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# Evaluating Climate Change Scenarios For Regional Hydrological Management In Mountainous Semi-Arid Environments

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# EVALUATING CLIMATE CHANGE SCENARIOS FOR REGIONAL HYDROLOGICAL MANAGEMENT IN MOUNTAINOUS SEMI-ARID ENVIRONMENTS

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In this study, regionalized data of Global Circulation Model have been used to simulate, at basin scale, the impacts on the hydrological cycle in a semi-arid and mountainous environment, highlighting the hydrological processes most sensitive to meteorological changes. The results obtained showed a significant change in the rainfall-runoff relationship in autumn, conditioned by the decrease in snow precipitation. This pointed toward a greater severity of floods during this season. Furthermore, a loss of 40% of water resources was observed, related to a decrease of 2/3 in snow inputs in winter and spring.

## INTRODUCTION

Snow processes play a relevant role in semi-arid mountainous basins, where snowmelt dynamics conditions the availability of water resources. In such environments, many rivers keep on flowing during the dry season due to the water storage in the snow cover, while heavy rainfall events sporadically trigger severe flood events. These particularities confer a special interest on these areas due to their high sensitivity in the hydrological response to changes in the meteorological conditions. This issue could be critical in many regions of the world linked to semi-arid mountain areas (e.g., the Atlas Mountains, Andean Cordillera) and presents a real challenge for future modifications of water management policies.

The recent work developed by the Intergovernmental Panel for Climate Change (IPCC) predicts a significant climate change over the following decades in Europe. This analysis confirms a global increase in the mean temperature, accompanied by an increase in the sea level and a decrease in snow cover. Taking into account the expected increase in the frequency of extreme events, these changes could cause important alterations in the hydrological cycle. This is especially true in mountain and semi-arid environments [1], where uncertainties in predictions related to the complexity of the processes involved (e.g. irregular distribution of precipitation in time, space and intensity, evapotranspiration effects, etc.) could be considerable.

The impact of climate change on hydrology has been tackled by several authors for different basins (e.g. [2] [3] [4] [5] [6]). These studies are based on the results given by General Circulation Models (GCMs), described through different IPCC reports, and indicate the multiple sources of uncertainties in regional approaches by using GCMs. These uncertainties are mainly related to the GCMs configuration, the downscaling approach of GCMs outputs, the specifications of the climate change scenarios and the errors from hydrological modeling [7].

This study highlights the utility of generating regionalized climate change scenarios in semi-arid environments to assess the most sensitive hydrological processes. This approach allowed us, not to make predictions due to the high level of uncertainty of this kind of study, but to focus our attention on those processes of a greater vulnerability. To do that, climate change scenarios from the ICCP have been set up at the Guadalfeo River (southern Spain), where the fluvial dynamics is bound to the intermittent persistence of snow throughout the year. For this purpose, statistically downscaled data from the Canadian Centre for Climate Modeling Model (CGCM2) given by a previous study were used and adding the local topographic effect on precipitation and temperature. In addition, a physically-based model, calibrated and validated at the study site, has been used to reproduce the seasonal changes in forcing agents-discharge relationship and the availability of water resources.

## STUDY AREA

The study area comprises a significant part, 650 km$^2$, of the headwaters of the Guadalfeo River (1250 km$^2$) located in the south-east of the Iberian Peninsula. The mountainous influence of Sierra Nevada, with 3780 m.a.s.l. conditions the hydrological dynamics and the pluvio-nival character of this semi-arid basin. The annual precipitation is marked by a great spatio-temporal variability, important altitudinal gradients and the occurrence of extreme events that may exceed 300 m$^3$/s [8]. The annual precipitation data show notable spatio-temporal gradients with average values of 460 and 630 mm/y in the valleys (600–800 m.a.s.l.) and mountain areas (1500 m.a.s.l.), respectively, as well as periodic extreme events. At heights of 2500 m.a.s.l., over 70% of the annual precipitation occurs as snow.

