ENSO FLOODS ON RIVER ECOSYSTEMS: FROM CATASTROPHES TO MYTHS

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Abstract Very extreme floods from 38000 to 62000 m^3s^{-1}, draining a 2 million km^2 catchment area and with severe inundation downstream of Paraguay-Parana Confluence in South America, are related to El Niño Southern Oscillation –ENSO-. This paper links ENSO's floods to natural ecosystems, e.g. the flood-plain patchiness, the biodiversity and the ecosystem structure. River behaviour may be described with parameters as frequency, intensity, tension, regularity, amplitude and seasonality. According to the 20th century river time series, noteworthy fluvial changes are related to extreme floods through actual time. Nevertheless, the ecosystem recovers itself by means of resilience assessed by remote sensing. This lack of understanding determined enormous economic losses on ecosystems impacted by ENSO´s floods along the 1983-98 period reaching to catastrophes and myths. Although flood-plain ecosystems are often well adapted to ENSO's floods, their risk analysis patch assembles must be properly addressed. Therefore, adaptations to land use are discussed, regarding an attitude's change of society in front of river behaviour to cope with ENSO's flood myths.

Keywords: ENSO-flooded ecosystems, remote sensing, river catastrophes & myths

Introduction

During the 20th century, eight runoff El Niño Southern Oscillation extremes -as ENSO's floods- at the La Plata transboundary catchment in South America produced inundation of low-lands located downstream of the Confluence of Parana-Paraguay rivers (Fig.1). These inundations, i.e. from 38000 to 62000 m^3s^{-1} affected numerous cities built over the river flood-plains, with damages on bridges, roads and crops, and even led to human deaths. Until the '90s, ENSO-related floods were only analysed as "catastrophic events" which had impacts difficult to predict on man-made structures. ENSO floods and their inundations downstream were treated with reductionism and, so, erroneous management of flooded areas were repeatedly adopted resulting in high reconstruction costs of structures and services. Thus, these ENSO floods were partially approached, i.e. uniquely hydrologists evaluated inundations through discharges data with, say, the "annual maximum floods" (AMF) and/or "peaks over threshold" (POT) models. But today, it is well known that these theoretical models are strongly depended on hypotheses of randomness, independence, homogeneity and stationarity, almost poorly-satisfied by typical river time series around the world whose length records barely exceed fifty years of collection (Ashkar 1995; p.76); and/or constrained by inherent uncertainties in their rating-curve conversion (Clarke *et al* 2000). Moreover, probability models do not take account of the non-structural measures necessary for putting in practice the co-operation between authorities, affected population and insurance industry to cope with future risk of flood disasters pointed (Berz 2000). For the case of Paraguay-Parana system, since 1993 the ENSO floods have been treated taking account the variability of natural systems and the adaptive capacity of populations which supports the ENSO phenomenon: ecosystems, cities, services (Schnack *et al* 1995) to: (i) defend the cities with dikes against floods and pump-stations to drainage rainfall precipitated over flood-protected cities, (ii) carry out territorial planning, at the hydrological catchment scale, of urban tributary rivers, (iii) discourage urban growth in river flood-plains, (iv) invest in improving services of frequently inundated cities, i.e. health, education, security, and (v) observe rules of urban and territorial ordering. Likewise, only after the 1997-98 inundation, the Government of Argentina decided to invest US$ 420 million to find feasible solutions of ENSO inundation (Table 1).

