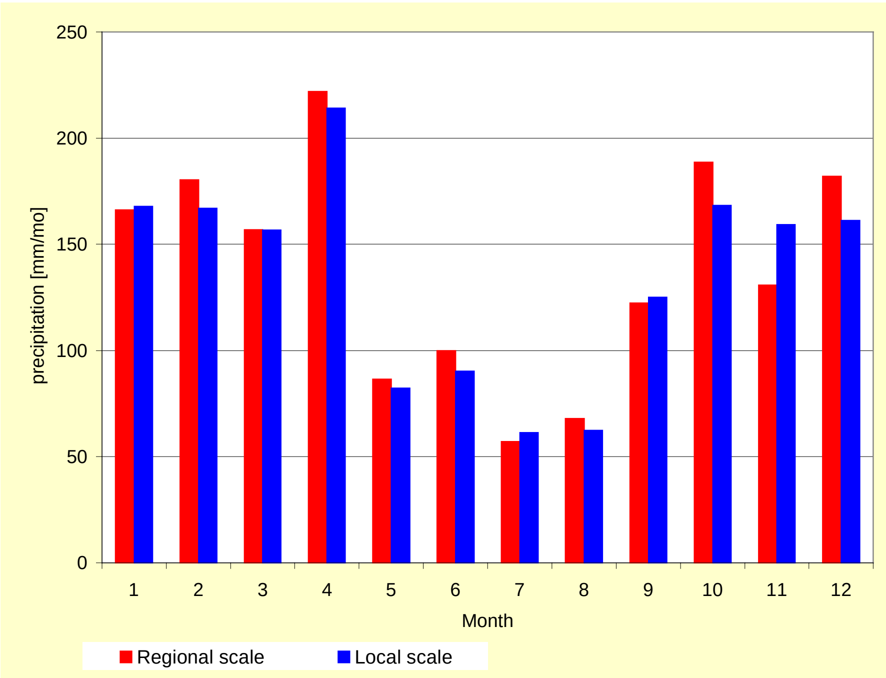


Figure 34.b: Mean Monthly Distribution of Precipitation at Regional and Local Scale

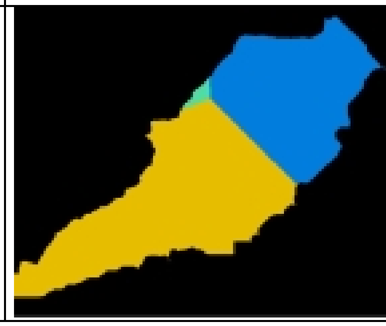
YEAR	Annual Precipitation at the Ibera System (mm/year)		Difference (%)
	Regional Scale	Local Scale	
1977	1633	1473	-9.8
1978	1210	1106	-8.6
1979	1521		
1988	1182	1067	9.7
1989	1560	1592	-2.0
1990	1922	2034	-5.9
1994	1767	1653	6.4
1996	1650	1822	-10.4
1997	1866	1582	-15.2
1998	2159	2124	2.3

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.

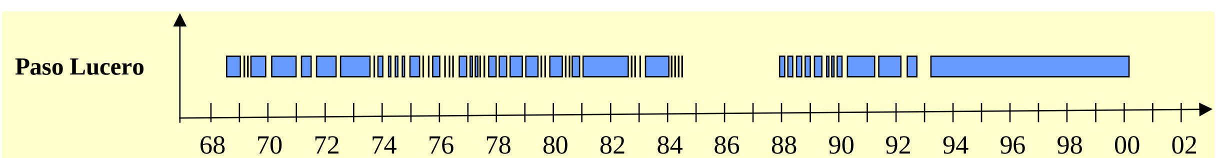


Figure 35. Series of mean daily discharges at Paso Lucero.

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.

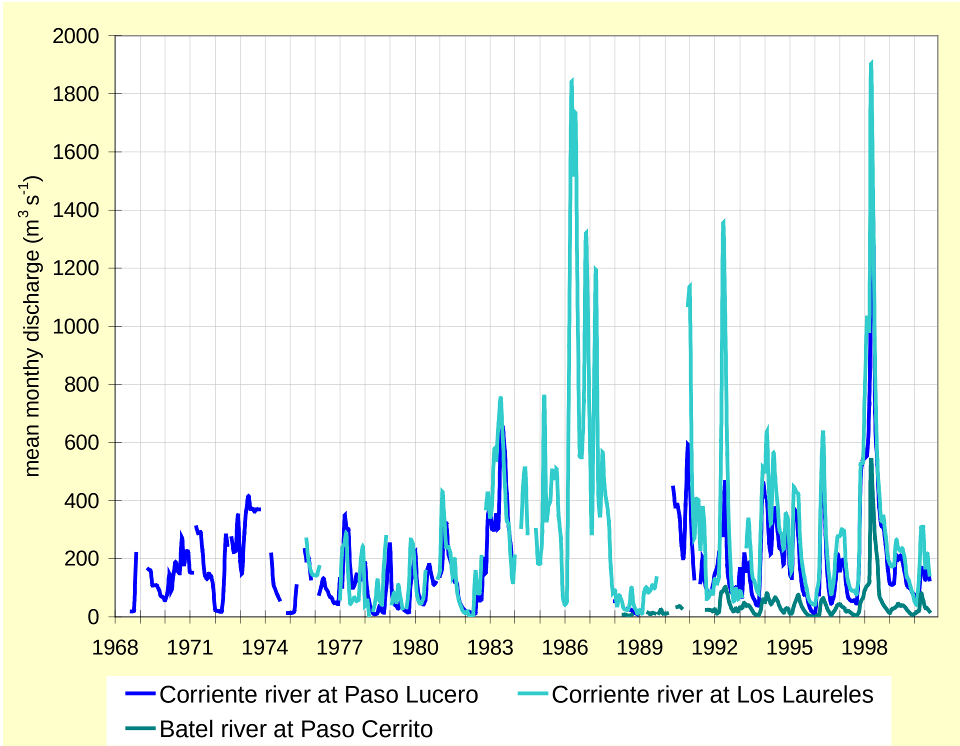


Figure 37. Monthly discharge hydrograph at Paso Lucero, Los Laureles (Corriente River) and Paso Cerrito (Batel River).

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.

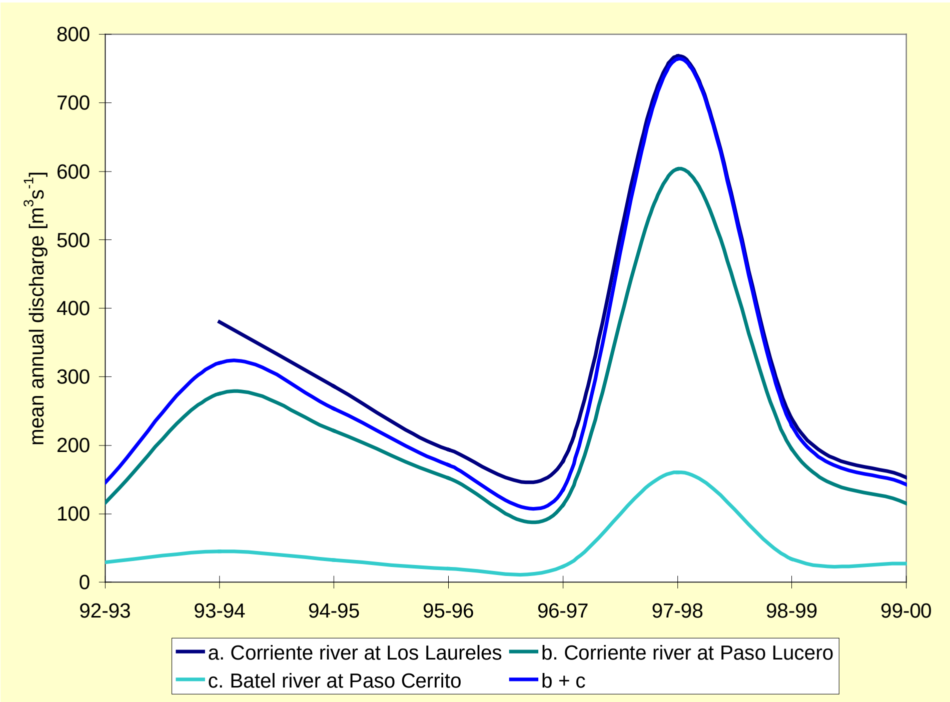


Figure 38. Mean annual discharge at the three gauge stations.