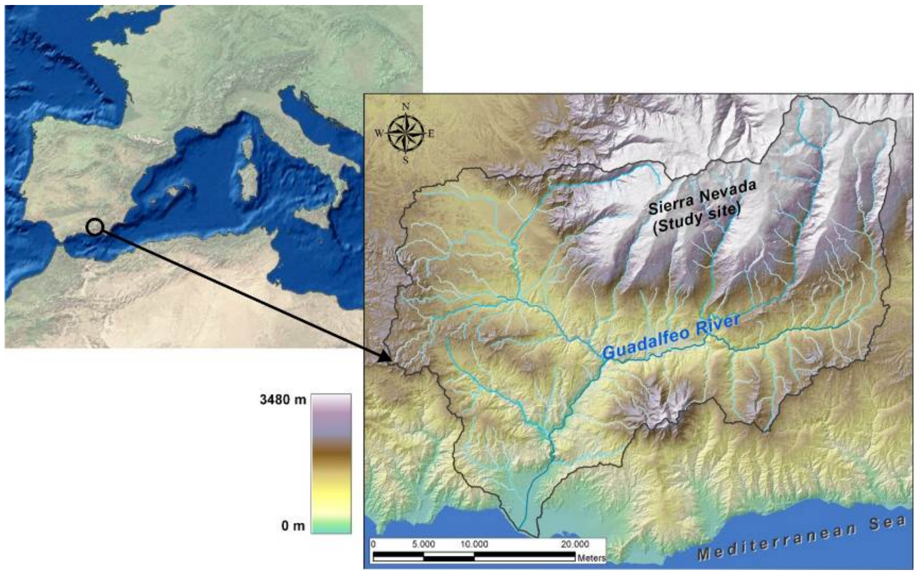


Figure 1. Study site location and basin configuration of the Guadalfeo river.

The geological setting of the study area consists of metamorphic materials from the Sierra Nevada massif. There are numerous published studies analyzing the nature of this particular aquifer, which exhibit a significant volume of water flow throughout different configurations of fractures ([9], [10]). Millares *et al.* [11] remarked on the importance of considering snowmelt in the recharge of this aquifer, defining two responses depending on the depth of these fractures. The result is the existence of many sources; some of them provide starting points for a shallow subsurface flow, with a quick response in terms of storage-discharge relationship, while others have a greater inertial flow with a slower response, which maintains the surface flow of these mountain rivers during the summer.

## METHODS

The methodology followed in this work was based on the study proposed by Steele-Dunne *et al.* [6]. Firstly, for the calibration of the model, meteorological data available from the Meteorological State Agency (AEMET) of temperature (maximum and minimum) and daily precipitation series (mm/d) for the period of 1960-2008 were taken. This calibration and validation methodology using AEMET data has been developed in previous works [12] [13]. The Nash–Sutcliffe coefficient from four years of validation data showed a range of 0.61-0.71 and a good relationship between the observed ($Q_o$) and modeled flow ($Q_{w,a}$) at the Órgiva gauge station.

The second and third steps were based on the downscaled GCM's results. The significant differences in resolution between the results given by GCMs and the hydrological studies, where the processes (e.g. evapotranspiration, snowmelt, seepage) were developed at a local scale, required a downscaling process to increase the resolution of the GCM results.

Basically, the downscaling process can be achieved through two different approaches [14]. On the one hand, with statistical ones [15] where empirical relationships are obtained between the variables or, on the other hand, with dynamic approaches where the downscaling is performed using Limited Area Models, or by increasing the GCM's grid.

Various authors [16] note that the statistical downscaling process has important limitations due to uncertainties in assuming the high resolution surface effects as a function of dynamic conditions at a large scale, ignoring meso-scalar changes (soil moisture, albedo, vegetation roughness, etc.) However, despite the high precision of the dynamic downscaling, their resolution is still insufficient to correctly simulate at the local scale, especially in mountainous areas with complex topography. Furthermore, the high computational costs of these techniques restrict their use to a small number of large research centers. In this work, statistical regionalized data from a previous study [17] have been used to generate the hydrological settings of the area using an IPCC-A2 scenario.

The results of these meteorological data are compared with the ERA-40 data for the reference period 1960-1990 in order to verify the statistical downscaling methodology. The mean errors were calculated for the 28 precipitation and the 5 temperature stations selected within the study area. The largest errors in the precipitation results were related to the summer period, when the simulations over-predicted the values at almost all the stations due to the small amount recorded [17].

Finally, two simulations of the basin were executed with the physically-based and distributed hydrological model WiM-Med [18]; firstly using the reference period given by GCM model ($Q_{cgmPas}t$), and secondly by modifying the meteorological data in relation to the variations simulated with the future period ($Q_{cgmFut}$). The configuration model included spatial and altitudinal interpolation of precipitation and temperature values, representing more appropriately the gradients in high mountain areas.

