Water availability for a growing population in the face of climate and land use change

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In Argentina, about three million people depend on water coming from the Córdoba mountain region. A recent increase in population and climate variability has augmented and intensified events of water scarcity with direct social and economic impacts. Moreover, the effects of ongoing land use changes on the basin hydrology are poorly understood and accounted for in current water management planning. To establish an Integrated Water Resources Management (IWRM) in the region, it is crucial to estimate the water availability during the dry season, the effects of land use changes and to assess drought events. A distributed and continuous hydrological model (J2000) was built to estimate storages and runoff levels of a meso-catchment. Different climate scenarios were evaluated for short term forecast and the effects on water cycle were analyzed based on different simulations. The use of different indexes and scenarios proved to be very useful in understanding how different drought periods may have different effects on the hydrology of the San Antonio River Basin.

Keywords: Hydrological model, Drought, Climate scenarios

Introduction

The mountain regions usually have a very important role in the water cycle, being responsible for capturing the rainfall and forming the head waters of the river systems. That is why managing the river basins at their sources have a great economic, sanitary and recreational importance (Baron *et al.,* 2003). The vegetation is one of the more conspicuous characteristics of the basin and it plays a fundamental role in many ecosystem services like flood/drought mitigation, surface runoff modulation and soil protection (Clearwater, 1999; Jackson *et al.,* 2001). To generate information for integrated water management it is fundamental to know the spatial-temporal distribution of at least the most important variables of the hydrological cycle. Relating the behavior of the soil-vegetation to the meteorological variables may produce valuable information on the basin water dynamic and helping to predict the consequences of both land cover and climatic changes.

The Córdoba province located in central Argentina has a central mountain range which delimits the sub humid region from the arid and semiarid areas. The Sierras Grandes of Córdoba also holds the water sources of the more important rivers of the region. These torrential river basins are responsible for the water supply to more than 3 million people, farms and industries. The general climatic condition is defined as monsoonal with convective rain events concentrated in the summer, followed by a dry and cold season. Recent drought events have put the water supply systems under pressure, making more relevant the need for monitoring and early warning systems to delineate mitigation measures in due time.

Our goal is to contribute to the understanding of the eco-hydrological processes of the Cordoba Mountains, and to generate tools for a sustainable and integral water management. To study the hydrological processes in this region requires dealing with two major problems: a highly variable mountain landscape and poorly gagged basins. To overcome this complex setting, we are using a multidisciplinary approach with tools like remote sensing and geographic information systems for geomorphic modeling and hydrological modeling. The linking of these tools allows us to analyze important characteristics of a basin, i.e. flow regime, soil water distribution, etc., under real and simulated conditions.

In this paper we are presenting the implementation of a distributed and continuous hydrological model and the first results on the exploration of the San Antonio basin water dynamics under its natural condition and simulated scenarios.

Methods

Study area

The study area is the San Antonio river Basin, located in the central portion of the Sierras Grandes of Cordoba, Argentina (Figure 1). The basin has an area of 520 km2 and the water sources are located at 2200 meters over the sea level. The main direction of the flow is west, ending in the San Roque Lake, one of the main water reservoirs of the province. The gauge station is located 3 km upstream from the lake at 640m asl; producing a difference of 1560 m in altitude for the 30km direct distance between the head and the mouth of the river.

