Impact of climate variability and land use in the La Plata River basin

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Abstract

Short and long term climate variability is fundamental for water resource management. Forecasting or prognosis of such conditions enables to reduce vulnerability of water resources against climatic effects and risks in agricultural production, energy supply, navigation and transport.

Significant flow variability was observed in the Rio La Plata basin after the 1970s, resulting in a non-stationary hydrological flow serie (Tucci and Clarke, 1998). Such variability might be a consequence of precipitation variability or of land use. In the first case, there is a chance that the climate variability could be a result of an inter-decadal sample period or even a result of greenhouse effect.

Searching for answers to such questions, the present article analyzes the effects of (discharge) elasticity (increase or proportionally greater decrease) in relation to precipitation in a hydrographic basin, the effects of land use. Based on these conditionings the variability in the Paraná River basin and evidences in the Uruguay and Paraguay rivers are examined. It was verified that there exists a combination of effects, yet the main sign is in regards to climatic variability. Furthermore, a correlation was emphasized between discharge of the three rivers and anomaly of the Pacific Ocean, demonstrating that the variability effects are of global processes. These variations are analyzed, as well as the results of such effects and the relation against the indicators in the La Plata River basin. Lastly, the present article emphasizes the need to go forward in analyses of inter-decadal processes with the objective of distinguishing the sample variability of the potential effect as a result of the greenhouse effect.

INTRODUCTION

Economic and social development is subject to frequent short and long term risks. As society develops and undergoes sophistication, by demanding much more from natural resources, the effects of such pressure are felt in natural resources, such as hydric resources, and at some point, the climate.

Governments are frequently involved in international decision-making discussions concerning climatic alterations such as maintaining large natural reserves and of gas emission. Strategies for development in different social economic sectors depend primarily on water resources. Their short, medium and long term variability can compromise this development.

This publication aims at uniting existing information and analyzes potential impacts for water resources in the La Plata River Basin, considering land use and natural and anthropogenic climatic variability.

Following is a summary of concepts on impacts of land use, hydrological variability and the relation between output and precipitation in the hydrographic basin and the analysis of the Parana River in Itaipu, Paraguay and Uruguay River.

PROCESSES

Effect of land use on flows:

Undertakings of mankind on land use can produce considerable alterations in terrestrial hydrological processes, such as: reduction or increase of medium, maximum, or minimum flows of a hydrographic basin, as well as water quality. A summary of such conclusions are the following:

- Deforestation increases mean flow of a basin by reducing evapotranspiration (Sahin and Hall, 1996; Bruijnzeel, 1996). The impact of chance vegetation may depend on scale effects. Literature has little evidence on land use effect on flow of large basins (Tucci e Clarke, 1998);
- Most hydrological information has been observed in smaller basins internationally and in Brazil, and knowledge of ecohydrological behavior of national biomass is largely reduced due to lack of monitoring and to uncontrolled anthropogenic factors;
- The impact of urban growth also shows significant effects on the environment by creating extremely unfavorable conditions in neighboring rivers near urban centers, besides flooding generated by completely inadequate drainage projects in almost every city of the basin (Tucci e Bertoni, 2003);

Hydrological variability:

The definitions used in the present article are: *Climatic variability*: climate variations on account of natural processes in the world and its climatic variations; *Climatic modification*: alterations in climatic variability as a result of human activity.

Assessment of hydrological processes in different studies of water resources are based on homogeneity of hydrological series, the statistics of the hydrological series do not alter with the passing of time. In reality, this is not the dynamics that has been observed, non-homogeneity of series have appeared due to isolated causes and combined with: (a) climatic modification as defined above; (b) lack of representativeness of historical series to identify the natural variability of climatic processes; (c) alterations in the physical/chemical and biological characteristics of the hydrographic basin as a result of natural and anthropogenic effects. The potential climatic alteration occurs due to gas emissions and increase of the greenhouse effect (IPCC,2001).

Hydrological variability is understood as alterations that can occur at the entrance and exit of the hydrological systems. The main entrances are precipitation and evapotranspiration (which depends on other climatic variables), while the main exit variable is the flow related to: (a) Natural variability of the climatic processes; (b) Impact of climatic modification; (c) Effects of land use and alterations of the river systems.

Relation between Precipitation and Output:

The relationship between hydrological entrance and exit variables exhibits a non-linear behavior. The precipitation alteration exhibits a contrast impact on the output of the hydrographic basin. In the years of extreme values (floods and droughts) the basin non dimensional flow (flow divided by its mean) amplifies its variation as compared to non-dimensional rainfall variation (output elasticity). In the more humid years the rainfall increase produces greater flow increase since there is little infiltration increase and potential evapotranspiration diminishes due to increase of rain, which proportionally increases outflow. Contrary to this, in the dry years, rainfall reduction, evapotranspiration increase reduces output to a higher degree. Therefore, output anomaly (response of the hydrographic basin) amplifies the precipitation effects, if we consider only the rainfall anomaly effect (Figure 1).