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*).

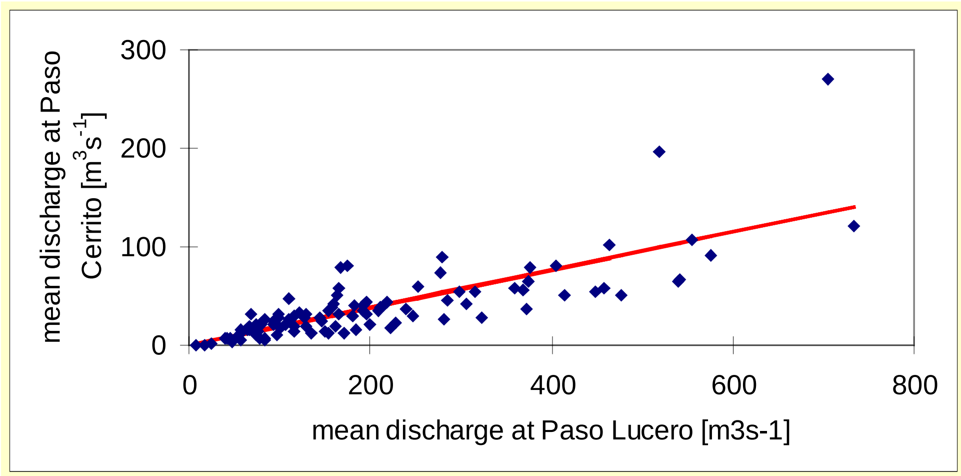


Figure 39. Linear regression of discharge data at Paso Lucero/Paso Cerrito

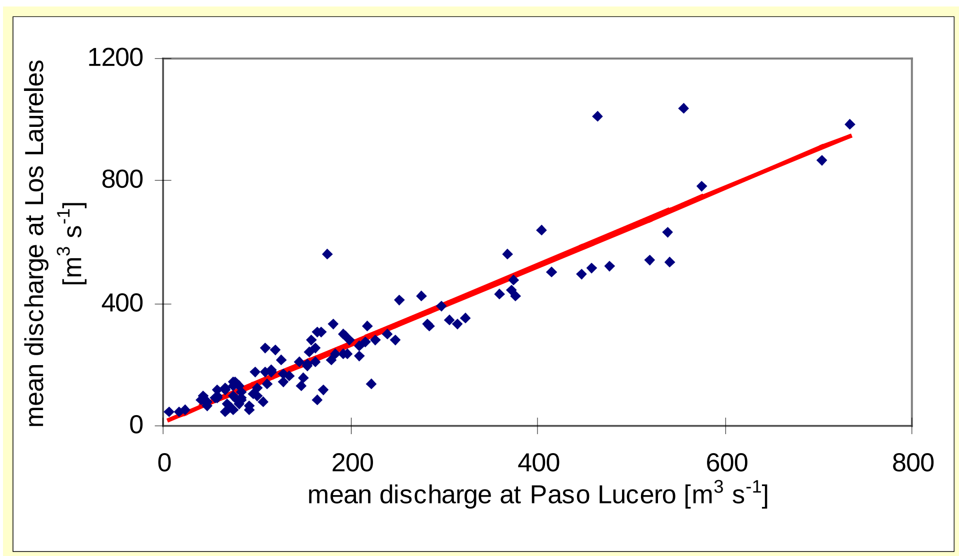


Figure 40. Linear regression of discharge data at Paso Lucero/Los Laureles

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).*

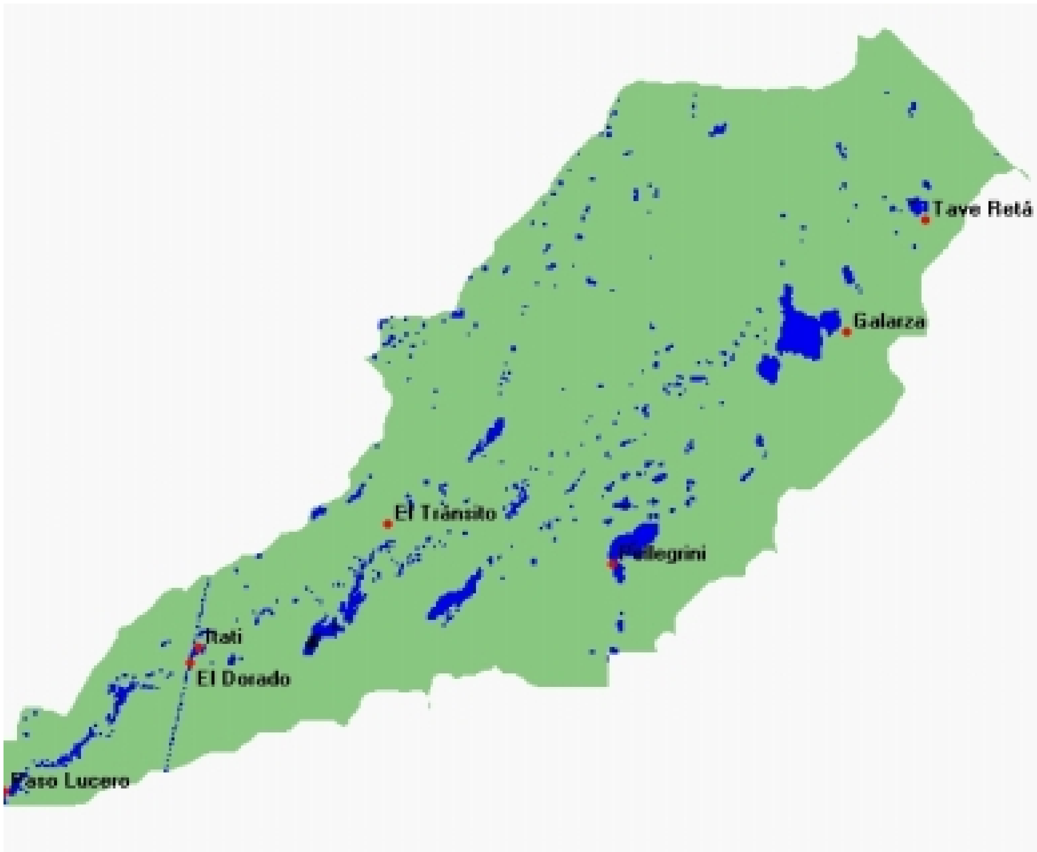


Figure 41. Location of hydrometric stations

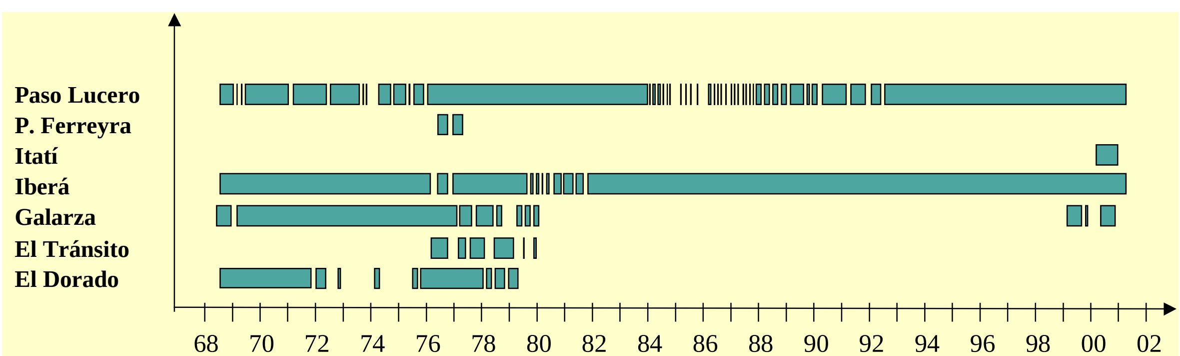


Figure 42. Series of hydrometric data.