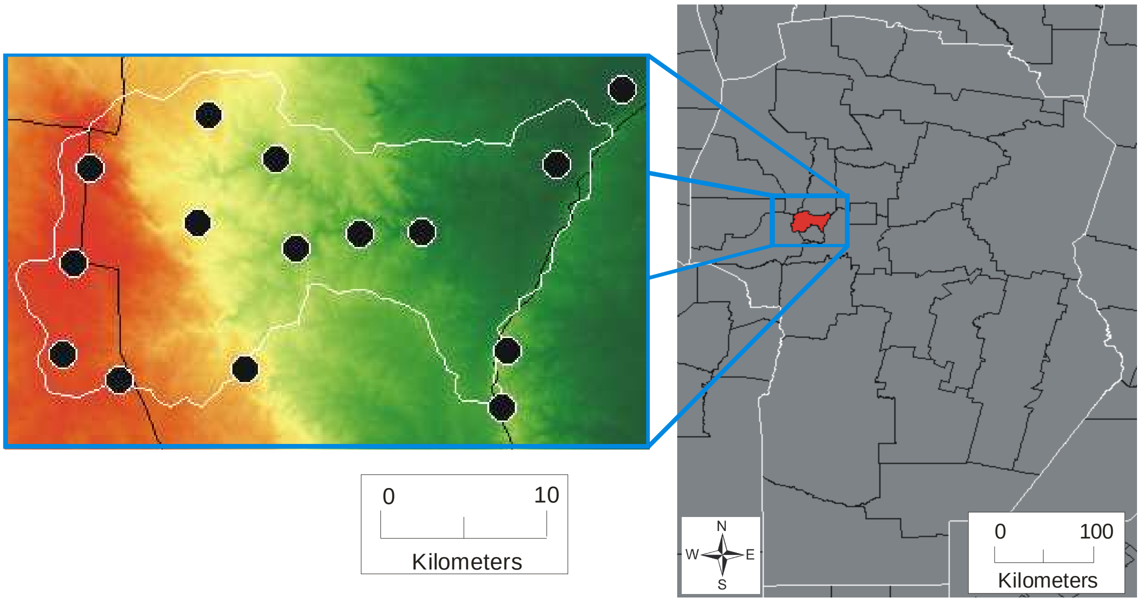

Figure 1: Study area and distribution of the weather station network from CIRSA-INA.

The land cover of the area can be defined as highly patched grassland, tussocks, shrubland, with different intensity of granite outcrops. Some native forest patches can be found in the steepest areas of the high mountains, while mixed forest can be found in the lower areas of the basin. The basin morphology is generally a rolling mountain relief with both highly stepped escarpment and plateaus in the highlands.

The mean annual precipitation of the basin is 818 mm and it has a high annual variability as can be seen in Figure 2. The distribution of rainfall during a year cycle has a well defined wet/dry season. An annual precipitation distribution can be seen in Figure 3, showing the start of the rainy season in October simultaneous with the beginning of the Spring season.

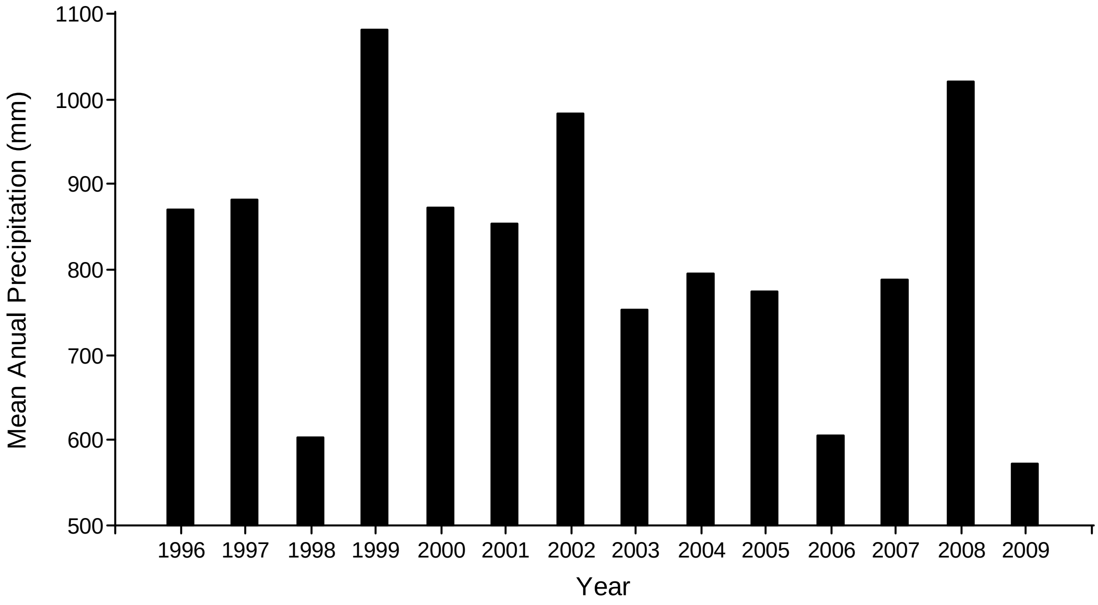

Figure 2: Mean annual precipitation for the San Antonio River Basin.