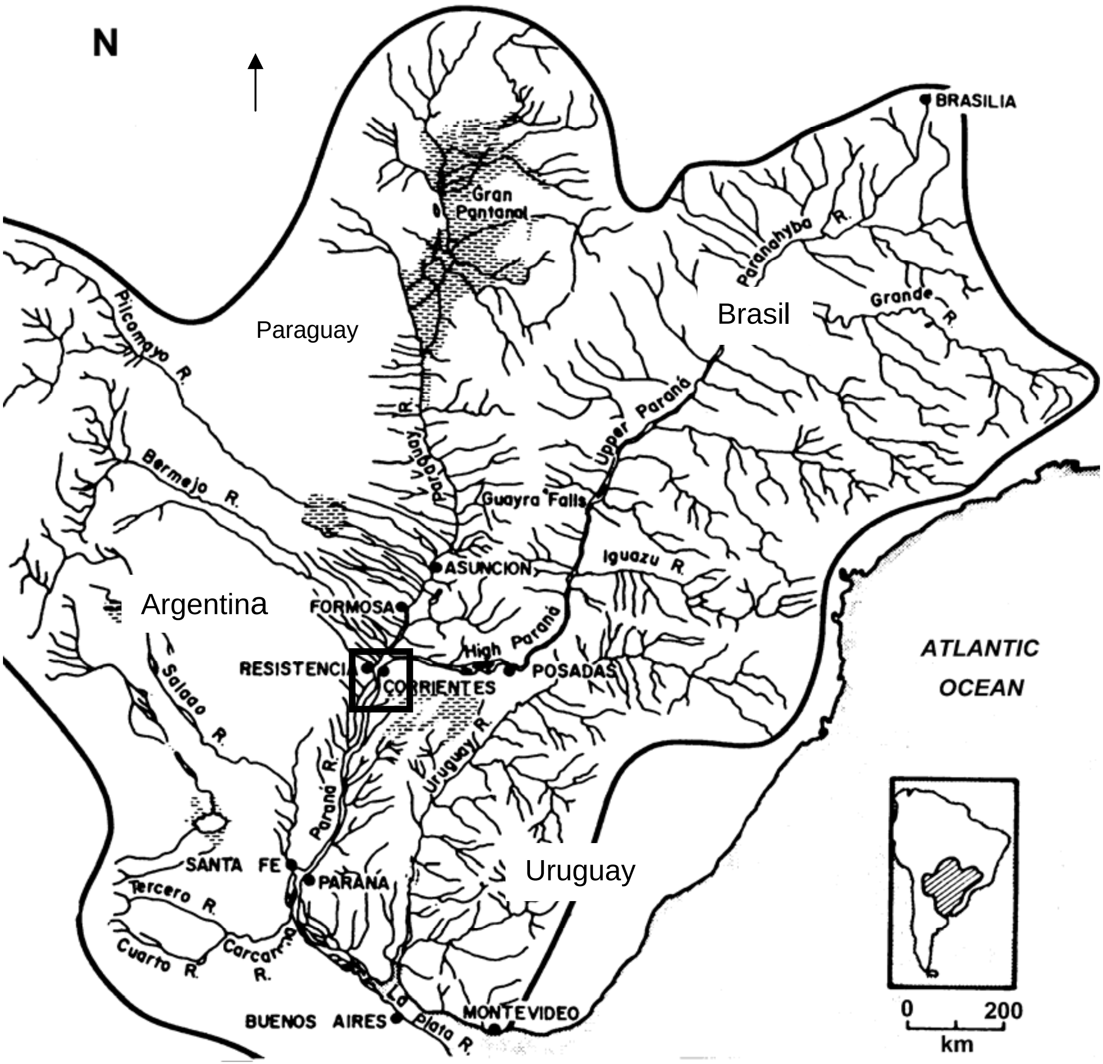


Figure 1. La Plata catchment with the confluence of Parana-Paraguay rivers (inner frame).

Destination	Works	Refugees	Housing	Institutions	Totals
Capital Federal	5843			1432	7275
Buenos Aires	30246	1440	2021	1335	35042
Chaco	41723	1600	5851	3399	52573
Corrientes	48846	2640	9010	4092	64588
Entre Ríos	60890	961	1802	4596	68249
Formosa	23612	2000	5851	2054	33517
Misiones	11983	1360	3145	1048	17536
Santa Fe	103256	2400	7653	8044	121353
Others				19944	19944
Totals	326399	12401	35333	45944	420077

Table 1: Argentina's budget (1000 US$) for controlling ENSO-floods (Núñez & Vargas 1998)

Despite this effort to resolve the problem, it is possible that definitive solutions will not be reached. Nevertheless, an inundation pattern, which has a common sense perception of "flooded land where discharges are not evident but its consequences" does remain as an applied challenge of linking the gap between river ecosystem theory and society's short-term needs. With a real example, we enhance the needs for holistically-based options on either temporal or spatial scale to approach the problem for feasible mitigation strategies.

Area and Methods

Although the causes of an inundation are primarily hydrological, their consequences could be received and transformed by ecological and human actions. The example of cross section of Corrientes Port, where maximum historical flows raised up to 62000 m^3s^{-1} (main river plus local tributaries) is re-examined. To analyse the hydrological dynamics, time series of hydrometric measurements taken at the Corrientes Port left margin-30 km downstream from the confluence of the Paraguay and Paraná rivers by the National Office of Port Buildings and Waterways during the 20th century, were considered. The daily water levels higher than 7.5 m, measured at Corrientes' staff gauge, was chosen to define "extraordinary floods". In Figure 2, only monthly water levels during the 1904-99 period are presented. The overflow in the floodplain is not instantaneously produced from a determined level, but gradually, through lateral banks, paleochannels and natural levees, when the river level reaches 5-6 m in the staff gauge. When the river exceeds the level of 7.5 m, the whole floodplain is covered, except the sites protected by flood defences (Depettris *et al* 2000). Our methodology encompass: (i) a theoretical approach, (ii) an impact assessment summary and (iii) an eco-hydrology approach on ENSO impacted flood-plain wetlands. First, the impact of inundation on natural and human systems was considered, taking into account the effect of frequency, magnitude, duration and seasonality of inundation pulse (Neiff 1996, 1997, 1999) on the landscape (Table 2). *Frequency* phases of flood-pulses along various decades may select plant and animal bioforms in wetlands and must select the real permanence of the people in different areas of the floodplain. *Intensity* may temporally exclude determined populations that live in the margins of the river. *Tension* allows to establish the variability of the events of inundation. *Recurrence* is the probability during time. *Seasonality* could select the organisms that live in floodplains (except for man) which have their reproductive rhythms adjusted to the season in which the inundation and/or drought occurs. If only the pulse seasonality would be modified, impacts on biodiversity could be produced. In fact, all plants of South

