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INFLUENCE OF THE INTERANNUAL VARIABILITY OF METEOROLOGICAL DROUGHT ON THE CROSS-INTERACTIONS OF ECOLOGICAL AND HYDROLOGICAL DROUGHT IN THE CENTRAL SPANISH PYRENEES

[1]Sergio M. Vicente-Serrano, [1]Ahmed El Kenawy, [1]Javier Zabalza-Martínez, [1]Iván Noguera, [2]Dhais Peña-Angulo, [1]Carmelo Juez, [1]Magí Franquesa, [1]Beatriz Fernández-Duque, [1]Fernando Domínguez-Castro, [3]Lars Eklundh, [3]Hongxiao Jin, [4]Tobias Conradt, [5]Conor Murphy, [1]Jesús Julio Camarero, [6]Jorge Lorenzo-Lacruz

[1a]Instituto Pirenaico de Ecología, Consejo Superior de Investigaciones Científicas (IPE–CSIC), Zaragoza, Spain
[2]Department of Geography, University of Zaragoza, Zaragoza, Spain
[3]Department of Physical Geography and Ecosystem Science, Lund University, Lund, Sweden
[4]Potsdam Institute for Climate Impact Research, Potsdam, Germany
[5]Irish Climate Analysis and Research UnitS (ICARUS), Department of Geography, Maynooth University, Maynooth, Ireland
[6]Department of Human Sciences, Area of Physical Geography, University of La Rioja, Logroño, Spain
[a]svicen@ipe.csic.es

ABSTRACT

This paper analyzes the influence of the interannual variability of climatic drought on ecological and hydrological droughts for a basin in the central Spanish Pyrenees using variables derived from observations and hydro-ecological simulation in order to determine the possible connection between meteorological, ecological and hydrological drought considering a cascading approach and encompassing different variables that give insights into water availability in the basin (*e.g.*, soil moisture, streamflow, reservoir storages and releases). Using different climatic, ecological and hydrological standardized drought indices, we show the greater role of meteorological droughts in hydrological systems than in ecological systems, and the small influence of vegetation activity and growth in explaining the interannual variability of water resources in the basin. By contrast,hydrological droughts are strongly affected by precipitation variability with relationships characterized by seasonal differences and the role of different time-scales in the standardized drought metrics.

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Keywords: drought; Pyrenees; drought indices; soil moisture; vegetation; streamflow; reservoir storages.

INFLUENCIA DE LA SEQUÍA METEOROLÓGICA SOBRE LAS INTERACCIONES EXISTENTES ENTRE LA SEQUÍA ECOLÓGICA E HIDROLÓGICA EN EL PIRINEO CENTRAL ESPAÑOL

RESUMEN

Este trabajo analiza la influencia de la variabilidad de la sequía meteorológica sobre las sequías ecológica e hidrológica en una cuenca del Pirineo central español. Para ello se utilizan variables derivadas de observaciones y simulación hidroecológica con la finalidad de determinar la posible conexión entre la sequía meteorológica, ecológica e hidrológica considerando un enfoque en cascada, de tal manera que abarca diferentes variables que aportan información sobre la disponibilidad de agua en la cuenca (p. ej., la humedad del suelo, el caudal, la reserva embalsada y las descargas de agua fuera del sistema). Utilizando diferentes índices de sequía estandarizados, tanto meteorológicos, ecológicos e hidrológicos, se ha comprobado la mayor importancia de las sequías meteorológicas en los sistemas hidrológicos que en los sistemas ecológicos, y la poca influencia de la actividad y el crecimiento de la vegetación en la explicación de la variabilidad interanual de los recursos hídricos en la cuenca. Por el contrario, las sequías hidrológicas se ven fuertemente afectadas por la variabilidad de las precipitaciones, pero con importantes diferencias estacionales y escalas de tiempo a la hora de medir las sequías.

Palabras clave: Sequía; Pirineos; índices de sequía; humedad del suelo; vegetación; caudal; reservas en embalses.

1. Introduction

Drought is one of the most complex natural hazards given the challenges of quantification (Lloyd-Hughes, 2014), and the occurrence of different drought types: meteorological, agricultural, ecological and hydrological (Wilhite & Buchanan-Smith, 2005; Wilhite & Pulwarty, 2017). Drought severity strongly depends on the impacts that drought produces (Vicente-Serrano, 2016). Nevertheless, given the common lack of impact data, drought severity is usually quantified using drought indices based on different hydro-climatic variables (Mukherjee *et al.*, 2018). Drought metrics are typically constructed using one or a combination of variables, including precipitation, atmospheric evaporative demand (Tsakiris *et al.*, 2007; Vicente-Serrano *et al.*, 2010), streamflow (Shukla & Wood, 2008; Vicente-Serrano *et al.*, 2012) and other usually simulated by models such as evapotranspiration and soil moisture (Padrón *et al.*, 2020). These variables are commonly related to drought impacts (Bachmair *et al.*, 2018, 2016; O'Connor *et al.*, 2022; Quiring & Papakryiakou, 2003; Wang *et al.*, 2016) and used to assess drought hazard probability (Domínguez-Castro *et al.*, 2019) and to develop drought monitoring systems (Trnka *et al.*, 2020; Vicente-Serrano *et al.*, 2022).

A key challenge in assessing drought severity is the variety of its impacts since droughts affect different environmental systems and socioeconomic sectors, usually in a cascading way (Vicente-Serrano, 2021; Wilhite *et al.*, 2007). Thus, it is common to observe a spatio-temporal propagation of drought impacts through different systems and territories (Zhang *et al.*, 2022), which makes it very difficult to evaluate the severity of a particular event and develop drought thresholds and early warning approaches.

The effects of droughts on socioeconomic systems are widely recognized as being highly complex but the complexity of impacts for natural systems is also very important (Mcdowell *et al.*, 2008). Anomalies in climate conditions may cause a decrease in soil moisture and runoff (Barker *et al.*, 2016; Peña-Gallardo *et al.*, 2019; Tian *et al.*, 2018; Yuan *et al.*, 2020), with knock-on consequences for vegetation given water consumption by plants (Ukkola *et al.*, 2016; Zeng *et al.*, 2018). Thus, previous studies suggest that the partitioning of precipitation between vegetation consumption and runoff could affect the severity of hydrological droughts downstream (Orth & Destouni, 2018).

Moreover, different studies suggest that increases in vegetation coverage contributes to decreases in water yield at the basin scale (Filoso *et al.*, 2017; Hoek van Dijke *et al.*, 2022; A J Teuling *et al.*, 2019), particularly during dry years (Vicente-Serrano *et al.*, 2021a). The effects of these cross-interactions between vegetation effects and water resources availability are not well understood in regulated hydrological basins given dam management and the seasonality of water demands.

Numerous studies have provided evidence of the significant influence exerted by precipitation variability on water resources in the regions of the Mediterranean basin at various spatial scales (García-Ruiz *et al.*, 2011; A. J. Teuling *et al.*, 2019; Vicente-Serrano *et al.*, 2019a). Notably, in humid basins, responses to precipitation have larger magnitudes than responses to atmospheric evaporation demand. This can be linked to the relatively low temporal variability of evapotranspiration, which is attributable to the overall availability of water resources (Wouter R. Berghuijs *et al.*, 2017; Massari *et al.*, 2022). On the other hand, long-term changes in land cover could have a significant impact on streamflow trends by affecting landscape Evapotranspiration (García-Ruiz *et al.*, 2011). This phenomenon has been observed in a number of Spain's headwater basins (Beguería *et al.*, 2003a; Gallart *et al.*, 2011; Martínez-Fernández *et al.*, 2013a). Nonetheless, despite the recognition of the role of vegetation-hydrological system interactions in determining streamflow trends, little is known about how vegetation characteristics and various components of the hydrological cycle (such as soil moisture and streamflow) respond to meteorological drought and how drought conditions propagate through various environmental and hydrological system components. These issues are challenging to address as the focus is not on long-term changes (*e.g.*, land cover changes) but on the temporal variability of different vegetation and hydrology metrics at time scales from months to years. For some of these metrics (e.g., soil moisture, leaf area, vegetation production), observations are not available for the long-term and models are required to generate data to analyse cross-drought interactions.

Meteorological droughts usually reduce vegetation activity and growth in natural ecosystems, but also the availability of water in the soil, rivers and reservoirs. Nevertheless, we hypothesize a differential effect of meteorological droughts on vegetation and hydrological systems and that although long-term vegetation changes may have an effect on long term trends in streamflow, the impact of interannual vegetation variability on the interannual variability of water resources is likely to be small.

In this study we model the water cycle and assessed ecological processes in a case study basin located in the Spanish central Pyrenees. The water resources generated in the basin are very important for maintaining irrigated agriculture downstream (López-Moreno *et al.*, 2004; Vicente-Serrano, 2021). In the last decades, land use has been drastically transformed the basin as consequence of human depopulation and the abandonment of mountain agriculture and livestock. This has resulted in natural revegetation of the landscape with important morphodynamic and ecohydrological consequences (García-Ruiz *et al.*, 2015), causing a substantial decrease in water resources (Beguería *et al.*, 2003b; López-Moreno *et al.*, 2011). In addition, episodes of drought-induced forest decline have been reported in the study area (Camarero *et al.*, 2011; Peguero-Pina *et al.*, 2007).

The objective of this study is to analyse in detail how meteorological droughts differentially affect hydrological system components and ecological variables, and the possible interactions and links between ecological and hydrological drought conditions.

2. Study area

The upper Aragón basin is located in the Central Spanish Pyrenees (Fig. 1), with a total area of 2181 km^2. There are large topographic gradients in the basin, with elevations from 420 to 2883 m.a.s.l. The basin receives annual rainfall totals exceeding 1500 mm in the northernmost sector, declining to 800 mm in the inner depression. There is a summer dry season with higher precipitation totals recorded in spring and autumn. The mean annual air temperature is 10°C, and snow cover is recorded from December to April (López-Moreno *et al.*, 2020; López-Moreno & García-Ruiz, 2004). The basin contains a large reservoir, the Yesa reservoir with a capacity of 446.8 hm3, located at the outlet. It provides water resources for irrigation to the Bardenas region (81,000 has), located 80 km to the South (López-Moreno *et al.*, 2004).