Consider two periods denoted as 1 and 2. To verify output variation ($\Delta Q = Q_2 - Q1$) between the two periods in relation to mean output for period 1 ($Q_1 = Q$), precipitation variation ($\Delta P = P_2 - P_1$) was used in relation to mean precipitation of period 1 ($P_1 = P$). Considering the coefficient equation of runnof it is possible to demonstrate the following:

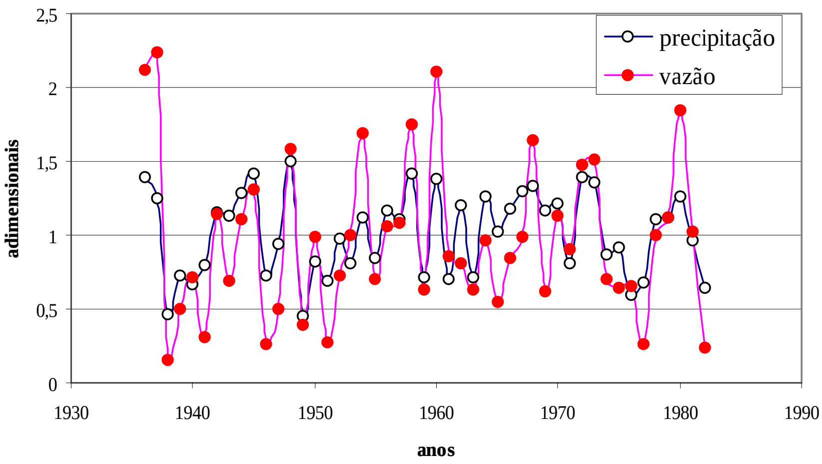

Figure 1- Rainfall and flow in Verde Pequeno river (output obtained by hydrographic model)

$$\frac{\Delta Q}{Q} = \frac{C_2}{C_1}(1 + \frac{\Delta P}{P}) - 1 \qquad (1)$$

where C_2 is the flow coefficient resulting from period 2; C_1 is the flow coefficient of period 1 (C_1= P/Q); There will be a function C =f(P) for conditions of land type and use. Through a mean tendency it is possible to estimate flow coefficient as a function of P variation. By using this mean function and equation 1 it is possible to estimate output variation as a function of rainfall and its percentage variation.

The effect of land use in the relationship between outflow and precipitation enables the relationship between the coefficient of outflow and the precipitation dislocates, as can be observed in Figure 2 (impermeability), since precipitation and output relation alters. Through deforesting there is flow increase due to reduction of real evaporation, thus increasing the flow coefficient. This increase is greater according to the substitution of vegetal coverage and its use.

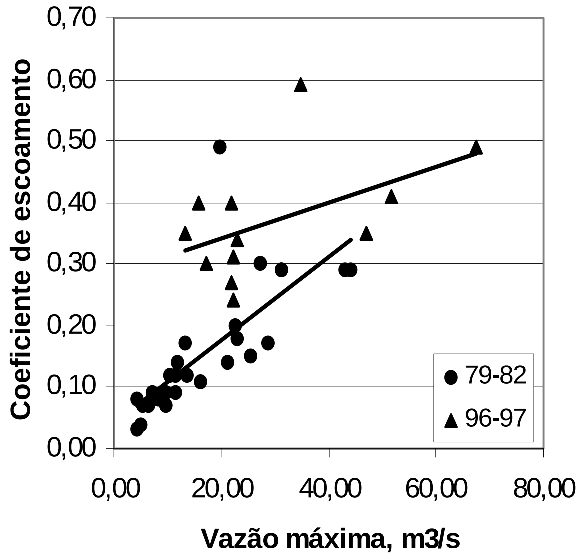

Figure 2 – Flow coefficient as a function of discharge to the basin arroio Dilúvio in Porto Alegre (Santos et al, 2001)

FLOW VARIABILITY IN THE RIO DA PRATA BASIN

Variability of flow series in the Paraná River

Alteration in the series

The flow series in the Paraná River basin exhibit a non-stationary behavior in the periods before and after the 1970s. Table 1 presents the statistics of these values for different sections of the River Parana. It can be observed that increase in discharge varies roughly 30%. This process can also be seen in many sub-basins of the River Parana in the Brazilian territory. Figure 3 also shows the minimum flow increase of 30 days in some of the sub-basins of the region. Resulting questions are mostly: *Is such flow variation the result of* *increased rainfall or alteration of land use? In the case increased rainfall, could it be due to climatic modification or natural climatic fluctuation?*

Potential causes of such flow increase are the following: (a) precipitation increase in the period due to climatic modification or sampling conditions; (b) land modification on account of deforesting; (c) sample variability of flow, combined with rainfall.

Table 2 demonstrates the increase of rainfall seen for both periods in incremental basins of the Parana River and flow increases, which are proportionally greater. Now the question is if in the flow variability the variation is incorporated due to land use?

Table 1 – Mean annual flow $m^3\ s^{-1}$. (Clarke and Tucci, 1998)

Local	Antes de1970	1970-1990	Aumento %
Rio Paraná in Jupiá	5,852 (+)	6,969	19,1
R. Paranapanema in Rosana	1,057 (+)	1,545	46,2
R. Paraná in São José	6,900 (+)	8,520	23,3
R. Paraná in Guaira	8,620 (+)	11,560	34,1
R. Paraná in Posadas	11,600(*)	14,255	22,9
R. Paraná in Corrientes	15,265	19,510	27,8

\+ series of 1930-1970; * series of 1901-1970

Table 2 – Output in the periods before and after 1970 in the sub-basins of the Paraná River (Muller et, 1998).

