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Drought Propagation under Combined Influences of Reservoir Regulation and Irrigation over a Mediterranean Catchment [†]

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Abstract: Drought is a natural phenomenon that is controlled by different factors such as natural climate and catchment controls, and in many worldwide regions, it is now driven by human activities (i.e., reservoirs, irrigation, groundwater abstractions). Reservoirs initially ensure water availability and help cope with drought, especially in semi-arid regions; however, this human modification of the environment may lead to both positive and negative effects on the hydrological cycle, which need to be understood. This involves a better understanding of hydrological processes and incorporating human interactions within coupled human–natural systems to improve drought management. We focused on a strongly irrigated area located in the northeast of the Iberian Peninsula, the northern part of the Canal of Aragon and Catalonia district supplied by the Barasona reservoir. We implemented a simple water management model to simulate the reservoir operation (human-influenced scenario) and examined the contribution of human activities, associated with irrigation, on the water budget and drought propagation. For this purpose, we used simulations performed by the hydrometeorological model SASER (SAFRAN-SURFEX-EauDyssée-RAPID), which provided a natural scenario (without human influence) to contrast with the human-influenced scenario. The model performance was evaluated through the Kling Gupta Efficiency (KGE) metric. The first results demonstrated satisfactory performance to simulate reservoir storage and outflows against observed data, with KGE values of 0.4 and 0.82, respectively. Then we explored the linkages between agricultural drought, associated with evapotranspiration, and hydrological drought. We applied standardized indices to identify different kinds of drought, compared them, and assessed changes induced by human activities. Human modifications modulate the hydrological response of the catchment, and alter the intensity of hydrological drought, while human activities reduce the intensity of agricultural droughts.

Keywords: drought propagation; water management; anthropogenic drought

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1. Introduction

Droughts are usually defined as prolonged periods of below-average precipitation conditions [1,2]. Droughts can be classified into several categories, including meteorological, agricultural, and hydrological [3]. Meteorological droughts are based on precipitation deficits, agricultural droughts refer to soil moisture deficits, and hydrological droughts are mainly based on streamflow. Each of them is characterized by different indices [3,4].

Recent studies have shown that in some regions of the world, such as southern Europe and West Africa, droughts have become more intense and prolonged in recent decades [5,6]. This trend is likely due to a combination of factors, such as climate change and the growing water demand from human activities, such as irrigation and urbanization, which can put additional stress on water resource systems, exacerbating the impacts of droughts [7–9]. Therefore, it is important to consider human influences in the assessment and management of droughts.

Land surface models (LSMs) have been widely recognized as a powerful tool for understanding and simulating the hydrological cycle, including droughts [10–13]. Particularly in Spain, LSMs have been used to evaluate and provide information on water availability and potential drought hotspots [14,15]. Nevertheless, for more realistic modeling of droughts, it is crucial to incorporate the representation of human factors in current-generation LSMs [16].

In this study, we investigate how human activities (irrigation and reservoir operation) impact drought propagation in a coupled human–water system. The twofold objective of this research is (i) implementing a prototype reservoir operation scheme that could be integrated into the SASER (SAFRAN-SURFEX-Eaudyssée-RAPID) modeling chain and which exploits the new SURFEX irrigation scheme [17] and (ii) quantifying the impact of human activities on drought propagation. To address this objective, we evaluate the ability of the new module that simulates reservoir operation and compare it against the simulation performed by the SASER model, which provided a natural scenario (without human influence) to contrast with the human-influenced scenario.

2. Data and Methods

2.1. Study Area and Data

We selected a strongly irrigated area located in the northeast of the Iberian Peninsula, the northern part of the Canal of Aragon and Catalonia (CAyC), with a size of 54,000 ha, which is supplied by the Barasona reservoir (Figure 1). This reservoir has a maximum volume capacity of 84 Hm^3.

