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The influence of precipitation and land use changes on water balance for a plain basin

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Abstract

Based on numerical simulations with a distributed in space, continuous in time, and properly calibrated and verified hydrological model, it is shown that though the increase in rainfall is the prime phenomenon explaining the increase in groundwater levels in the Argentine Pampas, one of the largest plains throughout the world, the trend towards agriculturization also plays a very significant role; moreover, the non-linear response of the hydrological system to changes in precipitation and land use is put into evidence, as the combination of both effects produces a result that is much less intense than the sum of each of the individual effects by themselves.

Keywords: Climate change; Land use change; Hydrological model; Groundwater level; Argentine Pampas

1. INTRODUCTION

The Argentine Pampas, one of the largest plains throughout the world, has experienced during the last 50 years a strong rise in the water table level, with the consequent increase in the frequency of floods. This dynamics is associated to two processes that took place over this zone. In the first place, the annual rainfall has shown a positive trend. Secondly, field crops have expanded throughout the Pampas, displacing grasslands and pastures, i.e., there has been a land use change.

In the present paper, the influence of precipitation trend and land use change on the evolution of phreatic levels of a zone of the Salado Basin (Figure 1), from the last decades of the XX century up to the present time, is studied through a hydrological model.

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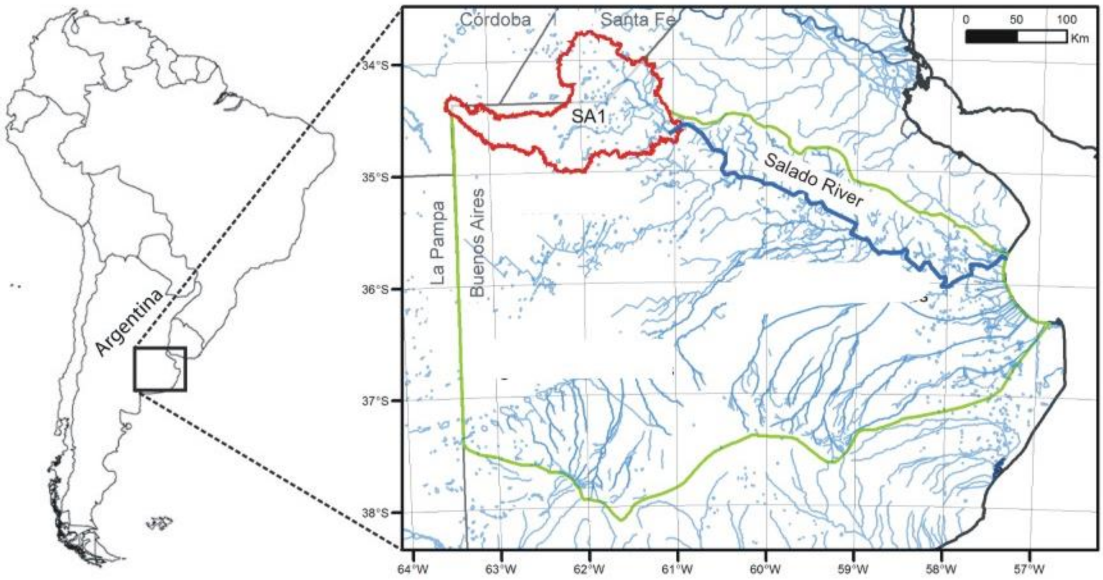


Figure 1. Study zone.

2. PROBLEM DESCRIPTION

The Salado Basin, with an extension of 170,000 km2, has a very flat topography. Hence, it shows the classic hydrologic behavior of a plain basin, with an essentially vertical water balance, and a close relationship between the water exceedance and the dynamics of the phreatic layer.

