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ASSESSING LONG-TERM DISCHARGES OF THE PLATA RIVER

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1. Introduction

The Plata basin is the second in size after the Amazonas basin in South America, with almost 3 million Km², and the fifth in the world. It includes parts of southern Brazil, eastern Bolivia, all Paraguay, western Uruguay and northeastern Argentina. The most important rivers are the Paraná River, which starts in eastern Brazil, the Uruguay River and the Paraguay River that runs southward from western Brazil joining the Paraná River near the Argentine city of Corrientes.

The Plata Basin is the most developed region of South America having most of the gross economic products of the continent. Its water resources are the basis of agriculture and power for the countries that share the basin. Therefore, it is important to foresee how climate change may affect the discharges of its rivers during the next decades.

Most part of the Plata River discharge originates in the Northern part of its basin (i.e., over Brazil and Paraguay), where the runoff accounts for only 30% of the mean precipitation volume (Berbery and Barros 2002). In this paper, this northern part of the basin was divided into five sub-basins. The first one corresponds to the Upper Paraguay River from its origin to Ladario (Brazil) (SB1 from hereon); the second one (SB2) covers the rest of the Paraguay River excluding the Chaco, where the runoff is very small (Berbery and Barros 2002); the third sub-basin corresponds to the upper part of the Paraná basin in eastern Brazil up to the locality of Jupiá, including basins of tributaries that are the source of the Paraná River (SB3); the fourth one (SB4) stretches from Jupiá to the junction of the Paraná River with the Paraguay River and the last one is the Upper Uruguay basin (SB5). Figure 1 shows the Plata Basin and each of these sub-basins. The western and southern parts of the basin were not considered because their contributions to the total discharge were comparatively very small.

The discharge behaviour between sub-basins shows great differences and it has already been studied extensively in previous works (García and Vargas 1996; Berbery and Barros 2002). The annual precipitation cycle controls the discharge regime of the rivers. The northern part of the basin (SB1 and SB3 and the northern part of SB2 and SB4) has a monsoon climate with a definite precipitation maximum in summer. Over SB5 and in the south of SB2 and SB4 there is a more evenly distributed precipitation all the year round.

The Pantanal is one of the biggest wetlands in the world, characterized by its small slope (Tossini 1959), typically less than 1.5 cm Km^{-1}. For this reason, despite having most of the rainfall in summer, the Paraguay River discharge lags the precipitation maximum by almost 4 or 5 months, with a peak around May or June (Fig. 2). At the outlet of the SB3, the river discharge lags little behind precipitation because this sub-basin has a

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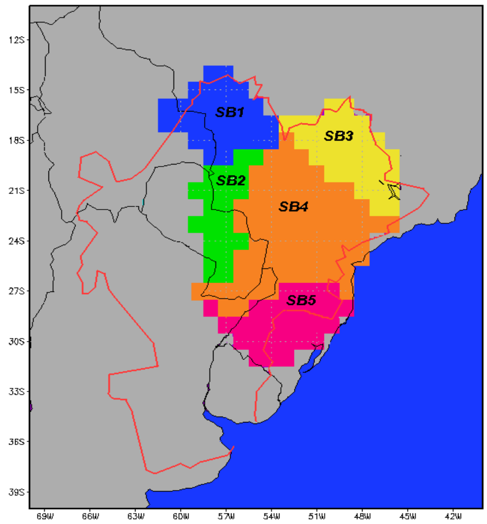

Fig. 1. The Plata Basin (delimited by a red line) and the SB1, SB2, SB3, SB4 and SB5 sub-basins. Sub-basin borders were defined to the nearest latitude-longitude entire degree.

predominantly steep terrain. Finally, at Corrientes, the annual regime of the discharge integrates the Paraguay contribution as well as the SB3 (monsoon type) and SB4 (evenly distributed rainfall along the year).