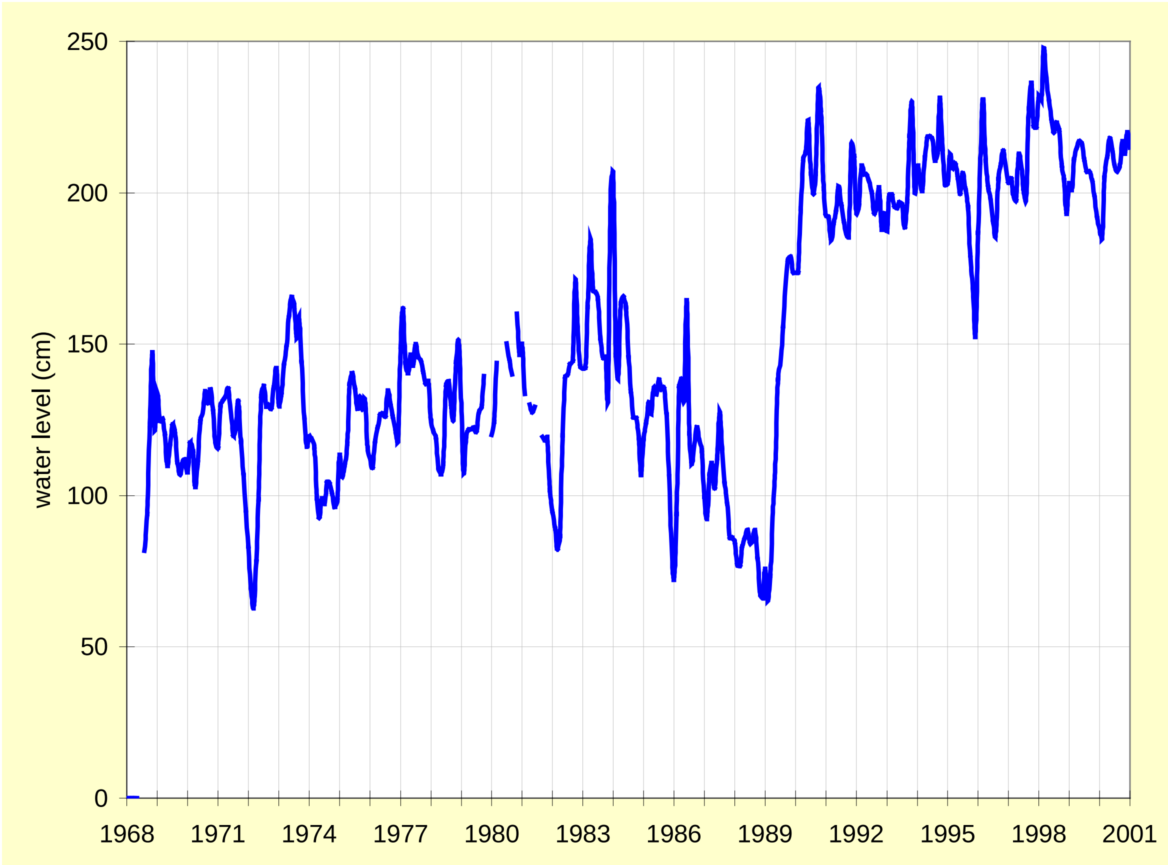


Figure 43. Water level records at Ibera Lagoon (Pellegrini).

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.

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?