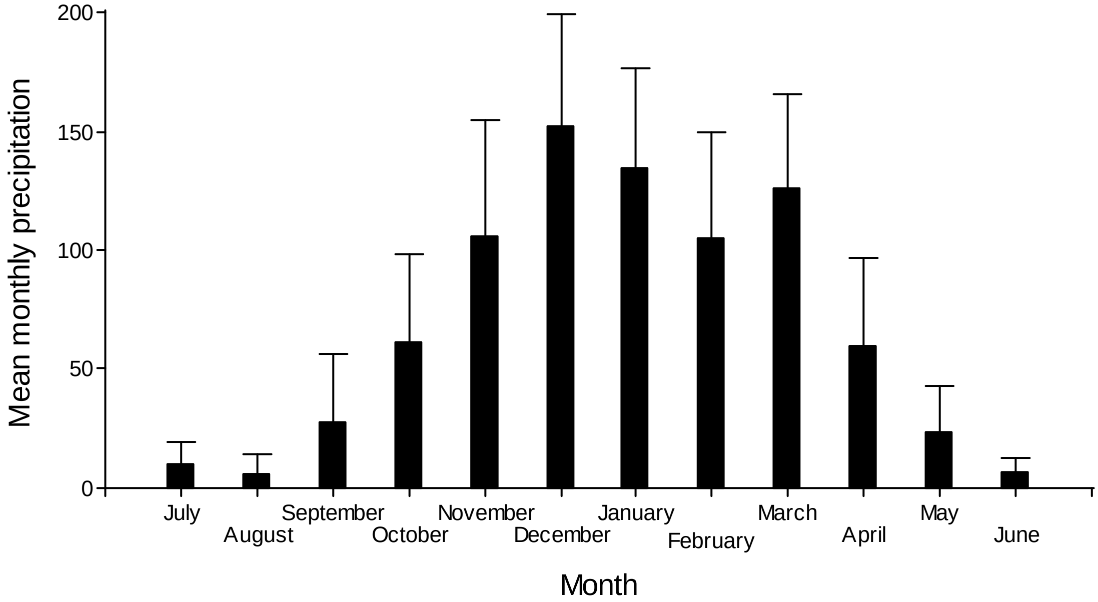

Figure 3: Mean monthly precipitation for the hydrological year.

The J2000g model

For this study, the conceptual, process-oriented and distributed model J2000g (Krause & Hanisch, 2009) was used. The development of J2000g was guided by the following requirements: (1) continuous and distributed simulation of important hydrologic characteristics in monthly and daily time steps; (2) applicability for meso- to macroscale catchments but also to smaller catchments; (3) process oriented and spatially distributed modeling; and (4) robust predictive ability with a small number of calibration parameters.

The J2000g model was adapted from the J2000 model (Krause, 2001 and 2002) within the JAMS modeling framework system (Kralisch and Krause, 2006) and can be categorized as a spatially distributed conceptual hydrological model (Figure 4). The primary goal of the modifications was to simplify many of the complex hydrological relationships within J2000, resulting in a significantly reduced number of calibration parameters while maintaining, as much as possible, the characteristics of the seasonal hydrological variability exhibited in many catchments. The model J2000g requires spatially distributed information related to topography, landuse, soil type and hydrogeology to estimate specific attribute values for each modeling unit. A modeling unit can be a raster cell, a process unit, or a subasin provided that spatial information is available for each attribute within each unit. J2000g also requires meteorological inputs (precipitation; minimum, average and maximum temperature) from one or more observation stations. The measured point data are transferred to each model unit using the spatial interpolation approach available in J2000 which is a combination of elevation correction and inverse-distance-weighting (IDW) interpolation. The elevation correction is made when the degree of correlation (calculated with a linear regression for each time step) between the variable values and the respective station elevation shows a coefficient of determination (r^2) equal or greater than 0.7. In this case, the specific elevation dependent lapse rate, calculated from the regression, is used for the further processing along with IDW. If r^2 is smaller than 0.7 then only IDW is used.

Then potential evapotranspiration (PET) is computed according to Hargreaves-Samani (Samani, 2000) method which has a low data requirement. Snow accumulation and snowmelt are simulated with a simple approach that estimates snow accumulation depending on a base temperature (Tbase) and snowmelt with a time-degree-factor (TMF). During time periods when air temperature is above Tbase, precipitation and snow melt is transferred to the soil-water module. This module consists of a simple water storage with a capacity defined from the field capacity of the specific soil type within the respective modeling unit. For calibration purposes, the entire distribution of storage capacity values for all modeling units can be shifted up or down with a multiplier (FCA) that has the same value for all modeling entities. Water stored in the soil-water storage can only be taken out through evapotranspiration. The actual evapotranspiration is determined by the saturation of the soil water storage, the potential evapotranspiration and a calibration coefficient ETR. The ETR coefficient has a range between 0 and 1 and controls how potential evapotranspiration is reduced due to limited water availability. Runoff is generated only when the soil-water storage reaches saturation. The partitioning of generated runoff into direct runoff and percolation is based on the slope of the modeling unit and a calibration factor LVD and the underlying hydrogeological unit. The percolation component is transferred to a groundwater storage component; outflow from this storage is simulated using a linear outflow routine in order to calculate baseflow with the help of a recession parameter GWK. The total streamflow at the outlet of a catchment results from the summation of the direct runoff and the baseflow components from each modeling unit. The primary purpose of the J2000g model is to provide spatially distributed long-term estimates of the amount and seasonal distribution of the following hydrological quantities: actual evapotranspiration, runoff generation, and groundwater recharge. Because of this, runoff concentration processes are not explicitly considered and streamflow is computed by simply summing up the runoff components generated in each modeling unit of the catchment. Due to these simplifications, the model cannot account for losses and transformations during runoff concentration such as streamflow and groundwater losses in karst regions or water extraction for human activities.