General Circulation Models (GCMs) project a mean temperature rise over the Plata Basin for this century (Camilloni and Bidegain 2005) under all global socioeconomic scenarios. Accordingly, evaporation would also be considerably increased affecting the runoff and the streamflows of the rivers. However, it is worth to keep in mind that these climate models do yet have considerable errors in the simulation of the temperature and precipitation fields over the Plata Basin. Therefore, there are still considerable uncertainties about the potential climate changes that global warming may cause in this region. Nevertheless, given the serious impacts that a diminution of the runoff would cause in the Plata Basin, it is worthwhile to make a rapid exercise to assess the order of magnitude of the potential change in the discharges of its main rivers.

The objective of this paper is to show the adjustment of a simple hydrologic model

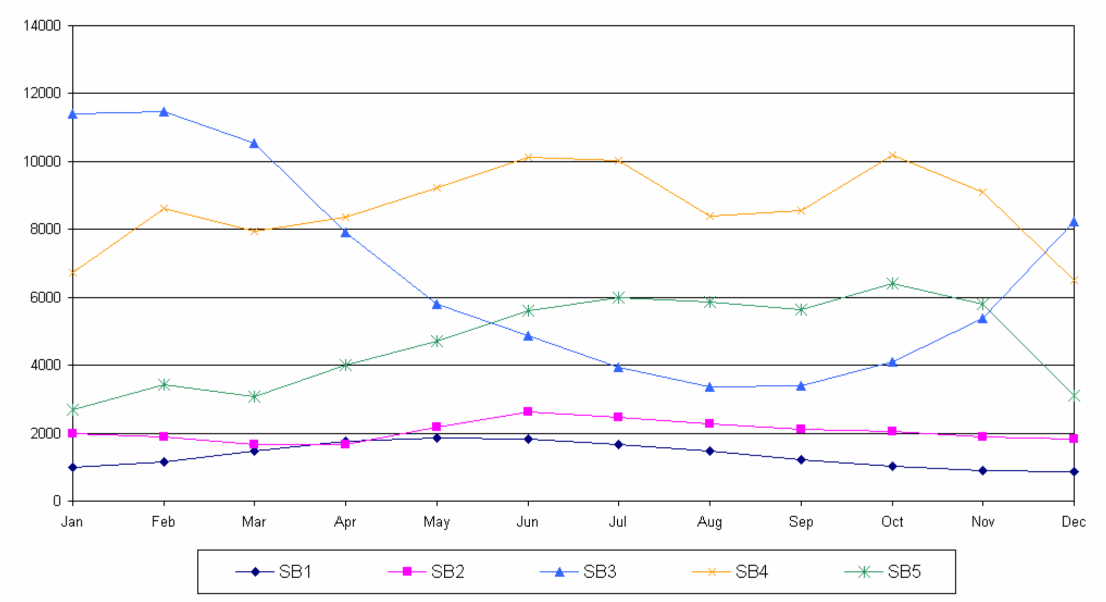

Fig. 2. Monthly mean discharges over the five sub-basins. Units are $m^3\ s^{-1}$.

to the mean decadal discharges of the Plata River and to make a sensitive study of discharges of the main river to a mean temperature rise.

2. Data

To assess long-term mean river discharges, a simple hydrology balance model was adjusted. The balance included precipitation, evapo-transpiration and discharges. Monthly discharge data at Corrientes (27° 27'S, 58° 49'W) and Paso de los Libres (29° 43'S, 57° 04'W) were obtained from the Argentine Undersecretary of Hydrology; discharge measurements at Asunción (25° 16'S 57° 38'W) were taken from the Hydraulic Laboratory of the National Administration of Navigation and Ports of Paraguay, while Ladario

(19º 00'S, 57º 35'W) discharges were calculated from the Paraguayan river levels with a rating curve based on measurements taken in 1996 for the study of the navigation system of the Paraguay and Paraná Rivers (Hydroservice-Louis Berger-EIH 1996). Finally, discharge measurements at Jupiá (20º 48'S, 51º 37'W) were obtained from the Operador Nacional do Sistema Elétrico (ONS) of Brazil. Discharge data covered the period January 1963 to December 1999, with only some months lacking in Ladario and Asunción during the 1990-1999 decade. Figure 3 plots the location of the closing points used in the five sub-basins.