As a consequence of the topographic conditions and climate variability, the Salado Basin has reported a succession of floods and droughts since colonial times (Herzer, 2003; Seager et al., 2010; Kuppel et al., 2015). On the other hand, since the 1980 decade, soy turned into the most significant crop for the region (Bert et al., 2011; Delvenne et al., 2013). Due to its lower evapotranspiration rate and shorter radicular system in comparison with grass, this land use change influences the evolution of the phreatic level (Viglizzo et al. 2009; Contreras et al., 2011).

For the present study, the sub-basin known as Subregion A1 (SA1) was selected, with an extension of about 14,500 km^2 (Figure 1).

3. DATA BASE

Figure 2 shows the evolution over more than five decades of the (relative) area with different land uses for SA1. Note that approximately since 1990 a practice known as ‘double crop’ was implemented within each yearly cycle, with a ‘second class’ soy following the harvest of wheat.

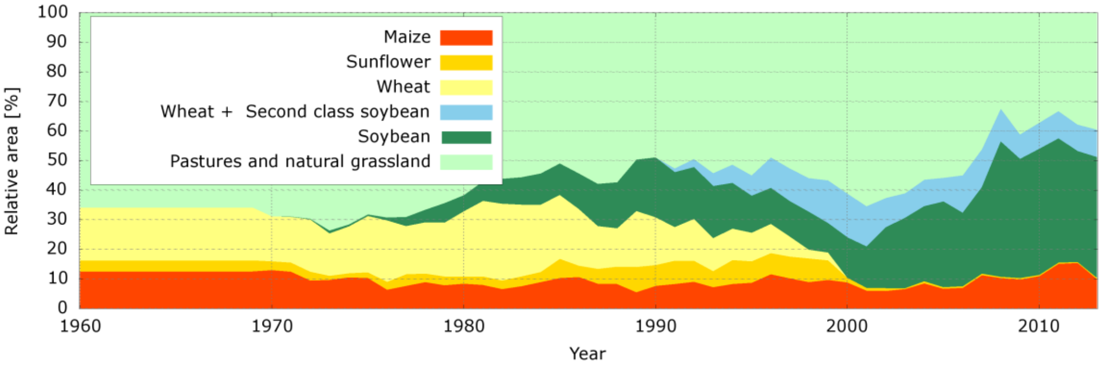


Figure 2. Evolution of relative area for different land uses in Subregion A1 (SA1).

Figure 3 presents the evolution of the spaced averaged annual precipitation for SA1, together with its linear trend (7.73 mm/year) and its time averaged value (930 mm).

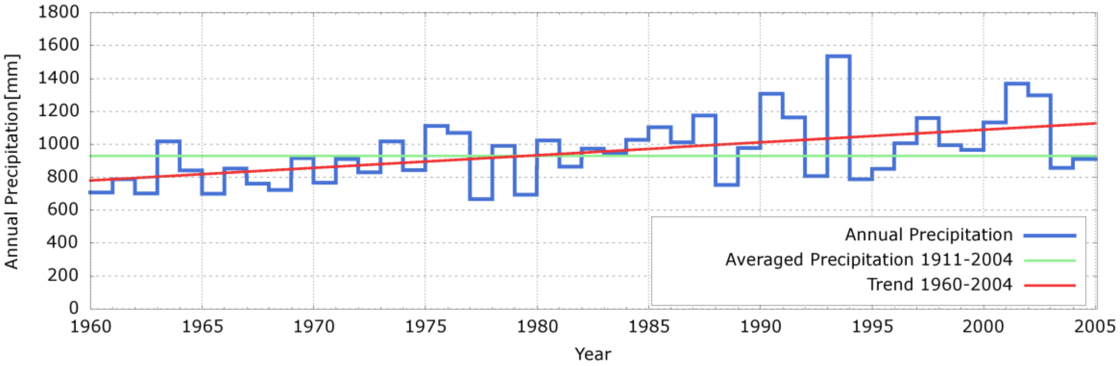


Figure 3. Evolution of space averaged annual precipitation in Subregion A1 (SA1).