Vegetation cover in the upper basin is characterized by the dominance of conifers (*e.g.*, *Pinus sylvestris* L., *Pinus uncinata* Ram., *Abies alba* Mill., *Pinus nigra* J.F. Arn.) and hardwood species (*e.g.*, *Fagus sylvatica* L., *Quercus faginea* Lam.), while shrubs dominate the understory (*e.g.*, Buxus sempervirens L.) and are distributed on steep slopes and poor soil areas (García-Ruiz *et al.*, 2015). Vegetation cover in the basin has been strongly impacted by human activities. Historically, cultivated areas were found below 1600 m a.s.l. in valley bottoms, perched flats, and steep, south-facing hillslopes, which were managed even under shifting agriculture systems (Garcia-Ruiz & Lasanta-Martinez, 1990). The basin has undergone a land cover transformation in the 20th century, due to rural depopulation (Garcia-Ruiz & Lasanta-Martinez, 1990), resulting in a gradual natural revegetation process (Lasanta-Martínez *et al.*, 2005; Sanjuán *et al.*, 2018). Since the 1960s, vegetation changes have been characterized by secondary succession, with coniferous forests being replaced by mixed and broadleaf forests and some croplands and grasslands being invaded by shrubs and conifers.

3. Data and methods

3.1. Data

Two different climate datasets were used in this study. First, we employ daily precipitation and temperature series from available meteorological stations in the basin (14 series of daily precipitation and daily maximum and minimum temperatures from 1970 to 2020). These series were used to run the hydro-ecological model described in section 3.2, which requires daily meteorological data. Second, we employ weekly gridded climate data at a spatial resolution of 1.1 km, averaged over the whole basin (Vicente-Serrano *et al.*, 2017). The variables contained in the weekly climate data were precipitation, maximum and minimum temperature, relative humidity, solar radiation and wind speed. Atmospheric Evaporative Demand (AED) necessary to calculate some of the drought metrics was calculated using the FAO-56 Penman-Monteith equation (Pereira *et al.*, 2015).

Data on surface flows and storage levels for the Yesa reservoir were obtained from the Ebro Basin Management Agency (Confederación Hidrográfica del Ebro; http://www.chebro.es/), and includes monthly inflows into the reservoir and downstream releases (i.e. to the Aragón River and the Bardenas channel). Inflows are primarily influenced by climatic conditions since there is no other regulation upstream, while all other hydrological variables (Yesa storage, Bardenas channel and the Aragón flows downstream Yesa) largely depend on water management.

To validate vegetation variables simulated by the model we used tree-ring width data collected from six representative tree species listed above in the study area description. Data from 37 sites with forest growth were used in this work. Overall, the tree-ring width data were processed using dendrochronological methods (Fritts, 1976). Further details of this processing can be found in (Vicente-Serrano *et al.*, 2021b). We also used satellite derived Normalized Difference Vegetation Index (NDVI) from 1981 to 2020 at a biweekly scale obtained from the fusion of a NOAA-AVHRR NDVI dataset from 1981 to 2015 (Vicente-Serrano *et al.*, 2020) and the MODIS NDVI dataset (Huete *et al.*, 2002). NDVI data were used to evaluate the Leaf Area Index (LAI) output simulated by the eco-hydrological model.

Finally, we used land cover and topography information necessary for the modelling. We used a 25 m spatial resolution digital elevation model to describe the topographical features of the study area. Forest and land-cover types were obtained from the Spanish National Forest Map and the Third National Forest Inventory (period 2006–2016). Soil classes were taken from the European Soil Database (available at http://eusoils.jrc.ec.europa.eu).

3.2 Eco-hydrological modelling

We used the RHESSys hydro-ecological model (Tague & Band, 2004) to model the eco-hydrological processes in the basin from 1970 to 2020. RHESSys couples an ecosystem carbon cycling model with a spatially distributed hydrology model to simulate integrated water, carbon and nutrient cycling and transport over complex terrain at small to medium scales. More recent refinements of energy, moisture and carbon cycling model are described on RHESSys website (https://github.com/RHESSys/RHESSys). We used the model to obtain reliable estimates of variables like soil moisture, net primary production and leaf area, which are not available from observations for the whole period considered in this study. The RHESSys model has been previously used to simulate hydrological and plant processes in different vegetation and basin types including mountain areas (Chen *et al.*, 2020).

RHESSys distributes the basin in a hierarchical way and has a library of definition files with several parameters. Each definition file is associated with each level of the spatial hierarchy, from basin to stratum. In the case of land use maps (stratum), the definition files describe characteristics of different vegetation types and associated processes such as carbon allocation, radiation interception, respiration, stomatal physiology, phenology, etc. Most of the parameters were collected from the available literature (White *et al.*, 2000). Soil parameters in RHESSys typically require calibration since soil and geologic inputs do not account for complex controls on drainage rates such as hillslope scale preferential flow path distributions. The following four parameters were calibrated: (i) depletion of hydraulic conductivity with depth (m); (ii) hydraulic conductivity in saturated soils (K); (iii) infiltration through macropores (gw1); and (iv) lateral water fluxes from hillslopes to the main channel (gw2). Parameters were selected using a Monte-Carlo procedure based on 1600 simulations run. Parameters that produced monthly streamflow estimates that gave a Nash–Sutcliffe (NSE) efficiency coefficient > 0.7 where retained.

We must note that the modelling of ecological variables may be affected by important uncertainties given simplification of plant hydraulic processes, usually governed in the models by fixed stomatal conductance parameters (Ball *et al.*, 1987) and no representation of hydraulic processes within plants, which are known to determine the regulation of plant water use (Eller *et al.*, 2020). This issue may generate important errors in the simulations (Liu *et al.*, 2020). For this reason it is necessary to evaluate the simulations by means of independent data. This is sometimes difficult given the common limitation of observations. In this study, we have used some empirical data that can be compared with the model outputs. Figure S1 shows the monthly evolution of different key variables in the basin simulated by RHESSys for the period 1970-2018. NPP, soil moisture and LAI represent the average over the whole basin. Validation of model simulations was undertaken using observed streamflow data, the average tree-ring width of the samples available in the basin (see 3.1) and the NDVI data from NOAA-AVHRR and MODIS satellites. Despite the potential divergence in temporal patterns between tree ring width and Net Primary Productivity (NPP), it is important to note that tree growth is often not limited by carbon availability (Körner, 2015). However, over extended time periods, the cumulative NPP can serve as an indicator of total carbon storage and can be associated with secondary growth observed in forests within the study domain (Vicente-Serrano *et al.*, 2015). Figure 2 shows the relationship between the average annual tree-ring growth and the cumulative NPP recorded at different time-scales (1-24 months), the evolution of the observed and simulated monthly streamflow and observed NDVI and simulated LAI in the basin. Tree-ring growth shows a correlation of 0.53 with the 10-month NPP in September, which suggests a good agreement with the tree growth. In addition, agreement between simulated and observed streamflow is also high ($r = 0.79$), with the model performing well during periods of high and low flows. Temporal variability of the simulated LAI shows high agreement with the NDVI ($r = 0.84$), which suggests that the model simulated variables show a reasonable robustness and can be used for comparisons to observations.

3.3. Drought index calculations

To assess the influence of meteorological droughts on hydrological and ecological variables, we used the Standardized Precipitation Index (SPI) (McKee *et al.*, 1993) based on precipitation, the

Standardized Precipitation Evapotranspiration Index (SPEI) (Vicente-Serrano *et al.*, 2010) based on the difference between Precipitation and AED, the Standardized Evapotranspiration Deficit Index (SEDI) (Kim & Rhee, 2016), based on the difference between actual evapotranspiration (Eta) and AED, the Standardized Precipitation minus Evapotranspiration (SPET) and the Evaporative Demand Drought Index (EDDI) (Hobbins *et al.*, 2016), which is based on the AED. The hydrological and ecological variables obtained from the hydro-ecological modelling (soil moisture, NPP and LAI) and from observations (streamflow, reservoir storages and outflows) were also standardized at time scales from 1 to 36 months. Soil moisture was transformed to a Standardized Soil Moisture Index (SSMI), streamflow to a Standardized Streamflow Index (SSI) and also Standardized reservoir storages and outflows were calculated. For this purpose, we used the probability distribution that showed the best fit with the monthly series of each variable and time scale, following the procedure used to calculate the Standardized Streamflow Index (SSI) (Vicente-Serrano *et al.*, 2012).

3.4. Analysis

We calculated the Pearson's correlation (r) between de-trended drought indices at time scales between 1 and 36 months. Correlations were calculated for each monthly series to determine the month and timescale that meteorological drought has greatest influence on other variables. We also calculated partial correlations (Baba *et al.*, 2004) to determine the independent role of each metric on the others, thus allowing analysis of the propagation of drought effects across systems and the most important effects among different variables. We must note that some of the correlation analyses relate response variables to explanatory variables that have been used as model inputs in the estimations (e.g., the relationship between the climate drought indices and the soil moisture and the ecological variables) so some variables are not generated independently from each other. However, we believe that this aspect does not have a detrimental impact on the obtained results. This assertion is based on the understanding that the relationships between these variables are not expected to be linear. Moreover, these relationships are qualified by the complex ecohydrological processes included in the model and the range of soil and vegetation parameters considered.

4. Results

4.1 Influence of meteorological drought on eco-hydrological variables

Figure 3 shows the correlations between the values of SPI obtained at time-scales from 1 to 36 months and soil moisture, LAI and NPP from RHESsys simulations aggregated over the basin and observed streamflow, reservoir storages and outflows. The results show strong correlations between SPI and soil moisture at time scales longer than five months for the majority of months. Correlations with LAI are weak and statistically non-significant but there are significant correlations between NPP and SPI in summer months. Correlations with streamflow are strong at short time scales (1-5 months), particularly during the winter season. Correlations of SPI with reservoir storages and outflows are also strong and statistically significant, with the strongest correlations recorded at time scales between five and ten months.

Correlations of each variable with SPEI and the standardized difference between Precipitation and Et are similar to those for SPI (Suppl. Figures 2 and 3). Nevertheless, the correlations between SEDI and the different eco-hydrologic variables show interesting differences (Figure 4). The first is related to the soil moisture which shows strongest positive correlations with SEDI during the summer months at time scales between 4 and 12 months. LAI also shows positive correlations with SEDI, statistically significant from May to September for longer time scales (15-20 months). There are also statistically significant positive correlations between SEDI and NPP from June to September at time scales between 1 and 10 months. For hydrological variables (streamflow, reservoir storages and outflows) the strongest correlations with SEDI are found during the summer months, showing differences with the other drought indices.

