environmental sciences proceedings

Proceeding Paper

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

Omar Cenobio-Cruz [1,*], Pere Quintana-Seguí [1] and Luis Garrote [2]

[1] Observatori de l'Ebre, Universitat Ramon Llull–CSIC, Roquetes, Spain; pquintana@obsebre.es
[2] Department of Civil Engineering: Hydraulics, Energy and Environment, Universidad Politécnica de Madrid, 28040 Madrid, Spain; l.garrote @upm.es
* Correspondence: ocenobio@obsebre.es; Tel.: +34-977-500-511

† Presented at the 7th International Electronic Conference on Water Sciences (ECWS-7), Online, 15–30 March 2023.

Abstract: Drought is a natural phenomenon that is controlled by different factors such as natural climate, 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 to the environment may lead both positive and negative effects over 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 examine the contribution of human activities, associated with irrigation, on the water budget and drought propagation. For this purpose, we use simulations performed by the SASER model which provided a natural scenario (without human influence) to contrast with the human-influenced scenario. Here, we explore the linkages between agricultural drought, associated with evapotranspiration, and hydrological drought. We applied standardized indices to identify different kinds of drought, then we compare each other and assess changes induced by human activities. 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. The human modifications modulate the hydrological response of the catchment, and alter the intensity of hydrological drought, while human activities reduced the intensity of agricultural droughts.

Keywords: drought propagation; water management; anthropogenic drought

Citation: Cenobio-Cruz, O.; Quintana-Seguí, P.; Garrote, L. Drought Propagation under Combined Influences of Reservoir Regulation and Irrigation over a Mediterranean Catchment. *Environ. Sci. Proc.* **2023**, *5*, x. https://doi.org/10.3390/xxxxx

Academic Editor(s):

Published: 15 March 2023

1. Introduction

Droughts are usually defined as prolonged periods of below-average 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 are referred on 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 resources 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 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 on drought propagation in a coupled human-water system. The two-fold objective of this research is (i) implementing a prototype reservoir operation scheme that could be integrated into the SASER (SAFRAN-SURFEX-Eaudyssee-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 have selected a strongly irrigated area located in the northeast of the Iberian Peninsula, the northern part of the Canal of Aragon and Catalonia, with a size of 54,000 ha, which is supplied by the Barasona reservoir. This reservoir has a maximum volume capacity of 84 Hm^3.

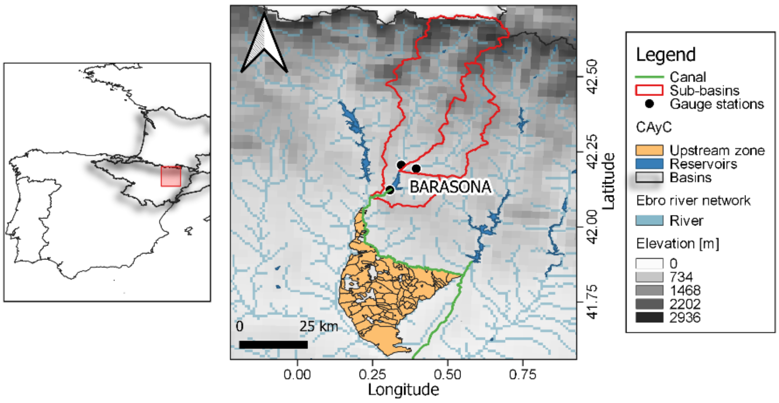

Figure 1. Location of the study area.

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, provides runoff and evapotranspiration (ET) data. Precipitation data is obtained from the gridded meteorological dataset SAFRAN, as depicted in Figure 2. The version of SASER used in this study incorporates a conceptual reservoir to post-process the drainage with regionalized parameters named SASER-reg [19].