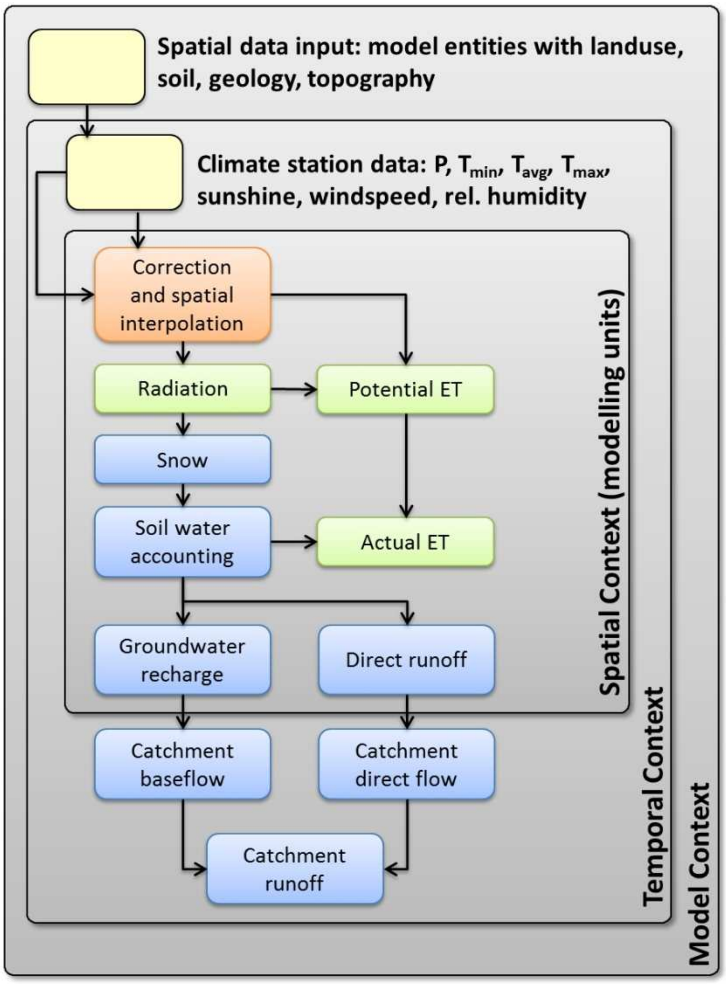

Figure 4: shows a diagram of the model structure

Data sources and information preprocessing

The available meteorological information for the study area is produced by a telemetric network belonging to the CIRSA-INA (Centro de la Region Semi-Arida – Instituto Nacional del Agua). The climatic stations are part of an Early warning system for flash floods, and they distribution over the basin area can be seen in the Figure 1. The stations contain different sensors that can provide time series of data for many variables such as: Precipitation, Temperature, Relative humidity, wind speed and direction, and solar radiation. To quantify the outflow, there is a gauge station with a sensor measuring the level of the river, which is then converted to m^3/s by a calibrated equation. All the data was converted into time series and was incorporated into RBIS (Kralisch et al 2009) to correct the errors, fill the gaps and produce daily time series in the J2000g input format.

The modeling units are defined as HRUs (hydrological response units, Flügel, 1995) and they represent areas that will have a homogeneous hydrological response. To delineate the HRUs for the catchment we constructed a stratification of the spatial information which consisted in: Land cover map, DEM, Soil type map. The land cover was derived from a LANDSAT TM image classified with supervised and unsupervised techniques, the DEM was obtain from the SRTM mission and the soil map was extracted from the Soil Atlas of the National Institute of Agricultural Technology. To obtain the HRUs from the input maps, we used the HRU Delineation Toolbox (Schwartze, 2008) with a threshold of 6 Ha as minimum unit size. The processing yielded 4271HRUs of varying size depending on their geomorphology and soil-vegetation composition (Figure 5).

