Integrated hydrological modelling to asses flood and drought risk under climate and land use change

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Abstract The effect of climate and land use changes on the hydrologic response of a very mild slope basin is studied, through a properly calibrated, integrated surface-groundwater, spatially distributed, time continuous hydrologic model. Flood risk is associated to higher intensity impulsive responses of the flow discharge, while drought risk is linked to lower base flow discharge and phreatic level. The increase in precipitation and agriculturization leads to an increase in flood risk and a decrease in drought risk. The inverse holds for an increase in mean temperature. For a decrease in precipitation, flood risk remains practically unchanged, but drought risk increases. These risk changes are quantified for the study basin, then constituting a valuable input to formulate management plans.

Keywords numerical simulation; surface water; groundwater; climate change; land use change

INTRODUCTION

The Salado Basin, in the Province of Buenos Aires, Argentina, has an extension of 17 million hectares. As a part of the Argentine Pampas, it includes highly productive agricultural land. As a very mild slope basin, without a well developed fluvial net, it is subject to periodical floods, with a relatively high permanence, which affect both productive land and cities. Periodical droughts are also frequent.

Historically, the basin has undergone dry and wet hydrological cycles. Since the 80s, a trend of increased precipitation, which has been linked to Climate Change, has led to an increase in the phreatic water level, thus triggering stronger and more frequent floods, reaching catastrophic consequences at the beginning of the present century. In order to mitigate them, a huge river channelization plan has been defined, which is being implemented through different project stages.

Additionally, a significant change in land use is taking place, from cattle-raising to agriculture (mainly soybean, maize and wheat). This is also introducing variations in the infiltration rate.

An integrated surface-groundwater, spatially distributed, time continuous hydrological model is available, which was built to provide support and optimize the design of the channelization plan. As a physically based hydrological model, it constitutes a formidable tool to investigate the effects on the hydrological balance of the system drivers (linked to climate) and conditioners (linked to land use).

In the present paper, using observed or possible projected changes in the variables that characterize climate and land use, the model is applied to discriminate their associated effects.

HYDROLOGIC MODEL

Physical Basis

Commercial software MIKE SHE was used. It was initially applied to study the channelization plan for the Salado Basin (UTN-FRA, 2007). The methodology and results were presented in Badano et al. (2008), and in Re et al. (2008). An undergraduate thesis on this subject was recently issued (Badano, 2010).

MIKE SHE (Refsgaard and Storm, 1995) is a deterministic, spatially distributed, physically based hydrological model, coupling the surface and groundwater flow. It derives from the *Système Hydrologique Europèen* or SHE (Abbot et al., 1986), collaboratively developed by some European laboratories.

Evapotranspiration is modelled based on Kristensen & Jensen (1975) method. Surface flow is solved as a 2D kinematic wave for runoff, coupled with a 1D dynamical model (implemented in software MIKE 11) for concentrated flow. The interchange between groundwater and concentrated surface flow is accounted for. Flow in the vadose zone is modelled through Richards (1931) equation. Groundwater flow is represented through the 3D Boussinesq equation.

Model Implementation

Eight sub-basin models were implemented in order to represent the whole basin. For the present application, one of those sub-basins ('A1') was selected, a typical vey mild

Fig. 1 Location of study basin.

slope basin, with an area of 14,515 km^2 (Figure 1)

A horizontal spatial step of 1 km was selected, which is a compromise between a sufficiently dense grid (14,000 cells), and a reasonable computer time per run.

The land surface Digital Elevation Model (DEM) was built based on the SRTM (Shuttle Radar Topographic Mission) data, with a 90 m step, adjusted to be consistent with contour lines from the Argentine topographic institute (IGM). Concentrated flow paths (permanent and ephemeral water courses) were obtained from cartography.

Three hydrogeological layers (Post-Pampeana, Pampeana and Puelche) were distinguished, resting on a practically impermeable layer. DEMs for the interfaces (5 km step) were available.

This basin is full of wind-generated depressions, where water is storage after storms. Their integrated effect was represented as an initial abstraction, with their volumes arising from the DEM for the land surface.

Highways and railroads were modelled as impermeable 1D obstructions, traversed by short concentrated flow segments which represent the integrated effect of bridges and culverts.

Rainfall and potential evapotranspiration time series, the driving forces, were available from a net of meteorological stations.