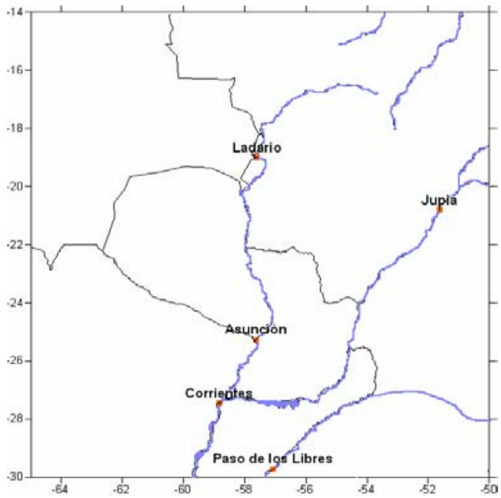

Fig. 3. Closing points of the five sub-basins.

Real evapotranspiration (RET) was estimated from potential evapotranspiration (PET) using the Blaney and Criddle formula (Blaney and Criddle 1950). This formula takes into account mean temperature and latitude. Monthly mean surface temperatures over the Plata Basin were obtained from two datasets, the NCEP/NCAR reanalysis dataset (Kalnay et al. 1996) and the Delaware University surface temperature dataset (Willmott and Matsuura 2001). The NCEP/NCAR surface air temperature dataset has a resolution of 2.5º latitude x 2.5º longitude. The Delaware monthly mean values of surface air temperature have a spatial resolution of 0.5º latitude x 0.5º longitude. Both datasets were regridded into 1º latitude x 1º longitude grids and then averaged for each sub-basin.

Time series of the NCEP/NCAR surface temperature dataset minus the Delaware surface temperature dataset for the entire period (January 1963 to December 1999) for each sub-basin are shown in figure 4. It can be seen that differences between both datasets are quite large for some months of the year, reaching values of up to 5ºC. The Delaware dataset has greater temperature amplitude throughout the entire period than the NCEP/NCAR's (that is to say, warmer summers and cooler winters). The surface temperature fields of these two datasets have been constructed from different data. Delaware's surface temperatures were interpolated from the surface station network, while the NCEP/NCAR's surface temperatures were extrapolated from upper air analysis. The first one has the disadvantage of being built from scarce observations across the Plata Basin, while the second one was not constructed using actual observed surface data. In spite of this, the annual means of the difference between dataset temperatures were relatively small, and did not exceed 1ºC. As it will be seen later, these differences do not affect the bulk estimate of discharges. There was a clear improvement in the agreement between both datasets from the mid- to late- 70's, coinciding with the beginning of the systematic use of satellite soundings in the reanalysis. The exceptions are the SB1 that includes the Pantanal, where surface observations are very scant, and the SB5 where Delaware data seem to have a spurious trend.

Future temperature data were obtained from the A2 scenario outputs (available at, for example, Camilloni et al. 2005).

Monthly precipitation data included 3009 series of surface observing stations over the basin (Fig. 5). These data were interpolated into a 1º latitude by 1º longitude grid, and then averaged over each of the five sub-basins. These 1º by 1º grid data are available online at the website of the Regional Climate Lab of CIMA www-atmo.at.fcen.uba.ar/~lcr/datos/pp.htm, for the area covering the Southern Hemisphere part of South America. Long term runoffs over the five sub-basins were considered equal to the respective discharges or contribution to discharges at the closing points of the sub-basins. To obtain discharges over the five sub-basins, monthly discharge values from the five different closing points were used, i.e., Ladario, Asunción, Jupiá, Paso de los Libres and Corrientes. For the SB1, the discharge was given by the values measured at Ladario. For the SB2, the contribution to the discharge was calculated by the difference between Asunción and Ladario that would measure the runoff generated in this sub-basin. Jupiá's discharge represents the SB3 discharge and the SB4 contribution to discharge was calculated as the difference between Corrientes minus Jupiá minus Asunción. Finally, discharges measured at Paso de los Libres represent the SB5