Basin	$P_2 - P_1$ mm	$Q_2 - Q_1$ Mm	Q_1/P_1	Q_2/P_2	P_2/P_1	Q_2/Q_1
Grande	228	90	0,33	0,34	1,17	1,18
Tietê	193	101	0,24	0,28	1,15	1,34
Paranapanema[1]	183	153	0,25	0,32	1,16	1,45
Incremental[1]	127	199	0,29	0,39	1,10	1,44

1 1931-1994; "incremental" refers to the basin contributory of the Paraná River to the section of the Itaipu hydropower installation; P_1 is mean rainfall up to 1970, with series that vary from 1930 to 1940 up to 1970; P_2 are rainfalls from 1970 to 1990 or 1994; Q_1 is streamflow in the period before 1970 and Q_2 corresponds to streamflow for periods after 1970

Assessment of effects:

The literature is unanimous regarding experiments, demonstrating that deforestation produce increase on the mean annual flow. In relation to the dry spells, deforesting can provoke diminishing or increase of minimum flow, in accordance to ground conditions and with the type of treatment used in deforesting and land use, after deforesting.

However, such conclusions refer to, mainly, small basins where experiments can be controlled. For larger basins the literature is scarce because spatial variability of the different factors that interfere with discharge is quite considerable. However, some important evidence in the incremental basin must be observed (between the Paranapanema and Itaipu river):

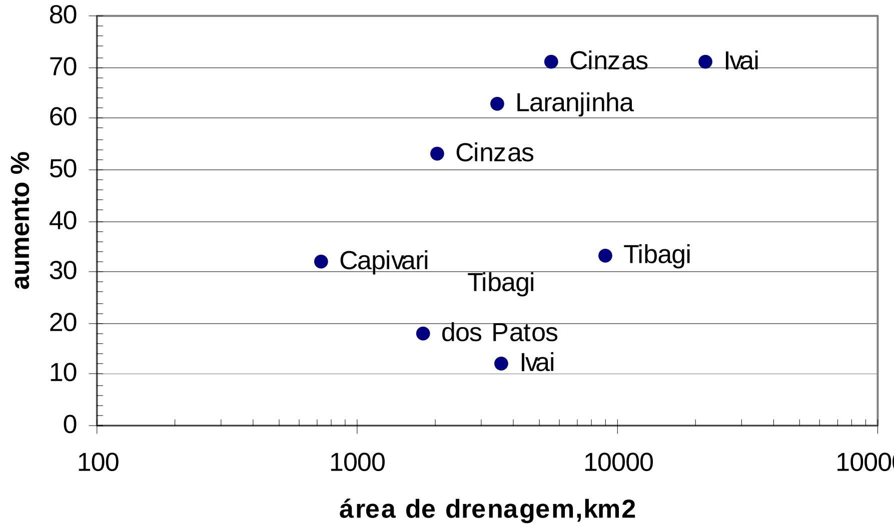

Figure 3 – Percentage increases in 30-day minimum discharge for sub-basins of the Paraná River between the periods: before and after 1970 (data from Mueller et al, 1998).

- A great part of the area flowing directly into the Itaipu lake had not yet been deforested in 1965. Settlement of West do Paraná and deforesting for annual crops in the contributing basins occurred between 1965 and 1980.
- In the remaining incremental area, initial deforesting (until 1970) was for coffee planting in the northern region of the state of Paraná. Coffee has similar characteristics to a forest region, referring to the flow effect, since soil is protected and leaf canopy is maintained;
- The following processes began in the 1970s: (a) noticeable increase of annual cultures as soybean, corn and wheat, creating more flow which maintained year after year; (b) increased mechanization, which raises mean flow still more, due to soil compaction; (c) increase of deforestation in the west part of Paraná. This type of land use lead to conditions that provoke a more important increase in mean flow.
- Where there is deforestation followed by annual cultures, the basin never recovers water balance, as it does when natural forest growth occurs.

This evidence leads to the belief that part of the increased flow occurred due to deforestation of the incremental basin. The greatest difficulty is to know the real impact of deforestation in basins of the size of the incremental basin of the Paraná River in Itaipu, a hydrology scale dilemma. The main doubts regarding the problem are the following:

- Increase of flow in a small basin (some hectares) as a result of deforesting may have its effects reduced if, for the water to be dislocated over the basin, hydrological conditions of evapotranspiration of the surplus flow are created, which replace, at a greater scale, previous conditions of the forests or minimize its effects;
- Potentially the main conditions can be the following:

(a) Greater flow may result in flood plains, and since they occur during the period of potentially greater evaporation, the excess could be replaced to the atmosphere;

(b) The water flowing in the rivers and in the groundwater, along the basin, enables that the volumes, before being intercepted and evaporate. These effects can be superior along a large basin.

From this analysis one can observe that there are many uncertainties that difficult a solid identification if the effects are due to climatic variability or land use and/or combined effects. In fact, there are many indications. Therefore, the main question is the following: *Are the flow alterations permanent or transitory?*

This is an obvious question because increase of water availability influences many sectors of water resources such as energy, water supply, irrigation, etc. Thus, combining the elements herein dealt with, we can conclude the following:

- Evidence existing up to now show that the increase result (if not by sampling conditions) of outputs can be due to a composition of two effects: (a) rainfall increase in the period; (b) modification of land use;
- Rainfall increase has higher probability of being sampling effect, therefore its permanence is not guaranteed, perhaps in the future going through less precipitation cycles;
- Increase due to changes in land use must be permanent;

An approximate quantitative analysis with macro values was performed considering the following:

- Increase in flow is smaller in the drainage basins in the State of São Paulo where deforestation had already occurred before 1970, therefore it can be expected that the analyzed flow will be able to reflect only climatic variability. In Table 2 one can see that the increase of flow coefficient between both periods was not very high for the Grande and Rio Tietê basins. By using the equation and estimating the runoff coefficients based on data of the basins, values of 20,9 and 34,6% flow increase were obtained, respectively. In Table 2 the values are 18% and 34%.This indicates that difference in flow only depends on rainfall increase;
- In the Paranapanema and Incremental basins, where deforestation occurred in the 1960s and changes in annual crops occurred after 1970 (see previous items), there is significant increase in runoff coefficient observed for both scenarios, which are not justified only by rainfall increase. Based on equation 1 there was a flow percentage of 35% and 20%, respectively. Table 2 shows that increases were 45% and 44%. In a simplistic assessment it can be concluded that difference between the values of 10% and 24% would correspond to the effect of land use in the basins. Such values represent 25% and 55% of total variation in the period, respectively;

These conclusions were obtained on macro data and some simplifications, but can be considered an initial estimative of impacts seen in this region.