4.2 Relationship between different eco-hydrological variables recorded on different time-scales

Figure 5 shows the correlations between LAI anomalies recorded at time scales between 1 and 36 months and other eco-hydrological variables. The different plots show very weak correlations of LAI with other metrics, with the exception of NPP, where long time scales of LAI show a positive correlation with NPP. Standardized values of NPP show positive and significant correlations with soil moisture in summer months, especially at short time scales, and also with streamflow and reservoir storages and outflows, suggesting that higher values of carbon uptake in the basin are in agreement with higher water generation and availability (Supplementary Figure 4). Correlations between soil moisture and different hydrological variables are also significant, especially for soil moisture anomalies at short time-scales, and particularly during the summer season (Figure 6). Correlations between streamflow and reservoir storages and outflows are in general strong in all months, but particularly during the winter season. Nevertheless, there are some particularities. While correlations between streamflow and reservoir storages are strong between June and August, weaker correlations are found with outflows for the same months (Figure 7). Finally, the relationship between the standardized reservoir storages and the outflows is strong, especially at short time-scales and from July to December (Figure 8).

4.3. Isolation of the role of different interactions

Partial correlations between EDDI, SPI, LAI, NPP and SSMI show that variations in soil moisture are mostly determined by precipitation variability, with a small role played by variability in AED and vegetation variables (NPP and LAI) (Figure 9). NPP is mostly dependent on soil moisture conditions during summer whereas the independent roles of AED, precipitation and LAI on NPP are small (Supplementary Figure 5). LAI variability is most strongly connected with NPP at longer time scales, meaning that the previous year's NPP may have an important influence on LAI of the following year (Supplementary Figure 6). The influence of climate, soil moisture, NPP and LAI variability on streamflow shows some interesting patterns. First, the ecological variables LAI and NPP do not appear to influence streamflow variability when the influence of other variables is removed. The main independent role is associated with precipitation, particularly from September to May. During the summer months SSMI is the most important variable of those considered in explaining interannual streamflow variability (Figure 10). For reservoir storage precipitation during the cold season is the primary control variable, principally at long time scales. By contrast, at shorter time scales reservoir storage is heavily influenced by streamflow and soil moisture (Figure S7). Finally, the outflows are mostly controlled by reservoir storages throughout the year, especially in summer months, but outflows are more affected by streamflow than by reservoir storages in some winter months. In addition, outflows are strongly determined by precipitation recorded over long time scales (Figure 11).

5. Discussion and conclusions

This study analyzed the relationship between different drought metrics that provide information on meteorological, hydrological and ecological drought severity in a mountain basin in the central Spanish Pyrenees with the purpose of determining: i) the possible propagation of drought conditions between systems and ii) to identify possible cross-interactions among hydrological and ecological drought conditions. Such assessments are important for the basin given that water resources generated are widely used downstream for irrigation agriculture and urban supply (López-Moreno *et al.*, 2004; Vicente-Serrano, 2021).

First, we analyzed the response of hydrological and ecological metrics to the variability in meteorological droughts, showing that the main response is recorded through precipitation with other variables (e.g., the actual evapotranspiration -Et-, and atmospheric evaporative demand –AED-) showing a smaller influence. This behavior is not specific to the Aragon basin, as different studies have shown that precipitation is the main meteorological variable controlling the temporal variability of streamflow worldwide (Wouter R Berghuijs *et al.*, 2017; Vicente-Serrano *et al.*, 2019b; Yang *et al.*, 2018). Although AED influences long term trends and temporal variability of surface water resources in Spain (Vicente-Serrano *et al.*, 2014), its role is still small in comparison to precipitation variability. An interesting finding of this study is that Et does not appear to be important in explaining variability in soil moisture and streamflow since the magnitude and seasonality of correlations using Precipitation minus Et are similar to those using SPI, which is only based on precipitation. Some studies in central Europe (Teuling *et al.*, 2013) have suggested that land ET could have an important role in depleting soil moisture and increasing the severity of hydrological droughts. Thus, Et can be very important in determining the partitioning of total precipitation between blue and green water during drought periods (Orth & Destouni, 2018). Et does play an important role in explaining the trend of water resources in the Pyrenees (Beguería *et al.*, 2003b; López-Moreno *et al.*, 2011) as a consequence of rural abandonment and land cover changes characterized by natural revegetation (García-Ruiz *et al.*, 2015). Moreover, the influence of increased Et on streamflow is most relevant during the driest years (Vicente-Serrano *et al.*, 2021a). Nevertheless, in this study we found that in terms of explaining interannual variability of the hydrological and ecological metrics considered, Et plays a smaller role than precipitation, likely due to the fact that AED is smaller in this cold upland region (Vicente-Serrano *et al.*, 2007).

An important finding of our study is the very differential response of ecological and hydrological metrics to meteorological drought. Ecological metrics are less sensitive to meteorological drought in comparison to the hydrological metrics analysed. This is common in cool and humid areas where water availability is usually sufficient to maintain vegetation activity and growth even in the driest years (Vicente-Serrano, 2021). Several previous studies have demonstrated a relationship between drought variability and tree growth in certain species within the upper Aragón basin (Camarero *et al.*, 2011; Antonio Gazol *et al.*, 2018). However, it is worth noting that the magnitude of this response is considerably lower compared to the adjacent semiarid regions of the Ebro basin (Pasho *et al.*, 2011; Vicente-Serrano, 2021). These results are not likely to be biased by model simulations since we find that summer NPP is correlated with precipitation recorded in the previous months. Nevertheless, the response of LAI to meteorological drought is very small and not statistically significant and cannot be related to the variables obtained by the hydro-ecological simulation. Thus, using remote sensing measurements of vegetation activity, which are highly related to the leaf area (Carlson & Ripley, 1997), and tree-ring width measurements, as metric of tree growth and carbon uptake, the response is always greater between climate indices and tree growth, independent of the forest type considered (A. Gazol *et al.*, 2018; Peña-Gallardo *et al.*, 2018). This suggests a low sensitivity of vegetation activity and leaf area to climate variability in the upper Aragón basin, with plants optimizing respiration and photosynthesis under periods of water deficit, while carbon uptake may be constrained by limited water conditions in summer months, as suggested by the response of NPP.

The influence of meteorological drought conditions is much greater on hydrological subsystems of the basin (including soil moisture) and on ecological systems, with water availability strongly determined by the interannual variability of precipitation, although the time-scales of response vary as expected (Barker *et al.*, 2016; Wang *et al.*, 2016). Significant seasonal variations have been identified in the time scales of response, with generally longer response periods observed during the summer months compared to winter, across various hydrological variables. This issue is probably related to the lags in the baseflow during summertime, which is largely impacted by the dominant climate conditions for longer periods. However, it is worth noting that the observed seasonality tends to diminish when the hydrological variables represent systems with more robust management practices. For example, the outflows, although more sensitive to the water availability during summer, they are also highly sensitive to the streamflow and reservoir storages during wintertime. The most representative example of this seasonal response is the SEDI, which showed weak correlation with the different ecological and hydrological variables in winter, while it exhibited high correlation in summer, the season in which vegetation can be affected by water stress (Vicente-Serrano *et al.*, 2021; Vicente-Serrano *et al.*, 2015). In fact, this is observed with LAI and NPP, which show higher response to the evapotranspiration deficit represent by the SEDI than to precipitation. The effect of the SEDI on hydrological variables is probably indirect as low values of SEDI would represent low water availability in the soil and low streamflow.

A novel approach of our study has been the assessment of different meteorological, ecological and hydrologic metrics in order to determine relationships and cross-interactions between them. Previous studies have suggested a significant role of vegetation dynamics in explaining changes in runoff generation across Spain (Beguería *et al.*, 2003b; Martínez-Fernández *et al.*, 2013b). In our domain, experimental studies have shown that runoff generation is strongly determined by the percentage of vegetation coverage (García-Ruiz *et al.*, 2008). Nevertheless, although long-term changes in vegetation plays an important role in determining trends in water resources, the role of interannual variability of plant conditions seems to be small as our results suggest. This finding suggests that years characterized by high vegetation activity and growth did not exert a negative impact on water availability in the basin. This is likely linked to the similar influence of climate variability on ecological and hydrological droughts, as higher precipitation is associated with positive anomalies in both metrics. Thus, although in humid years vegetation growth would be higher and Et would increase given higher photosynthesis, water availability would be sufficient to maintain positive anomalies in the surface water resources in the basin. The connection between different hydrological drought metrics in the basin is very strong and modulated by the seasonal response to precipitation and the reservoir management.

We must stress that the use of meteorological, hydrological and ecological indices introduces a complete assessment of the possible drought propagation mechanisms in the basin. Considering the correlative nature of the various analysis systems employed, caution must be exercised when inferring causal factors. While the correlations observed provide valuable insights into potential relationships, they do not necessarily establish causation. Nevertheless, we can confirm that the effect of meteorological drought variability in the upper Aragón basin is much stronger in hydrological systems than in ecological systems. Indeed, we find little evidence for a strong role of vegetation in influencing hydrological drought variability in the basin at interannual timescales. These findings are highly relevant for evaluating how ecological and hydrological droughts are related in complex hydrological basins.

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Appendix

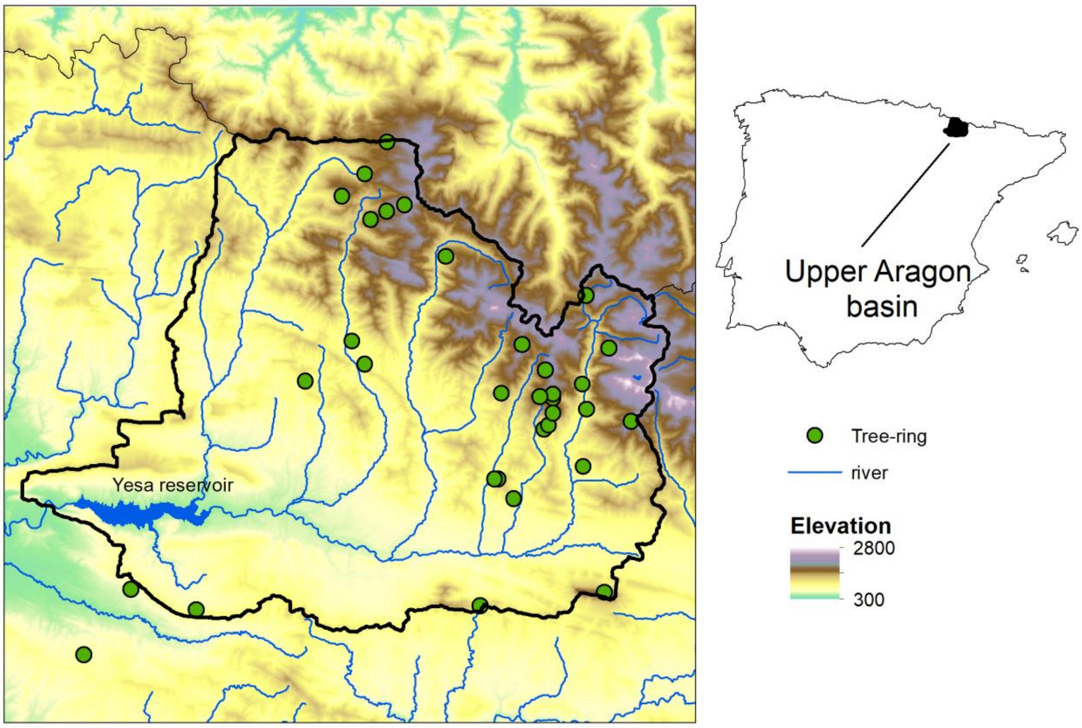


Figure 1. Location of the study area, topography and hydrological network, including the Yesa reservoir.