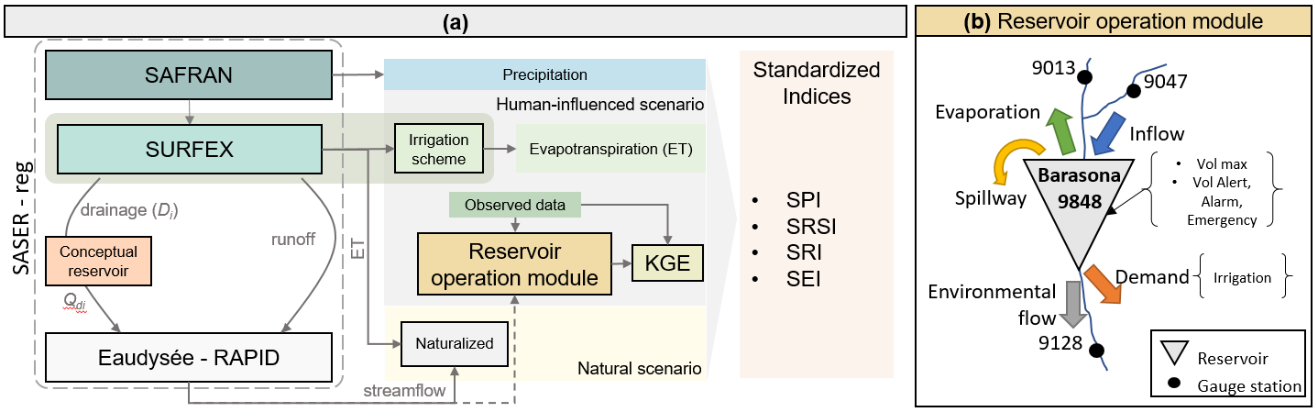

Figure 2. General framework used in our analysis, and (**b**) schematic representation of the reservoir operation model.

2.2. Reservoir Model Scheme

We implemented a simple reservoir operation scheme as depicted in Figure 2b, based on the WAAPA model [20]. This model simulates the reservoir operation considering the environmental flows and evaporation losses. The model requires input: streamflow, demands, and environmental flows. In this research, before connecting SASER outputs, we assess the ability of the module to reproduce the dam behavior. Therefore, we first use observed streamflow data as input to the module and then compare 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 use 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 compare 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 the agricultural drought we use a procedure similar to SPI and calculates 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.

It is worth highlighting that for the reservoir simulation, the same irrigation demand was assumed 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 that 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.

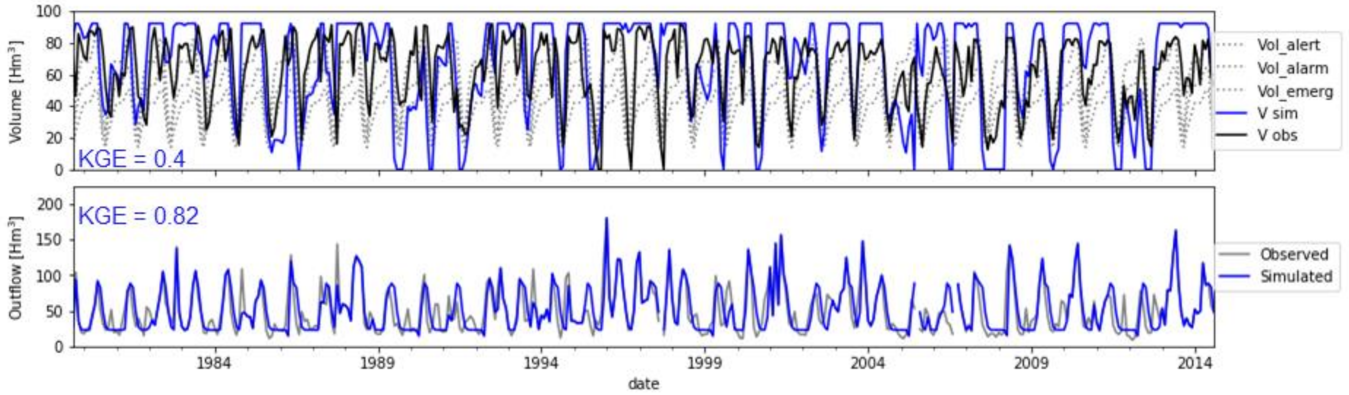

Figure 3. Observed (black line) and simulated (in blue) reservoir storage and outflow for the Barasona reservoir.