Variability of the series in the Paraguay River:

Throughout the 20th century the basin of the Paraguay River showed significant hydrological variability. Figure 4 shows the maximum annual levels at Ladário for the entire period registered. It can be observed that between 1900 and 1960 the maximum levels were averaged around 4,00 m, while between 1960 and 1972, they were at around 2,00 m. However, between 1973 and 1995 they varied about 5,0 m. Figure 5 shows the same results of permanency levels for the three periods (Tucci,2005).

Considering that the beds are unstable and moving and erosion and sedimentation are significant, the first questions that came up are the following: (a) can transition of the river bed explain level variations observed in the 1960s? (b) could the Ladario scale have changed position or location during the period? (c) can these variations be completely explained by land use variation? (d) can these changes be explained by climatic variability or climatic modification?

The first two questions can be discarded since other basins exhibit similar pattern (Tucci,2005). However, regarding the last two questions, the answer is more complex.

During the 1970s two important circumstances occurred, the first one was a considerable migration to the Plateau and the introduction of annual culture plantations (as soybean) and increase of cattle ranching, mainly in the Plateu of the river Taquari. Annual cultures produce two fundamental effects in the hydrological cycle: increase in mean flow due to deforestation and continuous soil alteration and sediment build up. The ground in the Alto Paraguay Plateau is very fragile and expansion of cattle and soybean generated significant increase in producing sediment. However, the area that is occupied by soybean is insignificant when compared to the area with cattle (Figure 6). Furthermore, the land occupied by cattle is hardly productive and is fragile. Such fragility favors erosion, especially in the tracks created by moving cattle.

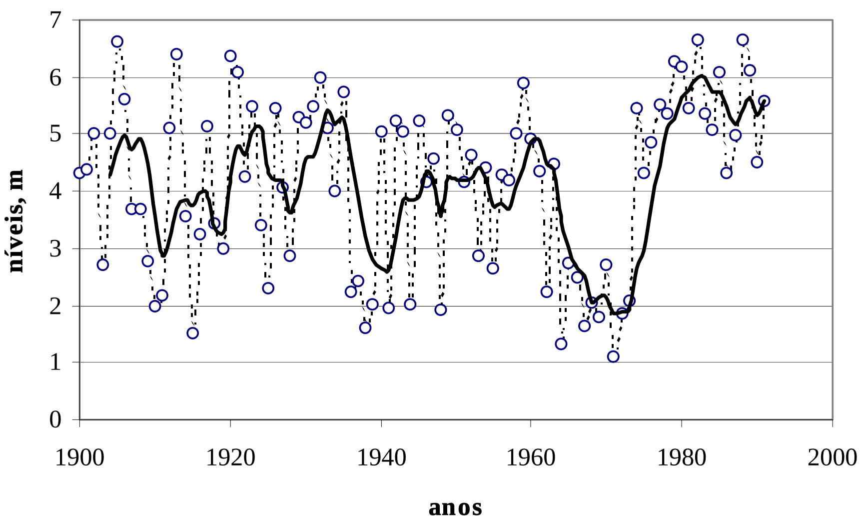

Figure 4 – maximum levels in Ladário and 5-year moving average.

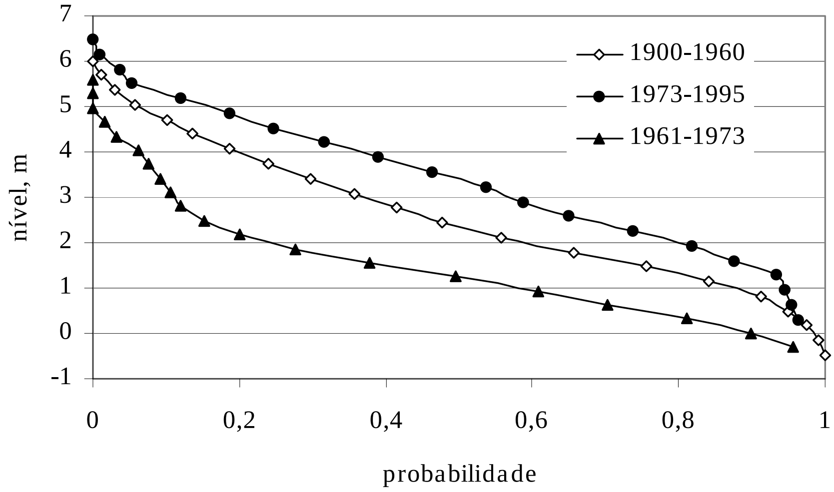

Figure 5 – permanence curves for the three periods: 1900- 1960; 1961-1972 and 1973 - 1995.

The second important consideration was increase in rainfall, which elevated erosion capacity and mean flood flows. The results showed that during the 1960s rainfall was below average for the long period, approximately 15% (average of the period) throughout all those years.