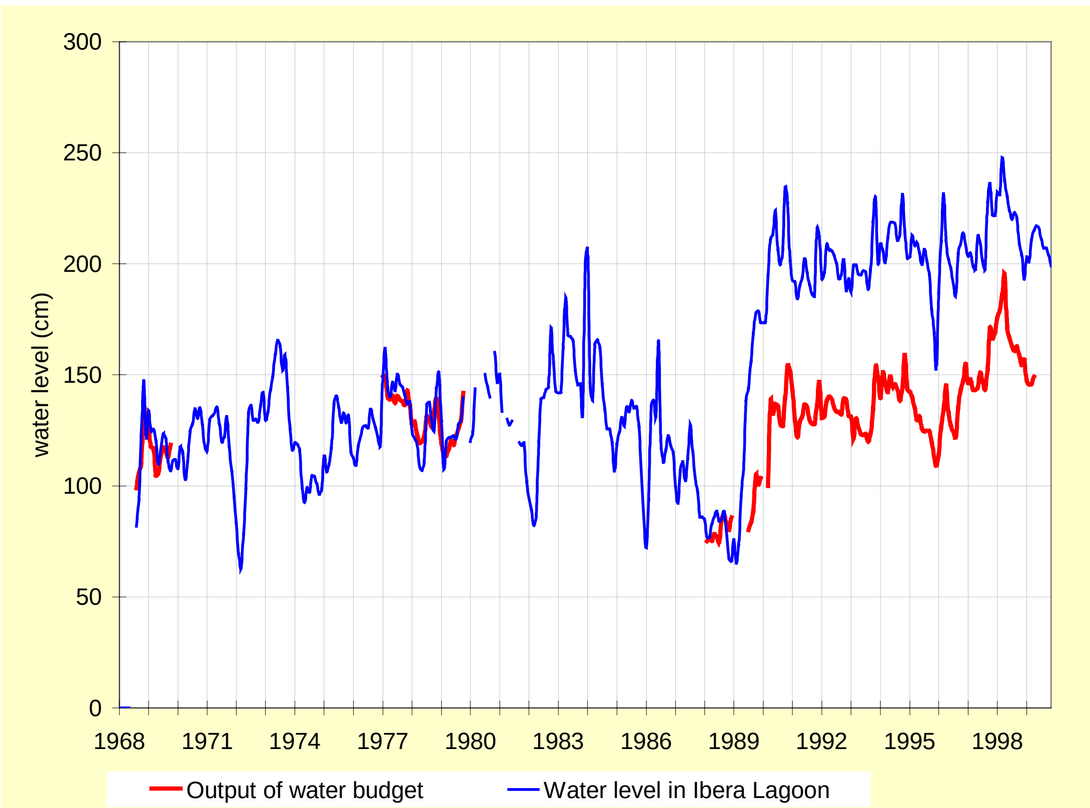


Figure 44: Water level variation in Ibera Lagoon and calculated values

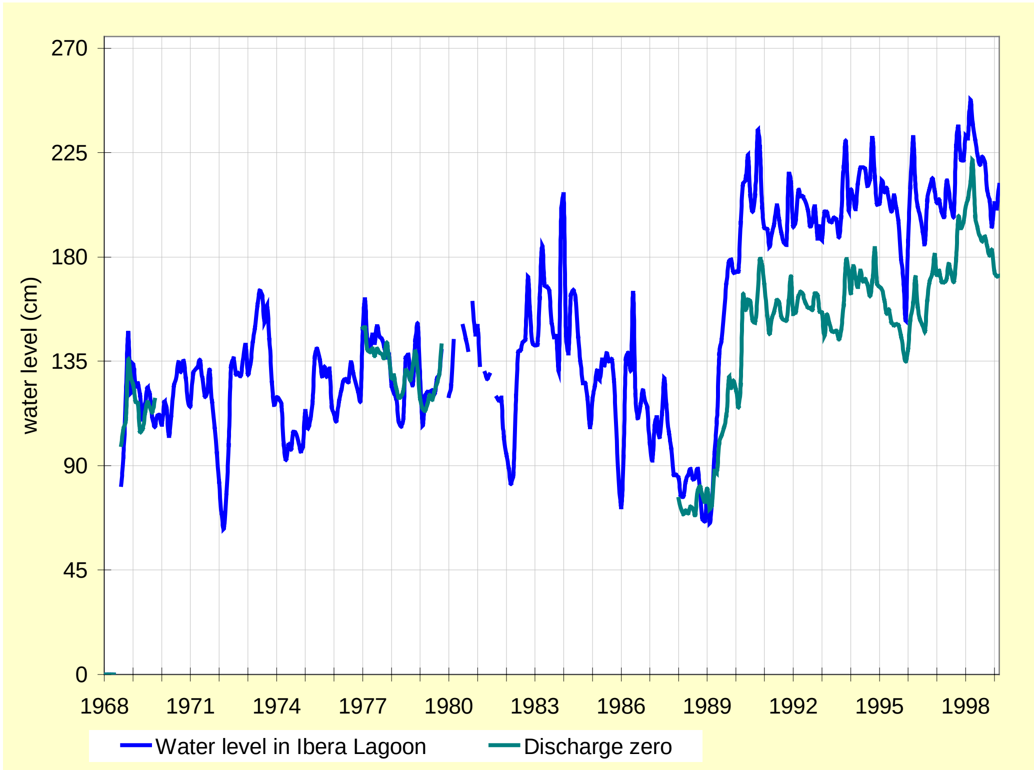


Figure 45: Water level variation in Ibera Lagoon and calculated values considering discharge zero in place of missing data

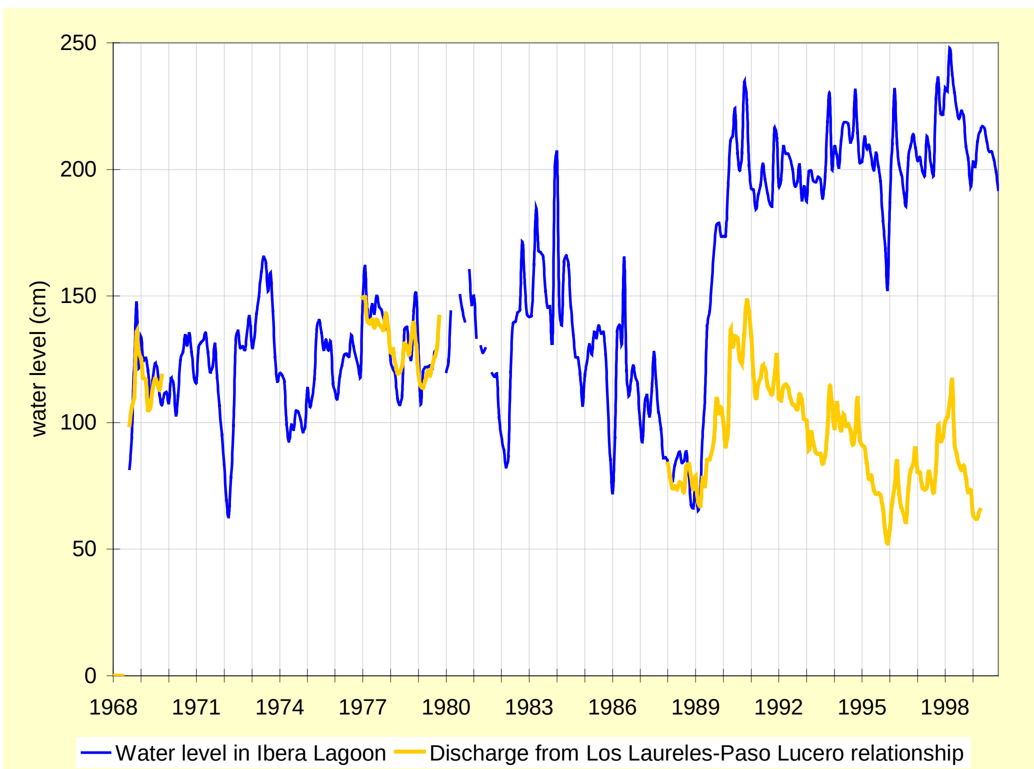


Figure 46: Water level variation in Ibera Lagoon and calculated values considering discharge interpolated from Los Laureles-Paso Lucero relationship in missing data

- ***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.

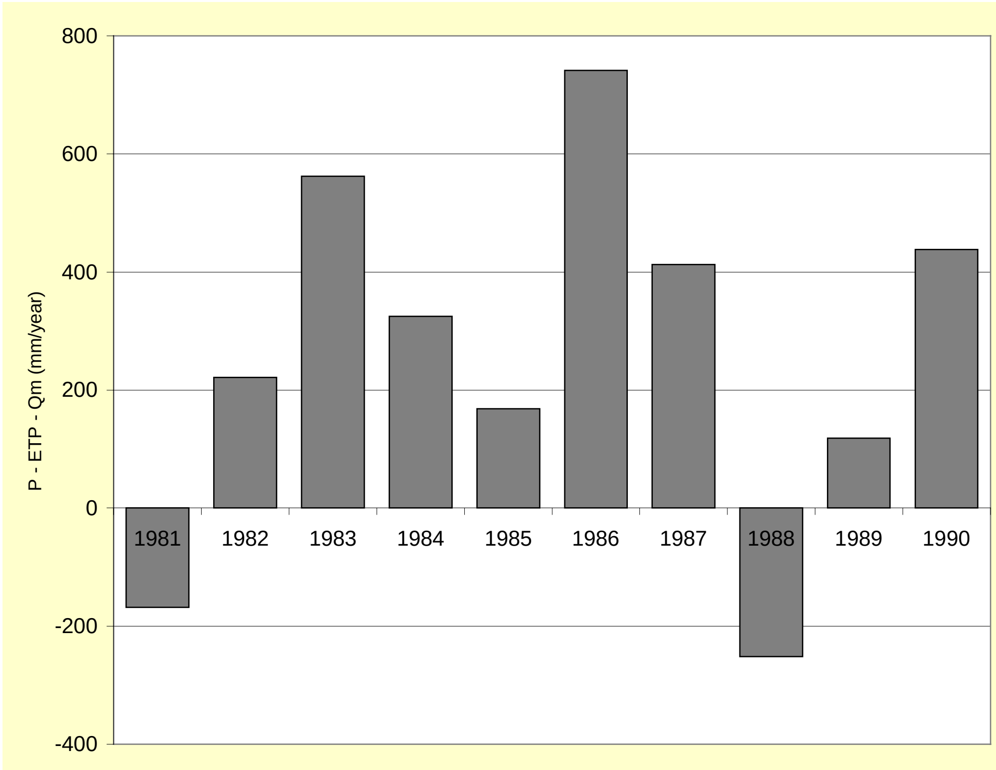


Figure 47. Annual balance considering average annual runoff calculated from series 1968-1977.