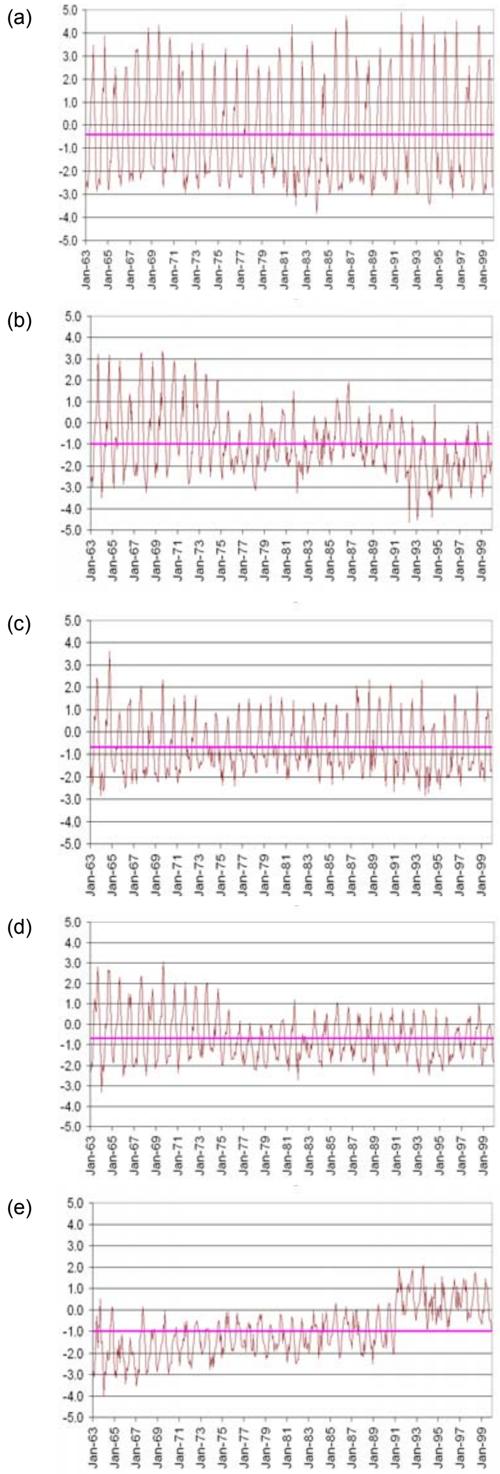

Fig. 4. Time series of the difference between NCEP/NCAR and Delaware temperature datasets (brown line) for (a) SB1, (b) SB2, (c) SB3, (d) SB4 and (e) SB5. Units are ºC. The mean difference value is shown with a pink line.

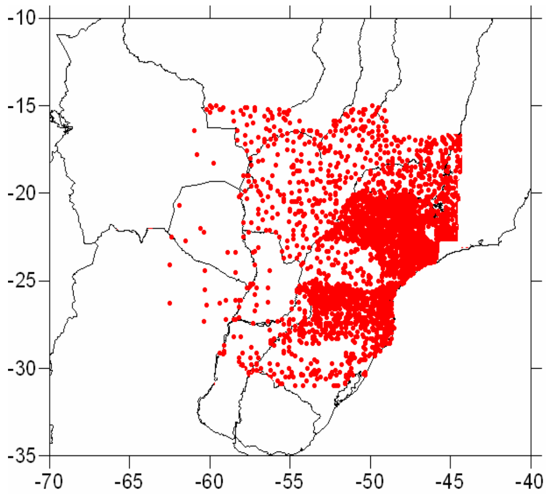

Fig. 5. Plot of the available 3009 precipitation stations.

discharge. The contribution of the Lower Paraná to the Plata River total discharge is small and poorly measured (Berbery and Barros 2002), and measurements suggest it should be no more than 2,500 $m^3\ s^{-1}$ (Argentine Secretary of Energy 1994), and for this reason this part of the Plata Basin was not considered in the present article.

3. Model development

The Blaney and Criddle PET formula has been found empirically (Blaney and Criddle 1950), and its adjustment was performed over the western part of the United States, equation (1). For this reason, the value of the parameters contained in the formula, namely α = 0.014, β = 0.363 and γ = 1.95, are suitable for the type of climate of that area but may not be as appropriate for other climates. The use of this equation has become quite widespread because of its evident simplicity. In equation (1)

$$PET = p(\alpha T^2 + \beta T + \gamma) \tag{1}$$

PET represents the monthly potential evapotranspiration in mm/month; p is the monthly percentage of sunlight hours and T is the monthly mean temperature, in units of ºC.