American wetlands "known" that they cannot germinate with the soil inundated below a water sheet of 5 cm. The later clearly suggests that larger river systems, especially the South American examples, may be approached as binary systems (Neiff 1996). Of course, Table 2 could also be approached with drought-pulses.

Second, impacts on crops, cities and routes are analysed in parallel. For crop damage, observations were done on natural resources (agriculture, cattle, forestry, etc) during the 1982-83 and 1997-98 ENSO's floods. As a consequence of the ground inundation, a *high damage* was pointed when more than 70 % of crop broke; *moderate damage* when damage did not exceed 40 % of the crop, and *low damage* when it was lower than 25 % of crop loss. When young crops had a height lower than 10 cm, *high damage* was considered in all cases. For city damages, a *high damage* it was considered when the water was flooding the city for more than 2 weeks, producing strong interference in energy services, housing, health and education; a *medium damage* when it was necessary to re-localise from 5 to 10 % of the population in higher areas, and a *low damage* when there were only alterations in the access roads to cities, lower interference in services and low losses of properties (it was possible to occupy housings after the inundation finished). For impacts on route-road structures, after there had been a closing of main routes because of hydric erosion (dike-breaks, piping, gullies, etc.), a *high damage* was attributed, or a *medium damage*, when inundation and damages in routes could be controlled using mounds and temporary defences, and a *low damage* when minor reparations had to be done after the inundation took place (Neiff *et al*. 1985).