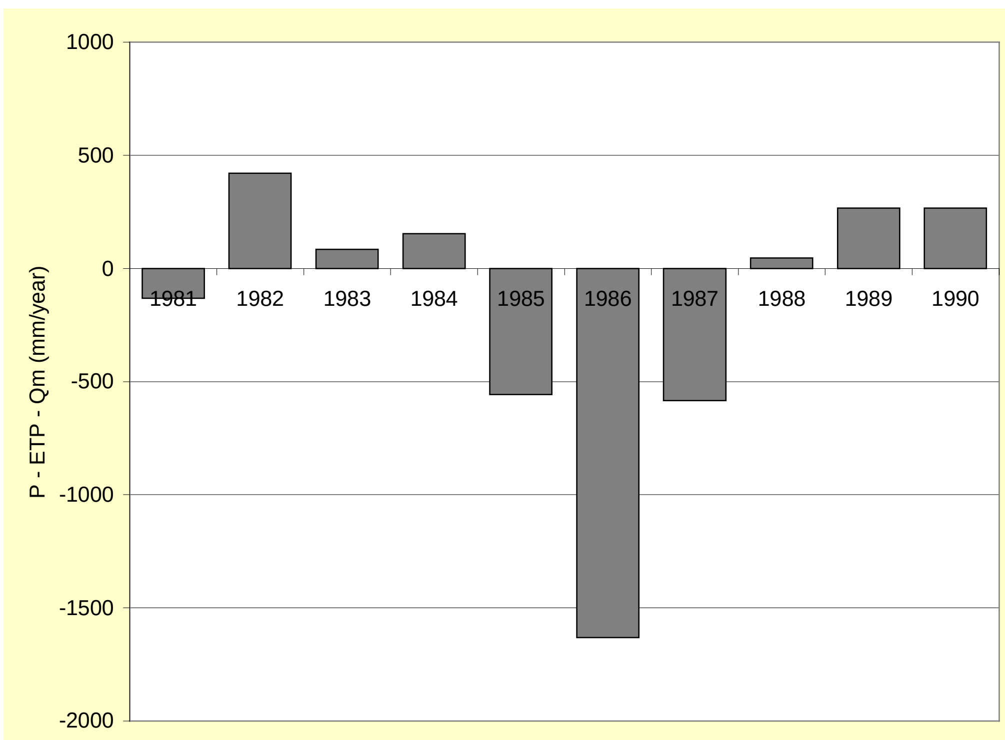


Figure 48. Annual balance considering interpolated annual runoff from Los Laureles station.

- ***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.

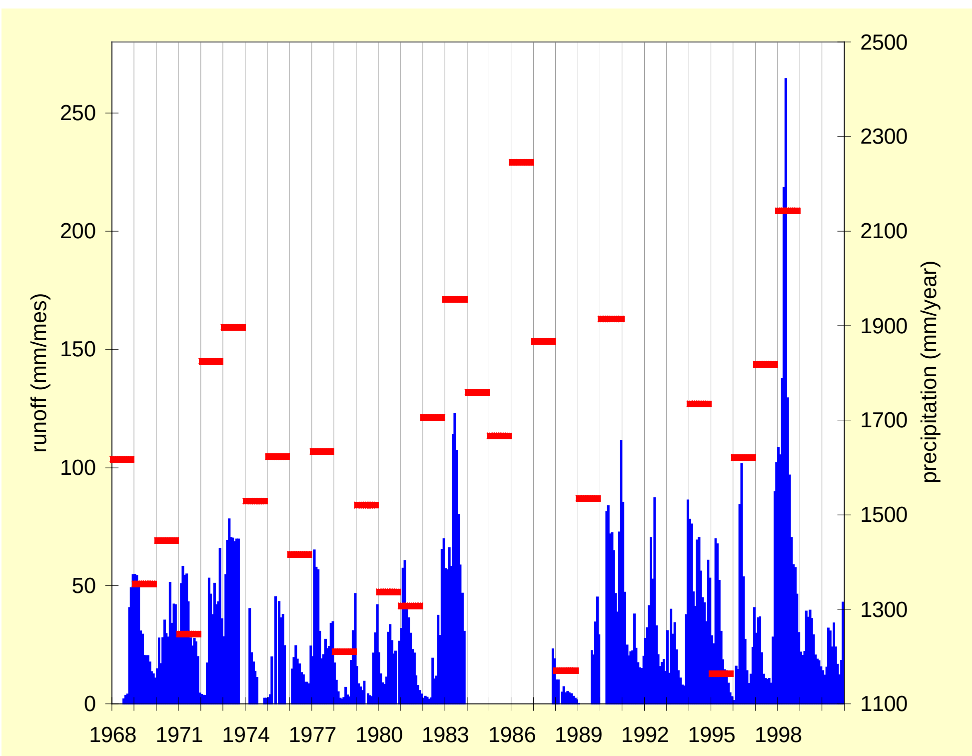


Figure 49. Annual precipitation depth (regional scale) in red and monthly mean runoff across Paso Lucero stream gauge station in blue.

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.

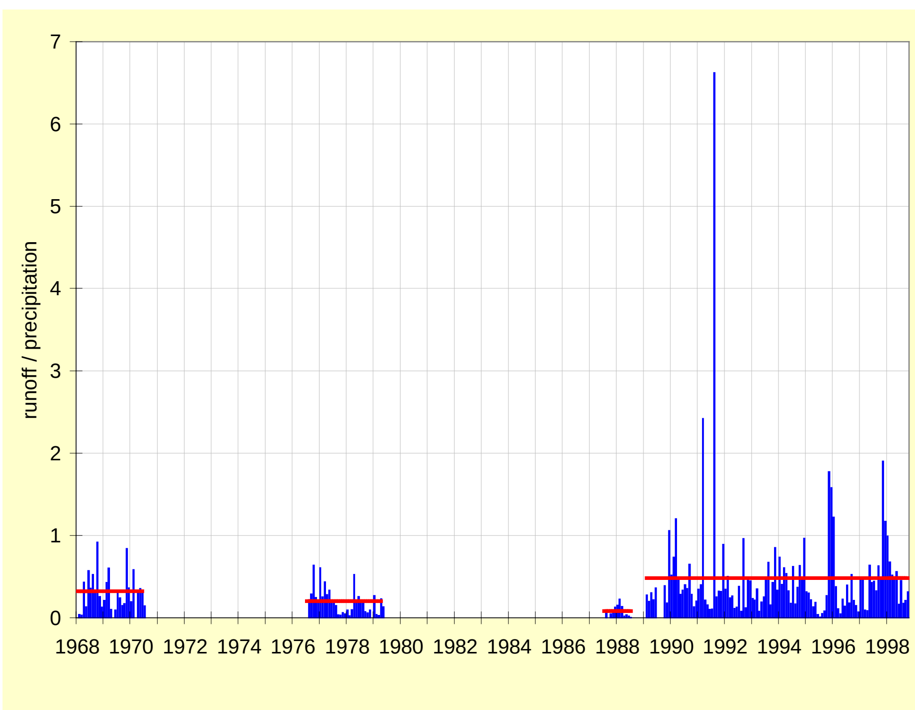


Figure 50. Runoff at Paso Lucero relative to antecedent precipitation.

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.