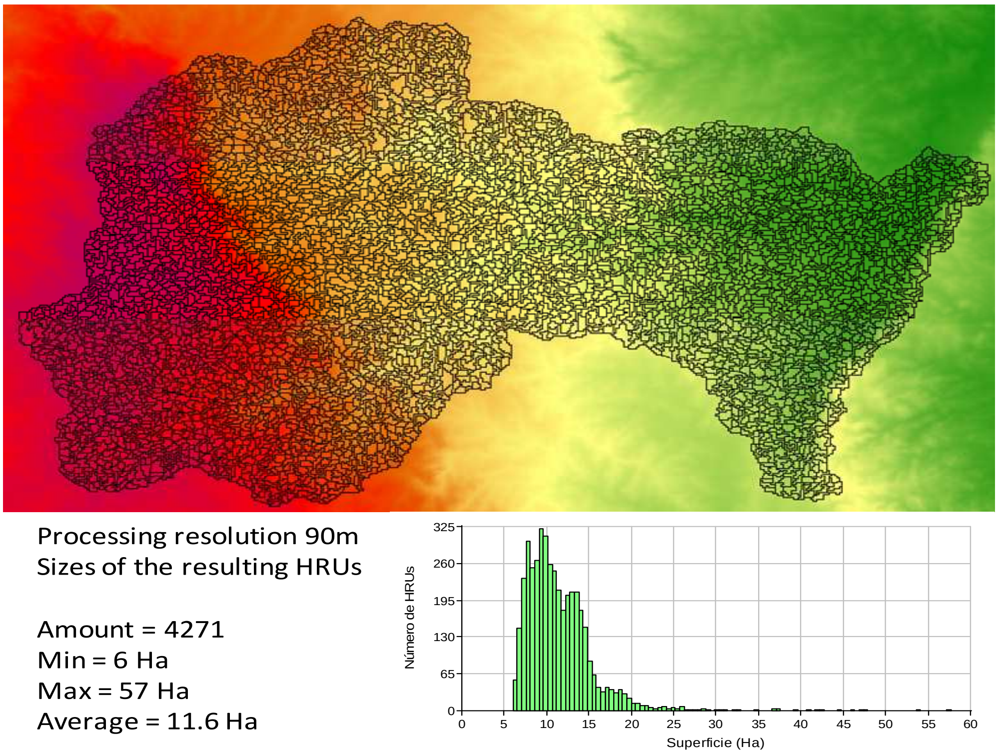

Figure 5: HRUs geographic distribution and histogram of its size distribution

Real data and simulated scenarios

The model was set up to run with available meteorological data from 1996 to 2009 inclusive. It was set to run in daily time steps, and good model efficiencies were achieved for the whole period in which outflow data was available (Nash–Sutcliffe 0,62, PBIAS -1.5%).

Depending on the goal of the study, there are many possibilities in creating scenarios with simulated data and conditions, ranging from long term projections of actual trends, to short term changes of conditions. In this case we aim to understand the simple effect of short term climatic change and land cover transformations. To quantify the effect of the proposed scenario means to compare the output of a real situation vs. the simulated condition.

One of the major problems of working with the whole simulated period is that the gauging station time series presents a massive amount of gaps and erroneous data due to lack of maintenance and structural failures (Vicario *et al.*, 2007), specially in the low flow measurements. Under this condition, model performance cannot be fully accessed in most of the years since observed runoff is not complete. To solve this issue, we have chosen a period in which to compare the real and the simulated conditions 1996-1998. The year 1997 has a complete record of observed data, allowing a good comparison between the modeled and the simulated hydrograph. The gauge data is not affected by damages and changes in the station, and the measuring errors are the lowest. The 1997 rainfall amount is very close to the annual average rainfall. The model has very high efficiency in this year both in predicting the peaks and the base flow: Nash–Sutcliffe 0,77, Log_Nash–Sutcliffe 0,72 and PBIAS 1.7 (Figure 6).