## RESULTS

The results point to important changes in the hydrological dynamics of the Mediterranean basin. As shown in Figure 2, the snow precipitation decreased considerably, especially in autumn and winter, whereas the snowmelt accumulated throughout the study period showed an important reduction of volume contributions during spring (-73%) and winter (-65%) due to the increasing temperature and decreasing precipitation in winter. These changes led to important flow deviations (Fig. 2c) with a decrease of between 10-25 % during winter and spring. Conversely, while the flow in winter and spring decreased, in autumn these peaks presented sparser results with values equal or even greater than the flow simulated during the reference period. These results were influenced by the increase in precipitation during this season but also by the reduction of the accumulated snow cover. The snow precipitation fraction was lower and the local storms more significant. These storms, with a low amount of snow and large peak flows, have an important effect on flood risk in Mediterranean environments.

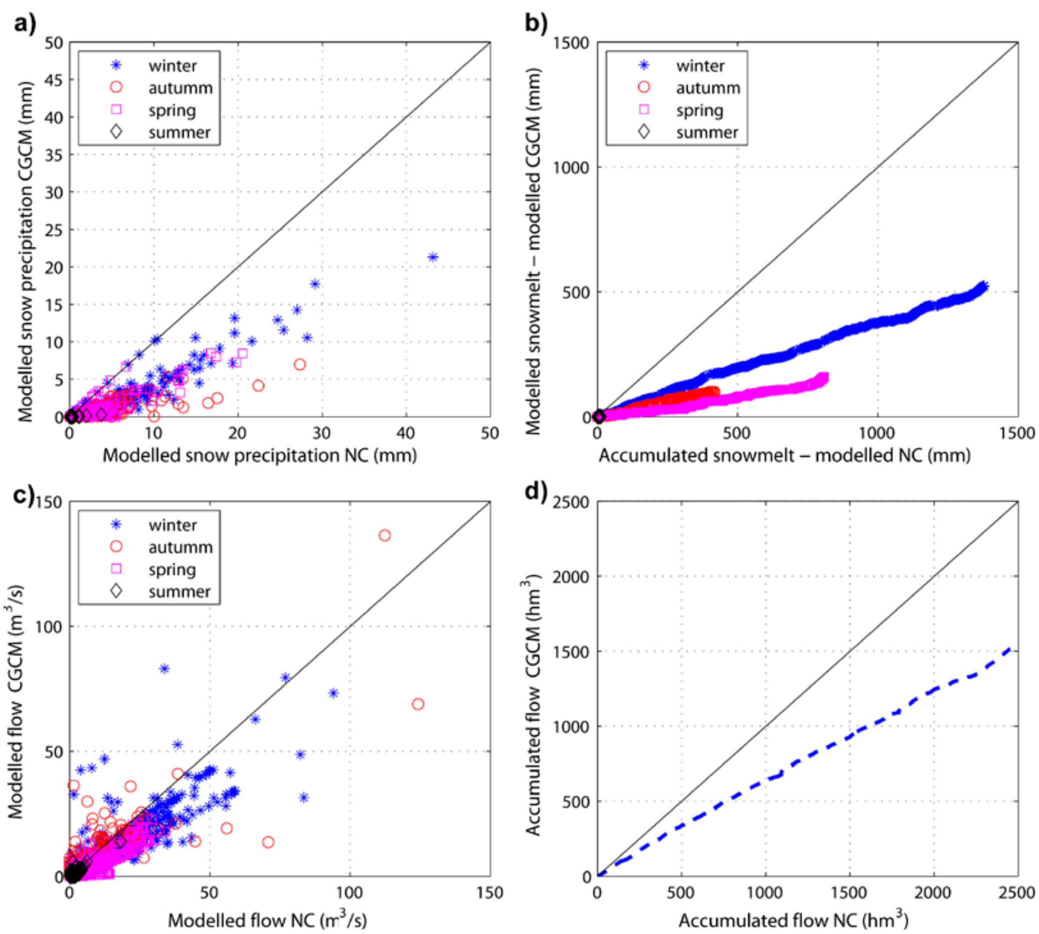


Figure 2. Modeled results related to; snow precipitation (a), accumulated snowmelt (b), and flow (c, d) under normal conditions (NC) and under GCM future predictions (CGCM2).

All in all, these results show on one hand an important reduction of water resources not only at event scale, but also at inter-event scales, with baseflow contributions altering the total quantity and quality of the river ecosystem during the dry season. On the other hand, a potential increase in floods within the study area was observed.

By studying the relationship between the measured/modeled flow at the gauging station and the accumulated precipitation throughout the event, significant changes in trend could be observed within the seasons. The fitted curves represent the relationship from the potential expression $Q=aP^b$ , where $Q$ is the flow (m$^3$/s), $P$ is the accumulated precipitation throughout the event (mm) and $a,b$ coefficients and presented reasonable $R^2$ values ranging from 0.51-0.71. The results obtained point once again to changes in severity of the events, especially in autumn, and the lesser response of the events during spring and summer.