The Leaf Area Index (LAI) and Rooth Depth (RD) are used to determine actual evapotranspiration. Their seasonal evolution was established based on the type of crop (including pasture), and time series of sowed area per crop. In this way, the observed agriculturization trend is accounted for.

The land surface roughness was characterized through Manning coefficient, with a value representative of agricultural land.

Two soil types, which condition infiltration, were distinguished, each one associated to a geological formation: one on the west (Junín), with predominantly fine sand and sandy silt, and the other one (Pampeana) on the east, with loam. Each soil type has its own horizontal and vertical conductivity, and saturated and residual humidity. The specific storage and specific yield were also established.

The soil column, with a máximum depth of 40 m, was discretized as follows: 34 cells for the vadose zone, and three cells for groundwater flow (coinciding with the three hydrogeologic layers).

A four decades long (1963-2004) time window was established for the simulations.

The initial conditions for the simulation, specially the phreatic level, have a long lasting effect on the system evolution. Hence, it was necessary to design a start up run of several years in order for the system to achieve regime conditions.

Model Calibration and Validation

The calibration of the model was undertaken so as to minimize the RMSE (Root Mean Square Error) with respect to the phreatic time series data. Figure 2 shows the comparison between measurements and model results for one of the stations. Note how the model correctly reproduces the signal modulation.

The validation of the model was performed by comparing the calculated and measured discharge for the concentrated flows. In Figure 3, the validation for the station at the sub-basin outlet (Junín) is shown. The agreement is considered as very satisfactory. Worthy of note is that the peak which occurred during 2001 was due to a small dike failure in Mar Chiquita Lake, not accounted for in the model. It is observed that, within the time window, both a dry and a wet period are included; in particular, the model correctly simulates the observed flood intensification effect which developed since the late 80´s.

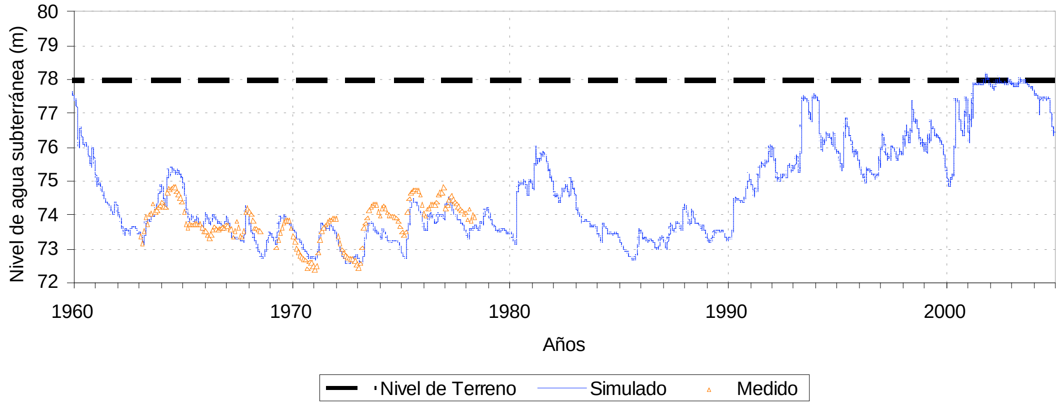

Fig. 2 Time series of phreatic level at Junín station.

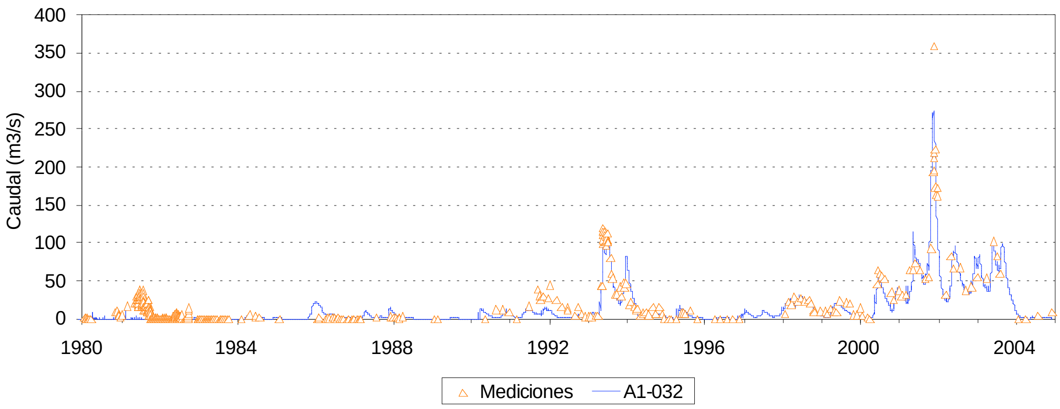

Fig. 3 Time series of discharge at Junín station.

