FLOOD DEFENCE STRATEGY AT THE CONFLUENCE OF THE PARANA-PARAGUAY RIVERS

by
Carlos A.Depettris[1], E. Mario Mendiondo[2,3], Juan J. Neiff [4] and Hugo R. Rohrmann [5]

[1] Dept of Hydraulics, Northeast National University-UNNE,
Av. Las Heras, 727. (3500) Resistencia, Chaco, Argentina
Tel: +54 3722 420076, FAX: +54 3722 425064. email: cdepettris@ing.unne.edu.ar

[2] Hydraulic Structures & Water-Resources Eng., Fb.14, University of Kassel - GhK,
Kurt-Wolters-Straße 3, D-34125 Kassel, Germany
Tel: + 49 561 804 3538 FAX: +49 561 804 3952 email: mendiond@student.uni-kassel.de

[3] Instituto de Peşquisas Hidráulicas, Universidade Féderal do Rio Grande do Sul, IPH-UFRGS,
Bento Gonçalves, 9500 Cx.P. 15029. CEP 91501-970. Porto Alegre, RS, Brazil

[4] Littoral Applied Ecology Center-CECOAL,
PoBox Nr.222- (3400) Corrientes, Argentina.
Tel: + 54 3783 454421, FAX: + 54 3783 454421. email: neiff@arnet.com.ar

[5] President of Chaco´s Water Administration – APA,
Marcelo de Alvear 32 (3500) Resistencia, Chaco, Argentina
Tel +54 3722 448040 FAX +54 3722 430942 e-mail h.rohrmann@ecomchaco.com.ar

Abstract

To satisfy public demands for integrated flood defences in the Chaco Province, Argentina, a survey on the right bank of the confluence of the Parana and Paraguay rivers was undertaken during the 1998 extreme ENSO flood when the peak discharge was 48248 $m^3 s^{-1}$ and the stage level 2 m higher than bankfull condition. When the banks were over-spilled downstream of the confluence, the flood inundated a flood plain more than 15 km wide. Singular hydrodynamics and non typical conditions were outlined due to human land use in the flood plains of the Chaco Province: dikes, roads, bridges and temporary flood defences with dams frontal to the flow current. New guidelines of land use on flood-plains are defined by the regulation. Indeed, ongoing non-structural measures and interdisciplinary initiatives of Argentine's Nation and Provinces are adopted to cope with non-stationary risk conditions as a consequence of changing return periods of the floods. Integrated research and development efforts by the university, the applied and administration centres tend to find a link multi-sources of information, in order to manage, to conserve and to restore these South American flood plains by flood defence strategy.

Keywords

Parana-Paraguay system, risk planning, integrated flood protection

1. Introduction

This paper analyses inundation patterns of large floods affecting Argentine's territory, South America, between the confluence of the upper Parana River and Paraguay River and 28 °S parallel (Neiff *et* al 2000). This river section has a catchment basin of 2 million km^2, while the study area represents 2500 km^2 (Fig.1). Downstream of the confluence of the two mentioned rivers there are two cities: Resistencia, on the right bank, with lower topography, and Corrientes, on the left bank with upper topography, encompassing 700000 inhabitants.