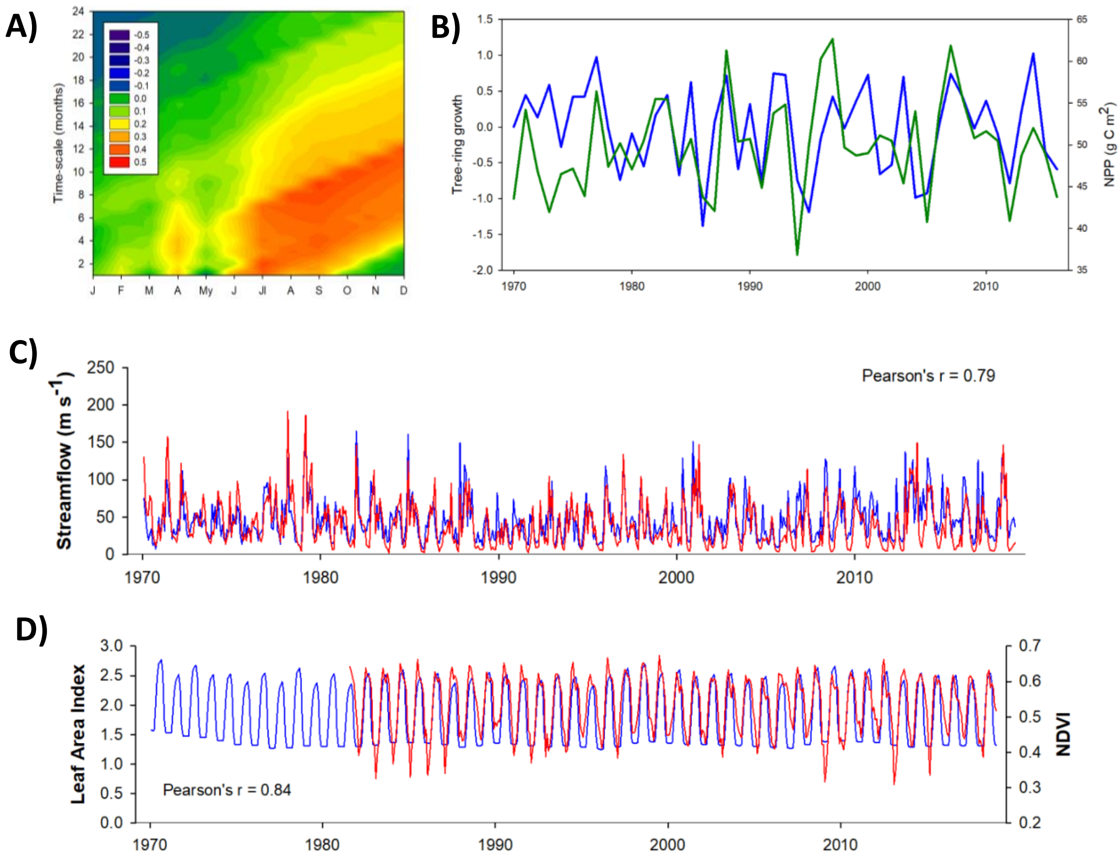


Figure 2. Validation statistics based on the comparison of simulated data of streamflow, NPP and LAI with observed streamflow, tree ring growth and NDVI. A) Correlation between the tree-ring growth and the NPP produced by the model summarized at different time scales. B) Evolution of the tree-ring growth (red) and the 10-month NPP (blue), C) Evolution of the observed monthly streamflow (red) and the modelled streamflow (blue), D) Evolution of the monthly NDVI (red) and the NPP obtained from the model (blue).

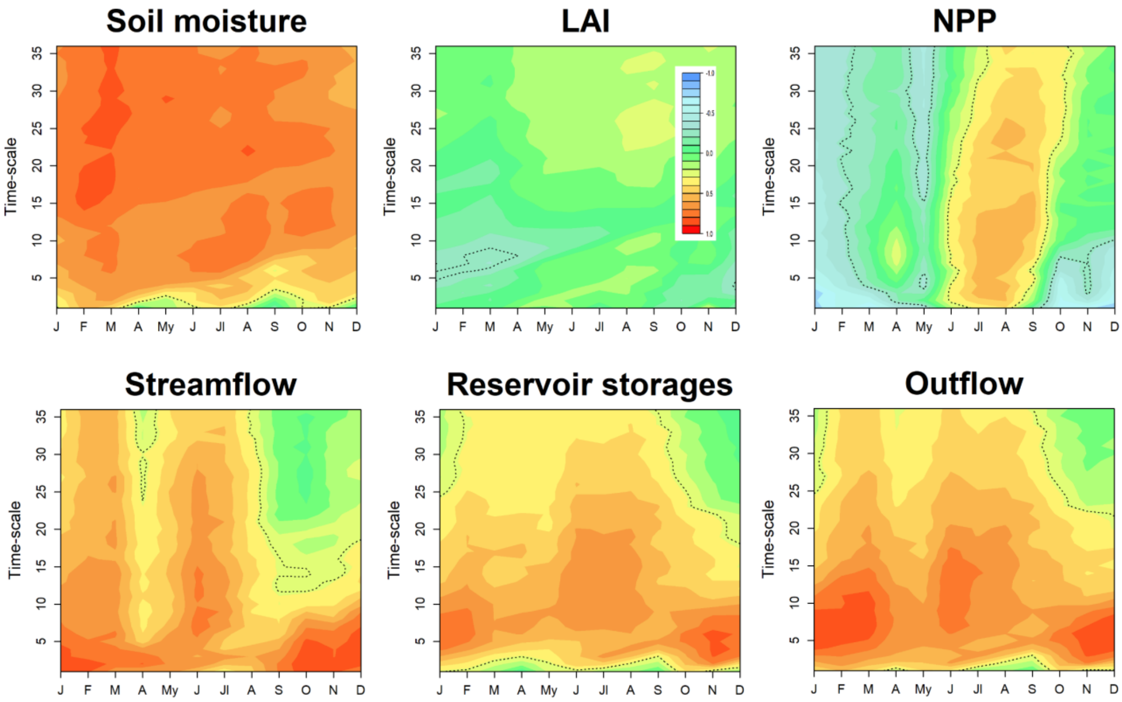


Figure 3. Monthly Pearson's r correlations between the basin Standardized Precipitation Index (SPI) and different hydrological and ecological variables. Dotted lines frame months and time-scales in which the correlations are statistically significant.

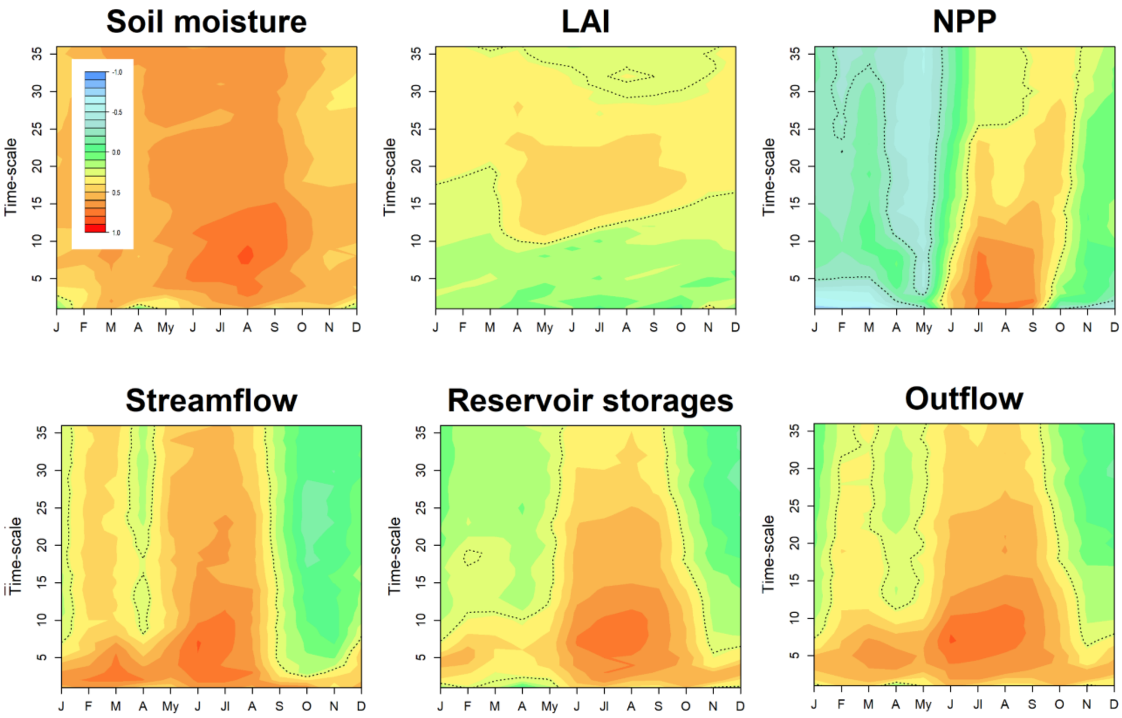


Figure 4. Monthly Pearson's r correlations between the basin Standardized Evapotranspiration Deficit Index (SEDI) and different hydrological and ecological variables. Dotted lines frame months and time-scales in which the correlations are statistically significant.