4. HYDROLOGICAL MODEL

The hydrological model of SA1 was implemented using code MIKE-SHE (Refsgaard & Storm, 1995; Refsgaard et al., 2010), a deterministic, distributed and physically based model, which links with MIKE 11, a 1D hydrodynamic model.

The model domain was discretized in square cells, 1 km side, for a total of about 14,000 cells. The computational time was approximately 1 hour for each simulated year.

The Digital Terrain Model (DTM) from the Shuttle Radar Topographic Mission (SRTM), with 90 m square cells, was used as the topographic base. The data were filtered out, and its regional trends were corrected using contour lines from the National Geographic Institute (IGN) of Argentina. From the DTM, the mean topographic level for each cell was determined. Additionally, the DTM was used to calculate the available storage volume in the (quite significant) terrain depressions for each cell, which was used as initial abstraction in the vertical water balance.

Hydraulic resistance of the terrain surface was characterized with a value of Manning roughness coefficient of 0.2 $m^{-1/3}s$ (Donigian & Davis, 1978). The main roads and railroads act partially as obstructions to sheet flow during floods, so they were represented as impermeable barriers with culverts implemented through MIKE 11.

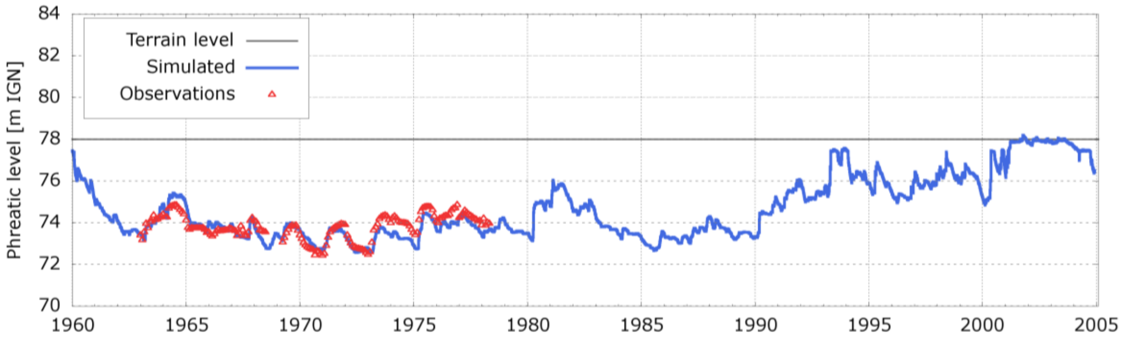
Precipitation data was built from records at 12 rain gages. Evapotranspiration for each crop was characterized through the leaf-area index (LAI) and root depth (RD) of vegetation, properly modulated along the year to represent the evolving phenological stage. From the annual time series of cultivated area for each crop, effective time series of LAI and RD for each cell were determined.

Groundwater flow in the saturated zone was modeled by discretizing vertically the terrain into layers with different thickness: 5 cm for the initial 40 cm, increasing to 20 cm and 1 m down to a depth of 20 m. Different types of soil were considered to characterize each one of the main geologic formations (Araucana, Puelche, Junín and Pampeana), which hydraulic properties were represented though parametric curves for retention and conductivity.

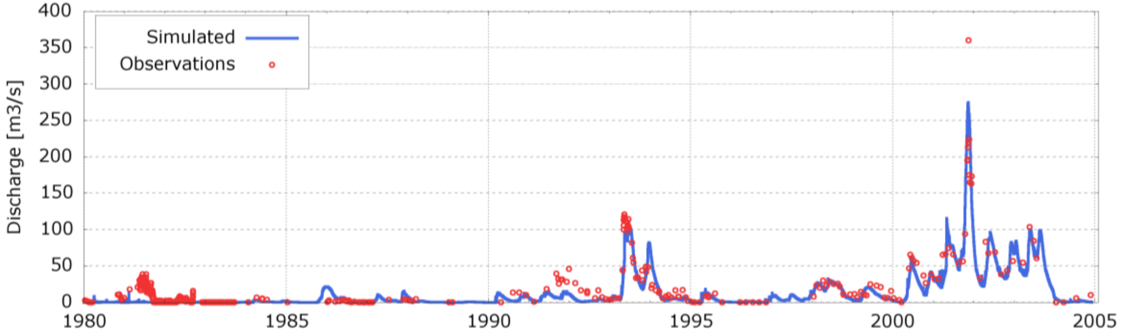
Water courses and lagoons were represented explicitly through an integrated 1D model with MIKE 11.