3.2. Drought Analysis

Standardized indices at 12-m time scale were considered to evaluate how meteorological drought signal propagates through the other variables. To understand drought processes, we calculate 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 scenarios Natural and Human, solid blue line and red line, respectively. However, the blue shaded area shows an opposite behavior of this index under the Human scenario, which is attributable to the reservoir operation.

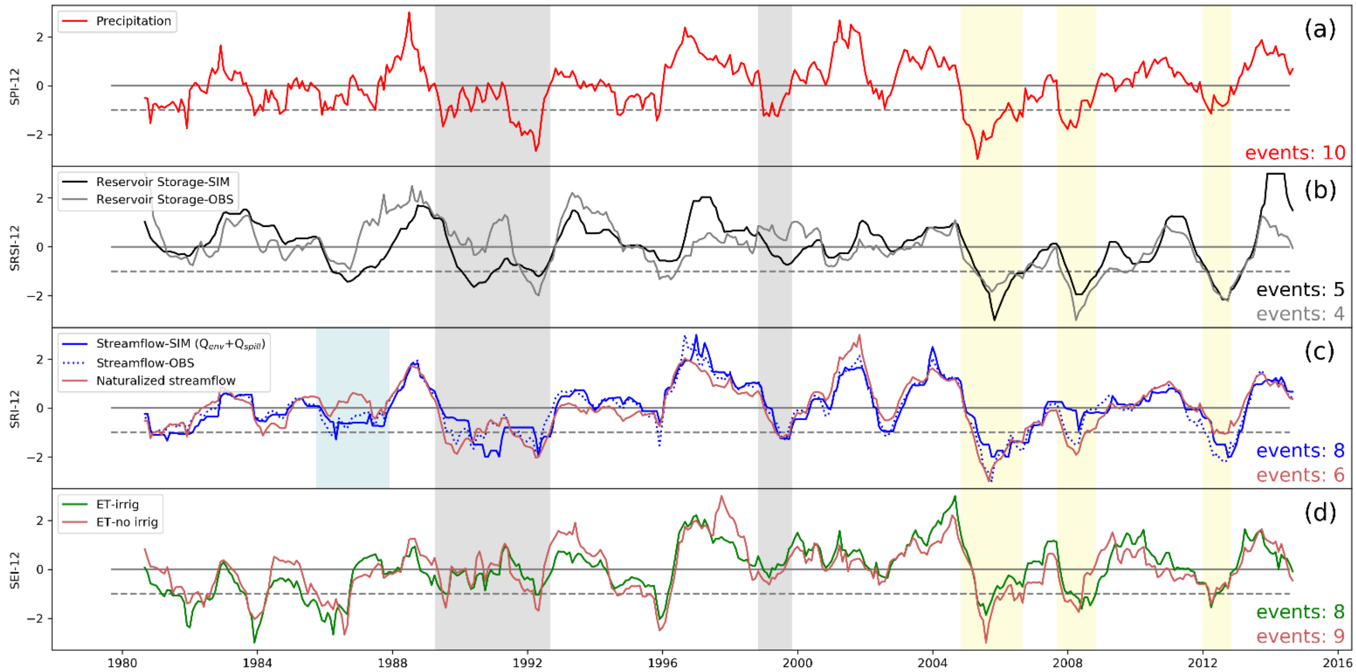

Figure 4. Droughts indices, all of them to 12 months. (**a**) Standardized Precipitation Index, SPI; (**b**) Standardized Reservoir Storage Index, SRSI; (**c**) Standardized Runoff Index, SRI; (**d**) Standardized Evapotranspiration Index, SEI. Number of drought events are reported in each corresponding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

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 the 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 the ET, the number of events is higher in the naturalized scenario than in the scenario where the irrigation is active (9 and 8 events, respectively). This was expected, as the streamflow decreases while ET increases due to the irrigation.

We also calculate the total number of months in drought (duration of drought), and we find that in the Human scenario, hydrological drought increased from 158 to 176 months, representing an increase of 10%, which suggest that the 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 find changes in hydrological drought intensities, for instance, the event between 2005-2008 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.

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 (only one and 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 yellow shaded areas in Figure 4) to exhibited differences in drought propagation under the Human scenario. We find 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, whereas the first decrease and the other increase, 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 developing a framework considering the evapotranspiration processes associated with the irrigation for the evaluation of 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 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 use different standardized indices It 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 an opposite effect on the intensity of droughts associated with evapotranspiration.