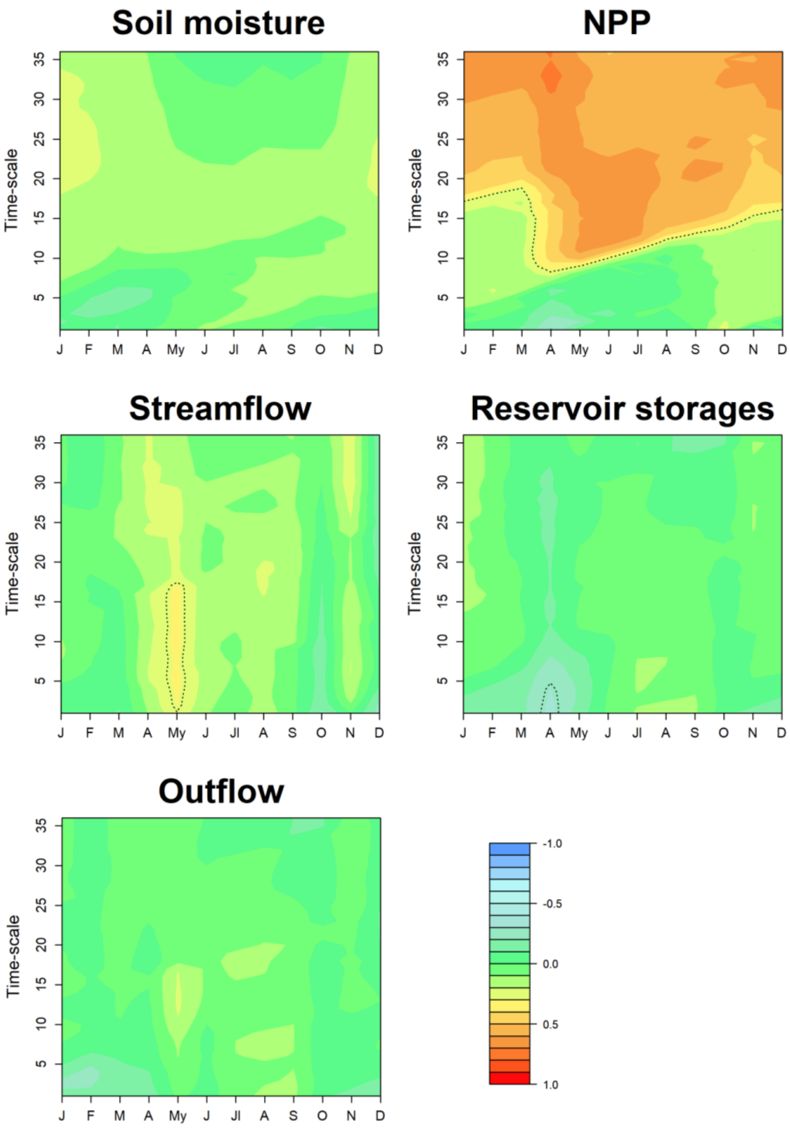


Figure 5. Monthly Pearson's r correlations between the basin Standardized LAI and the rest of hydrological and ecological variables. Dotted lines frame months and time-scales in which the correlations are statistically significant.

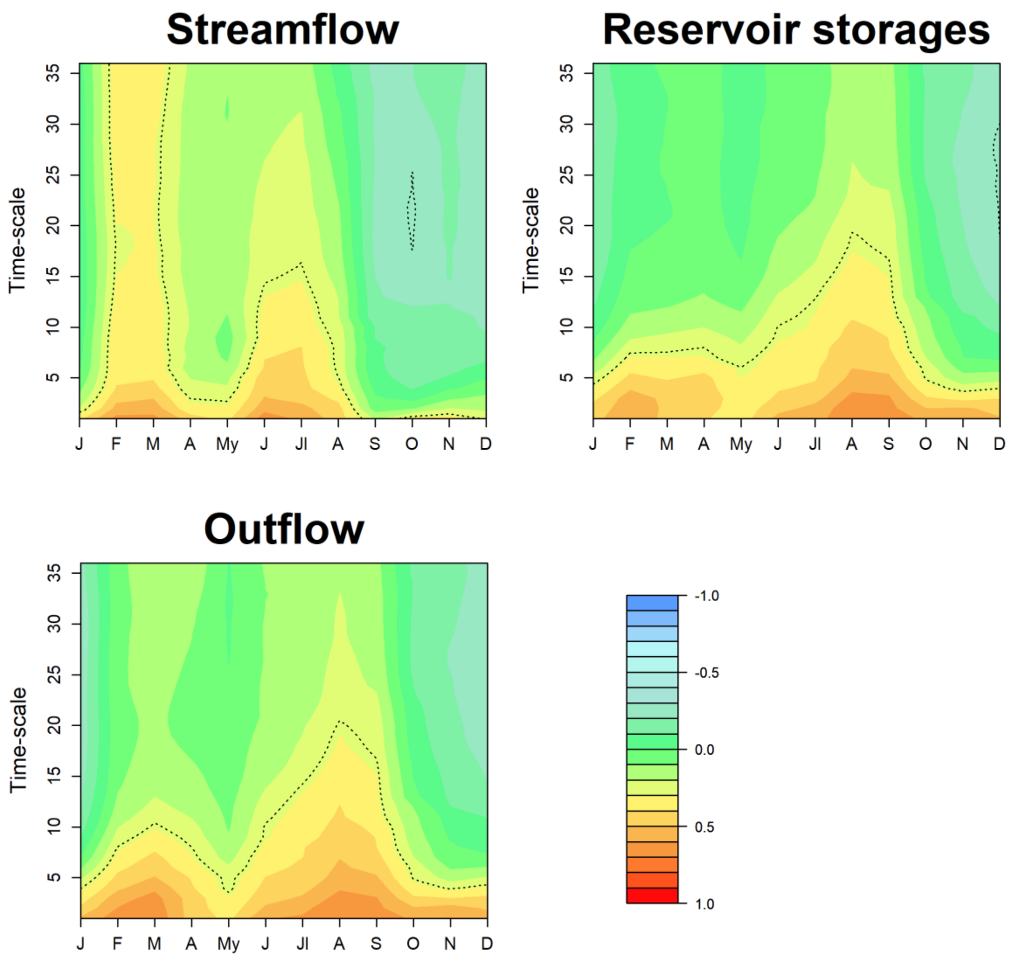


Figure 6. Monthly Pearson's r correlations between the basin Standardized Soil Moisture Index (SSMI) and the rest of hydrological variables. Dotted lines frame months and time-scales in which the correlations are statistically significant.

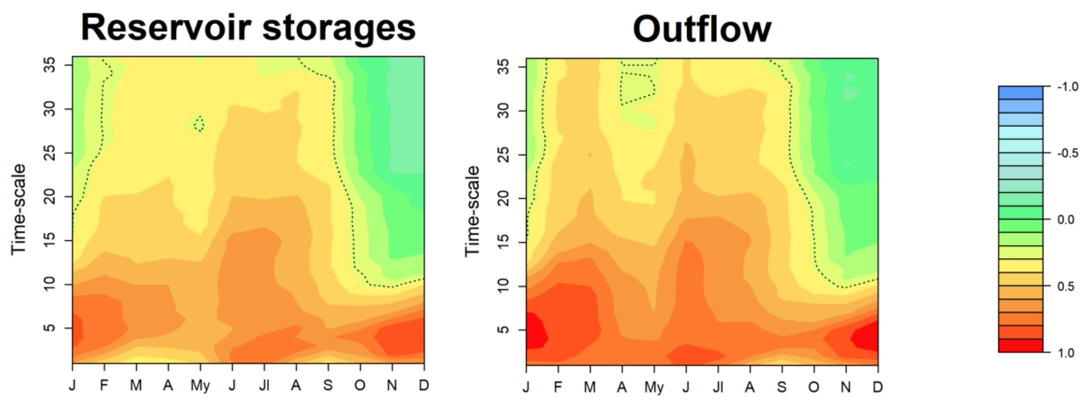


Figure 7. Monthly Pearson's r correlations between the basin Standardized Streamflow Index (SSI) and the rest of hydrological variables. Dotted lines frame months and time-scales in which the correlations are statistically significant.

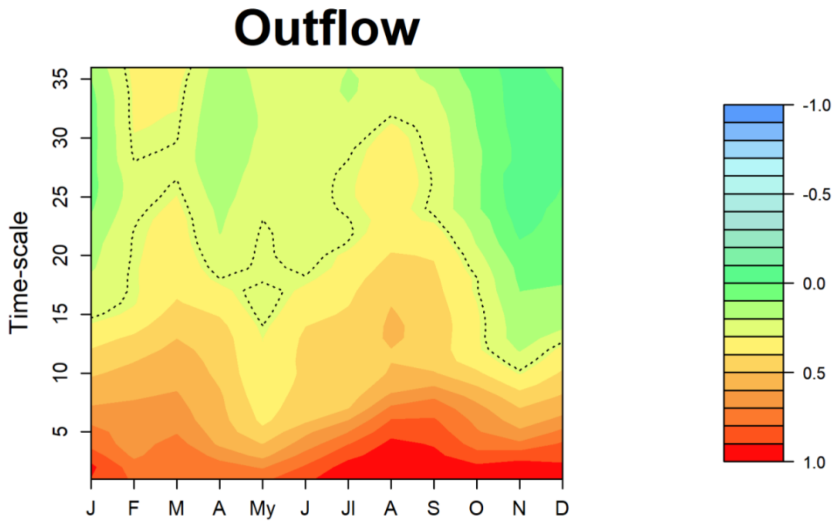


Figure 8: Monthly Pearson's r correlations between the basin Standardized reservoir storages calculated at time scales from 1 to 36 months and the standardized water outflows. Dotted lines frame months and time-scales in which the correlations are statistically significant.