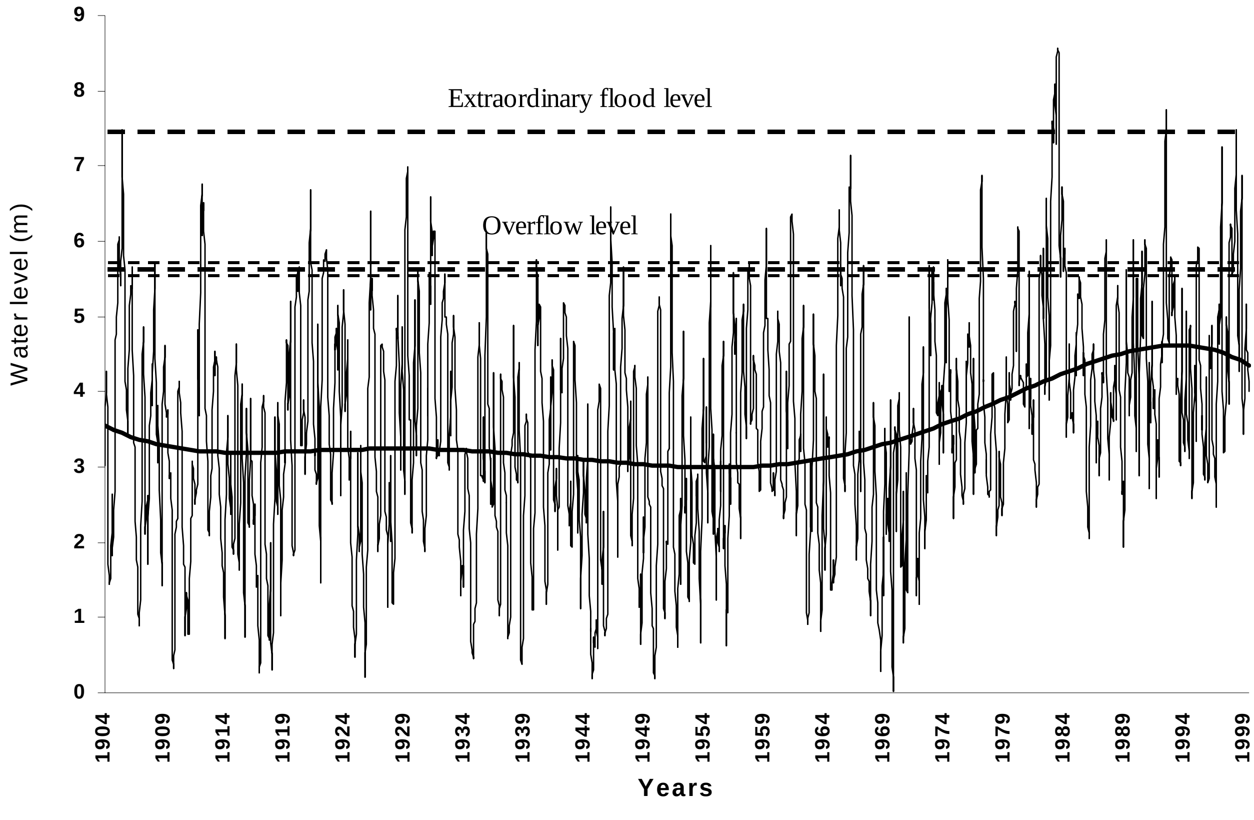


Fig. 2: Monthly water levels at Corrientes Port (1904-1999) downstream of the confluence of Parana-Paraguay rivers. The smoothed line shows the trend of time series.

Complementary discussions of ongoing initiatives studying eco-hydrology parameters over a 5000 km^2 flood-plain downstream of Corrientes Port (Mendiondo *et al* 2000) are outlined in this paper, using multi-temporal remote-sensing images and GIS techniques with spatial resolution of 1 km^2 and within a 10-day time composites during the 1992 ENSO flood.

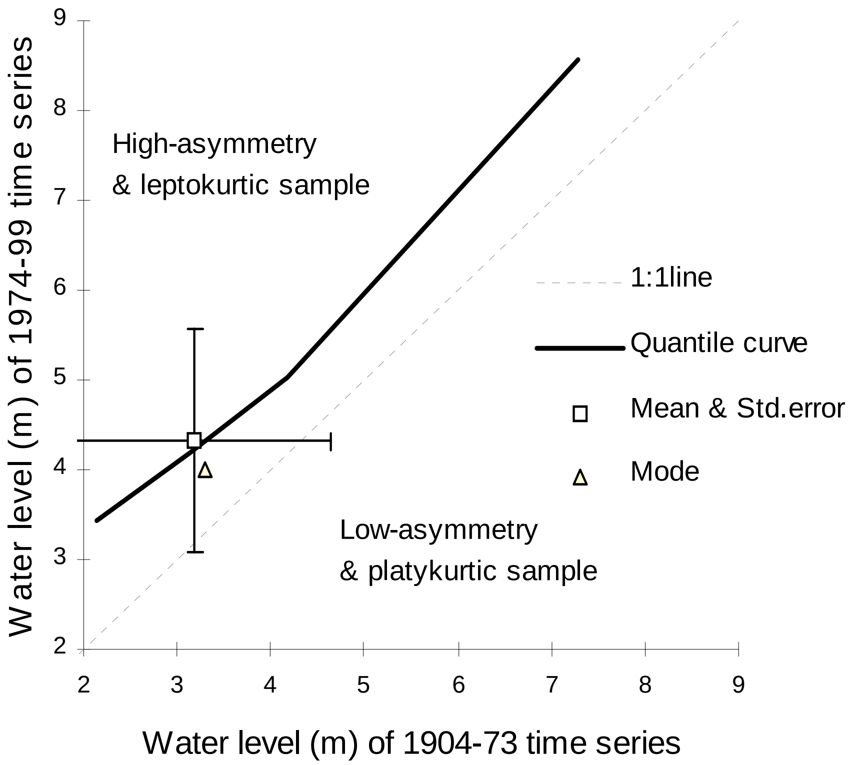
Letter	Parameters and definitions
F	*Frecuency* : phases of inundation in a temporal series
I	*Intensity*: magnitude reached by a inundation.
T	*Tension*: standard deviation from the maximum average in a pluriannual water curves
R	*Recurrence*: statistical probability that a determined flood occurs within a period time
A	*Amplitude*: time duration of inundation of a determined magnitude.
S	*Seasonality:* seasonal frequency with which the inundation occur.

Table 2: Environmentally-based approach of flood pulses causing inundation(Neiff 1996)

Results

Results point that the high catchment of the Paraguay-Paraná rivers is found through an humid period in the last quarter of the century, with much higher values than those of normal oscillations registered in the first half of the century (Fig. 2). For that reason, the 1904-1999 series was divided into irregular periods of time or sub-series. After finding the lowest deviation in relation to the mean, the duration of each sub-series was defined, i.e. 1904-54, 1955-73 and 1974-99 sub-series. The estimated statistics for the first two sub-series were rather similar, and mainly depicted the comparison between the 1904-73 composite period and the 1974-99 period respectively (Fig 3, up). The magnitude, amplitude and season (Fig.3, below) refer to the maximum value registered for that inundation, to the time during which the river exceeded the value of 7.5 m and to the months in which the inundation happened, respectively.