Collishonn (2001) analyzed the effects of land use and rainfall variability by means of a hydrological model. The model was adjusted for the period after 1973 and used to forecast for the period after 1973. The model overvalues the results for the period before 1973, thus indicating that the parameters do not represent physical conditions of this period, hence components exist of land use that were not depicted. The model was adjusted for the period preceding 1973 and verified for the posterior period, demonstrating that it tends to underestimate flows, a result of land use alteration and not only of climatic variability. The cited author preliminarily estimated that of the total alteration from 200 mm to 500 mm, between both periods, land use would correspond to values between 74 and 100 mm, of about one third of total alteration of flow variation.

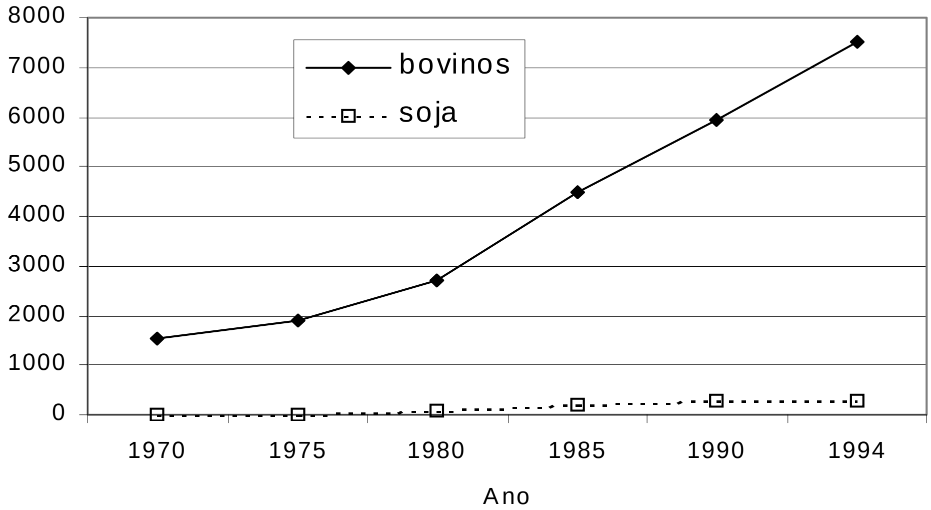

Figure 6 Land use area (ha) (Collishonn,2001)

Variability of flows in the Uruguay River:

The Uruguay River presented land use change during the second half of the twentieth century, with only 5% of native land coverage remaining. Analyzing the series of flow records of the Passo Caxambu (52.000 km^2) station in Alto (upper course) Uruguay inside the Brazilian part of the basin (Figure 7), a growing trend of flows can be observed (moving average of three years). In this series one can observe that between 1942 and 1952 flows are low and the period before that shows a growing tendency. When analyzing non-dimensional series (anomalies) in the lower course of the Uruguay River (Figure 8), it can be observed that the period after 1970 is maintained above the whole period before it, fluctuating in another baseline of mean flow. Moreover, both stations show that despite representing basins of very different dimensions, they shows a similar non-dimensional mean annual flow variability as well their moving averages (Figure 9).

The importance of these periods can be seen as data of rainfall anomalies in Passo Fundo in the Upper Uruguay (Figure 10). The rainfall variability can be observed as noteworthy in the 1940s (42-52). By using the flow series with data from 1940 for the dimensioning of a reservoir in the upper part of the basin, one can obtain useful volume of 100% more than what can be obtained with the series beginning in 1953 (IPH, 1991).

Regarding land use, the basin of the Uruguay River showed significant changes in land use after the 1950s, and more recently, after the 1970s with increase of soybean cultures. After 1994, there were considerable alterations in agricultural practices when farmers went from conventional cultivation to direct cultivation (after 1994).

Collishonn (2001) presented assessment results of land use using a hydrological model distributed to large basins. Table 3 exhibits results of simulating land use alterations. The current scenario exhibits a flow increase of 9% as a result of land use. By transforming the forest basin into annual cropping the flow increase is of 14,4% and for pasture it is of 13,2%. Therefore, the current impact of land use already represents 69% of maximum impact (worst scenario). These numbers do not justify all relative increase that occurred after the 1970s.

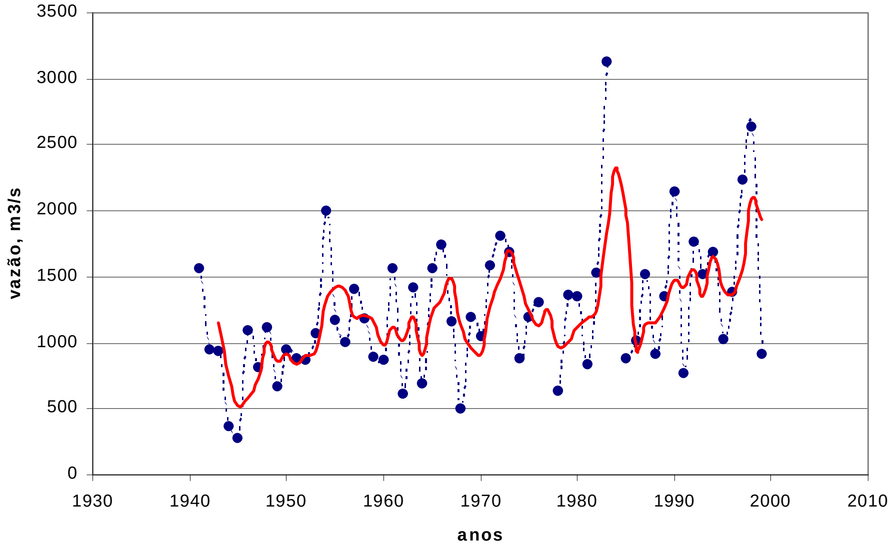

Figure 7 – Mean annual flows and 3-year moving average in Passo Caxambu in the Uruguay River.