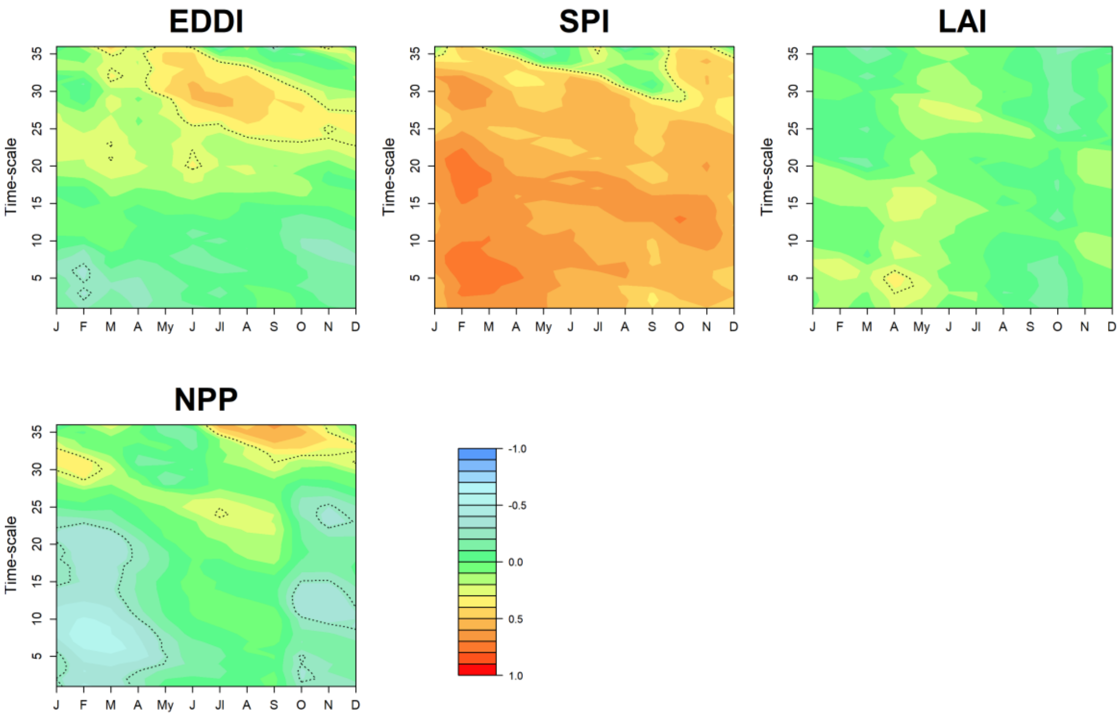


Figure 9: Monthly partial correlations between the basin Standardized Soil Moisture Index (SSMI) and the variables that may have a role on it (EDDI, SPI, LAI and NPP). Dotted lines frame months and time-scales in which the correlations are statistically significant.

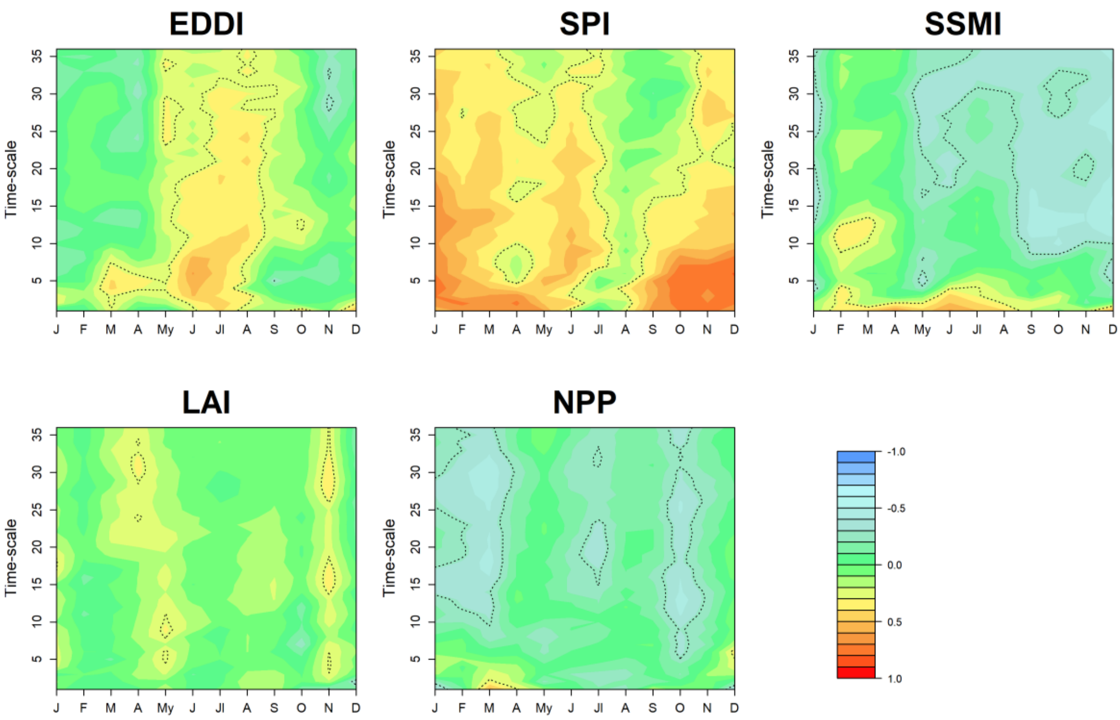


Figure 10. Monthly partial correlations between the basin Standardized Streamflow Index (SSI) and the variables that may have a role on it (EDDI, SPI, SSMI, LAI and NPP). Dotted lines frame months and time-scales in which the correlations are statistically significant.

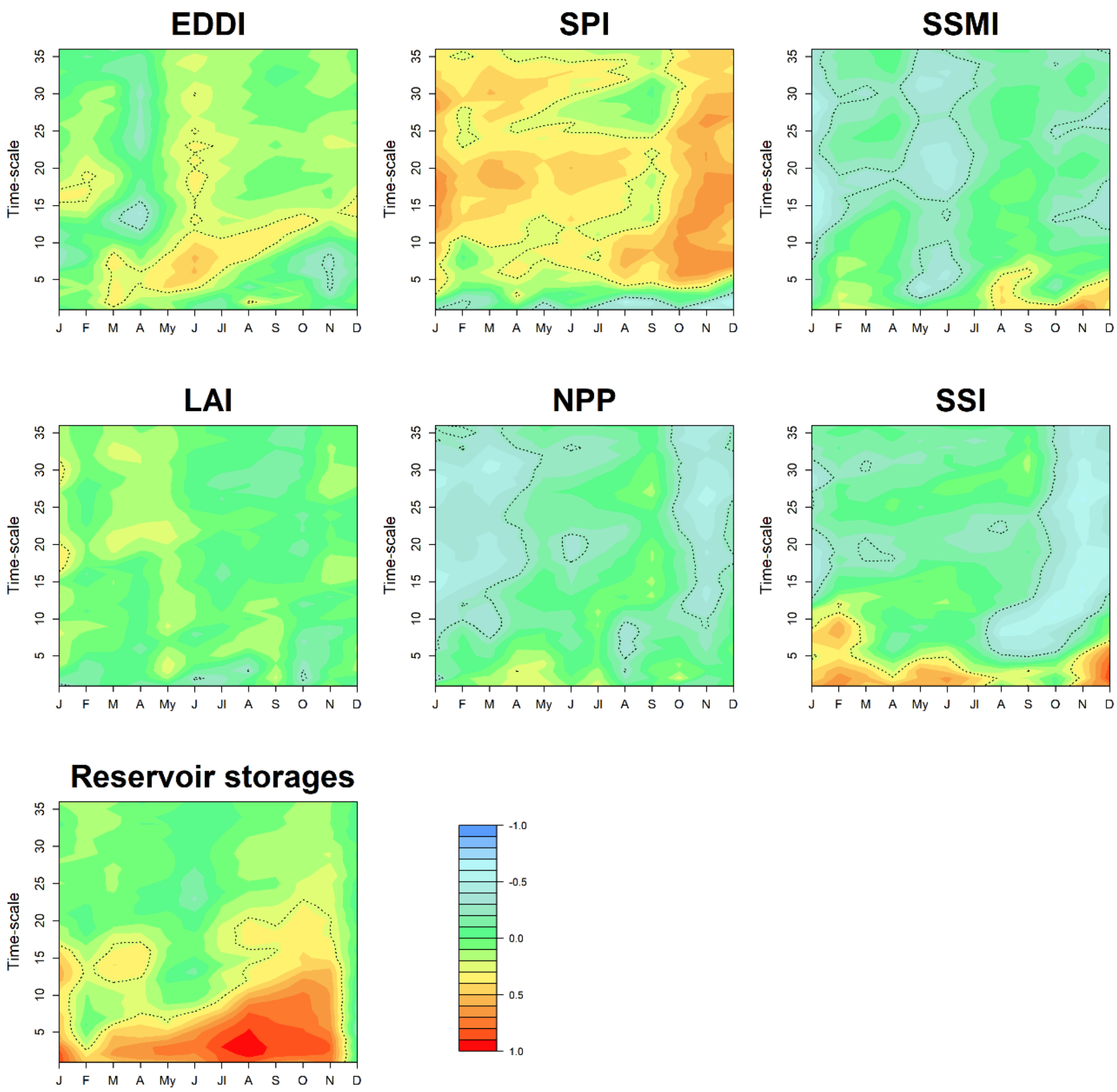


Figure 11. Monthly partial correlations between the basin Standardized OUTFLOWS and the variables that may have a role on it (EDDI, SPI, SSMI, SSI, LAI and NPP AND RESERVOIR STORAGES). Dotted lines frame months and time-scales in which the correlations are statistically significant.

Supplementary material for: INFLUENCE OF THE INTERANNUAL VARIABILITY OF METEOROLOGICAL DROUGHT ON THE CROSS-INTERACTIONS OF ECOLOGICAL AND HYDROLOGICAL DROUGHT IN THE CENTRAL SPANISH PYRENEES

[1]Sergio M. Vicente-Serrano, [1]Ahmed El Kenawy, [1]Javier Zabalza-Martínez, [1]Iván Noguera, [2]Dhais Peña-Angulo, [1]Carmelo Juez, [1]Magí Franquesa, [1]Beatriz Fernández-Duque, [1]Fernando Domínguez-Castro, [3]Lars Eklundh, [3]Hongxiao Jin, [4]Tobias Conradt, [5]Conor Murphy, [1]Jesús Julio Camarero, [6]Jorge Lorenzo-Lacruz

[1a]Instituto Pirenaico de Ecología, Consejo Superior de Investigaciones Científicas (IPE–CSIC), Zaragoza, Spain,