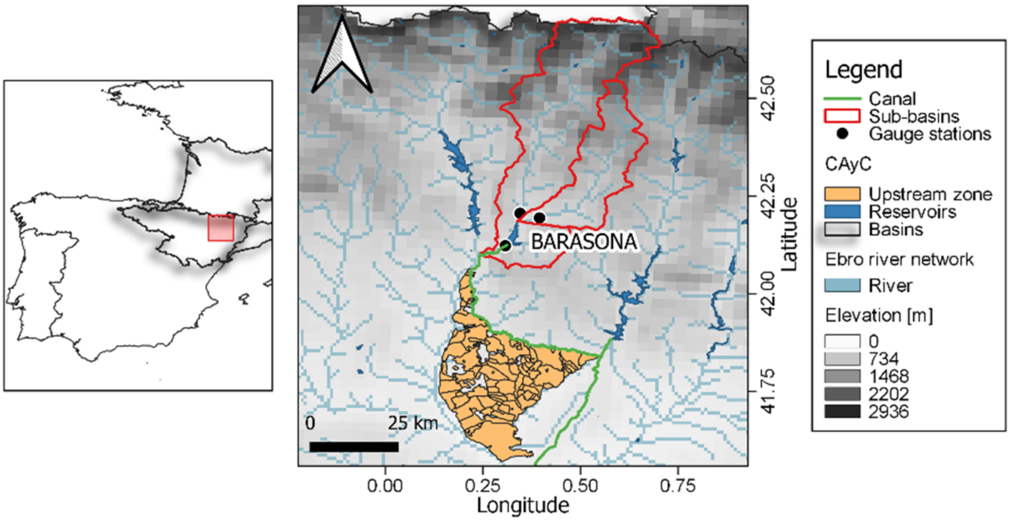

Figure 1. Location of the study area.

The main data used in this study, observed streamflow and reservoir volume, were obtained from the Automatic Hydrologic Information System, SAIH in Spanish. Irrigation demands were collected from the Ebro Hydrographic Confederation (CHE, in Spanish).

In addition, SURFEX-LSM [18], which simulates natural surfaces in the vertical soil column, provided runoff and evapotranspiration (ET) data. Precipitation data were obtained from the gridded meteorological dataset SAFRAN, as depicted in Figure 2a. The version of SASER used in this study incorporates a conceptual reservoir to postprocess the drainage with regionalized parameters, named SASER-reg [19]. In Figure 2a shows the general framework with the main steps used.

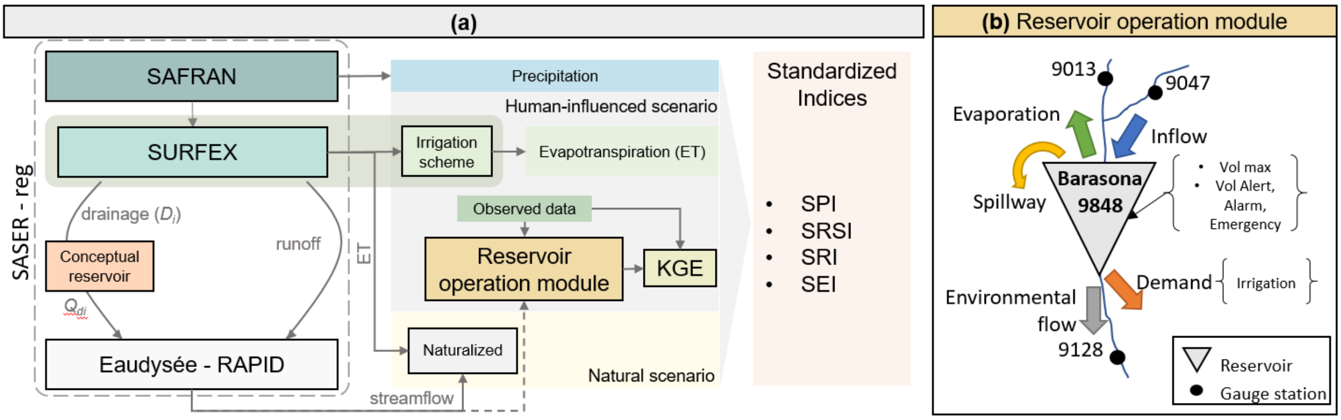

Figure 2. General framework used in our analysis (**a**), and (**b**) schematic representation of the reservoir operation model.