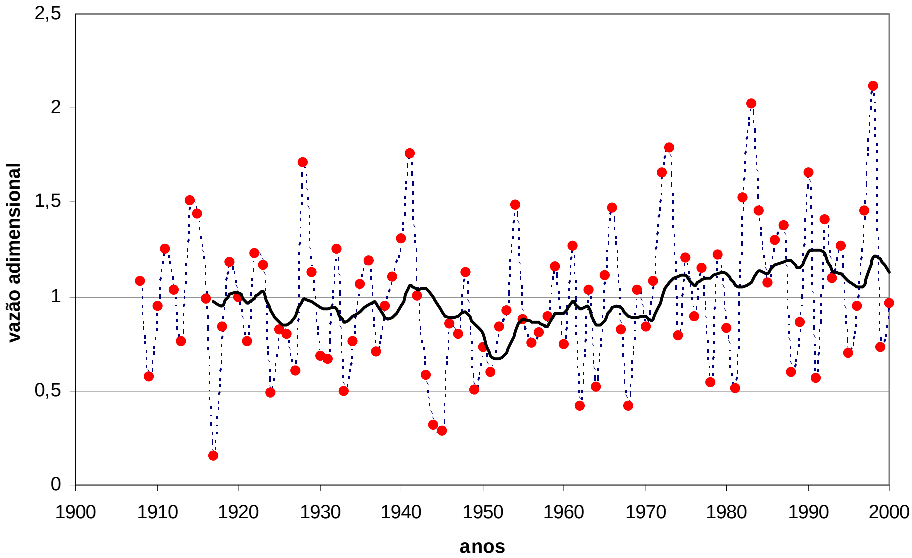

Figure 8 – 10-year moving average of flows in the Uruguay River in Paso de Los Libres.

Table 3: Average discharge, runoff lamina and runoff increase relative to hypothetical situation 100 F (column ΔQ indicates the difference of annual flow in relation to hypothetical situation 100 F, where the basin is completely covered by forests) (Collishonn, 2001)

Situação simulada	Q $M^3.s^-$	Q mm.	ΔQ $mm.ano^{-1}$

	^{1}	ano^{-1}	
ATUAL	653	765	62
100 F	600	703	0
90 F 10 P	607	712	9
90 F 10 L	608	713	10
100 P	679	796	93
100 L	686	804	101

L – culturas anuais   P – pasto - F florestas

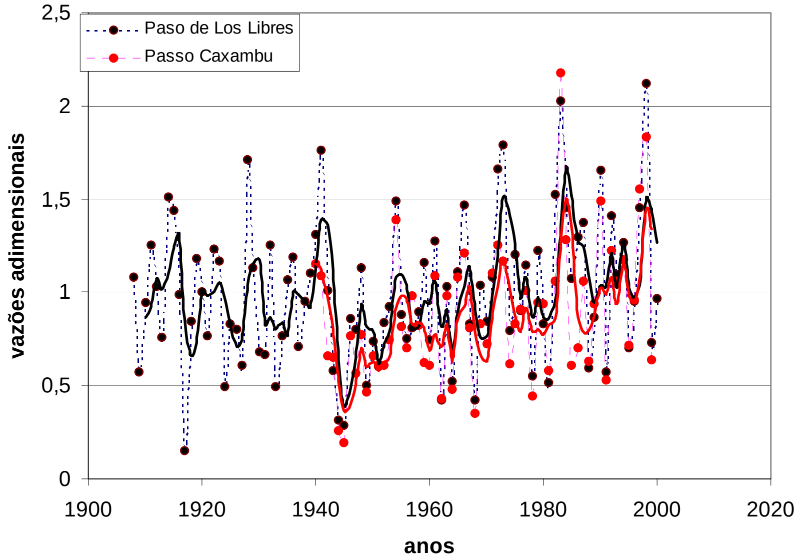

Figure 9 - Undimensioned outputs in Passo Caxambu (~52.000 km^2) and Paso de Los Libres (~200.000 km^2) stations in the Uruguay River

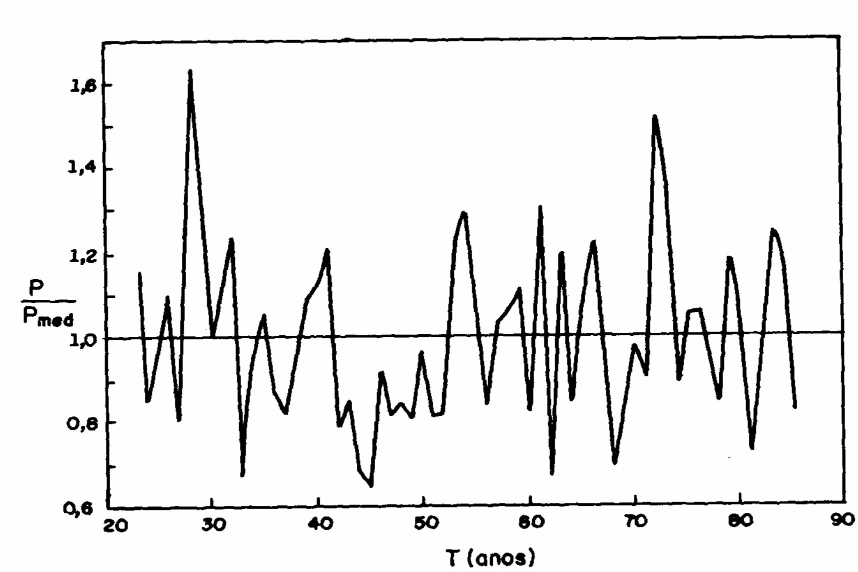

Figure 10 – Undimensioned annual precipitations in Passo Fundo in Upstream Uruguai (IPH, 1991).