Since 1974, quantiles, mode and median values were substantially modified. The 1904-73 composite sub-series (Fig.3, up, horizontal axis) presented low asymmetry and as a platykurtic sub-sample. The 1974-99 sub-series (Fig. 3, up, vertical axis) differs from the former, i.e. showing high asymmetry and leptokurtic sample. These differences outline the notorious bias between the two sub-series. Annual means of hydrometric values for the period 1901-1972 have a value 1.19 m lower than the corresponding to the period 1973-1999. By using the corresponding level-discharge curve, it is depicted that before the '70s the river transported 30 % less water than at present. The maximum historical value of the series was registered in 1983 and showed a categorical outlier of the time series. The 1982-83 ENSO flood (Fig. 3, below) quadrupled the duration of other extraordinary ENSO events. Other ENSO events with lower magnitude and amplitude were repeated with greater frequency in the second half of the 20th century. Thus, 62.5% of extraordinary ENSO's floods of this century occurred after 1970.



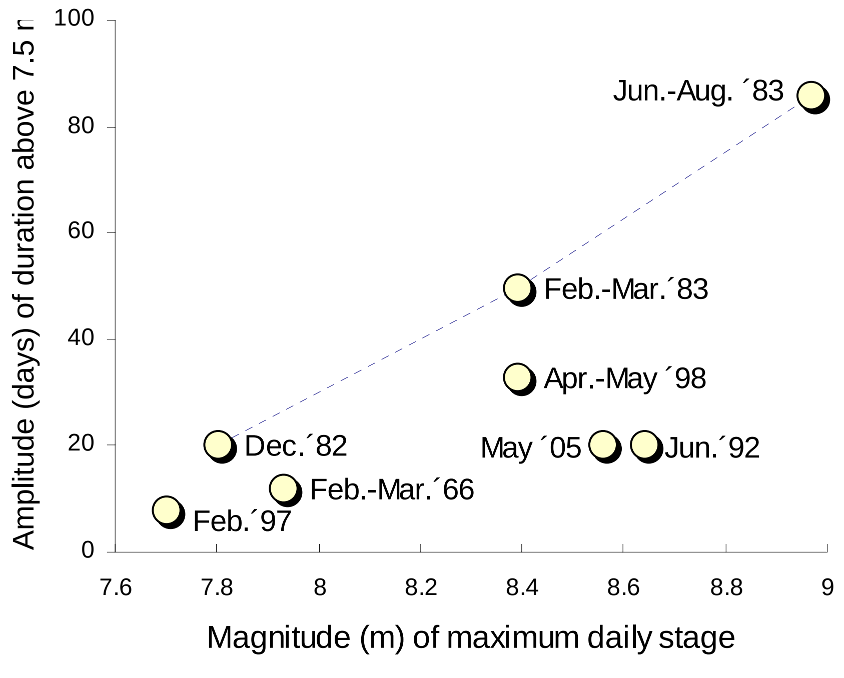


Fig. 3: Above: comparison of 1904-73 and 1974-99 water level records at Corrientes Port. Below: extraordinary floods (1904-99) with the 1982-83 ENSO outlier (dashed lines).

Impacts on the productive system

Our own information, obtained in the 1982, 1983 and 1997-98 ENSO's events regarding the tolerance of the vegetation in relation to the critical period of flooding or inundation, helps to illustrate the impacts (Table 3). For instance, a farming strip of 20 km width in the axis of the Paraguay-Parana rivers was severely affected by inundation. Moreover, a cultivation strip of 3 km width in each of the tributaries of the Paraguay-Paraná system received negative impacts with an almost total loss of production (15 % of the surface of the catchment considered in this study). However, a much larger extension, placed between the meridians 59º S and 61º 30´S, was benefited by the increase of precipitation from 1973 to 1999. In this strip, only minor damages were produced during ENSO's events in 1982 and 1997. On the contrary, receptivity for cattle raising went from 1 animal each 20 hectares to 1 animal each 6 hectares. The natural landscape in this area has also a change: vegetation of semi-arid environments of the so called *Dry Chaco* (Morello and Adámoli 1974) is being gradually substituted by the vegetation of *Humid Chaco*, especially at the herbaceous and shrubby layers.

In other hand, the vegetation of low Paraguay Islands during the 1982-83 ENSO flood suffered important impacts (substitution of bioforms of the herbaceous vegetation, coverage reduction, and also death of 40-60 % of gallery forest trees). Many species of trees persisted, although the ground stayed 1000 non-interrupted days covered by water in the 1978-1983 period (Neiff *et al* 1985). Fluvial forests of large tropical South American rivers are integrated by species that had become efficient to survive in environments of high variability (Neiff 1999). Analogously, some 500 families of fishermen and hunters live together *with* inundation, provoked by ENSO floods, in successive generations and through a life style appropriate to the fluctuations of resources (fishing, hunting, wood) that accompany these hydrological changes. Complementary, the prolonged flooding of the ground can affect many plants and animals (depending on species, growth state, etc.). However, many crops and cattle became less vulnerable.