MODEL SCENARIOS

The model scenarios were established by fixing the yearly modulation of the driving forces (rainfall and potential evapotranspiration), and running the model till regime conditions were attained. The yearly modulation for year 2004 was considered as the baseline scenario.

Different scenarios were defined, in order to understand and quantify the effects associated to possible projected changes in the variables that characterize climate and land use, namely:

A. Decrease (A1) or increase (A2) in rainfall;
B. Increase in ambient temperature
C. Increase in agriculturization.

Scenario A1 was defined to represent a reversion to rainfall conditions back in about three decades: the baseline rainfall data, for each station, were scaled down with the ratio between yearly mean rainfall for the period 1960-1980, and for the baseline year. Scenario A2 is a 30 years projection, from the baseline scenario, of the yearly mean rainfall increase trend (3 mm/year) detected during the last decades of the XXth century (Berbery et al. 2006).

Scenario B is also a 30 years projection, from the baseline scenario: a yearly mean temperature increase of 0.011°C (Baez 2006), which leads to an increase in potential evapotranspiration (determined through Thonthwaite formula).

Scenario C represents an extreme situation: complete agriculturization of the basin with soy, which reflects in an increase of the amplitude of oscillation of infiltration through changes in LAI and RD.

RESULTS AND DISCUSSION

Regime conditions for each scenario were attained after about 1 decade, as illustrated in Figure 4 for the mean phreatic depth, indicating that this is the response time scale of the system.

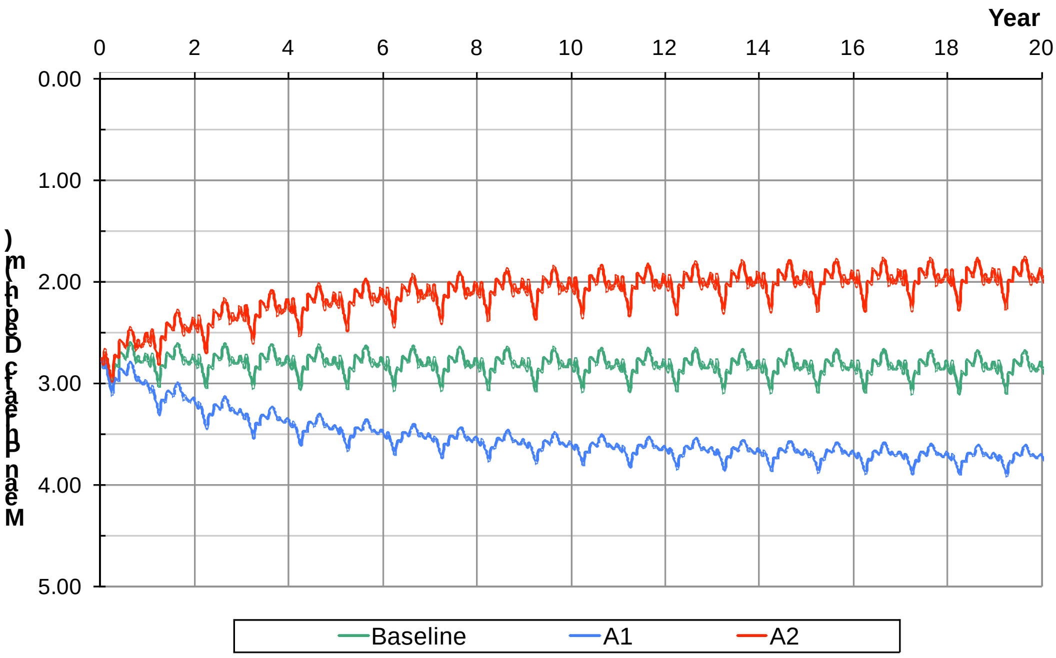

Fig. 4 Discharge for scenarios A1 and A2

Figures 5 and 6 show the discharge at the outlet (Junín) and the mean phreatic depth throughout the model domain, respectively, for the rainfall scenarios. It is observed that for scenario A1 the base flow discharge diminishes about one order of magnitude relative to the baseline scenario, but the peak discharges (and, hence, flooding) practically remains the same. For scenario A2 the base flow discharge increases about two orders of magnitude, and the storm effects do not only manifest as spikes – of about double intensity with respect to the baseline scenario –, but also as base flow increase during the winter time. The mean phreatic level decrease for the A1 scenario and the increase for the A2 scenario are similar, of about 1 m.