2.2. Reservoir Model Scheme

We implemented a simple reservoir operation scheme as depicted in Figure 2b, based on the Water Availability and Adaptation Policy Assessment (WAAPA) model [20]. This model simulates reservoir operation considering the environmental flows and evaporation losses. The model requires the following input: streamflow, demands, and environmental flows. In this research, before connecting SASER outputs, we assessed the ability of the module to reproduce the dam behavior. Therefore, we first used observed streamflow data as input to the module and then compared the simulated volume and reservoir's outflow against observed data, as Figure 2a indicates.

To evaluate the model performance of the reservoir operation module, we used the Kling–Gupta efficiency, KGE, [21]:

$$\mathrm{KGE} = 1 - \sqrt{(1 - \mathrm{r}^2) + (1 - \alpha) + (1 - \beta)}; \tag{1}$$

$$\alpha = \frac{\mu_s}{\mu_o} \text{ and } \beta = \frac{\sigma_s}{\sigma_o} \tag{2}$$

where r is the Pearson's correlation coefficient, α represents the bias component, and β is the ratio of variance; μ and σ represent the mean and standard deviation, respectively. Similarly, subscripts s and o represent simulated and observed variables, respectively.

To simulate the natural scenario (without human influence), we used a simulation performed by the SASER model, Figure 2a, and we compared it against the human-influenced scenario, which incorporates a new irrigation scheme developed within the SURFEX model [17], allowing us to estimate a realistic amount of irrigation water, and therefore the evapotranspiration associated with it.

To represent the different types of droughts, we used standardized indices. The Standardized Precipitation Index (SPI) [22] was utilized to characterize meteorological drought. To hydrological drought, we applied the Standardized Runoff Index (SRI) [23], and the reservoir storage was also standardized. For agricultural drought, we used a procedure similar to SPI and calculated the Standardized Evapotranspiration Index (SEI) using the evapotranspiration data associated with irrigation.

3. Results and Discussion

3.1. Reservoir Operation

The results of the reservoir operation module shown here indicate a satisfactory performance to simulate storage and outflows, with KGE values of 0.4 and 0.82, respectively (Figure 3). Creating a complete water management simulation that optimizes water resources by feeding the reservoir module with SASER results is the next step, which is beyond the scope of this study.