Calibration was achieved by adjusting time series of calculated phreatic levels to historical records (Figure 4a), in order to minimize the root mean square error (RMSE), using as calibration parameters the ones of the retention and conductivity curves (to which the results indicated the maximum sensitivity). Time series of discharge were used to verify the model (Figure 4b).

More details are presented in García (2020).



a) Phreatic level at SA1 outlet (Junín station).



b) Discharge of Salado River at National Route No. 7.

Figure 4. Calibration and validation of the Hydrological model.

5. NUMERICAL RESULTS

Numerical experiments were performed to simulate the response of phreatic levels, discharges and flooded areas to different land use and climatic scenarios. The simulations extended over the period 1960-2004, during which a strong rise trend in phreatic levels, discharges and flooded areas occurred.

Three different scenarios were defined: (i) scenario A, with the historical land use and climate evolutions (base scenario); (ii) scenario B, with the historical climate evolution, but a constant land use corresponding to 1960; (iii) scenario C, with the historical land use evolution, but filtering out the observed positive linear trend of precipitation, and imposing instead a time averaged value equal to the historical time mean over the period 1950–1960.

Figure 5a shows the evolution of the spaced averaged phreatic level for the three scenarios. In the case of the base scenario (A) two trends are distinguished: a decrease in phreatic level of around 2 m for the period 1960–1980, and a strong rise afterwards of around 4 m.

For scenario B the behavior is similar to scenario A until around 1980; this is because the phreatic level is so low that the crop suction effect on the water balance is not significant. From then on, there is a decrease of phreatic level relative to the base scenario, reaching that difference around 1 m for 1990; this is the effect of agriculturization. Afterwards that difference decreases, nearly disappearing in the last years; this change of trend is due, on the one hand, to the introduction of double crop (which induces an increase in annual evapotranspiration), and, on the other hand, to the closeness of the phreatic level to the soil surface (then minimizing the difference in evapotranspiration between crops and grass (Garcia et al., 2019).

For scenario C the phreatic levels are shallower in relation to the previous scenarios until the end of the 1980 decade, due to precipitations higher than the historical ones. On the contrary, for the remaining years the phreatic levels are strongly lower, with differences up to 3 m, related to precipitations lower than the historical ones. Additionally, this scenario shows a higher stability in the phreatic level, as expected due to the absence of a precipitation trend.