Author Contributions: Conceptualization, O.C.-C. and P.Q.-S.; methodology, O.C.-C., P.Q.-S. and L.G.; software, P.Q.-S. and L.G.; formal analysis, O.C.-C., P.Q.-S. and L.G.; investigation, O.C.-C.; resources, L.G.; data curation, O.C.-C.; writing—original draft preparation, O.C.-C.; writing—review and editing, O.C.-C., P.Q.-S. and L.G.; visualization, O.C.-C.; supervision, P.Q.-S. and L.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the HUMID project (CGL2017-85687-R, AEI/FEDER, UE), the predoctoral grant PRE2018-085027 (AEI/FSE), and the IDEWA project (PRIMA PCI2020-112043 / AEI / 10.13039/501100011033).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data will be made available on request.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Stagge, J.H.; Tallaksen, L.M.; Gudmundsson, L.; Van Loon, A.F.; Stahl, K. Candidate Distributions for Climatological Drought Indices (SPI and SPEI). *Int. J. Climatol.* **2015**, *36*, 2132–2138. https://doi.org/10.1002/joc.4564.
2. Wilhite, D.A.; Glantz, M.H. Understanding: The Drought Phenomenon: The Role of Definitions. *Water Int.***1985**, *10*, 111–120. https://doi.org/10.1080/02508068508686328.
3. Mishra, A.K.; Singh, V.P. A review of drought concepts. *J. Hydrol.***2010**, *391*, 202–216.
4. Keyantash, J.; Dracup, J.A. The quantification of drought: An evaluation of drought indices. *Bull. Am. Meteorol. Soc.* **2002**, *83*, 1167–1180. https://doi.org/10.1175/1520-0477-83.8.1167.
5. Seneviratne, S.; Nicholls, N.; Easterling, D.; Goodess, C.M.; Kanae, S.; Kossin, J.; Luo, Y.; Marengo, J.; McInnes, K.; Rahimi, M.; et al. Changes in climate extremes and their impacts on the natural physical environment. *Manag. Risk Extrem. Events Disasters to Adv. Clim. Chang. Adapt.* 2012, 109–230. https://doi.org/10.1017/CBO9781139177245.006.
6. Prudhomme, C.; Giuntoli, I.; Robinson, E.L.; Clark, D.B.; Arnell, N.W.; Dankers, R.; Fekete, B.M.; Franssen, W.; Gerten, D.; Gosling, S.N.; et al. Hydrological droughts in the 21st century, hotspots and uncertainties from a global multimodel ensemble experiment. *Proc. Natl. Acad. Sci. USA.* **2014**, *111*, 3262–3267. https://doi.org/10.1073/pnas.1222473110.
7. Bates, B.C.; Kundzewicz, Z.W.; Wu, S.; Palutikof, J.P. *Climate Change and Water*. 2008. https://doi.org/10.1016/j.jmb.2010.08.039.
8. Wada, Y.; Van Beek, L.P.H.; Wanders, N.; Bierkens, M.F.P. Human water consumption intensifies hydrological drought worldwide. *Environ. Res. Lett.* **2013**, *8*, 034036. https://doi.org/10.1088/1748-9326/8/3/034036.
9. Wanders, N.; Wada, Y. Human and climate impacts on the 21st century hydrological drought. *J. Hydrol.* **2015**, *526*, 208–220. https://doi.org/10.1016/j.jhydrol.2014.10.047.
10. Lehner, B.; Döll, P.; Alcamo, J.; Henrichs, T.; Kaspar, F. Estimating the Impact of Global Change on Flood and Drought Risks in Europe: A Continental, Integrated Analysis. *Clim. Chang.* **2006**, *75*, 273–299. https://doi.org/10.1007/S10584-006-6338-4.
11. Vidal, J.-P.; Martin, E.; Franchistéguy, L.; Habets, F.; Soubeyroux, J.-M.; Blanchard, M.; Baillon, M. Multilevel and multiscale drought reanalysis over France with the Safran-Isba-Modcou hydrometeorological suite. *Hydrol. Earth Syst. Sci.***2010**, *14*, 459–478, Mar. https://doi.org/10.5194/hess-14-459-2010.
12. Prudhomme, C.; Parry, S.; Hannaford, J.; Clark, D.B.; Hagemann, S.; Voss, F. How Well Do Large-Scale Models Reproduce Regional Hydrological Extremes in Europe? *J. Hydrometeorol.* **2011**, *12*, 1181–1204. https://doi.org/10.1175/2011JHM1387.1.
13. Van Loon, A.F.; Van Huijgevoort, M.H.J.; Van Lanen, H.A.J. Evaluation of drought propagation in an ensemble mean of large-scale hydrological models. *Hydrol. Earth Syst. Sci.* **2012**, *16*, 4057–4078. https://doi.org/10.5194/hess-16-4057-2012.
14. Gaona, J.; Quintana-Seguí, P.; Escorihuela, M.J.; Boone, A.; Llasat, M.C. Interactions between precipitation, evapotranspiration and soil-moisture-based indices to characterize drought with high-resolution remote sensing and land-surface model data. *Nat. Hazards Earth Syst. Sci.* **2022**, *22*, 3461–3485. https://doi.org/10.5194/nhess-22-3461-2022.
15. Barella-Ortiz, A.; Quintana-Seguí, P. Evaluation of drought representation and propagation in regional climate model simulations across Spain. *Hydrol. Earth Syst. Sci.* **2019**, *23*, 5111–5131, Dec. https://doi.org/10.5194/HESS-23-5111-2019.
16. Pokhrel, Y.N.; Hanasaki, N.; Wada, Y.; Kim, H. Recent progresses in incorporating human land–water management into global land surface models toward their integration into Earth system models. *Wiley Interdiscip. Rev. Water* **2016**, *3*, 548–574. https://doi.org/10.1002/WAT2.1150.
17. Druel, A.; Munier, S.; Mucia, A.; Albergel, C.; Calvet, J.-C. Implementation of a new crop phenology and irrigation scheme in the ISBA land surface model using SURFEX_v8.1. *Geosci. Model Dev.* **2022**, *15*, 8453–8471. https://doi.org/10.5194/GMD-15-8453-2022.
18. Masson, V.; Le Moigne, P.; Martin, E.; Faroux, S.; Alias, A.; Alkama, R.; Belamari, S.; Barbu, A.; Boone, A.; Bouyssel, F.; et al. The SURFEXv7.2 land and ocean surface platform for coupled or offline simulation of earth surface variables and fluxes. *Geosci. Model Dev.* **2013**, *6*, 929–960. https://doi.org/10.5194/gmd-6-929-2013.