[2]Department of Geography, University of Zaragoza, Zaragoza, Spain

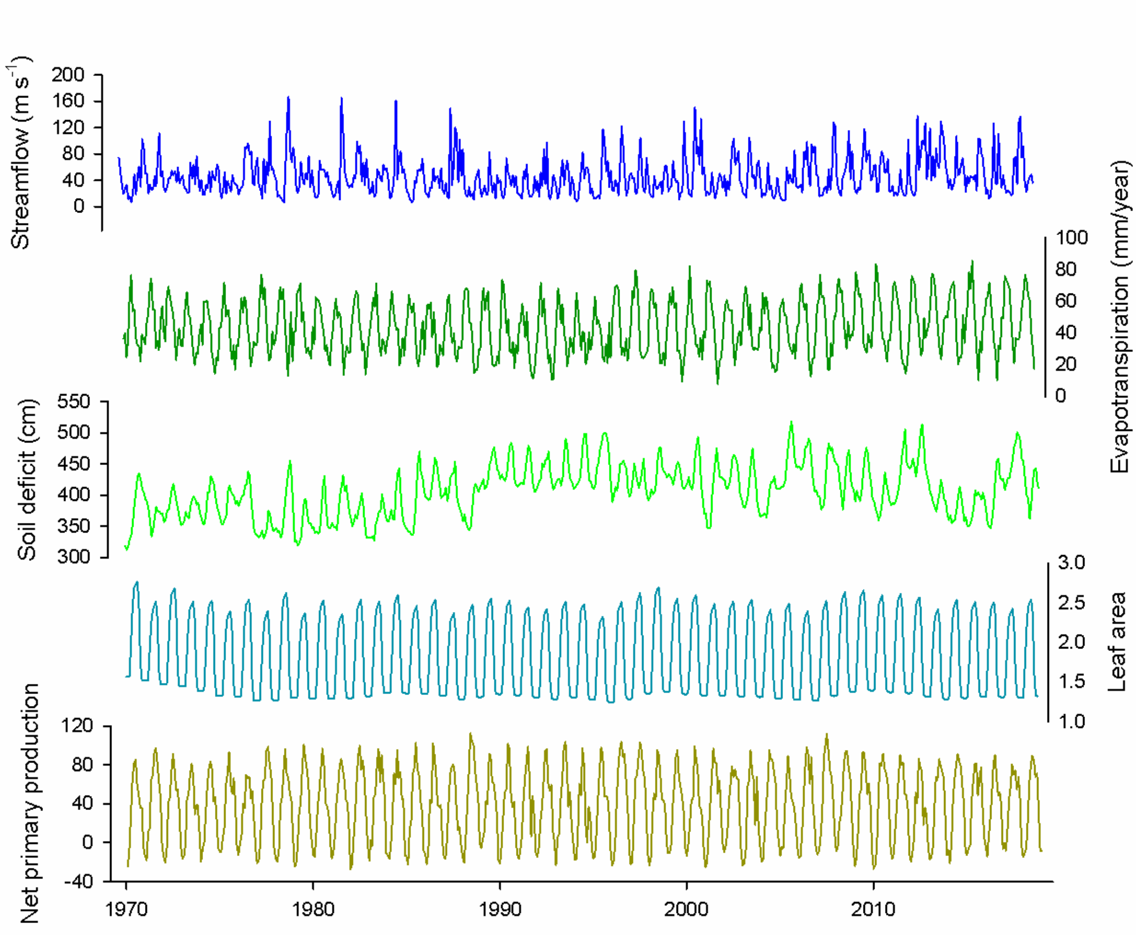
[3]Department of Physical Geography and Ecosystem Science, Lund University, Lund, Sweden

[4]Potsdam Institute for Climate Impact Research, Potsdam, Germany

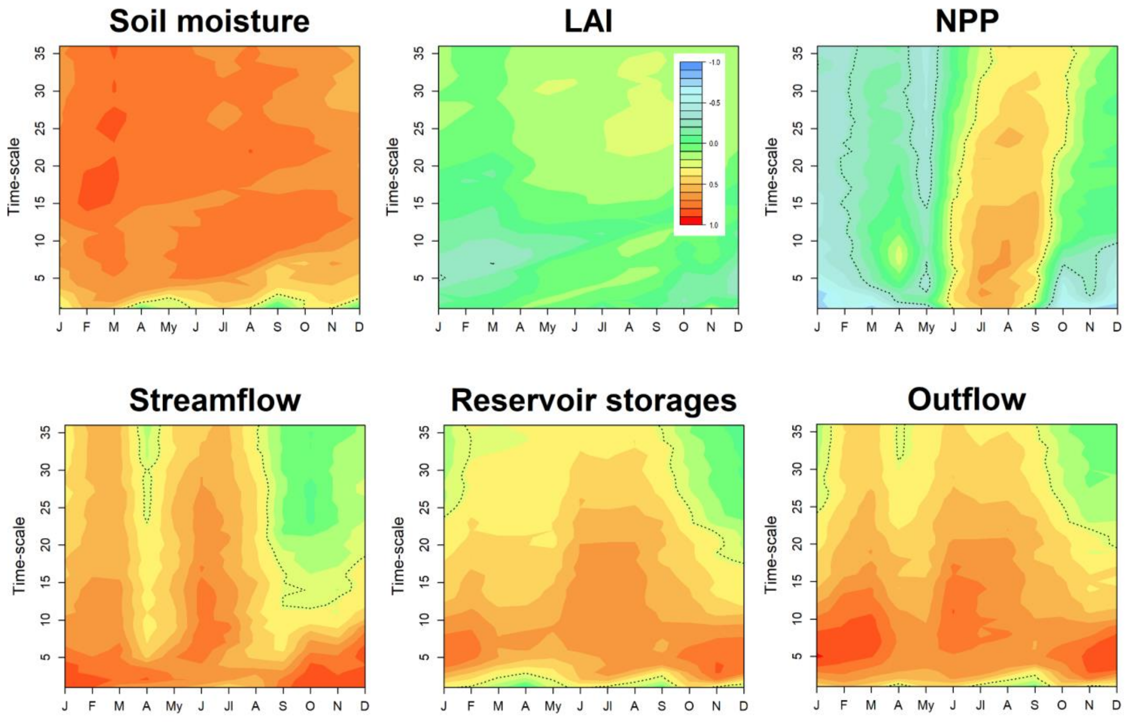
[5]Irish Climate Analysis and Research UnitS (ICARUS), Department of Geography, Maynooth University, Maynooth, Ireland,

[6]Department of Human Sciences, Area of Physical Geography, University of La Rioja, Logroño, Spain

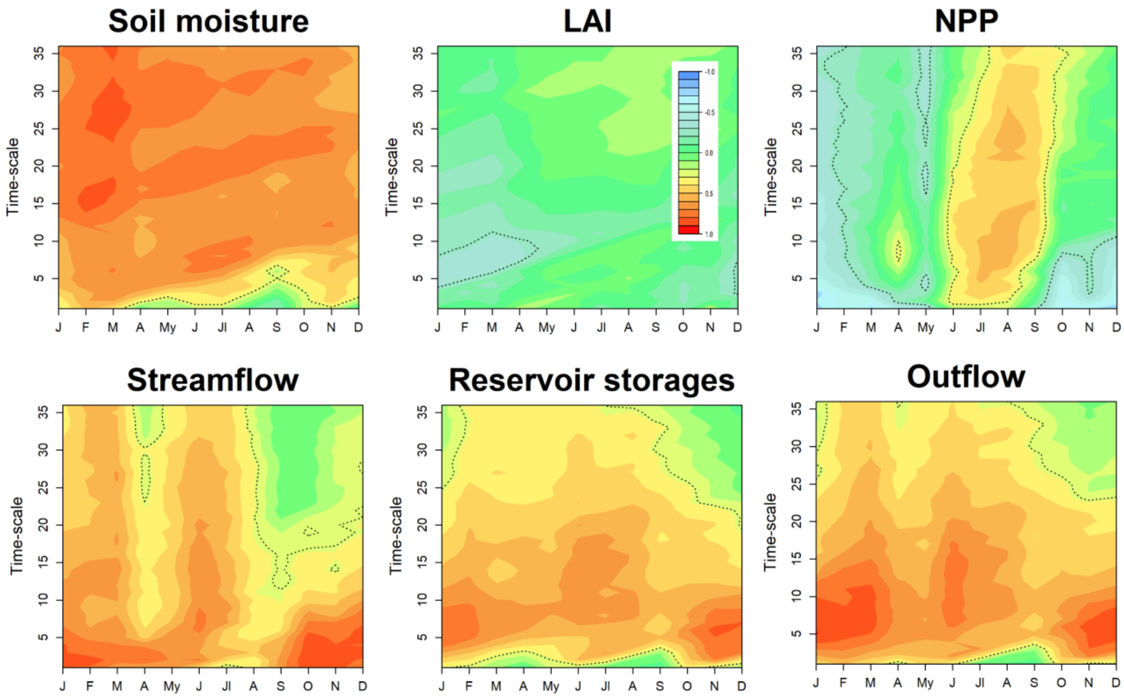
[a]svicen@ipe.csic.es



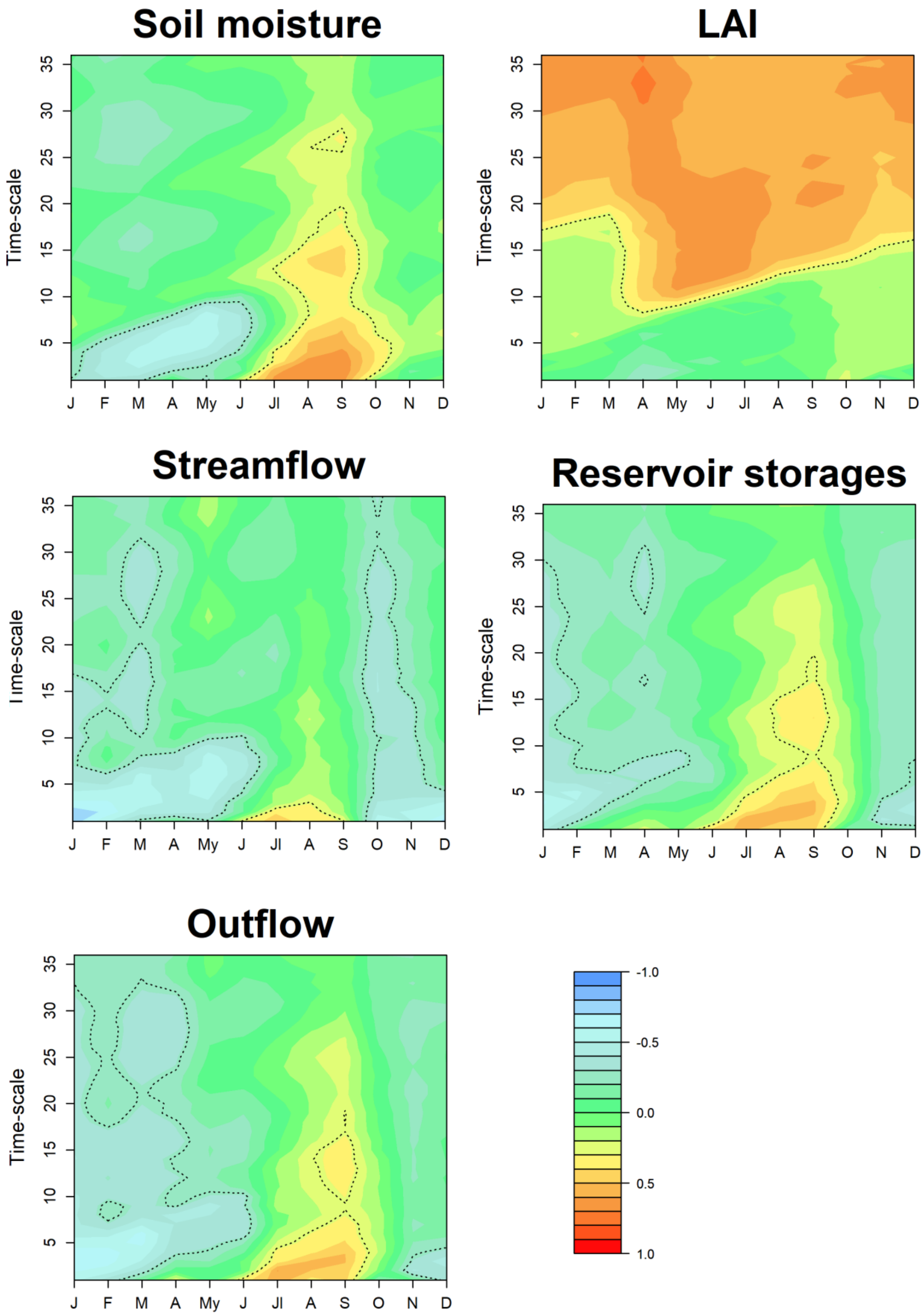
Supplementary Figure 1. Observed (red) and modelled streamflow (blue) and modelled eco-hydrological variables in the Aragon