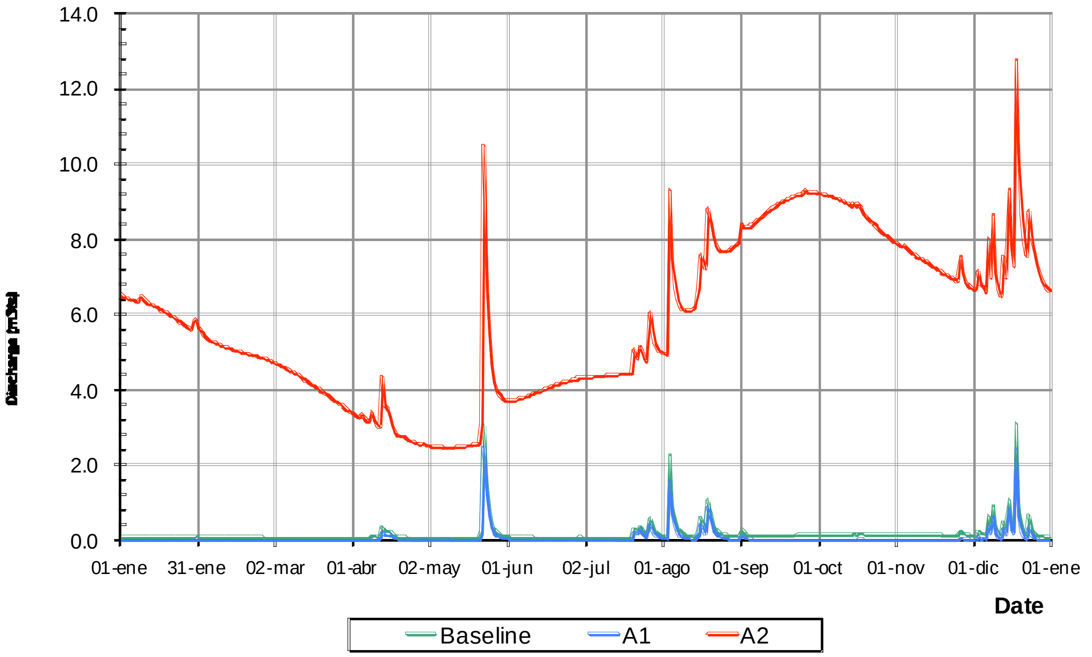

Fig. 5 Discharge for scenarios A1 and A2

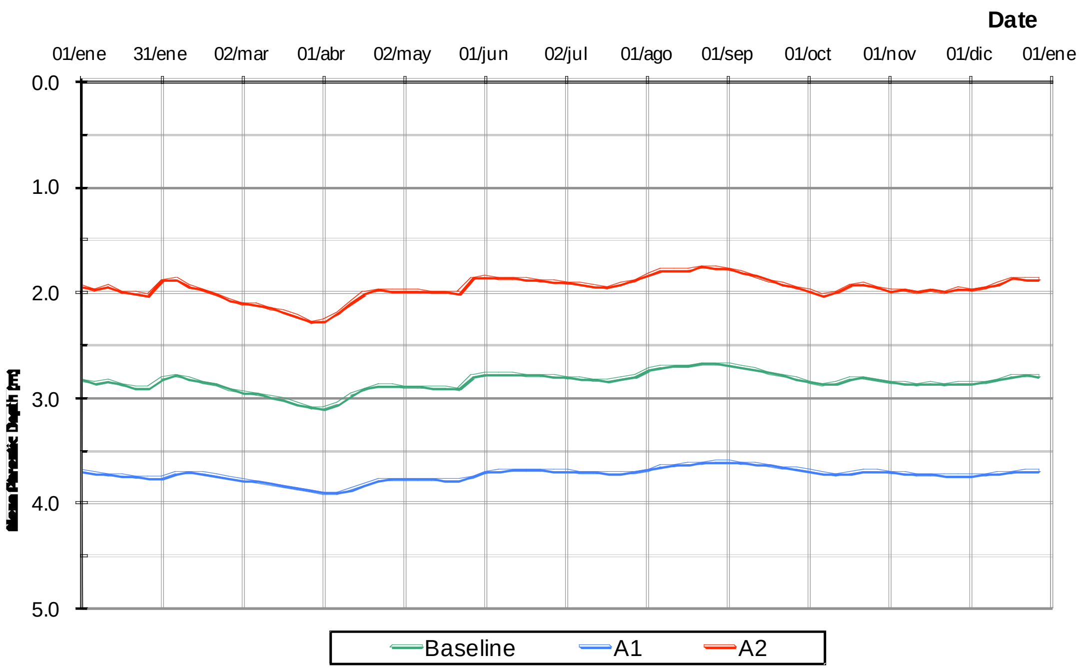

Fig. 6 Phreatic depth for scenarios A1 and A2

Figures 7 and 8 present the results for scenario B. A one order of magnitude decrease of the base flow discharge and around a 30% decrease of the peak discharges, relative to the baseline scenario, are observed. The mean phreatic level decreases in about 0.25 m.