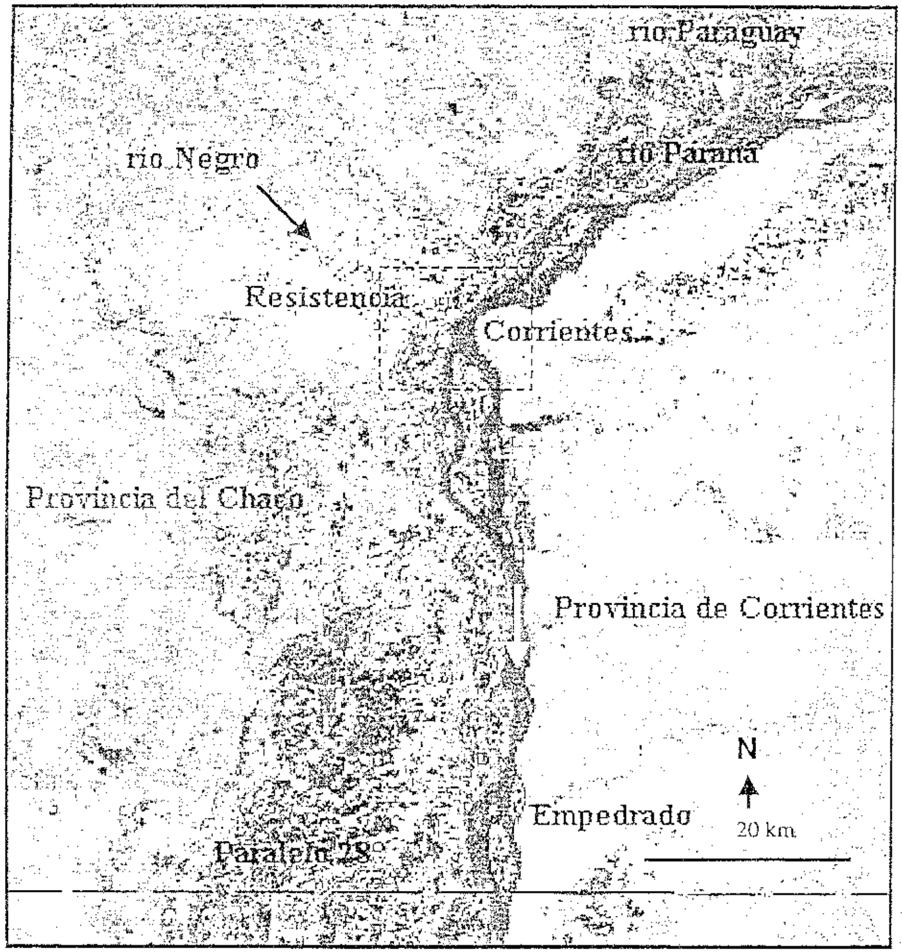

Fig. 1: Satellite image taken during the peak discharge of 48250 m^3s^{-1} on May 5, 2000, downstream of the confluence of the Parana-Paraguay rivers. The inner frame delineates the study area.

The objective of the paper is to depict the ongoing strategies with an integrated criterion for flood defence, to mitigate inundation damages on private property, facilities, and structures, especially roads, bridges, and dikes. In 1998, the Authority of the Water Code of the Chaco Province, by means of the Laws No.3230 and No.4255, approved the Resolution No. 1111/98 (APA 1998) which regulates the zoning and restrictions on land use in the alluvial valley of the Parana and Paraguay rivers. Also, this measure included the Metropolitan Area of Resistencia –MAR-. Nowadays, the above rule is being implemented. Hence, different land uses are specified, delimiting four zones : (1) the forbidden zone or "riverside line" which establishes the limits of public domain, (2) the strongly-restricted zone associated with a 20-year return period flood, (3) the moderately restricted zone associated with a centenary flood and, finally, (4) the warning zone at the geomorphological limits of the alluvial valley.

2. Transboundary Parana-Paraguay system

The characteristics of the Parana-Paraguay catchment are shown in Table 1, and pointed out in Neiff *et al* (2000). The 470000 km^2 catchment area extending downstream of the Parana-Paraguay confluence to the Parana-Uruguay confluence contributes only 10 % of the long-term river discharge. Frequently, big floods affecting the study area are explained by the fluctuations of the upper Parana, Iguazu and Paraguay rivers (Fig.1). Because of the combination of contributed volumes and duration of water levels, big inundation events occur downstream of the confluence. The floods produced by the Paraguay river can be better forecasted and prevented, because of (1) its well-behaved hydrologic regime, thanks to the natural water retention that occurs for longer periods of time inside the floodplains of the upper Paraguay River, also known as the *Pantanal* of Mato Grosso, with small regional slopes of 2-3 cm/km, and (2) the minor contributions of its tributaries of the lower catchment. Since 1970, the major causes of river floods at the confluence have been changes of the precipitation regime, known as ENSO floods (Neiff *et al* 2000), with higher rain concentration between November and April. Discussing climate variations, Tucci and Clarke (1998) presented hydrological records showing increases in rainfall and runoff after 1970, with important impacts in areas such as the Pantanal, and Paraguay and Parana rivers. On the contrary, main flood pulses in the upper Parana River are less predictable than those in the Paraguay river, because hydrographs can show rising limbs of 100 cm over 24 hours, but only of 30 cm at Corrientes (Valdez and Fattorelli 1999). According to historical data series of the 1901-1998 period with floods exceeding 7 m at the Corrientes gage (Table 2), a normal flood pulse of the lower Parana river can appear between January and June.