Way of Production	Tolerance (days)	Impact	Recovery	Adapted?	Predominates
Rice	60	medium-high	low	Yes *	F
Horticulture	5-10	high	low	no	F
Cultivation for flowers	5	high	low	no	F
Tobacco	10	high	low	no	F
Sunflower	30	low-medium	medium-high	variable	F
Cotton	20	medium	medium	no	F
Sorghum	65		medium-high	variable	F
Soya cultivation	10-20	low-medium	medium	No	F
Sugar cane	92	low	high	Yes	F
Banana cultivation	45	low	high	Yes	F
Mainland pastures	5-10	low	medium-high	No	F
Flooded pastures	300-400	low	high	Yes	I + F
Salix humboldtiana	310	low	high	Yes	I
Native Chaco forest	10-75	low	high	Yes	F + I
Eucalyptus saligna	30	high	variable	No	F
Pinus eliotii	80	low-medium	low	No	F
Buffalos	20-90	low	medium-high	Yes	I + F
Cattle	7-20	medium-high	medium	Variable	I + F

Table 3. Tolerance to flood and inundation, impacts, possibility of recovery, adaptation and predomination of some crops and other ways of production in North Eastern Argentina.
Notes: I : inundation, F: flooding, * : in controlled flooding.

Impacts on cities

Since the 15th century up to the middle of the 19th century, many cities of North-Eastern Argentina (i.e. the cities of Clorinda, Formosa, Resistencia, Reconquista and Santa Fe) were established mainly by European immigrants along the Paraguay and Paraná river floodplains, and though very different situations: the river was found in a low water phase. Also, there is only very general information available on the first great inundation of 1905. The second great inundation only occurred in 1966 and had *high* impacts on all the cities which had grown during the meantime. For this case, Resistencia city (see considerations in Depettris *et al* 2000) was flooded and its very precarious defences were built in the emergency and exceeded by water. In 1982-83 floods, most of the cities placed over the Paraguay and Paraná rivers were able to build precarious defences that functioned well in most of the cases. An exception was the city of Clorinda, whose defences were exceeded by the waters of the Paraguay river. A flooding was produced for a few hours in some cities due to the intense rains which occurred inside the dike protected area, since there were no efficient water extraction pumps to outside and because there were no rectification and detour works of some streams and rivers which went through the cities before running into the Paraguay-Paraná system. Impacts could be globally qualified as *medium-high*. During the extraordinary inundation produced by ENSO 1997-98, damages were *medium-low*, due to the construction of permanent defence works and service improvement. However, near 100000 people were affected by the 1997-98 ENSO flood.

Impacts on routes and road infrastructure

From the extraordinary inundation of 1966 to that of 1997-98, negative impacts have increased. The access to Buenos Aires city (more than 10 million people) by the Zárate-Brazo Largo bridge was temporarily closed in 1983. Both in 1983 and 1997, the National routes 11 and 12 were broken by hydric erosion (bridge breaks) in the same geographical points. Numerous provincial routes, some of them constructed a few years ago, of Chaco, Corrientes, Formosa and Santa Fe were over-flooded in various points.

Discussion and ongoing initiatives

First, and relating the impacts on the productive system, the ENSO's anomalies have been taken as a negative, catastrophic events that affect the Paraná-Paraguay riverine system producing severe economic losses in farming and forestry in a vast territory. This journalistic assessment had a strong impact in the economy of Provinces compromised by ENSO event. Important tax advantages and credits to production were given to these Provinces. In some occasions, such advantages were justified by damages provoked by the ENSO event, but not in other cases due to an incorrect assessment of ENSO’s impacts. Overestimation of ENSO’s damages was caused by the use of a wrong criterion. It was considered as *affected* the area of satellite images that was covered by waters without differentiating waters of local rains -or waterlogged areas- from those inundated by the river overflow - or inundated areas-. In the later case, the type of productive activity in the affected area was not taken into account either. In consequence, economic losses outlined were very large since they had to be unnecessarily subsidised by the inhabitants of the whole country. Some crops are very sensitive to inundation (Table 3), however, they are still being used since the beginning of the century, with supporting of credits and incentives from banks, government and other financing agencies. Although rains have increased 25-30 % in the region in the last three decades, these crops turned into highly unpredictable results. The explanation of why these crops are still in use in the region has two components: (i) passivity of the productive system, supported by credit facilities and incentives, and (ii) economic losses due to ENSO's inundation have not been so severe as they were estimated. So, there is an additional source of economic resources coming from the Catastrophe Program implemented by provincial and national governments.