Comparison among basins:

Figure 11 shows the series of moving 10-year averages of flow anomalies of the rivers Paraguay (Pilcomayo), Uruguay (Paso de Los Libres) and Paraná (in Posadas). It can be observed that for Paraná River, as well as for Uruguay River there are similar tendencies, but the Uruguay River presents more short term variability, characteristics of a smaller basin without seasonableness and without memory (less natural regulation). The basin of the Paraguay River showed great variability in the decade of 1960, going from very dry to very humid.

The three series show similar tendencies concerning the wet and dry periods. Note that the three curves follow a decreasing tendency along the first half of the century up to almost 1970, when all three curves begin to increase and after the 1980 they remain above average of the previous period.

Figure 12 shows the tendency relationship between pressure variation (standardized) between Tahiti and Darwin in Australia, indictor of conditions of the Pacific Ocean and the anomalies of the three rivers.

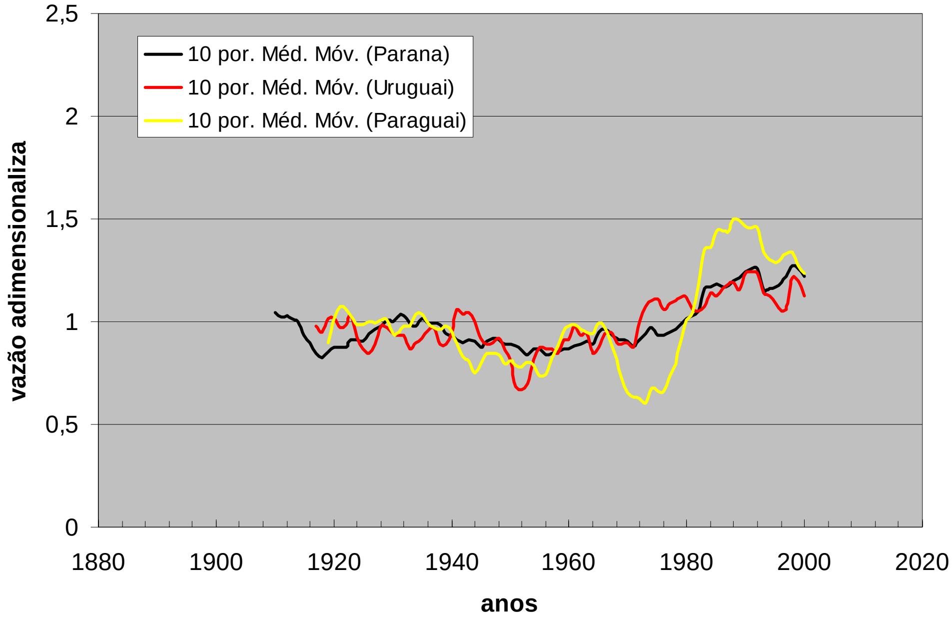

Figure 11 – 10-year moving average of flow in the Paraguay River in Pilcomayo, Uruguay in Paso de Los Libres and Paraná in Posadas.

In Figure 12 the values are negative (higher temperatures) or with decreasing tendency from the 1970s, oscillating in this zone up to 2001. This period coincides approximately with the mean flows above those observed for the Rivers Paraguay, Uruguay and Paraná. In the previous period there is also the inverse tendency. The period of negative periods indicate higher sea temperature tendency than when they are positive. In this case there is more evaporation of the sea in the atmosphere, causing greater quantities of potential precipitation. Such relations can be used for long term forecasting of increase and reduction humidity tendencies in the Brazilian basins of da Prata River. In Figure 13 one can observe the relationship between ten-year moving averages of the Parana River and of pressure differences in the Pacific. One can observe that the group with lesser dots, which portrays recent years, deviates less. Using moving averages enables to analyze how the tendencies of a longer period behave, since the interaction process of climate, atmosphere can have inertia. However, it should be taken into consideration that averages carry correlating values.

Collishonn et al (2001) showed the complementariness of the flow series between Africa and South America. While since 1970, in Africa, the periods are very dry, part of South America (R. da Prata basin) undergoes a wet period above average.

From this analysis it can be concluded that the observed climatic variability is a grand scale process which occurs in the planet and the effects in this region show increase in precipitation and discharge. On the other hand, as already known, there is correlating indication between the behavior of the Pacific and discharge of the R. da Prata River.

Conditions such as these lead to an obvious question: could a variability behavior be natural or a climatic impact? A simple question for a complex problem, which still demands more detailed assessment and comprehension of what is happening.