In equation (1), only monthly mean temperature and latitude are needed to calculate PET. The values of p, which depends on the latitude of the place where the equation is to be used, are tabulated. As this equation needs a unique value of p (and thus, of latitude), mean latitudes were obtained for each sub-basin. Mean latitude for the SB1 was set at 17ºS; for SB2, at 23ºS; for SB3, at 19ºS; for the sub-basin SB4 it was set at 23ºS, and at 29ºS for the SB5.

a. Evaporation and runoff modeling

The evaporation model uses PET calculated from equation (1). PS is defined as the difference between the monthly precipitation (PP) and the PET (Eq. 2). The soil water (SW) is considered as the water content over the entire soil layer and is defined as in equation (3), namely as the soil water of the previous month (SW_{-1}) plus PS minus the surface runoff of the previous month (SR_{-1}).

$$PS = PP - PET \tag{2}$$

$$SW = SW_{-1} + PS - SR_{-1} \tag{3}$$

The threshold (THR) is the amount of soil water that saturates the soil. Soil water values from equation (3) exceeding THR constitutes the runoff. If SWD is defined as the difference between THR and SW (Eq. 4), then when SWD >0, there is soil water deficit and there is not surface runoff. If SWD <0 there is soil water excess, which is considered surface runoff.

$$SWD = THR - SW \tag{4}$$

In those cases in which PP plus SW_{-1} exceeds PET, PET equals RET (Eq. 5) and, in this case, when PS is lower than or equal to SWD, the surface runoff SR equals 0 (Eq. 5i); otherwise, SR is equal to PP plus SR_{-1} minus PET minus THR, as it can be seen in equation 5ii.

$$PP + SW_{-1} \geq PET \Rightarrow RET = PET \tag{5}$$

$$\text{if } PS \leq SWD \Rightarrow SR = 0 \tag{5i}$$

$$\text{if } PS > SWD \Rightarrow SR = PP + SW_{-1} - THR - PET \tag{5ii}$$

On the other hand, when PP plus SW_{-1} does not exceed PET, then RET equals PP plus SW_{-1}, as it is considered that all the water contained in the soil layer is evaporated, and in these cases SR equals 0 (Eq. 6).

$$PP + SW_{-1} < PET \Rightarrow RET = PP + SW_{-1}$$

$$\Rightarrow SR = 0 \tag{6}$$

Alternatives where not all the soil water content under PET level evaporates were explored, but they did not make much difference in the long term discharge estimates.

An initial value of SW = 0 is assumed to begin the iteration. The model outputs are monthly values of SW, SR and RET. To compare the calculated runoff with discharge observations, they were multiplied by each sub-basin area (Table 1).

Table 1. Sub-basin areas in km².

Sub-basin	Area
SB1	271,000
SB2	239,200
SB3	395,700
SB4	734,900
SB5	238,900

b. Model calibration

The 1990-1999 decade was taken for model calibration. The first step was to adjust the first two parameters α and β of the PET formula and THR to minimize the error in the estimated runoff. The third parameter, γ = 1.95, was not changed as it was considered to be a reference value of PET at 0ºC.

In the first calculation, a THR value of 100 mm was assumed for the five sub-basins and α and β were set at the original Blaney and Criddle's values. This resulted in underestimations of the discharge values of the five sub-basins, Table 2. The differences between observations and values from the model were high over the five sub-basins.

Table 2. Comparison between estimated and observed decadal discharges for each sub-basin and for the entire Plata Basin using the original PET formula for the 1990-1999 decade. Percentage relative differences (PRD) in %. Discharge units are $m^3 s^{-1}$.

Sub -basin	Estimated	Observed	PRD
SB1	1,051	1,202	13
SB2	746	2,435	69
SB3	4,669	6,614	29
SB4	4,078	10,432	61
SB5	3,795	5,329	29
Total	14,338	26,012	45

The estimated discharges were nearly half the observed values, suggesting that the Blaney and Criddle formula could be overestimating PET values over this area and thus reducing the water availability for runoff. Among the five sub-basins, the one with the worst adjustment is the SB2, showing a difference of near 70%.