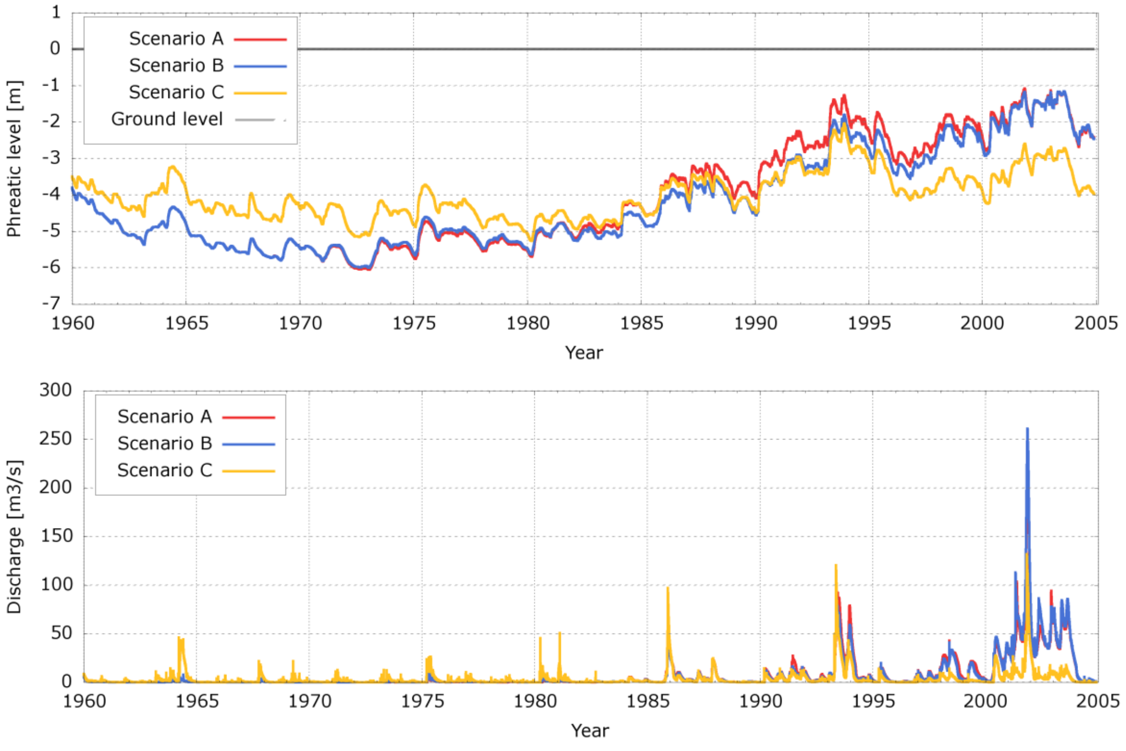
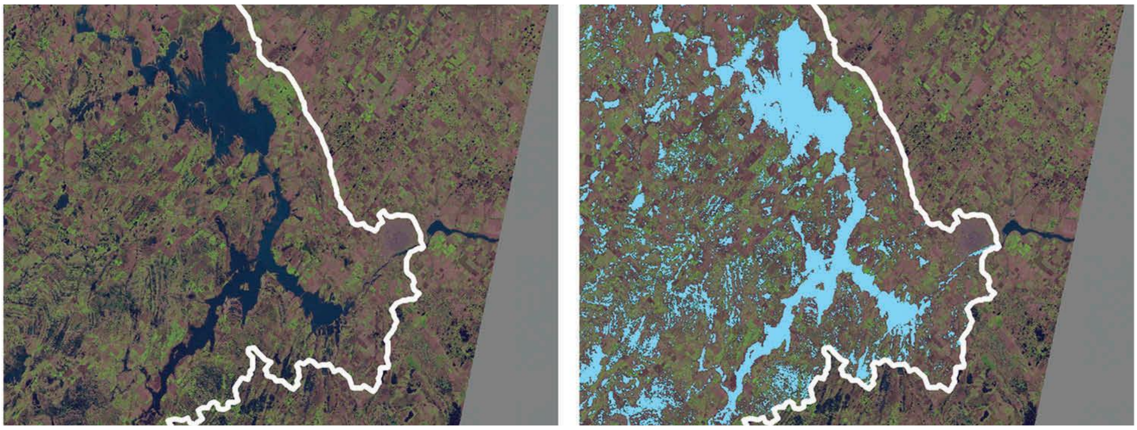


Figure 5. Evolution of (a) phreatic level and (b) discharge for the different scenarios.

Figure 5b presents the evolution of the discharge at SA1 outlet for the three scenarios. It is observed that the discharge for scenarios A and B are similar to each other until 1990, while larger discharges are associated to scenario C due to higher precipitations during this period. Since 1990 the trend reverses, with lower discharges for scenario C due to lower precipitations. During this period the discharges for scenarios A and B remain relatively similar, except for the 1990 decade in which higher values appear for scenario B due to agriculturization effects. These results indicate that the discharge is more sensitive to the precipitation trend than to land use changes.