Catchments and main tributaries	Area (km^2)	Discharge (m^3s^{-1})	Countries
Parana-Paraguay confluence	2 075 000	17 000	Argentina-Brazil-Bolivia-Paraguay
Paraguay	1 095 000	4 032	Argentina-Brazil-Bolivia
Tributary 1 : Pilcomayo	(130 000)	(159)	Argentina-Paraguay.
Tributary 2 : Bermejo	(115 000)	(465)	Argentina.
Upper Parana	980 000	12 968	Argentina-Brazil
Tributary 3 : Iguazu	(24 000)	(1604)	Brazil

Table 1: The Parana-Paraguay system at the confluence. (Secr. Natural Resources & Sustainable Development of Argentina 1997).

Month	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
%	10	14	13	10	16	16	7	2	0	4	1	7

Table 2: Monthly distribution (%) of occurrence of floods at Corrientes (Goniadzki 1999)

3. A case study : The 1998 ENSO inundation in perspective

The origin of the 1997/98 inundation, which started in March 1997 and continued until 1998 in the study area, has been verified using the Multivariate ENSO Index (Flamenco 1999) and the ecological flood pulses (Neiff *et al* 2000). The losses in crop and cattle in Argentinean provinces exceeded US$ 400 million, and affected 31000 km^2 (Rebella 1999). From February to May 1998, the inundation covered the whole Argentinean Parana floodplain and adjacent areas. The maximum stage level occurred on May 5 (Fig.1), with 8.39 m on the left bank (49.81 m above sea level) at the Corrientes gauge station, and of 8.17 m (49.97 m above sea level) at the Barranqueras gauge station on the right bank of the Parana river (Table 3). This flood was the fourth biggest throughout the 20th century.

The evolution of this inundation can be better understood by comparing the accumulated volumes and transforming the stage levels into discharges at Corrientes, applying the rating curves proposed by EVARSA (1998, pers. comm). The average year was obtained from the 1905-1997 period and can be compared, for instance, to the 1982-1983 hydrologic year, when the maximum flood event of the century occurred, and to the 1997-1998 flood pulse. The mean annual volume of 534 km^3 (Table 4) was exceeded by 120 % (1176 km^3) and 64 % (875 km^3) during the 1982-1983 year and the 1997-1998 year, respectively. Likewise, considering the time samples from September to April, with a mean volume runoff of 361 km^3, the 1982-1983 and the 1997-1998 years exceeded the mean value of the above-mentioned month period by 91 % (690 km^3) and 58 % (570 km^3), respectively. However, the floods show singularities after the beginning of the ENSO pattern. For example, the runoff volume until December 1997 was greater than the runoff volume until December 1982. In addition, for the period between September and May, the 1997-1998 inundation parameters were 17 % below the 1982-1983 ones. Moreover, the runoff of the first four months of 1998 was 26 % of the runoff during the same months in 1983 (Flamenco 1999).

Hydrologic year	Maximum level (m)	Date of maximum	ENSO episode
1904-1905	8.57	Jun. 5, 1905	warm
1965-1966	7.93	Mar. 1, 1966	none
1982-1983	9.02	Jul. 18, 1983	warm
1989-1990	7.93	Feb. 1, 1990	none
1991-1992	8.64	Jun. 8, 1992	warm
1996-1997	7.70	Feb. 11,1997	warm
1997-1998	8.39	May 5, 1998	warm

Table 3: Inundation characteristics (>7.50 m) at the confluence (Depettris & Rohrman 1998)

Period	Historical average volume (km^3)	1982-1983 inundation		1997-1998 inundation	
		Volume (km^3)	Variation (%)	Volume (km^3)	Variation (%)
Annual	534.2	1176.3	120	875.0	64
Jan.-Apr.	207.6	419.2	102	308.9	49
Sept.-Apr.	361.3	689.9	91	570.3	58
Sept.-May	408.6	817.9	100	680.2	66

Table 4: Runoff comparison of the Parana-Paraguay system downstream of the confluence

4. Land use of the alluvial valley - a survey of flood defences

The most affected areas by inundation at the confluence are located on the right bank, especially in the Metropolitan Area of Resistencia -MAR. On the left bank a cliff prevails that is higher than the maximum inundation height so that the latter has little impact on Corrientes city. Approximately 80 % of MAR is located inside the alluvial floodplain of the Paraná-Paraguay system, with an average height of 48 m above sea level (Fig.2). The situation becomes worse if one or more of the following factors prevail:

i. ENSO's floods, if the stage level exceeds 6.0 m at the Barranqueras gauge,
ii. Negro river floods, with an average value of 107 m^{3}s^{-1}, that flows into the main river,
iii. rainfalls of 45-70 mm, causing urban problems on more than 20 % of MAR.