In the following runs α and β were changed to reduce differences between model and observed discharges. However, in SB1 and SB2, it was not possible to reduce these differences by merely changing α and β. It was necessary first to increase THR. This reflects the fact that these sub-basins with low slopes retain water in swamps and lagoons.

Once the THRs were modified, values of α and β were revised in successive runs until long term discharges were adjusted to observations. The calibrated values of α, β and THR for the calibration period 1990-1999 are shown in table 3.

Table 3. Calibrated values of α, β and THR for the five sub-basins. Units of THR are millimeters.

Sub-basin	α	β	THR
SB1	0.013	0.31	150
SB2	0.013	0.17	130
SB3	0.011	0.28	100
SB4	0.013	0.18	100
SB5	0.011	0.30	100

Values of modeled discharges, as well as percentage relative differences with the observations, are shown in table 4.

With the calibration performed, the percentage relative difference between the observed and modeled Plata River discharge of the calibration decade becomes near 0%, and a good fit was also achieved in the five sub-basins, with differences not exceeding 1%.

Table 4. Idem table 2 but for the calibrated PET formula.

Sub - basin	Estimated	Observed	PRD
SB1	1,214	1,202	-1
SB2	2,419	2,435	1
SB3	6,617	6,614	0
SB4	10,498	10,432	-1
SB5	5,304	5,329	0
Total	26,052	26,012	0

The adjustment was performed to fit the discharge of the entire decade. Thus, there could be important differences between annual values. Figure 6 shows the time series of annual observed versus modeled discharges over the worst (SB1) and best annually fitted (SB5) sub-basins during the 1990-1999 decade. Years 1990, 1991 and 1999 are missing in the SB1 figure due to lack of data. The SB1 shows huge differences with the observations while the SB5 time series shows a very good fit between the modeled and observed discharge values, with a slight increase in the error toward the end of the period. These results indicate that the calibration was good even at annual level in the sub-basins that have acceptable data. It is known that the Pantanal region lacks enough surface temperature data. Furthermore, this model may not be adequate for this sub-basin, which has a topography that resembles a plate where discharges become important only after the depressed areas are completely flooded.

c. Model validation

The periods 1963-1969, 1970-1979 and 1980-1989 were used for validation. Sub-basin total discharges over these periods were obtained and used for comparison with the modeled values. Ladario and Asunción had several months lacking during the 1990-1999 decade, so these months were discarded in the measured discharges as well as in the modeled discharge values before making any comparison. This lack of data affected only sub-basins SB1, SB2 and SB4.

Validation results, using the PET formulas obtained in the calibration step with the validation decades observed discharge values, are shown in table 5. Among the five basins, the SB5 also shows the best fit in the validation decades. Relative percentage differences do not exceed 10% for this sub-basin in any decade. The SB1 is the worst calibrated, with differences of up to 51% in the 1963-1969 decade. This could certainly be due to the large lag between precipitation and runoff observed in this basin, which is not properly modeled with the hydrological scheme used here. When analyzing the entire Plata River basin discharges, validation results show errors not exceeding 11% (during the 1970-1979 decade), and as low as 1% for the 1963-1969 decade. Then, although inter-basin results show different behaviors, with some basins very well fitted (SB5) and some showing strong deviations, when the Plata Basin is considered as a whole the errors remain bounded at the 10 % level.

Using the Delaware dataset, PET was calculated again for each sub-basin and the same time periods, using the same parameters adjusted for the 1990-1999 decade with the NCEP/NCAR's data. In this case, then, all the periods (1963-1969, 1970-1979, 1980-1989 and 1990-1999) were taken as validation decades for the adjusted formulas. Table 6 shows the validation results using the Delaware dataset for the four decades. SB1 is also the worst fitted with this dataset, with relative percentage differences exceeding 70% in