Flooded areas maps were built using the fill/spill technique (Teng et al., 2017). Details are explained in Badano (2010). This methodology was validated comparing its results with LANDSAT satellite images, as illustrated in Figure 6. Additionally, a quantitative comparison of flooded areas was performed (Garcia et al., 2018, García, 2020).



a) Satellite image **b)** Model

Figure 6. Comparison of flooded areas (24/May/2003).

Figure 7 shows the evolution of the relative flooded area for the three scenarios. It is observed that the areas for scenario B are slightly smaller than the ones for scenario A until the end of the 1990 decade, but they become very similar thereafter. Scenario C presents larger areas than the previous ones until 1980, becoming significantly lower thereafter. These behaviors are compatible with the ones observed for phreatic levels and discharges, due to the same reasons.

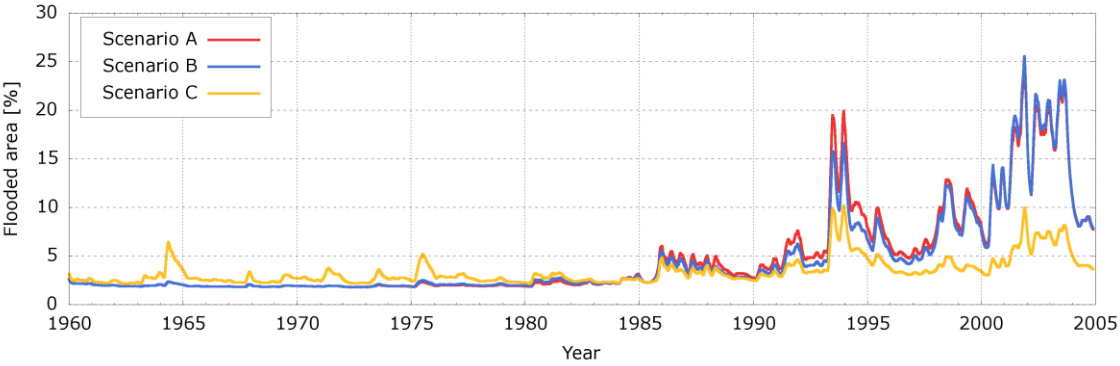


Figure 7. Evolution of flooded area for the different scenarios.

In these plane regions, the dynamics of the phreatic level controls the formation and expansion of free water bodies (Aragón et al., 2010, Kuppel et al., 2015, García, 2020). To illustrate this point, Figure 8 shows the correlation between phreatic depth and flooded area for the base scenario, indicating an exponential trend. While the phreatic depth lies between about 3 and 6 m, the relative flooded area is below 5%. When that depth decreases from 3 to 2 m the flooded area increases to 10%. Finally, for phreatic depths below 2 m the flooded area strongly increases, reaching about 30% for 1 m. This is due to the fact that, when the phreatic level approaches the ground level, the infiltration capacity collapses, significantly increasing the water exceedance on the surface, which tends to accumulate in the land depressions.