Firstly, when the maximum discharge occurs downstream of the confluence, i.e. 30000 m^{3}s^{-1} at Corrientes, the water height (above sea level) exceeds 47.72 m. Secondly, the catchment of the tributaries on the right bank, such as the Negro river, with an area of 338 km^2 and a long-term mean discharge of 21 m^{3}s^{-1}, presents natural responses to rainfalls. Thirdly, if rainfalls occur over the urban areas of Resistencia the situation becomes dramatic. It is frequent that 15 to 25 cm of standing water cover the streets for hours, because, either (1) the flood defence dikes and embankments (against river floods) hinder the stormflow to discharge by gravity, or (2) the maintenance of the stormflow sewage system is insufficient. To cope with this problem, a topographical survey on the right bank over the Antequera-Riachuelo transect was done before the maximum level of May 5, 1998, was reached, in order to understand the relationship between stage level and flood-protected areas in the MAR (Fig.3, Table 5). During this period, the peak discharge of the river was 48248 m^{3}s^{-1} (the annual discharge is about 17000 m^{3}s^{-1}) with a stage level increase of 2.1 m above bankfull condition.

Point	Site	Progressive (km)	Level (m)	Slope (cm/km)
1	Resistencia-Corrientes bridge (access)	0.0	50.42	
2	Barranqueras Port scale	6.0	49.91	8.5
3	"Tamet" provisory flood defences	11.9	49.85	1.0
4	San Martín Ave, Vilelas Port	12.4	49.16	138.0
5	Pluvial compensatory dam	16.1	48.84	8.6

Table 5: Stage levels on flood defence structures of the Metropolitan Area of Resistencia (see Fig. 4) . Survey sponsored by the Chaco Water Administration – APA , May 2, 1998.

Downstream of the confluence, the river has a width of 5 km, but when the banks are over-spilled, the floods inundate a 15 km wide flood plain, with severe changes of the flow current direction and of the hydrodynamics. For example, stage level differences of 1.58 m were measured over the right bank during topographical surveys. That is equivalent to a local slope of 1.37×10^{-4}, instead of an expected value of 7×10^{-5}. Hence, this non typical condition is enhanced by the increase of human land exploitation in the flood plains, i.e. lateral dikes from roads, bridges and, also, dams frontal to the flow current of the river at Vilelas Port.

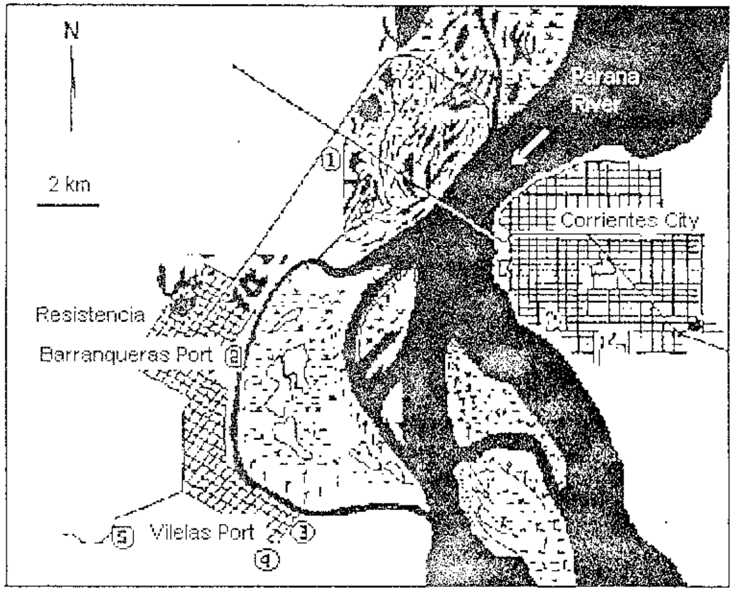

Fig. 2: Surveyed points No.1 to No.5 on the right bank (see Table 5)