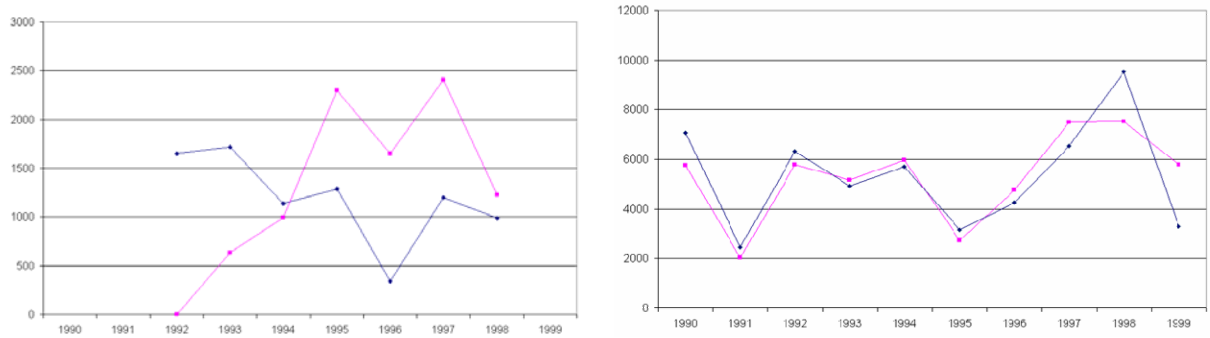

Fig. 6. Annual observed (blue) and modeled (pink) discharges over the (a) SB1 and (b) SB5, for the 1990-1999 decade. Discharge units are $m^3 s^{-1}$. Note the difference in the vertical axis scale between graphics.

the 1963-1969 decade, while the best fit is not the SB5, but the SB4, with errors not exceeding 13%. When taking the Plata Basin as a whole, the error ranges from 4 to 17%. This indicates that the sensitivity of the discharge assessments from the model to possible errors in surface temperature remains in a range no larger than 20 %.

Table 5. Idem table 4 but for the validation periods.

Sub-basin	1963-1969			1970-1979			1980-1989		
	Estimated	Observed	PRD	Estimated	Observed	PRD	Estimated	Observed	PRD
SB1	410	840	51	1,549	1,299	-19	1,285	1,762	27
SB2	1,550	1,296	-20	1,790	1,546	-16	1,966	2,663	26
SB3	6,851	5,982	-15	6,239	6,150	-1	6,592	7,853	16
SB4	6,623	6,777	2	9,642	7,515	-28	10,288	8,996	-14
SB5	3,507	3,881	10	4,117	4,489	8	5,180	4,835	-7
Total	18,941	18,777	-1	23,337	21,000	-11	25,312	26,111	3

Table 6. Idem table 5 but using Delaware monthly temperature data to compute PET values, and for the four validation periods.

Sub-basin	1963-1969			1970-1979		
	Estimated	Observed	PRD	Estimated	Observed	PRD
SB1	222	840	74	1,022	1,299	21
SB2	1,237	1,296	5	1,494	1,546	3
SB3	6,161	5,982	-3	5,738	6,150	7
SB4	5,879	6,777	13	8,508	7,515	-13
SB5	2,764	3,881	29	3,445	4,489	23
Total	16,263	18,777	13	20,206	21,000	4

Sub-basin	1980-1989			1990-1999		
	Estimated	Observed	PRD	Estimated	Observed	PRD
SB1	706	1,762	60	720	1,202	40
SB2	1,521	2,663	43	1,526	2,435	37
SB3	5,984	7,853	24	5,880	6,614	11
SB4	8,965	8,996	0	9,283	10,432	11
SB5	4,596	4,835	5	5,408	5,329	-1
Total	21,772	26,111	17	22,817	26,012	11

4. Results and discussion

The climate scenarios developed from global socio economic scenarios and GCMs project important mean temperature rises for most of South America. In particular, when considering the A2 scenario over the Plata Basin, these models are projecting an approximate increase in mean surface temperature of 2º C for the year 2050, and up to 5ºC of warming for the second half of this century (Camilloni and Bidegain 2005). These changes in temperature would undoubtedly have a great impact in evaporation and consequently in river discharges. Therefore, as a first approach to the potential changes in the basin discharge, increments of 2 and 5ºC in the mean annual temperature were introduced in the calculation of the PET and the model was run with these new values. These increments were performed for each month of the year, without distinction between seasons. No changes in precipitation were considered. Thus, this exercise is only a sensitive study to the surface warming. Results are shown in table 7.