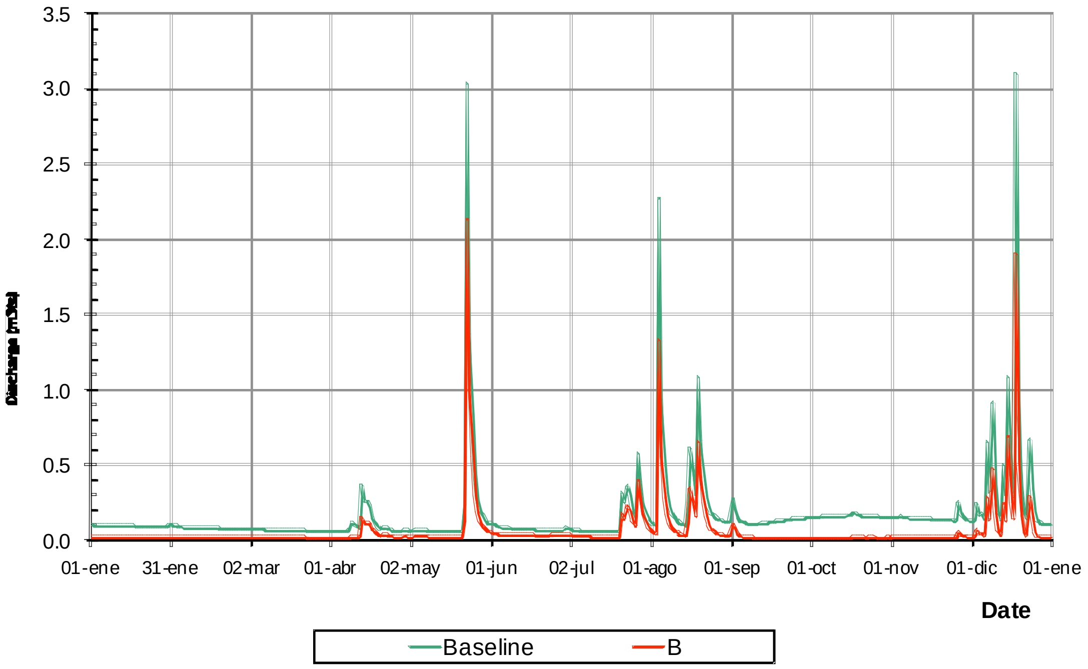

Fig. 7 Discharge for scenario B

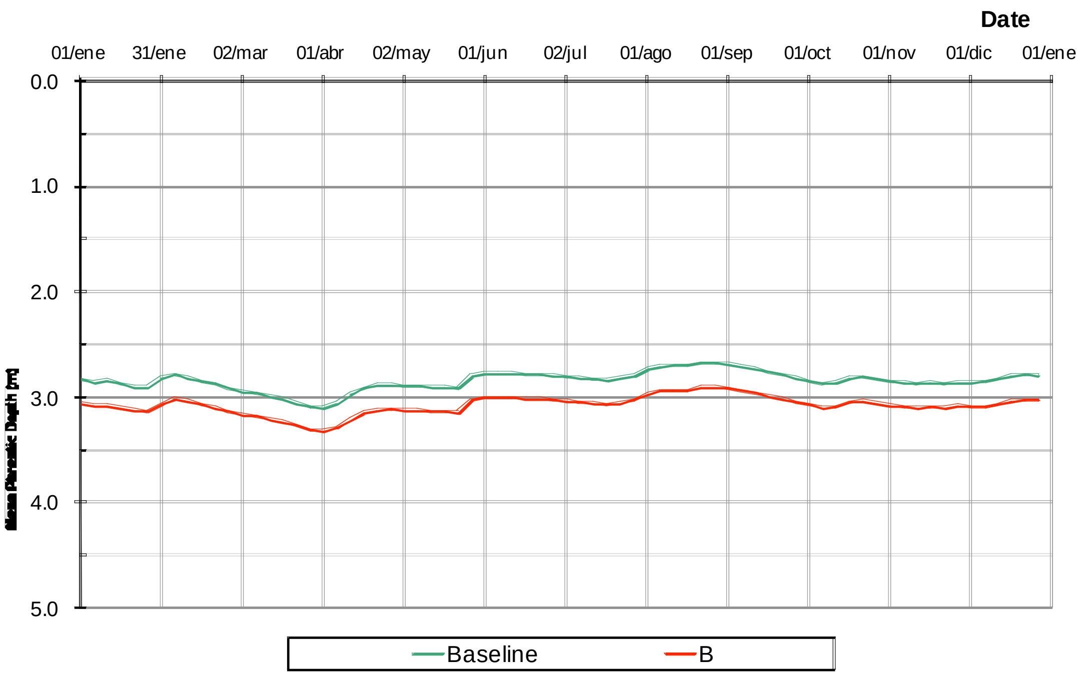

Fig. 8 Phreatic depth for scenario B

The results for scenario C are presented in Figures 9 and 10. The base flow discharge increases by about one order of magnitude relative to the baseline scenario. As for scenario A2, the storm effects manifest, in addition to an impulsive response – of a higher intensity with respect to the baseline scenario –, also as base flow increase during the winter time. The mean phreatic level increases by about 1 m