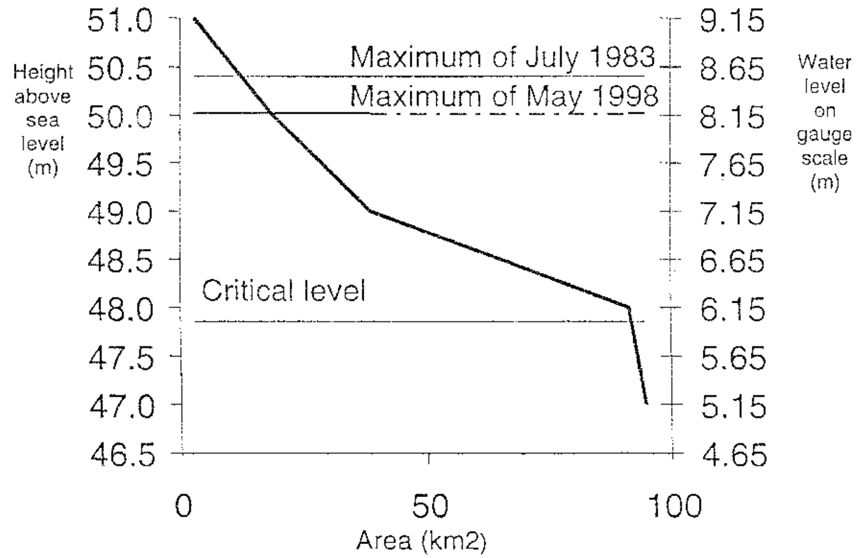

Fig. 3: Spatial distribution of the flood defences (bold line), and maximum and critical levels in the Metropolitan Area of Resistencia and Barranqueras bank.

From this survey the water inundation map, including the flood defences on the right bank of the river floodplain downstream of the confluence, was drawn. The slope of the stage level near the "closing-barrier" created for flood defence purposes underlines the following: (1) the degree of urbanisation inside the alluvial valley of the river, and (2) the need for dikes to protect the occupied area, even during lower return-period floods. The area actually protected against the Paraná river floods on the right bank at MAR is approximately 95 km^2 (Fig.3), if one considers the provisory and permanent constructions. The system of permanent flood defences is made of (1) contouring embankments of the urban areas, (2) one control station for pumping discharges from the Negro river into the Parana floodplain, (3) an internal pluvial drainage system supported by the storage capacity of the urbanised and natural lagoons with their own pumping stations, and (4) the control of floods in uplands and in middle lands of the Negro catchment before reaching the MAR, through by-pass, diversion and routing of the flow excess into the Salado river catchment.

5. Proposed non-structural measures and the legal context

The above-mentioned state-of-the-art flood defence measures on the right bank downstream of the confluence are the consequence of the Government's actions during the nineties. After the damage produced by the 1992 flood, a common decision was taken by seven Argentinean Provinces and the National Government to cope with flood problems of the Parana-Paraguay system, looking for integral flood strategies. Since 1994, actions and guidelines are introduced to coordinate the Nation and Province's management of flood risk areas. Not only defence constructions, or structural measures, but also regulations of land use, or non-structural measures, were developed to search for an integral component of floodplains, for the sake of reverting non-planned settlements. The regulation of the land use was based on three fundaments (Halcrow 1994) :

i. clear rules based on assessment of flood danger and urban vulnerability to the flood,
ii. application of these rules in the floodplain under supervision of legal authorities, and
iii. identification of land uses adapted to the flood risk, with alternative production activities

In the last years, integral studies are executed by the Central Unit of National Ministery of Interior (SUCCE) and the Province's Subunit of Coordination for Flood Emergency of the Chaco Province (SUPCE) to formulate a project law about Riverside Line and Adjacent Areas. Hence, the land use of inundated areas in the Argentina provinces involves structured zoning, with terrain cartography that supports hydrologic risk maps, and establishing not only (1) the forbidden zones (riverside line), the areas with severe restrictions, the areas partially-restricted and the warning zones, but also (2) legal considerations referred to Art. 2750 of the Argentina Civil Code which outlines that "...after defining the shore line, the riverside line and the lagoon lines, the Provincial administration must make their respective demarcation...".