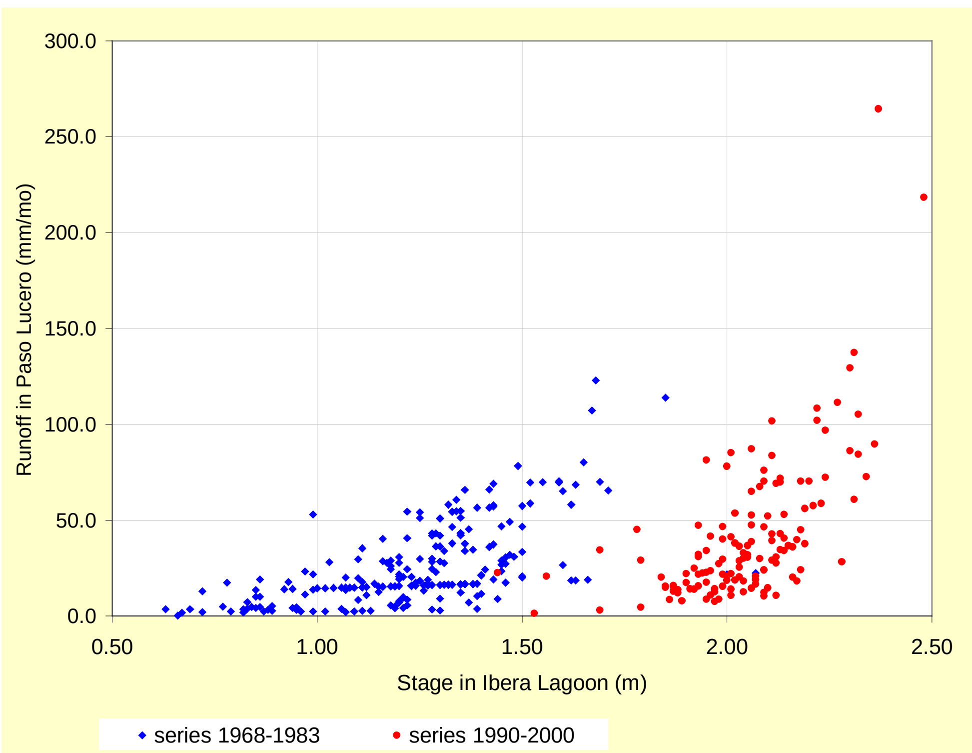


Figure 51. Discharge at Paso Lucero relative to water levels at Ibera Lagoon

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

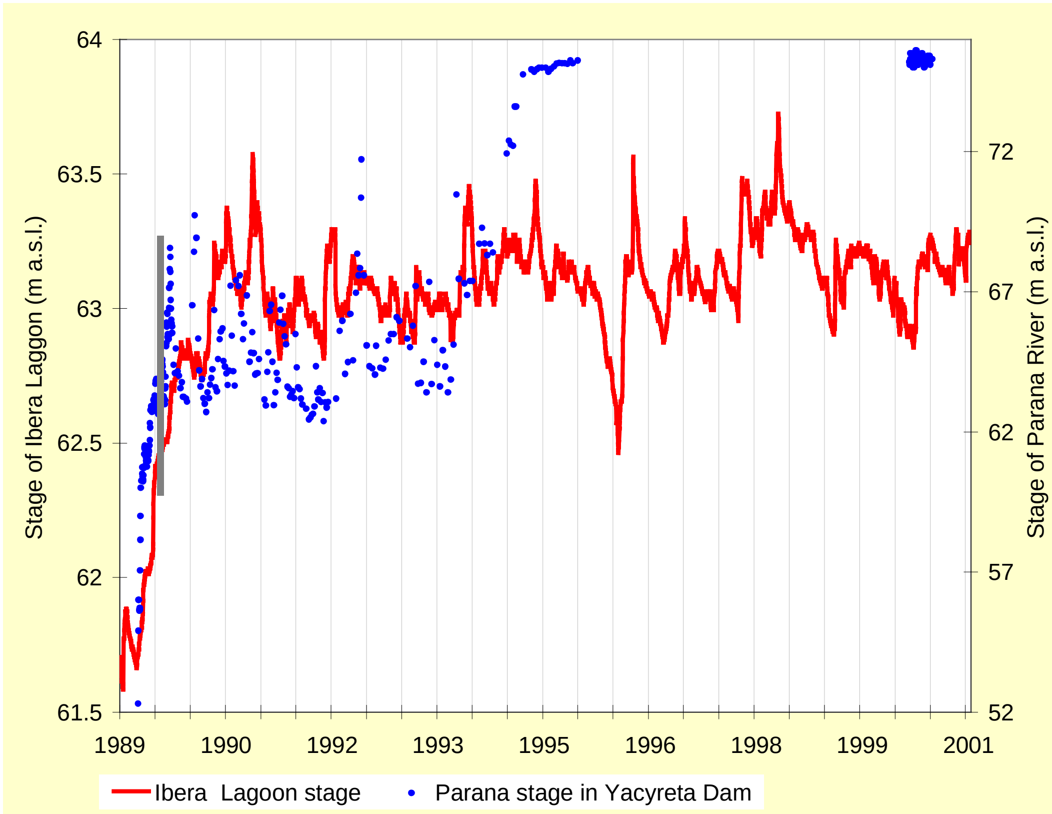


Figure 53. Comparison betwen water levels at Paraná River and Ibera Lagoon.

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.

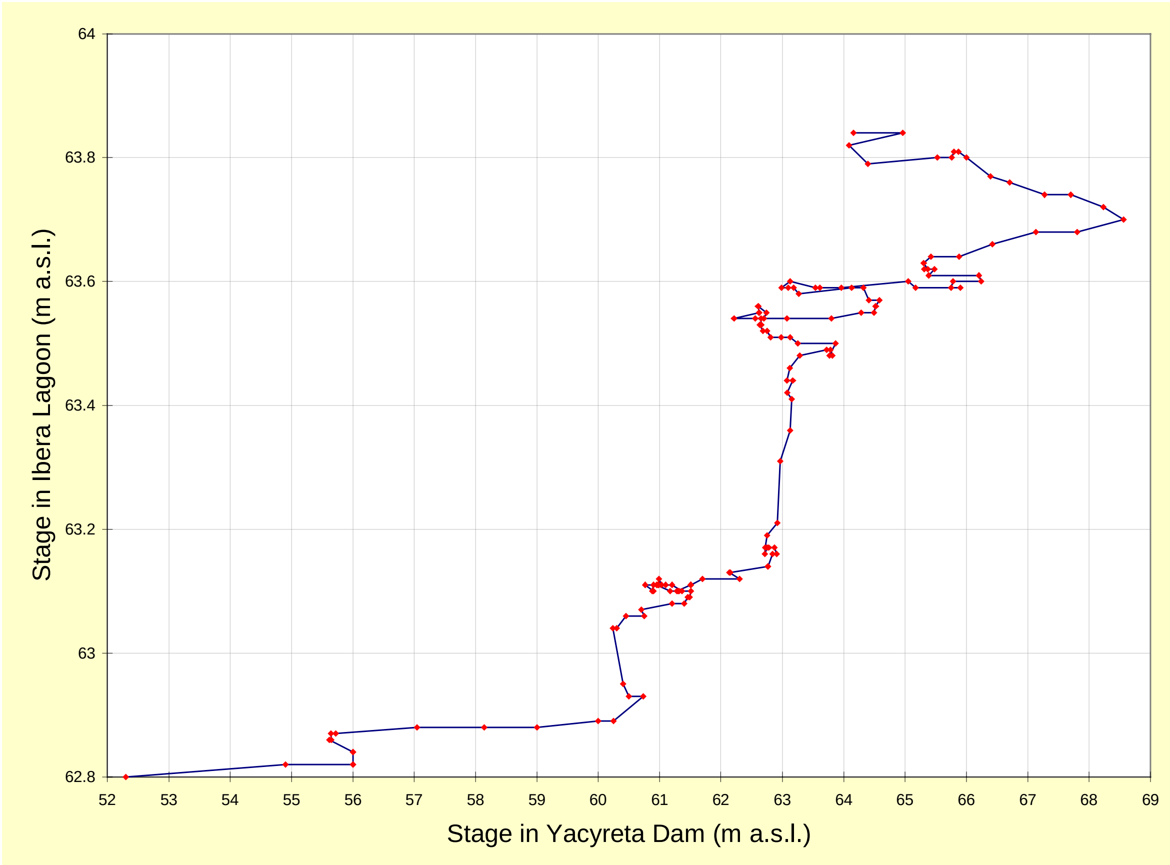


Figure 54. Water level at Ibera Lagoon relative to water level of the Paraná River at Yacyreta Dam.

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.