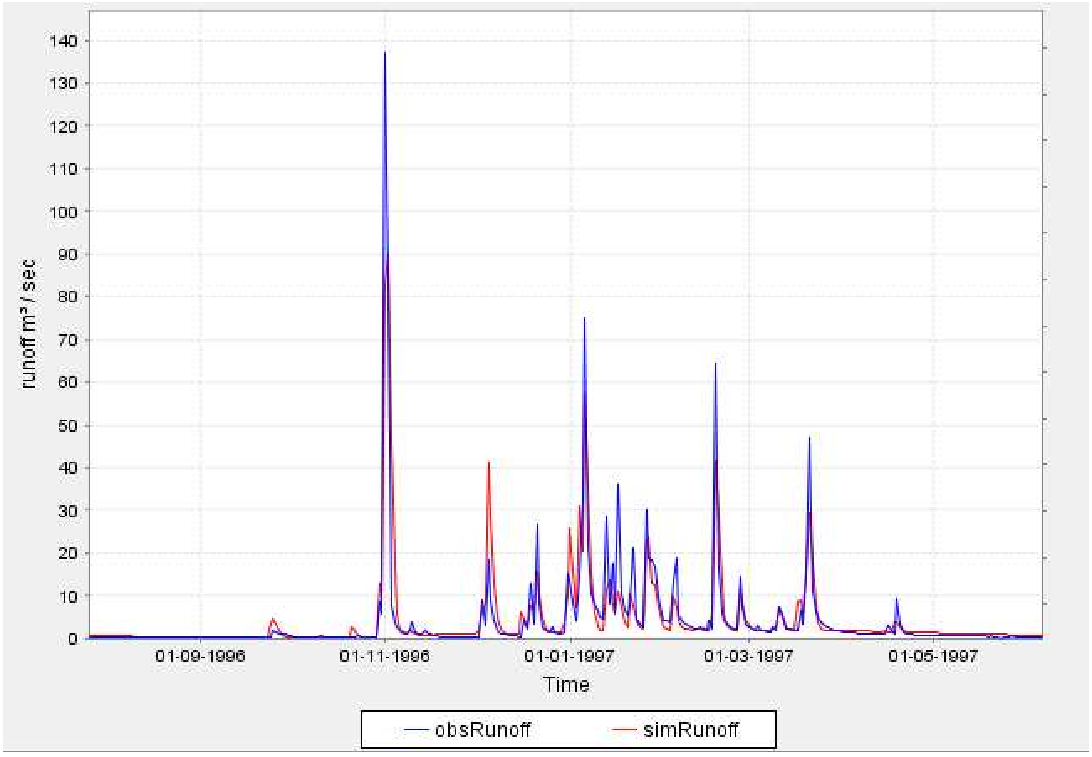

Figure 6: Observed and simulated runoff for the 1997 hydrological year.

For comparison purposes and for quantifying the effects of the proposed scenarios, the 1997 simulated hydrograph is used as control. In this way, the estimation errors of the real hydrograph can be separated, and the effect of the modeled scenario can be better appreciated.

During the simulation, the model will be run from the beginning of the time series in 1996 to help the model get into regime. The data from the hydrological year of 1997 will be change according to the type of simulation and the whole year 1998 will be also run but precipitation will be consider 0 (zero). The purpose of this over extension of the dry season is to evaluate at which time the river will run out of water. For quantifying the differences between control and simulated scenario we will measure the average peak change during the flash flows (APC), average baseflow change (ABC), total annual runoff (TAR), and dry out day (DOD).

Peaks are defined as flash floods higher than $24m^3/s$ according to the early warning system. DOD is defined as the lower possible measure at the output gauge, a 4cm level which is equivalent to 0.03 m^3/s. Baseflow is consider from the beginning of May to the end of August, period in which there is no precipitation.

Regarding the statistical procedures to compare results from different scenarios, t-tests were performed using InfoStat software (Di Rienzo *et al.*, 2011). Normality was tested with the Shapiro Wilks test.

Findings and Discussion

The test hydrological year, shown in Figure 6, reached the DOD value on the 22nd of October. Therefore, this date was considered as DOD cero and the results obtained in the scenarios are expressed as deviations from this value.

The first climatic scenario was prepared to test the response of the basin to rainfall variation. The precipitation of the year 1997 was augmented and reduced in 10% intervals. The limit was set to 30% since it represents levels of extreme drought and humid periods (Table 1).

Index	Rainfall variation					
	-30(%)	-20(%)	-10(%)	10(%)	20(%)	30(%)
APC	-54.72	-37.92	-19.78	20.44	41.09	61.47
ABC	-60.90	-43.15	-23.00	24.80	50.93	77.99
DOD	-39	-24	-12	10	18	24
TAR	-54.13	-37.98	-19.92	21.05	42.90	65.40

Table 1: Percentage of change in the river flow indexes (APC, ABC and TAR, in %), and deviation of the DOD value (in days) due to changes in the precipitation values of the 1997 hydrological year.

In the construction of this scenario rainfall distribution was not altered and all values where proportionally changed. We estimated the sensitivity of the basin to changes in the precipitated volume via the determination that APC and ABC are more sensitive to increasing rainfall intensities than drought simulation. The way APC grows with more precipitation is a useful measure in flood managing scenarios. Also TAR is highly correlated to APC, indicating that the main source of water for the San Roque reservoir comes from this source. But when looking at the effect on water availability for the dry season, the change in the DOD is fundamental for all the communities extracting water directly from the river flow. DOD changed more intensively regarding to TAR variation during the drought simulation than during the humid one (Figure 7). For water management of the river communities, the basin showed more sensitivity to drought, meaning that humid years bring little benefit, but dry years cause serious consequences.