6. Monitored flood risk areas and interdisciplinary approaches

The mentioned non-structural measures should be based on the hydrological risk, partly associated with flood recurrences that are at the origin of considerable losses for local people, structures and the Gross Net Product of the area, as shown by the statistical analysis of extreme floods. The potential to determine the importance of extraordinary river pulses occurred from 1980 to 1998, i.e. in 1983, 1992, 1997 and 1998, respectively. This methodology was performed with annual maximum discharges at Corrientes and annual maximum levels at Barranqueras. Moreover, the historical record was analysed according to : (1) full time series, i.e. 1904-1998 at Corrientes, and 1906-1998 at Barranqueras, and (2) splitted samples, i.e. 1961-1998. These two time series depict the differences in the return periods assigned to extreme floods (Table 6 and Table 7).

Order	Hydrological year (12 months)	Maximum discharge (m^3s^{-1})	Return period (yr) according to:	
			1904-98 record	1961-98 record
1	1982-83	60215	158.7	51.5
2	1991-92	53082	65.8	26.1
3	1997-98	48248	34.8	15.9
4	1965-66	43829	19.0	9.8
5	1989-90	43289	19.0	9.8
6	1996-97	41800	14.3	7.8
7	1986-87	38861	9.3	5.6
8	1981-82	38805	9.3	5.5

Table 6: Statistics of maximum daily discharges at Corrientes Port (left bank)

Order	Hydrological year (12 months)	Maximum water level (m)	Return period (yr) according to:	
			1904-98 record	1961-98 record
1	1982-83	8.60	196.1	44.4
2	1991-92	8.25	85.5	24.4
3	1997-98	8.17	71.4	21.5
4	1989-90	7.66	24.4	9.9
5	1965-66	7.63	23.0	9.5
6	1996-97	7.53	19.0	8.2
7	1986-87	7.28	12.1	5.9
8	1981-82	7.05	8.2	4.5

Table 7: Statistics of maximum daily water levels in Barranqueras Port (right bank)

Both statistical analyses were performed using theoretical probability distributions of extreme floods (e.g. Clarke, 1994). Among these, the GEV- and Pearson-theoretical frequencies of, respectively, maximum discharges and stage levels, were fitted to the sampled Hazen-empirical data. The results depict well the complexity of inundation in large fluvial systems, such as the Parana-Paraguay confluence, as well as their non-stationary conditions, as indicated by the length of time series records used. Maximum discharges, flood volumes and duration times over a critical threshold value must properly be assessed, in order to estimate the inundation volumes over the large flood valley of the lower Parana, downstream of the study area. At this point, pioneering statistical analyses calculated a return period of 250 years for the 1982-1983 inundation (Paoli 1987). Nevertheless, the present analysis (Table 6) attributes an average return period of 50 years to this extreme pulse. Therefore, these differences indicate that the regional scenario is being modified, and that the flood risk must be dynamically evaluated based on the extension of the time series records (Neiff *et al* 2000). Furthermore, the 1997-1998 extreme flood results in an average return period of 19 years, if the maximum discharges and stage levels are evaluated over the last thirty years. In short, this situation outlines that daily living with flood events like the last ones, has to be accepted as a non-extreme situation, since changes of relevant hydrometric and environmental parameters during floods can be predicted by a dynamical risk assessment in space and time.

The authors of this paper have developed the interdisciplinary RioSAC project (Neiff *et al* 1999), with a data collection system, remote sensing and GIS support, which allows to know objectively, and at low cost, the hydrological variability of the river under the impact of floods. In particular, some of these parameters are strongly correlated with the spectral response of multi-temporal remote sensing images (Mendiondo *et al* 2000) when monitoring floods downstream of the confluence of the Parana-Paraguay rivers. Both, non-structural measures and interdisciplinary projects, are being coordinated by Research & Development (R&D) centers, i.e. the Dept. of Hydraulics, the Northeast National University-UNNE and the Applied Ecology Center-CECOAL in order to integrate flood defence with the management, conservation and the restoration of flood plain wetlands of the Parana-Paraguay system.