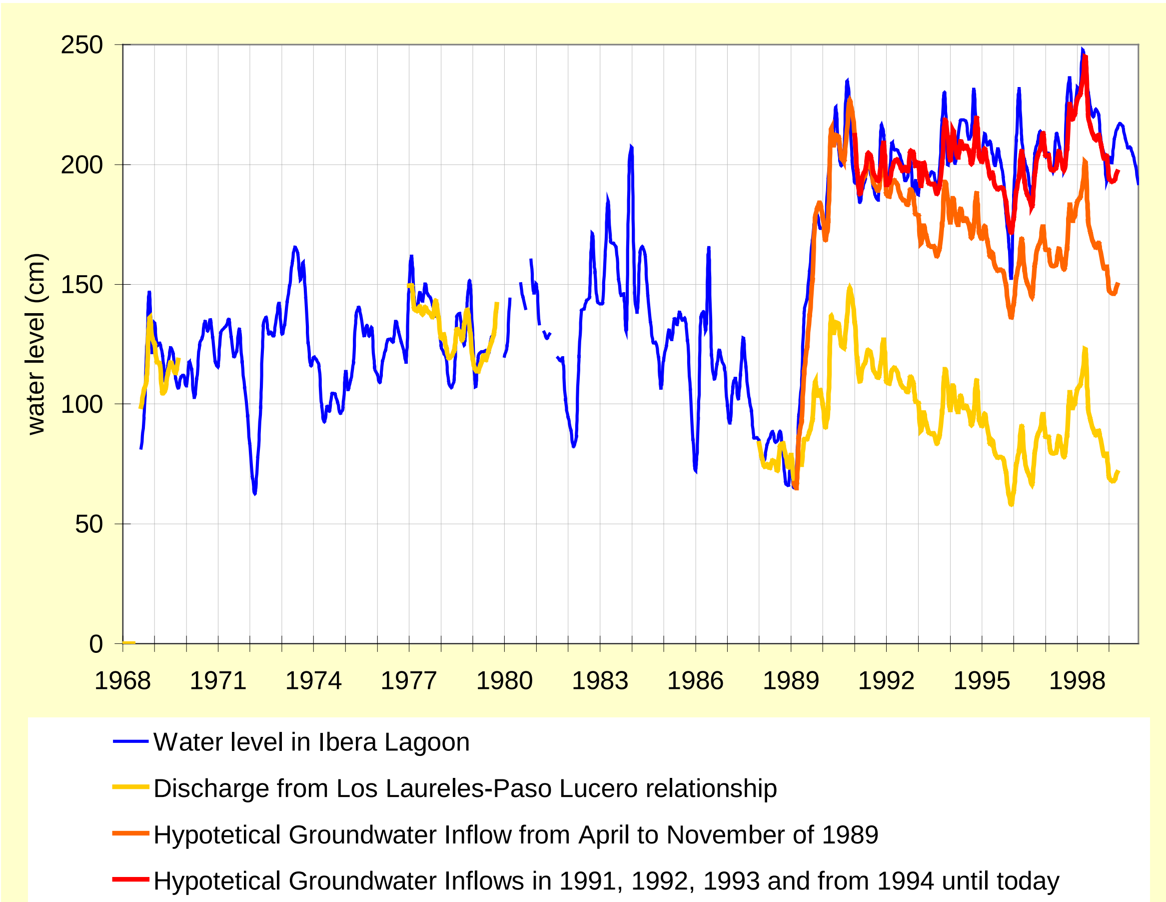


Figure 55. Corrected water balance model

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.

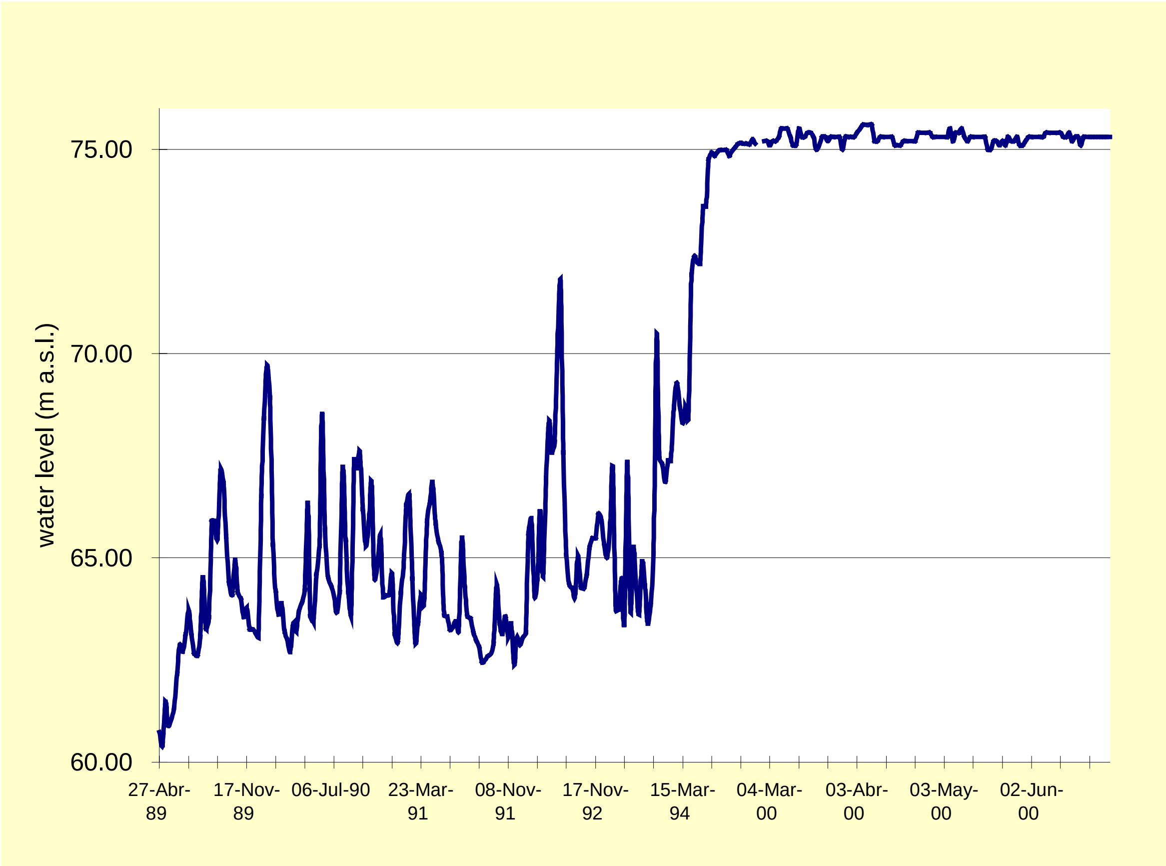


Figure 56. Water level at the Yacyreta Dam reservoir.

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.