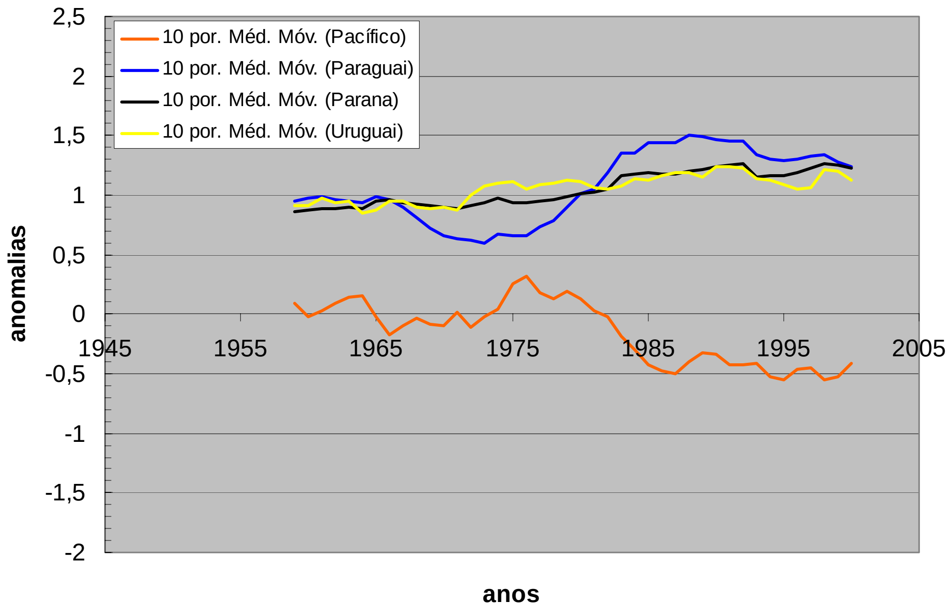

Figure 12 – Ten-year moving average of anomalies of the Paraná River and pressure difference in the Pacific Ocean.

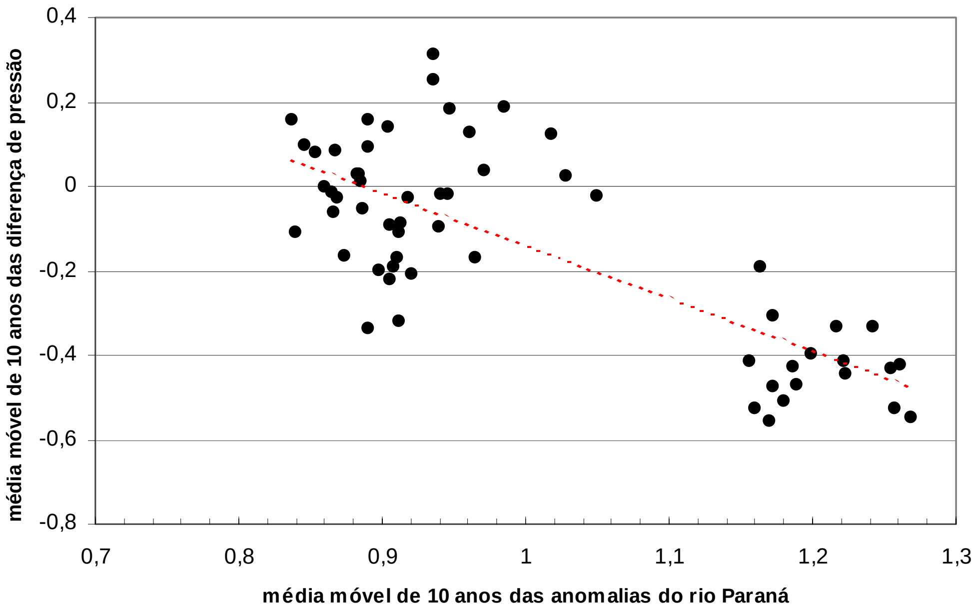

Figure 13 – Comparison of flow anomalies with pressure difference of Tahiti and Australia in the Pacific Ocean.

CONCLUSIONS

The progress of water resources throughout the twentieth century was based on techniques proposed by engineers for the dimensioning and planning of water systems. The bases of all such techniques are statistics of historical series of flows measured in the rivers. Thus, the following basic principles are initially admitted:

- The flow series are homogenous or stationary, their statistics do not vary with time;
- The samples used are representative.

The series is stationary when the statistics of the series do not alter with time. Non-stationary can occur as a result of one or more of the following factors:

- Climatic variability during the sample period;
- Climatic modification;
- Modification of land use.

Climatic varialbleness and sample representativeness are similar conditioners, since lack of representative sample data may not show all variables of the statistic population of the series. The last two factors represent anthropogenic effects on the system.

What is observed is that there are few series with a period superior to 80 years and only in the last decades increased the number of long series, pointing to inter decadal characteristics of climatic and hydrological processes. There are series of climatic variables obtained by correlations with ice or rainfall samples based on tree rings, yet this is indirect information that leads to an idea of behavior, but differ from effectively observed values.

Knowledge of climatic behavior has been assessed based on data series, for the most part 20 to 50 years of hydrological data. Series of 100 years are rare, thus, much of the research on climate variability and behavior are based on samples of short periods, which may be misleading.

Tucci and Clarke (1998) and Collischonn et al (2001) showed that large sized basins in South America (Paraguay and Parana River) and in Africa exhibited long periods with different trends. While South America exhibited rainfall and flow increase after 1970, in Africa there was substantial reduction. The questions that easily appear regarding the causes are: are these long term tendencies, which science has not been able to identify, due to the short periods of the information? Could this behavior have been influenced by anthropogenic conditions such as land use or warming due to the greenhouse effect? Answers to such questions require important scientific endeavor within an integrated and global view of the hydroclimatic processes at a global and meso-scale level. On the other hand, even if there is no complete understanding and no possibility of forecasting such processes beforehand, it is vital to understand the impacts that society is subject to due to these variables in order to plan mitigating measures.

The main conclusion taken from this analysis is that is vital to revise project and planning practices based on the concept of stationary series. The series must be revised and practices of non-stationary series treatments designed.

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