Second, and regarding urban impacts, cities placed on the river floodplains, in general, could tolerate inundation with a magnitude 10 % or higher than that of 1997-98. However, historical records obtained for the 19th century indicate that an inundation of a magnitude 16 % higher than that which occurred in 1997-98 must have happened in 1877, i.e. a water level 10.5 m in Corrientes. Another source of uncertainty, not yet resolved, is that only structural measures have been taken to correct vulnerability of cities and that the diagram of environmental action is still very incomplete. Some neighbourhoods continue to grow at insecure sites outside the defending area because the environmental education, the alert, protection as well the contingency programs are still very incipient.

Third, and regarding the impacts on routes and road infrastructure, the road net in the area included in this study is vulnerable in many cases, since it was designed and built in the first half of the 20th century, when rains and river levels were lower. But it does not seem logical that the same bridges were broken in 1983 and also in 1997-98. It neither seems logical that routes opened in these last years have remained at some points under the water. Obviously, for the calculation of the top level of these roads, the rains of the last three decades were not taken as a reference, but a whole series corresponding to the 20th century, so that the design and security margins become inadequate or insufficient today. For those reasons, it is evident that the routes built are "very rigid" (little adaptable) for a system of high variability.

Fourth, natural landscapes suffer changes in their structure and functioning during the extraordinary inundations, without producing drastic modifications in the landscape patterns. This is due to the fact that the components -relief shapes, plant and animal populations- have a structure that has been selected and adapted for thousands of years. It is also characterised by its plasticity (resistance) and by the capacity of recovering the equilibrium after an inundation (resilience). An example of this is being proposed (Mendiondo *et al* 2000) taking into consideration the analysis of time series of remote sensing satellite images with distributed estimation of vegetation biomass index. Figure 4 (up) shows the 1992 ENSO effects in Southern direction 150 km downstream of Corrientes Port, across 5000 km^2 of the flood-plain of Parana, according to biomass index (Fig.4, up, right ordinates) and non-inundated area of floodplain (left ordinates). The arrows depict the time steps along a river pulse for 140 days. In addition, Figure 4 (below) outlines a resiliency diagram of flood-plain. The time (abscissas) is measured in intervals of 10-day after the beginning of the rising-limb of flood and the statistical probability (ordinates) are related to permanency curves of the 1991-99 period. In addition, the radii of circles are proportional to biomass difference, expressed as a 10-day 1-km^2 Normalized Difference Vegetation Index NDVI from NOAA-AVHRR satellite images, between preserved areas without land uses and the entire floodplain, revealing positive (dark) and negative groups (white) of ecological self recovery, or resiliency, so that ecological tolerance threshold may be addressed with statistical probability. The working hypothesis lies on morphological design and the proportionality of biomass in the system could temporarily decay during extreme ENSO inundations and captured by NDVI relations.