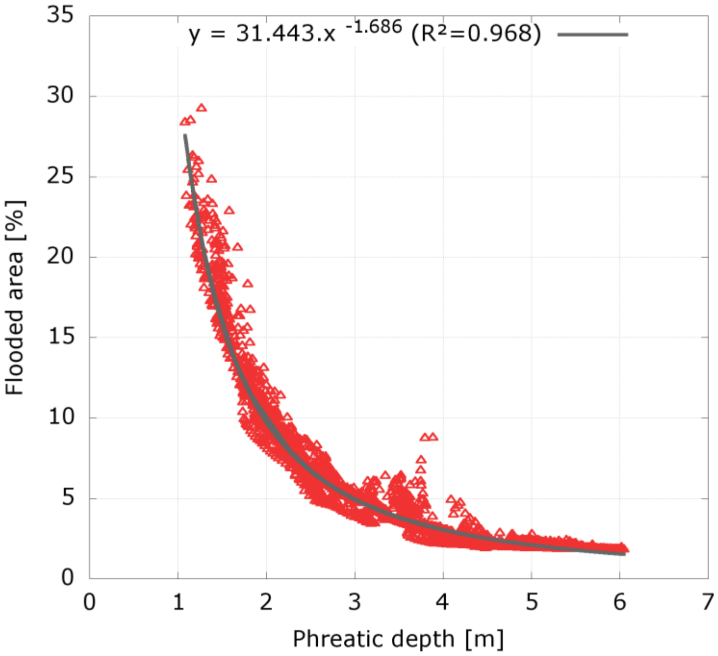


Figure 8. Correlation between phreatic depth and flooded area.

6. DISCUSSION

An analysis of the obtained results was undertaken, in order to discriminate the quantitative effects of changes in precipitation and land use. Within the time window of the numerical simulations, a period was identified during which a significant and consistent rising trend of the phreatic levels and discharges was observed for the three scenarios, simultaneously with variations in land use and annual precipitation. This period extends from 12/Dec/1973 to 12/Dec/1993, i.e., for exactly 20 years.

Table 1 presents the variations in phreatic level and discharge for the analyzed period, their annual variation rates, and the relationship between these rates and the ones for the base scenario (A). In the case of the phreatic level it is observed that, if the land use had stayed as in 1960 (scenario B), the variation exclusively due to precipitation change would have been 86% of the total variation effectively occurred (scenario A). Instead, if there had not been a positive trend in annual precipitation (scenario C), the variation exclusively due to land use change would have been 58% of the total variation effectively occurred (scenario A). This indicates that both effects have been significant, though the one from precipitation change is much greater. Worthy of note is the highly non-linear behavior of the hydrologic system, as the combination of both effects produces a result quite lower than the addition of each one by itself.

Analyzing the discharge, the responses are similar to the ones for the phreatic level, but lower in magnitude: the variation exclusively due to precipitation change would have been 71% of the total variation effectively occurred (scenario A), while the variation exclusively due to land use change would have been 48% of the total variation effectively occurred (scenario A). This decrease of the relative effects indicates a lower non-linear effect for the discharge. In any case, the relative consistency between the calculated rates of change for the phreatic level and the discharge provides robustness to these simple indicators of change.

Table 1. Change in phreatic level and discharge between 12/Dec/1973 and 12/Dec/1993.

	Phreatic level			Discharge		
Scenario	A	B	C	A	B	C
Change	4.14 m	3.55 m	2.42 m	61.9 m^3/s	43.9 m^3/s	29.5 m^3/s
Rate	0.21 m/y	0.18 m/y	0.12 m/y	3.1 $m^3/s/y$	2.2 $m^3/s/y$	1.5 $m^3/s/y$
Relative rate	100%	86%	58%	100%	71%	48%

The presented indicators have some limitations. On the one hand, as the analysis has been restricted to a time window smaller than the period of simulation, the precipitation for scenario C is not strictly free of trend. On the other hand, the initial condition for the phreatic level in scenario C is different from the one for the other two scenarios, which influences the hydrologic system response (higher sensitivity to land use change for scenario C). Due to these inaccuracies, the indicators should be considered only as providing representative values for the order of magnitude of the relative variations. However, it must be taken into account that any indicator would have limitations to characterize the response of a complex, non-linear system like the present one.

7. CONCLUSIONS

The increase in precipitation, which in the study zone presents a positive trend of about 7.7 mm/year, explains approximately 85% of the increase in the phreatic level in the Salado Basin, and 70% of the increase of discharge of the Salado River, while the increase in the cultivated area explains, respectively, 60% and 50%, i.e., its effects are lower. These results show the high non linearity of the hydrological system, as the combination of both effects produce a result significantly lower than each one by itself.

An exponential correlation between the phreatic depth and the relative flood area was established, with a threshold value of 2 m below which the flooded area grows significantly.

8. ACKNOWLEDGEMENTS

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