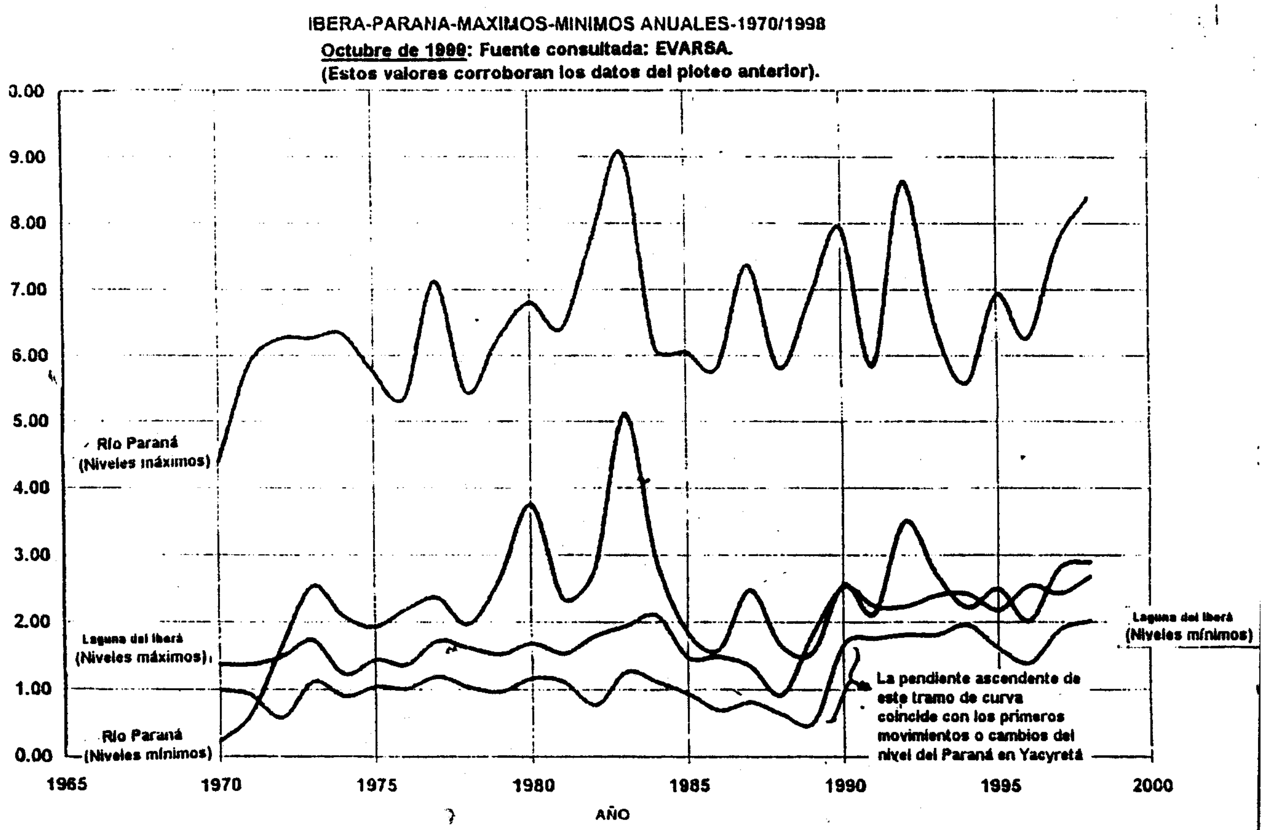


Figure 57. Annual minima and maxima stages of Ibera lagoon and Parana River (source EVARSA)

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).

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

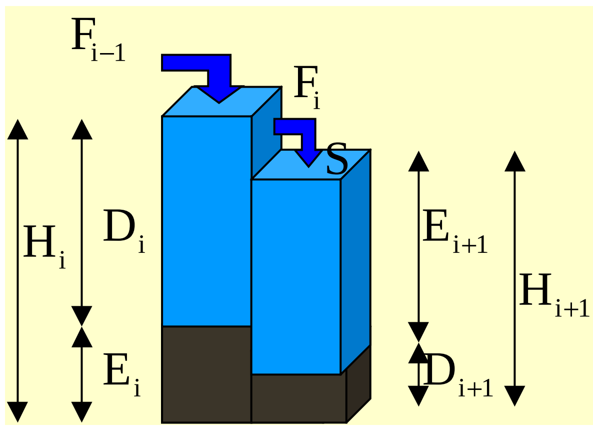
were R is the hydraulic radius, G is the slope of the energy gradient and M is the coefficient of Manning of surface roughness.

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

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

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

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

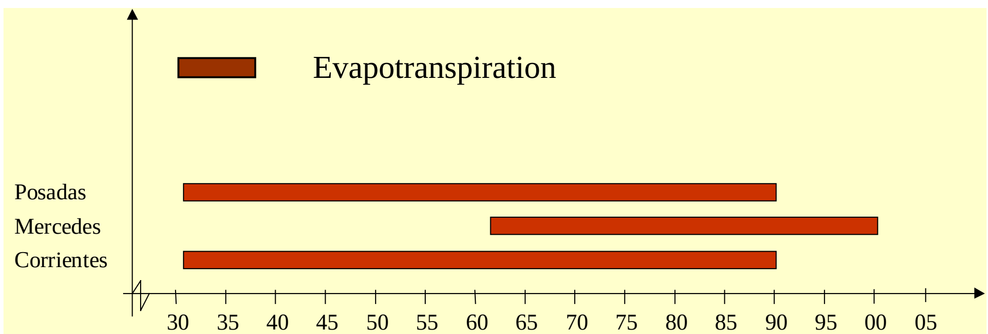


Figure 58: Records of available data

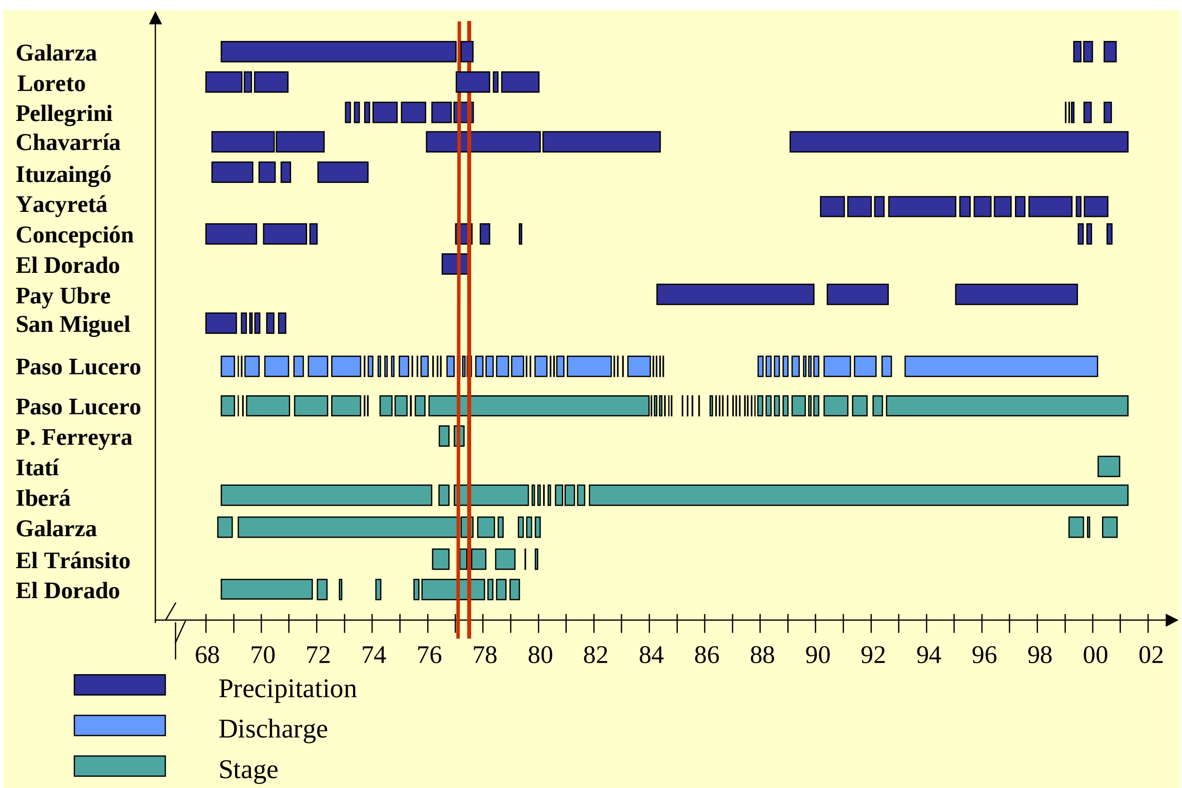


Figure 59: Records of available data

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.

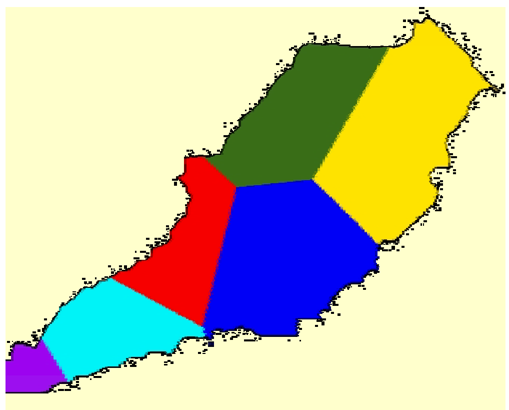


Figure 60: Spatial distribution of rain stations

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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