19. Cenobio-Cruz, O.; Quintana-Seguí, P.; Barella-Ortiz, A.; Zabaleta, A.; Garrote, L.; Clavera-Gispert, R.; Habets, F.; Beguería, S. Improvement of low flows simulation in the SASER hydrological modeling chain. *J. Hydrol. X* **2023**, *18*, 100147. https://doi.org/10.1016/J.HYDROA.2022.100147.
20. Sordo-Ward, A.; Granados, A.; Iglesias, A.; Garrote, L.; Bejarano, M.D. Adaptation effort and performance of water management strategies to face climate change impacts in six representative basins of Southern Europe. *Water* **2019**, *11*, 1078. https://doi.org/10.3390/w11051078.
21. Gupta, H.V.; Kling, H.; Yilmaz, K.K.; Martinez, G.F.; Kling, H. Decomposition of the mean squared error and NSE performance criteria: Implications for improving hydrological modelling. *J. Hydrol.* **2009**, *377*, 80–91. https://doi.org/10.1016/j.jhydrol.2009.08.003.
22. Mckee, T.B.; Doesken, N.J.; Kleist, J. The relationship of drought frequency and duration to time scales. *AMS 8th Conf. Appl. Climatol.*1993, 179–184, doi: Citeulike-article-id:10490403.
23. Shukla, S.; Wood, A.W. Use of a standardized runoff index for characterizing hydrologic drought. *Geophys. Res. Lett.* **2008**, *35*. https://doi.org/10.1029/2007GL032487.