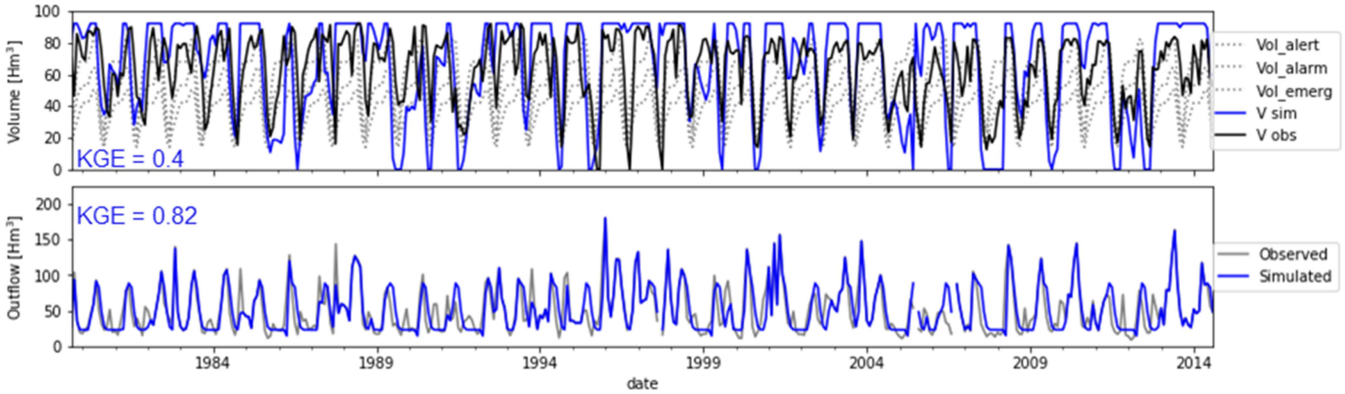

Figure 3. Observed (black line) and simulated (in blue) reservoir storage and outflow for the Barasona reservoir.

It is worth highlighting that for the reservoir simulation, the same irrigation demand was assumed for every year, which does not accurately reflect realistic conditions. Nevertheless, this approach has yielded reasonably good results.

The simulated volume storage follows the same dynamics as observed data (upper panel in Figure 3), except for the events from 1995 to 1997, which correspond to other factors and not to irrigation demands. The simulated and observed outflows show a very good agreement, with a high value of KGE.

3.2. Drought Analysis

Standardized indices at a 12 m time scale were considered to evaluate how the meteorological drought signal propagates through other variables. To understand drought processes, we calculated the frequency of drought events.

Meteorological drought is represented in Figure 4a, and anomalies in the reservoir storage are depicted in Figure 4b. The hydrological drought depicted in Figure 4c shows a similar pattern in both the natural and human scenarios, the solid blue line and red line, respectively. However, the blue shaded area shows the opposite behavior of this index under the human scenario, which is attributable to the reservoir operation.

Anomaly analysis also allows for quantification of the impact of human activities. The frequency, total number of drought events (index < -1), is shown in the bottom right of each panel in Figure 4. For meteorological drought, 10 events are reported. For hydrological drought, in the observed situation, the number of events is higher than for the naturalized scenario (blue and red lines in Figure 4c, respectively). The opposite occurs in the anomalies associated with ET: the number of events is higher in the naturalized scenario than in the scenario where irrigation is active (nine and eight events, respectively). This was expected, as streamflow decreases while ET increases due to irrigation.

We also calculated the total number of months in drought (duration of drought), and we found that in the human scenario, hydrological drought increased from 158 to 176 months, representing an increase of 10%, which suggests that reservoir operation increases the duration of drought events. Whereas for drought associated with evapotranspiration, a similar total duration was obtained in both scenarios (167 months for the human scenario and 163 for the natural scenario).

We observed changes in hydrological drought intensities; for instance, the event between 2005 and 2008 shows lower values in the natural scenario, which suggests that reservoir operation mitigates the effect of drought. Conversely, in 2012, the lower values occurred in the human scenario, suggesting that the reservoir could be aggravating the drought.