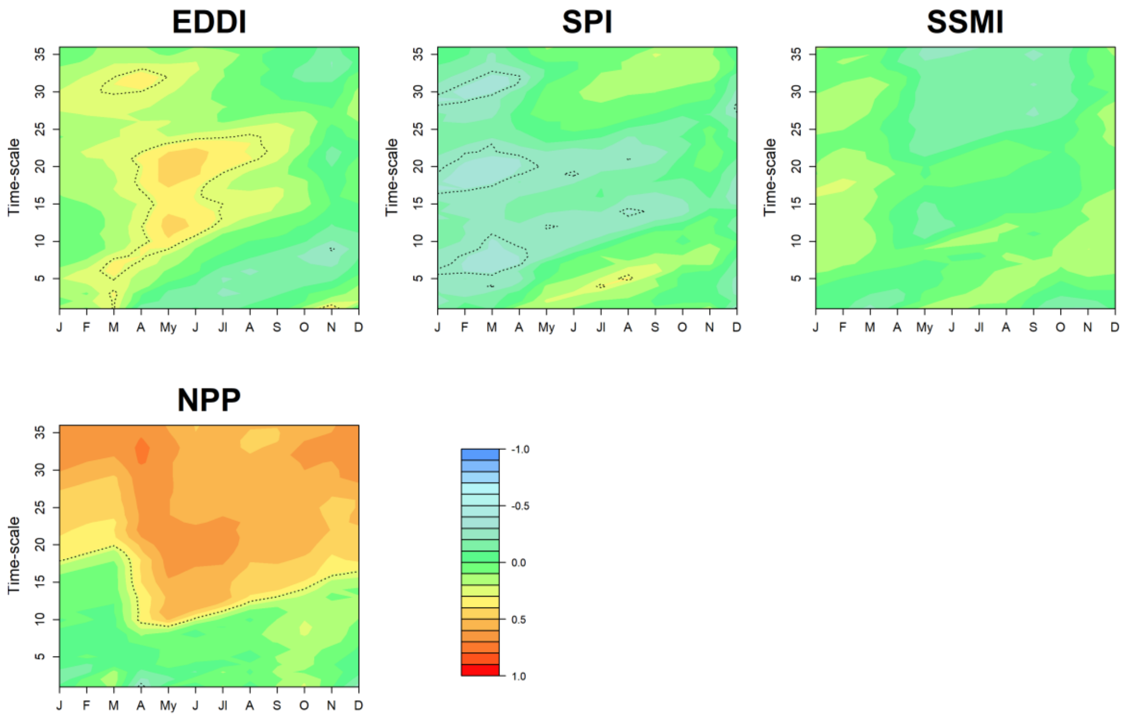
Supplementary Figure 2. Monthly Pearson's r correlations between the basin Standardized Precipitation Evapotranspiration Index (SPEI) and different hydrological and ecological variables. Dotted lines frame months and time-scales in which the correlations are statistically significant.



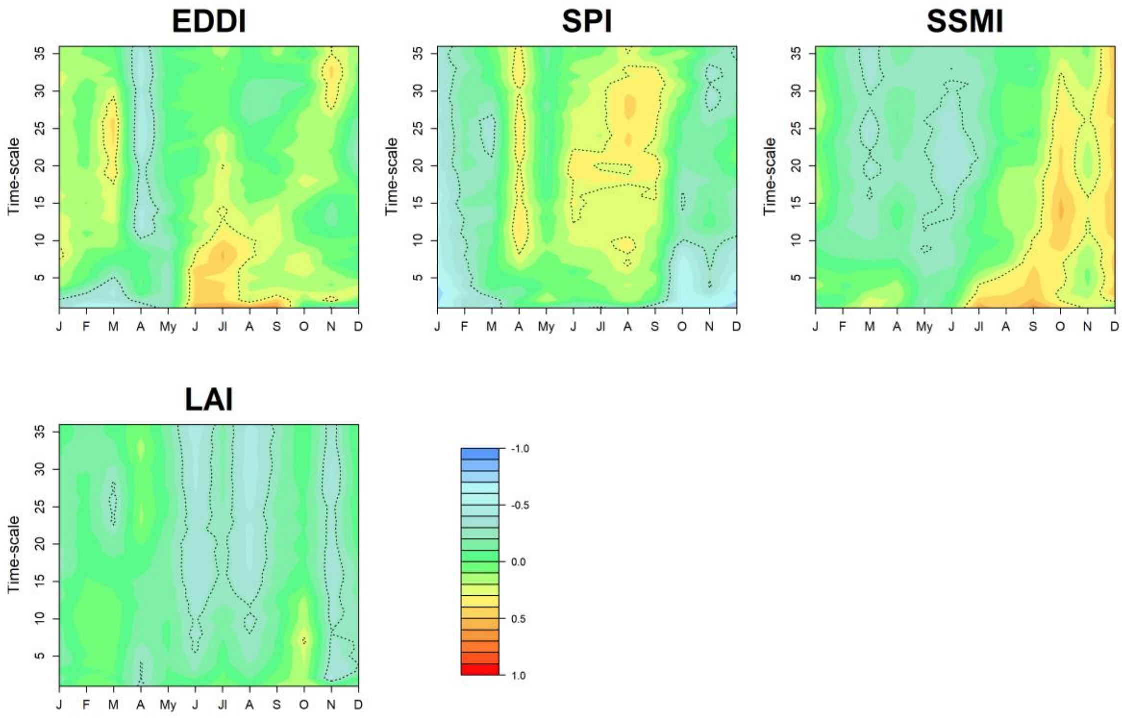
Supplementary Figure 3. Monthly Pearson's r correlations between the basin Standardized difference between Precipitation and Evapotranspiration and the different hydrological and ecological variables. Dotted lines frame months and time-scales in which the correlations are statistically significant.



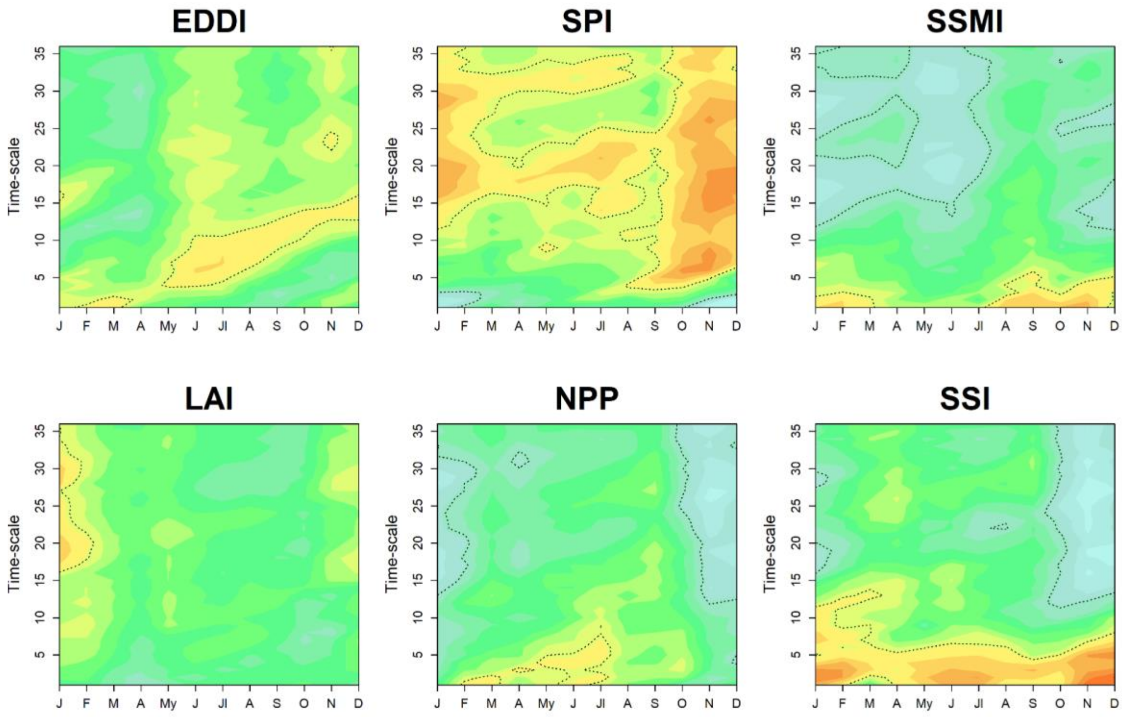
Supplementary Figure 4. Monthly Pearson's r correlations between the basin Standardized NPP and the rest of hydrological and ecological variables. Dotted lines frame months and time-scales in which the correlations are statistically significant.



Supplementary Figure 5. Monthly partial correlations between the basin Standardized LAI and the variables that may have a role on it (EDDI, SPI, SSMI and NPP). Dotted lines frame months and time-scales in which the correlations are statistically significant.



Supplementary Figure 6. Monthly partial correlations between the basin Standardized NPP and the variables that may have a role on it (EDDI, SPI, SSMI and LAI). Dotted lines frame months and time-scales in which the correlations are statistically significant.



Supplementary Figure 7. Monthly partial correlations between the standardized reservoir storages at Yesa reservoir and the variables that may have a role on it (EDDI, SPI, SSMI, SSI, LAI and NPP). Dotted lines frame months and time-scales in which the correlations are statistically significant.