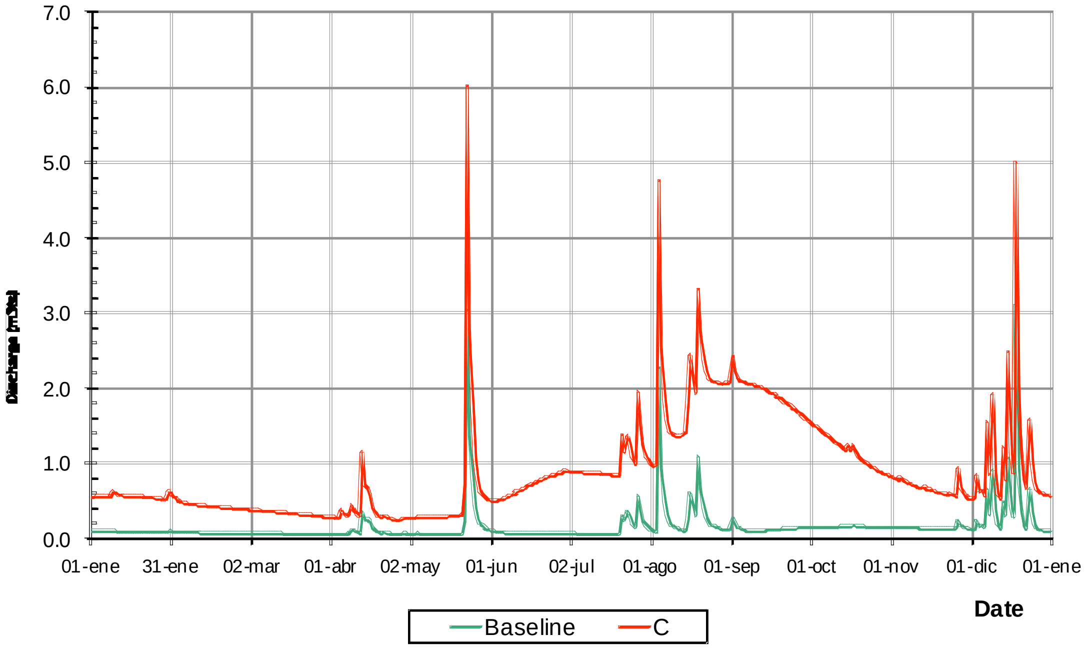

Fig. 7 Discharge for scenario C

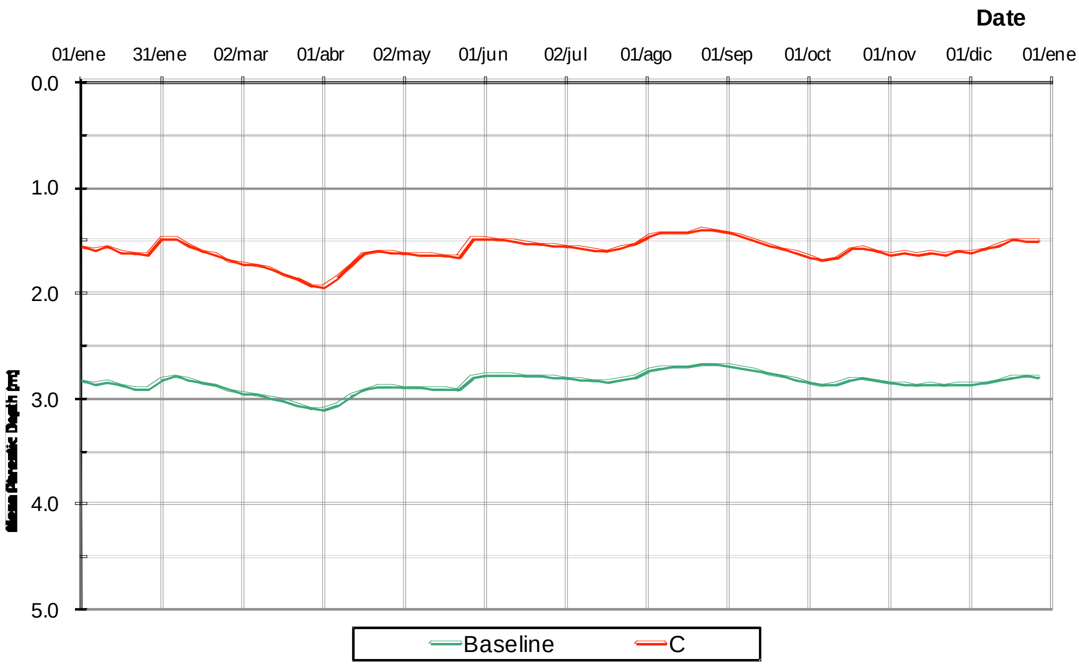

Fig. 8 Phreatic depth for scenario C

These results indicate that the possible changes in climate and land use over a planning horizon (three decades) would significantly affect the hydrologic response of the basin. For scenarios A2, and C, flood risk will increase due to higher intensity impulsive responses of the flow discharge; drought risk, in turn, will decrease due to the rise in base flow discharge and phreatic level. The inverse situation will occur for scenario B:

a decrease in flood risk, due to lower peak discharges, and an increase in drought risk, due to lower base flow discharge and phreatic level. In the case of scenario A1, drought risk will increase, as for scenario B, but flood risk will remain practically unchanged.

CONCLUSIONS

Through an integrated hydrologic model, it has been shown that possible changes in climate and land use over a planning horizon (three decades) would significantly affect the hydrologic response of a very mild slope basin. Under the established trends of increase in mean precipitation and agriculturization, flood risk will increase due to higher intensity impulsive responses of the flow discharge, while drought risk will decrease due to rise in base flow discharge and phreatic level. The opposite will occur under the established temperature increase trend. Should the precipitation decrease, flood risk would remain practically unchanged, but drought risk would increase. As the hydrologic model has been properly calibrated for the study basin, these risk changes have been quantified, constituting a valuable input to formulate management plans in order to maintain the sustainability of the agricultural production. In any case, the time lag of about a decade between changes in the variables, that characterize climate and land use, and the system response, should be taken into account. Combined scenarios with simultaneous changes in more than one variable, should also be studied.

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