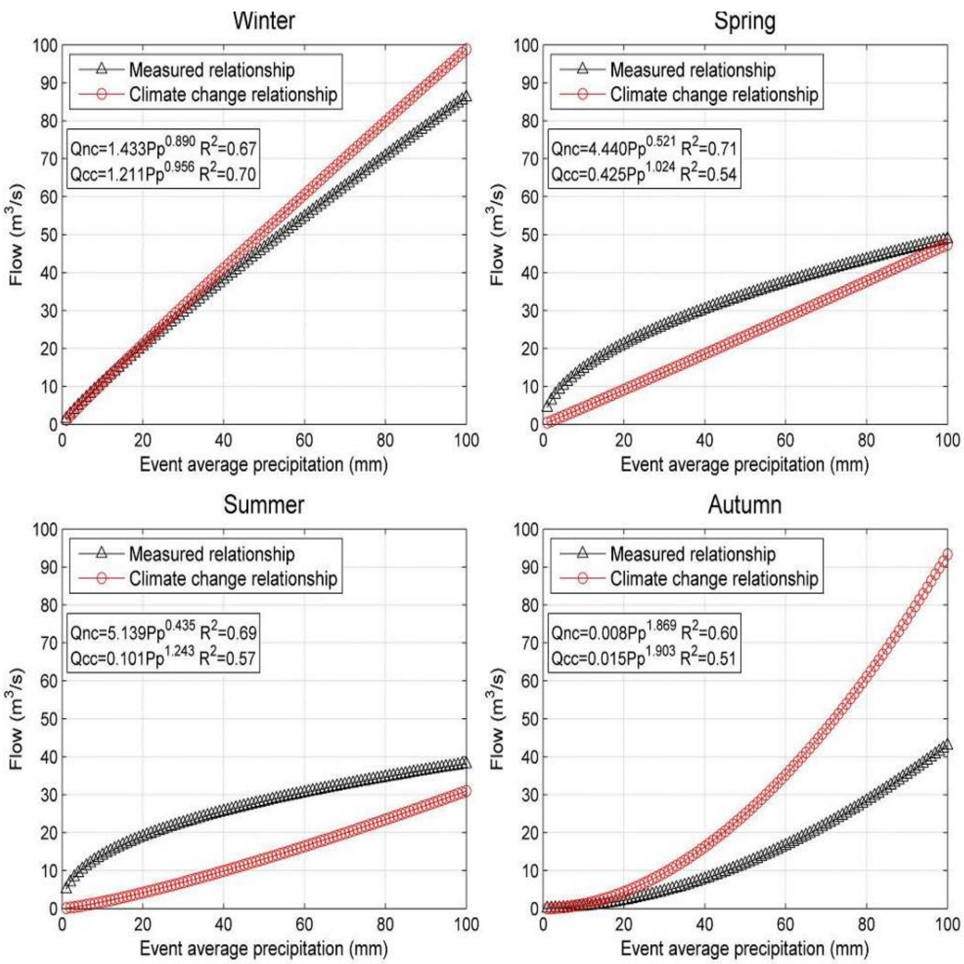


Figure 3. Fitted relationship between averaged flow (measured and modeled under climate change scenario), and the accumulated precipitation during the events for each season.

## CONCLUSIONS

A first approach to quantifying the expected impact of climate change on hydrology in a Mediterranean basin has been performed. The downscaled data for precipitation and temperature resulting from the CGCM2 and IPCC-A2 scenario pointed to a considerable increase in temperature for all seasons with a higher gradient in summer and a strong decrease in precipitation in winter and spring. This scenario led to important changes in the local hydrology patterns observed at the study area.

The uncertainties of the downscaled approach, particularly for the summer and autumn periods due to the influence of local convective storms, limit any conclusions on these types of events, of importance in Mediterranean areas because of their effect on flooding. Despite this, and from the regionalized data of the CGM used, a substantial increase in the severity of the events during this season could be regarded as being a possible situation.

The results also emphasize the important role of the snow, snowfall and snowmelt, in water resources due to their sensitivity to meteorological changes. The simulated changes in precipitation and temperature cause a decrease in hydrological resources of up to 40%, 1000 $hm^3$ in 30 years, mainly related to a lower storage of snow in the mountainous areas, which were quantified as being close to 60%.

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