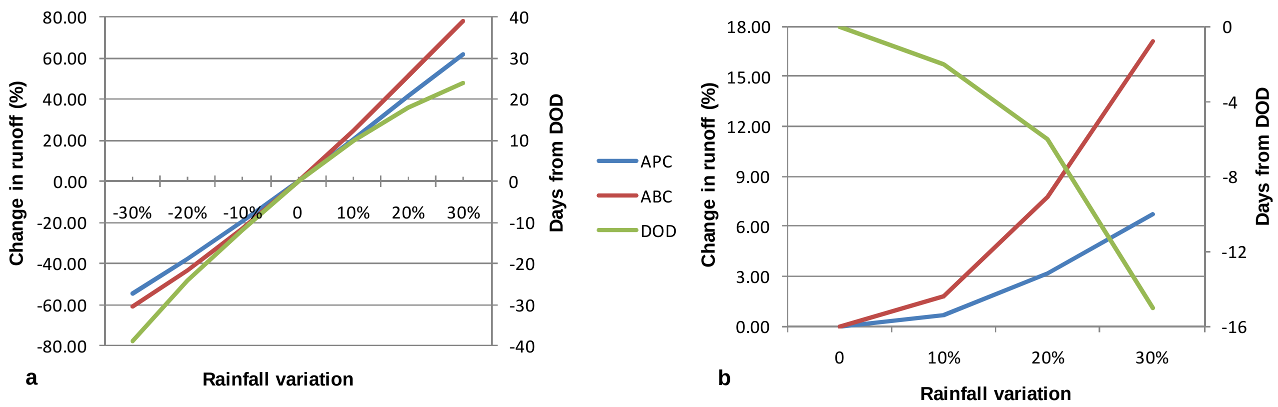

Figure 7: a) Change in indexes values as showed in table 1. b) Difference between the negative and positive impact of rainfall for the same level of rainfall variation.

The second scenario was designed to explore how rainfall distribution may affect the basin response, which was not tested in the first case. We explored the consequences of a 20% annual rainfall reduction (average drought period) under 2 different climatic conditions. The first condition is the product of reducing convective events with a mean areal precipitation (MAP) higher than 15 mm; the second condition is the result of reducing convective events with a MAP equal or lower than 15mm. To consider different combinations of rainfall distribution, four different scenarios were built for each of the two conditions. The results were averaged and compared (Table 2).

Index	Climatic scenarios -20(%)	 -20%, >15mm	 -20%, <15mm	 p-value
APC	-37.92	-43.98 (± 4.23)	-16.37 (± 2.82)	0.0018
ABC	-43.15	-30.74 (± 3.05)	-38.51 (± 2.13)	0.0675
TAR	-37.98	-36.21 (± 1.89)	-20.82 (± 0.60)	0.0002
DOD	-24.00	-15.33 (± 2.12)	-22.50 (± 1.76)	0.0345

Table 2: Percentage of change from the control year for all the hydrograph indexes given 3 different climatic conditions (precipitation reduction): Total 20% reduction and 20% reduction with MAP> 15mm and MAP<15mm respectively.

In drought scenarios, APC and TAR were significantly lower in those where drought periods were produced by a reduction of big convective events than in scenarios where small rainfall events (MAP <15m) were reduced (Table 2 and Figure 8). Even with the same mean average rainfall, total annual runoff (TAR) was more affected by a drought period if the climatic behavior tends to reduce the amount of big convective storms (MAP >15mm). This kind of climatic condition would have a greater impact on the San Roque reservoir, jeopardizing the water allocation downwater from the basin.

On the other hand, a drought period characterized by a reduction of small convective events (MAP <15mm), presented a more pronounced reduction of base flow volume than the opposite scenario. Under this condition, the values of ABC and DOD indicate that the river have less runoff during the dry season, getting faster to its minimum flow value, jeopardizing the allocation of water to the San Antonio River communities.