7. Conclusion

Almost 90 % of runoff at the confluence of the Parana-Paraguay rivers is generated in the Republic of Argentina. These discharge volumes are routed across the transboundary catchment and may be predicted only 7-10 days before. Topographical surveys of the state-of-the-art of flood defences built on the right bank provide the water inundation map downstream of the confluence, supporting ongoing and future actions. Firstly, the alarm forecast network demands updated hydrological modelling coupled with GIS techniques, in order to outline dynamically risk mapping. For this reason, real-time-data-collection systems with training programs and personnel for the acquisition, valuation and processing of hydrometeorological data are being proposed under interdisciplinary initiatives of the R&D centers, i.e. the RIO-SAC project. Secondly, the non-structural measures, during the actual phase, are crucial for a sustainable development of urban areas located on the right bank. Risk mapping of the ongoing settlements, although strongly restricted by regulation Chaco Res. 1111/98, has to be carried out. Finally, the flood dikes under construction in the North of Resistencia will really produce hydrological modifications which must be studied as part of a new phase of integral flood defence strategies.

Acknowledgements

We thank Prof. Dr. F. Toensmann and Prof. Dr. M. Koch, Co-Chairmen of the Int. Symp. Flood Defence, for their useful suggestions to this paper, and Eng. D. Fontana-EVARSA and the Argentinean Ports & Waterways Office for kindly providing the data.

References

APA – Administración Provincial del Agua, 1998: Resolución Nº 1111/98 - Línea de Ribera y Restricciones al Uso de la Tierra. APA Press, Resistencia (Chaco), Argentina.

Clarke, R. T., 1994: Statistical modelling in hydrology. Wiley, New York.

Depettris, C & Rohrmann, H., 1998: Las crecidas e inundaciones recurrentes en el Litoral Argentino". Rev. Vivienda 1998: Buenos Aires (Argentina).

Flamenco, E. 1998: Evaluación de los pronósticos estacionales y pronóstico del volumen de escurrimiento basado en el fenómeno acoplado océano-atmósfera. Dep. Investigación.-ÁreaPronósticos-EVARSA, Buenos Aires.

Halcrow Ass. 1994. Estudio de regulación del valle aluvional de los ríos Paraná Paraguay, y Urugay para el control de inundaciones. Min.Interior-SUCCE Press, Buenos Aires.

Mendiondo, E.M., Neiff, J., Depettris, C. 2000. Eco-hydrology of wetlands aided by remote sensing. In: U. Maione, B. Majone L. & R. Monti (eds) New Trends in Water & Environ. Eng. Balkema, Rotterdam.

Motor Columbus & Ass. 1979. Estudio de crecidas ríos Paraná y Paraguay. Hidrología básica- Vol. 2. Ent. Yaciretá Press, Bs.As.(Argentina) & Asunción (Paraguay).

Neiff,J.J., Mendiondo,E.M., Depettris,C.A. 2000: ENSO floods on river ecosystems: catastrophes or myths?. Int.Symp.Flood Defence, 2000. Herkules Vg., Kassel. [illegible] edition).

Neiff, J.J., Mendiondo, E.M., Iriondo, M., Poi de Neiff, A., Orfeo, O., Depettris, C., Patiño, C. 1999: Respuesta Espectral de la vegetación fluvial en humedales del Bajo Paraguay y Bajo Paraná bajo la Misión SAC-C. Proj.43 CONAE Press, Buenos Aires.

Paoli, C., 1987: Control y protección de crecidas. Análisis probabilístico y perfiles de niveles máximos. Centro Regional Litoral-INCYTH Press, Santa Fe (Argentina).

Rebella, C. 1999: Evento El Niño 1987-98. Utilización de información satelital en la evaluación del impacto de las inundaciones sobre las producciones agropecuarias y forestales. INTA-CONAE Press : Buenos Aires.

Secretary of Natural Resources & Sustainable Development of Argentina . 1997. Hydrologic Statistics of Argentina. SNRSDA Press, Buenos Aires.

Tucci, E.M. & Clarke, R.T. 1998 Environmental Issues in the La Plata catchment. Water Resources Development 14(2), p.157-173.

Valdez, J., Fatorelli, S, 1999: Sistemas operacionales de pronóstico hidrológico a las Cuencas de los ríos Paraná, Paraguay, y Uruguay". Pág.88 a 97. Buenos Aires.