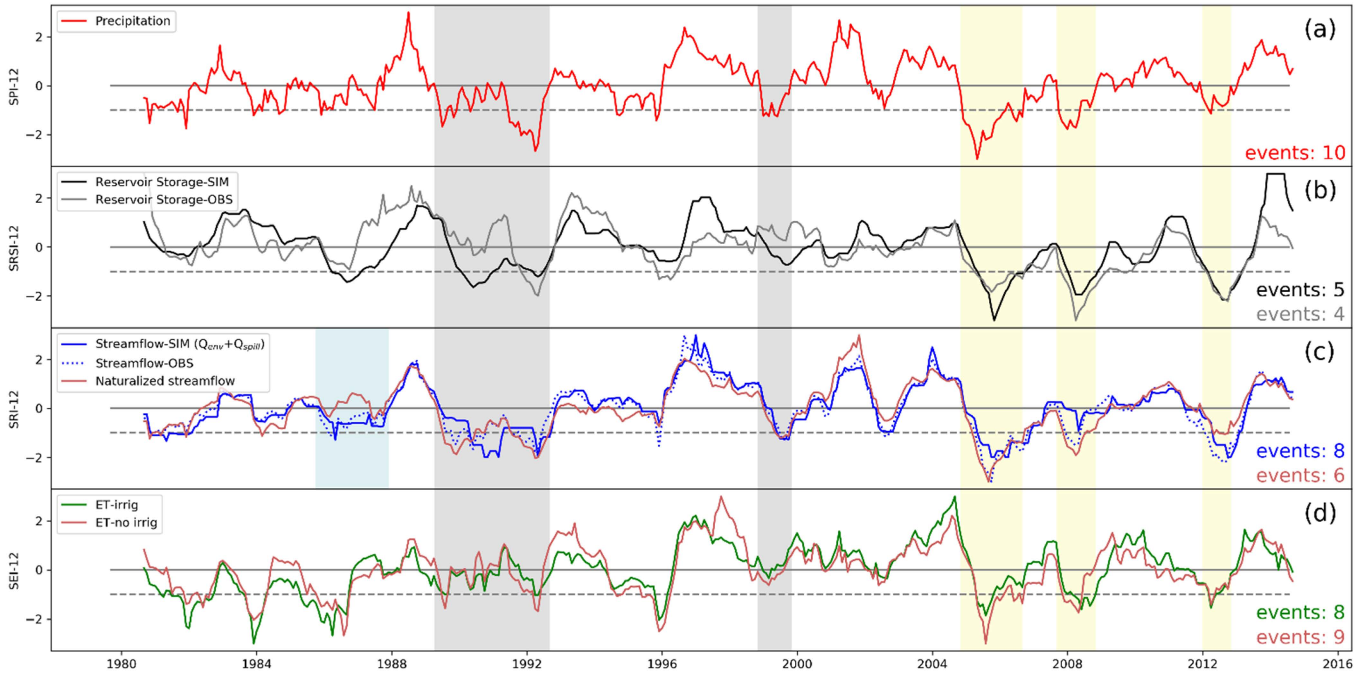

Figure 4. Droughts indices, all to 12 months. (**a**) Standardized Precipitation Index, SPI; (**b**) Standardized Reservoir Storage Index, SRSI; (**c**) Standardized Runoff Index, SRI; (**d**) Standardized Evapotranspiration Index, SEI. Number of drought events is reported in each corresponding panel.

In Figure 3, the gray shaded areas show differences in drought propagation and correspond with the meteorological drought event of maximum duration (40 months). The hydrological drought (a single long event) responds directly to meteorological drought; this response is not reflected in agricultural drought (two short events are reported).

Additionally, we selected three severe droughts (2004–2005, 2008, and 2012, indicated in the yellow shaded areas in Figure 4) to exhibit differences in drought propagation under the human scenario. We found that drought directly propagates from meteorological to hydrological, but not with agricultural (evapotranspiration associated with irrigation) drought. If we focus on the linkage between SRI and SEI, a pattern was found, whereby the first decreases and the other increases, and vice versa. These results show how human interventions contribute to modulating the evapotranspiration and runoff due to extensive irrigation practices.

4. Conclusions

We are currently developing a framework considering the evapotranspiration processes associated with irrigation to evaluate the role of human activities on agricultural and hydrological droughts in a Mediterranean catchment. Thus, we implemented a reservoir simulation scheme as an external module, which allows for a flexible approach (rapid iteration process). The reservoir model shows good performance, considering the model's simplifications. The KGE is good, especially for outflows. Through the SURFEX irrigation scheme, dynamic irrigation demands can be used, which provides a more realistic analysis.

To investigate the impact of human activities on the water cycle and droughts, we used different standardized indices. This allows for analyzing and characterizing drought events (e.g., intensity, duration) and investigating the drought dynamic under a coupled natural–human system. Finally, the impact of irrigation and reservoir operation on the catchment modifies the hydrological response, leading to variations in the severity of hydrological droughts, while at the same time, these human activities have the opposite effect on the intensity of droughts associated with evapotranspiration.

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