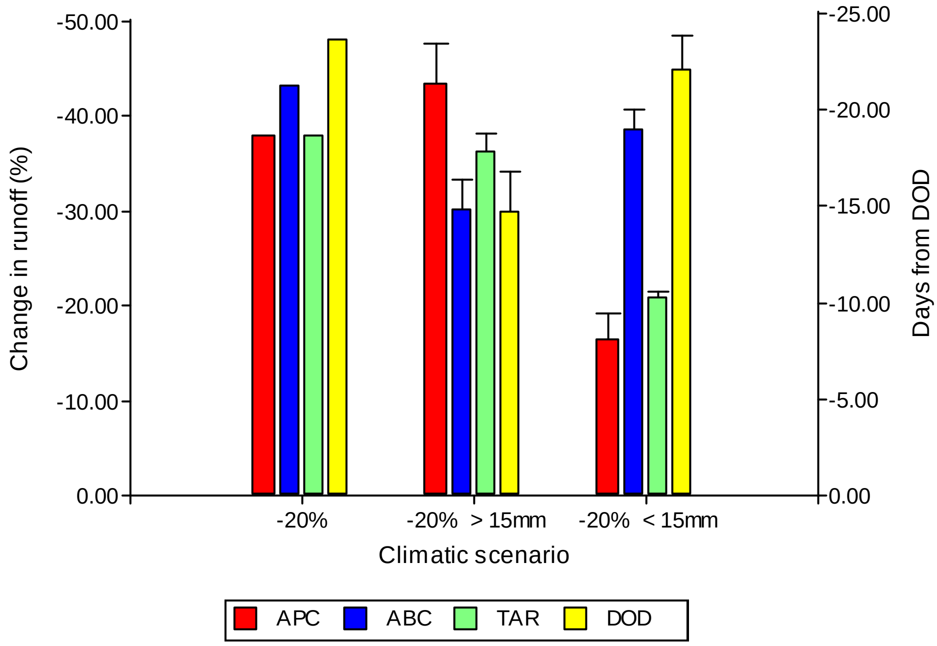

Figure 8: Changes in runoff components due to the climatic scenarios presented in Table 2.

After testing the effect of the type and intensity of storms on the basin dynamic, we developed another simulation to determine the effect of the temporal distribution of rainfall. Three different scenarios of a year with a 20% less rainfall were produced by simulating drought periods at the beginning, middle and end of the hydrological year. The results indicate (Figure 9) that a delay in the start of the precipitation period, even if it does not recover and the mean annual precipitation suffers a 20% reduction, does not produce much change in the base flow (ABC) and the DOD. Conversely, if the drought periods are produced by a sudden end of the rainy season, ABC and DOD were greatly affected, producing the worst scenario for the San Antonio River communities.

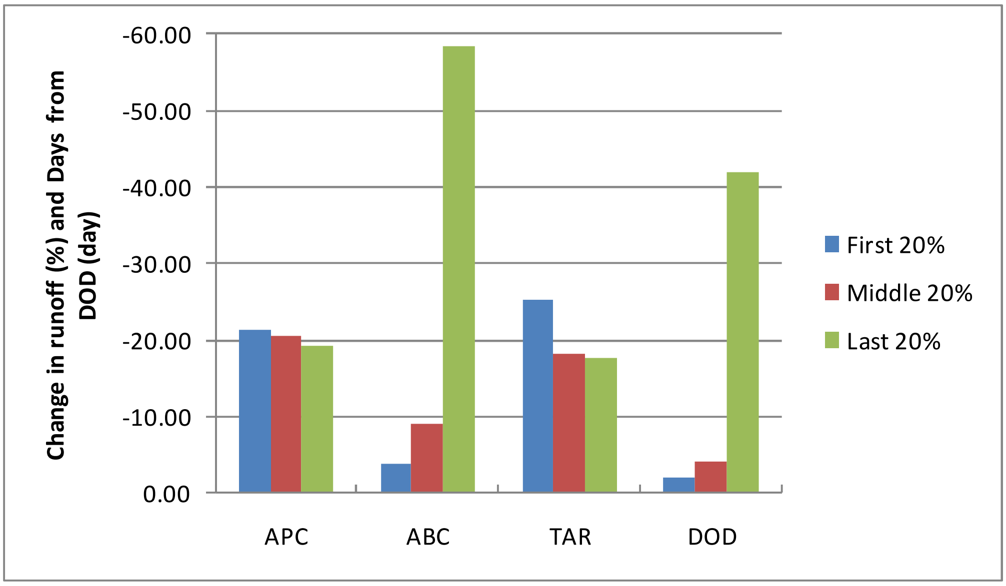

Figure 9: Changes of the hydrograph indexes due to different temporal appearance of a drough period (-20% of MAP).

Conclusions

When run on the whole period and during the simulations, the J2000g model demonstrated to be a very powerful tool, and versatile enough to deal with discontinuous time series of basic climatic variables.

Analyzing the model run with real and simulated situations can provide information about the mechanisms of the basin. The approach taken in this study proved to be useful to understand the water cycle, the basin dynamic and determine simple indexes to probe its condition. Work still needs to be done in improving the implementation of model in San Antonio River Basin and construct more realistic scenarios to study the river flow under complex spatio-temporal variations of rainfall. Also, having HRUs characterized by land use and soil type, allowed us to produce scenarios in which we can simulate structural changes in different areas of the basin. This is a very useful capability that will be interesting to develop for land change scenarios.

Our results show that not only the amount but also the distribution of rainfall are important to consider in forecasting for water allocation management. Also, water managers from the downstream reservoir and the San Antonio River communities may have to delineate different action plans during drought years, depending on these variations. The results from the climatic scenario simulations illustrate the basin behavior as a response to storms of different kind and intensity. Intense events are very important for the water reservoir, but for the communities that depend on the surface runoff, more small events would provide a long lasting base flow.

The different indexes and scenarios helped in understanding how different drought periods may have different effect on the hydrology of the San Antonio River Basin. If the DOD is calculated and updated regularly, it is a good indicator that can help water managers of the region to set up a better water distribution system, especially in the communities that depend entirely on the runoff.

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