For a 2ºC warming, SB1 appears as the most affected sub-basin with a decrease of 37% in its discharge and the least affected is the SB3, in the Upper Paraná with a decrease of 15%. In the Plata Basin as a whole, the potential impact of a 2ºC warming over the entire basin would be a 21% decrease in the mean discharge. This value exceeds by a little margin the range of uncertainty that may be attached to the model assessments, Tables 5 and 6.

Table 7. Comparison between estimated and observed decadal discharge values for the decade 1990-1999 using the calibrated PET formula. Estimations suppose an increase of 2 and 5ºC. Discharge units are $m^3 s^{-1}$. PRD is in %.

Sub-basin	+2ºC	1990-1999	PRD	+5ºC	1990-1999	PRD
SB1	760	1,202	37	329	1,202	73
SB2	1,612	2,435	34	691	2,435	72
SB3	5,652	6,614	15	4,230	6,614	36
SB4	7,993	10,432	23	4,541	10,432	56
SB5	4,293	5,329	19	2,836	5,329	47
Total	20,311	26,012	21	12,627	26,012	51

According to the model, with a mean temperature increase of 5ºC there would be a 51% reduction of the Plata discharge, which is far more than the uncertainty of the model estimates. The same can be said for the projected discharges for every basin, except SB1, Tables 5 and 6. Thus, the effect of such a warming will have a considerable impact in the river discharges of the Plata Basin. The qualitative impact of this important warming could be anticipated without the use of the model, but its use allowed to asses the bulk numbers of such impact.

5. Conclusions

The simple hydrological model used in this paper calculates soil water content, real evapotranspiration and runoff. The model was adjusted to reproduce mean long term runoff that was considered equivalent to mean long term basin discharges. The validation of the model indicates that the Plata River basin long term discharges (decadal averages) are estimated with errors ranging from 1 to 11%. At individual sub-basin level, errors are larger, but except for one period in the Pantanal basin were lower than 30 %

The lack of enough surface temperature observations in some of the sub-basins is a potential source of error in the estimates of evapotranspiration and consequently in the long term estimates of discharges. An assessment of the magnitude of such errors was done comparing results of long term discharges calculated with two different surface temperature datasets. Results indicate that changing the surface temperature database has some impact in some sub-basin discharges in some periods, but it has little effect in the total basin discharge.

The potential impact of a 2ºC warming over the Plata Basin is a reduction in the long term mean discharge of about 20%, which is only a little over the range of uncertainty that could be attached to model assessments. With a mean temperature increase of 5ºC, the estimate of the reduction of the Plata discharge is of 50%, which is far more than the uncertainty of the model estimates. Therefore, it is possible to anticipate the bulk magnitude of the discharge reductions in the Plata River discharge if such a warming actually takes place.

Before considering these estimates as future scenarios, some issues should be pointed out. First, there could be future changes in precipitation that were not included. For the time being, not including precipitation changes may be the best option as most of the climate scenarios for the Plata Basin do not project statistically significant precipitation changes for this century, and they differ from one model to other, including in sign (Camilloni and Bidegain 2005). More serious is the limitation of GCMs in simulating present climate over the Plata Basin. In general, GCMs underestimate precipitation by 30% or more (Camilloni et al. 2005). Consequently, as expected for a subtropical climate, surface temperature is overestimated. This poor simulation of the present regional climate adds uncertainty to the projection of future climate, even when this one is assessed through the differences with present GCMs outputs.

Furthermore, as atmospheric carbon dioxide concentration grows, the evapotranspiration rate from many plants may become lower because their stomas would need to be less open to capture CO_2.

In view of all these uncertainties, the results here presented only can be considered a first order assessment of the potential discharge changes in the Plata Basin that could outcome from global warming. However, the potential impacts of such reductions in the river discharges should be a matter of great concern as they would compromise a great part of power generation, navigation, ecology and water quality and supply. In addition, the increase of evapotranspiration will enhance water stress with negative impacts in agriculture. It is therefore necessary to reduce the present uncertainties by not only developing more sophisticated hydrological models, but also by the improvement of the regional climate simulation.

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