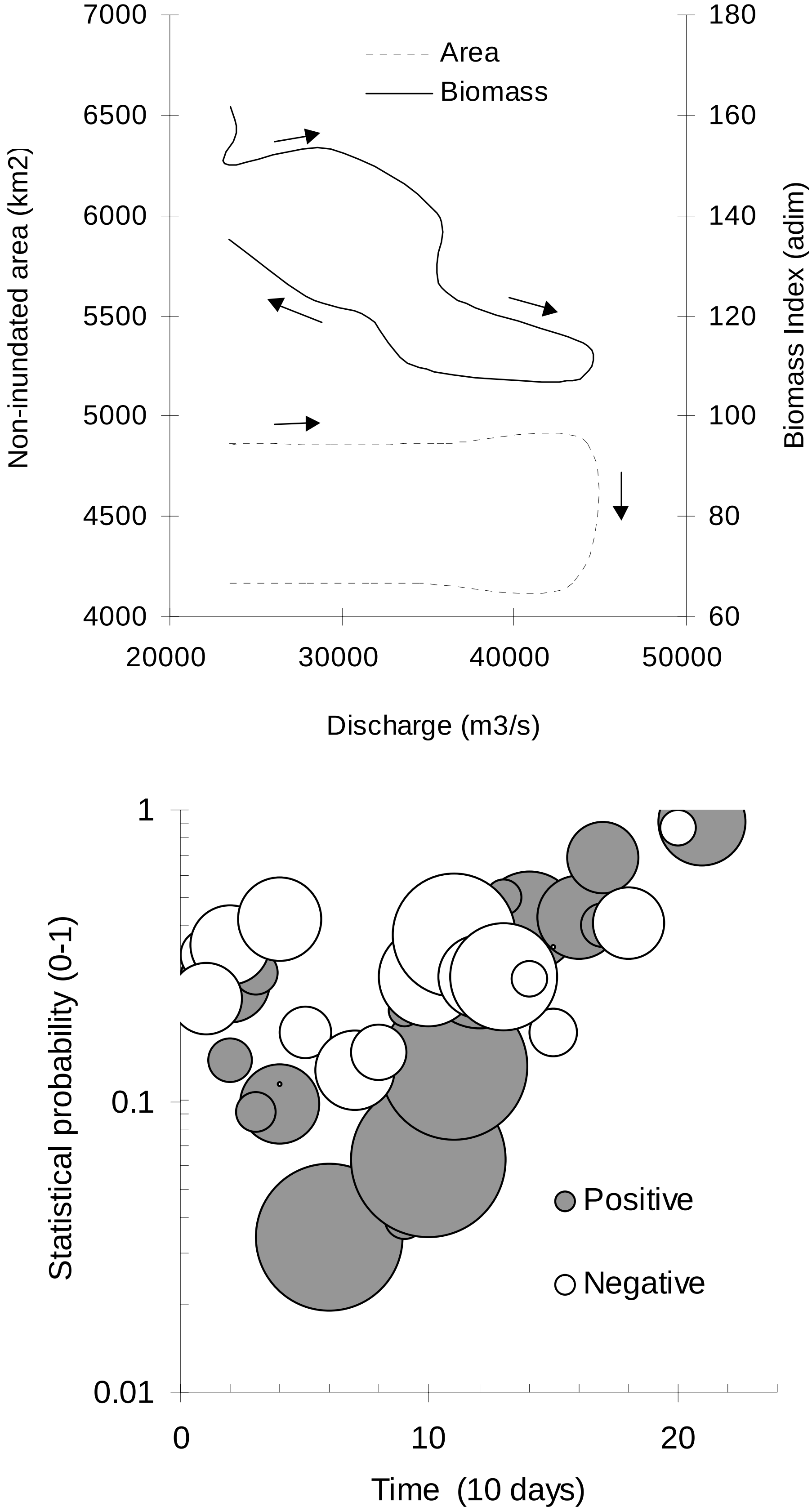


Fig. 5. Above: the 1992 ENSO flood over 5000 km^2. Below: resiliency diagram of 1991-99 period in which three ENSO floods occurred (Mendiondo *et al* 2000). See details on text.

Summary - coping with ENSO’s myths

ENSO's flood impacts depend on the vulnerability of human groups. For their evaluation it is required to discriminate better the differences of risk, uncertainty, ignorance and indeterminacy. First, the *risk* is proposed when the system is known, and the variable intervals and probabilities associated to them could be predicted. Second, the *uncertainty* appears when the system’s parameters are known but not their associated probabilities. Further, the uncertainty also depends on the preceding state of the system and part of it could be supported by the ability of giving rapid responses assessed with technology and available economic resources. Third, the level of *ignorance* is when professionals are surprised by a result but do not know the cause/s or relationships which caused this result -although, sometimes they can give their own explanations!. Finally, the *indeterminacy* is when knowledge is inadequate, the functional relationships are not understood, and the function and structure of the system are not well related between themselves. To summarise, ENSO’s floods are transformed into catastrophes only when they are phenomena in which risk becomes uncertainty.

Likewise, the 1992 ENSO example shows that flood flood-plain ecosystems are well adapted to ENSO’s floods when they are properly approached by adequate techniques and hydro-ecological criteria (Fig.4, up). For instance, a discharge cycle between 22000 and 48000 m^3s^{-1} along 140 days impacts over 700 km^2 inundated flood-plain which decays its biomass index but with a residual difference of only 4 % of initial values. In the other ENSO examples presented here, similar approaches may be done and coupled with river forecast -whether they will occur or not- within 1 or 2 years. Furthermore, the wave flood routing over the whole system may be predicted from 1 week to 1 month. Consequently, there has been a great advance in the cities in relation to the structural measures for the protection of ENSO’s inundations. However, these efforts may become incomplete unless a better environmental action based on education are achieved. The ENSO-impacted routes are also vulnerable because the old engineering criteria have not assumed that the physical environment has very high margins of variability which do not behave within a continuous function but in a series of steps. So, security margins could be better complemented with maximum absolute values than only using the more probable values of a historical series through AFM or POT models, so that the slight frontier between risk and uncertainty in front of ENSO’s floods is traced by the extension (or limitation) of the time series available.

In a brief period of a century, hydrometric measurements of the first 70 years could be 30 % or more below than those of the last 30 years. Therefore, a century of measurements does not allow to dimension security margins for the construction of many hydraulic works in order to roughly define catastrophes as local/regional phenomena of a sudden appearance in which *risk* is transformed into *uncertainty* by means of physical attributes and actions, i.e. management under climate change scenario. Their effect depends on the *vulnerability* of human groups that suffer from them, and also on the preceding social and economic structure and the cultural level of the people. The repetition of the same social and economic problems in succesive ENSO’s inundations shows defects of the environmental comprehension which could and should have been corrected. From what was mentioned above, inundations, in this case, are closer to myths than to catastrophes.

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