Nature based-solutions may increase the severity of hydrological droughts in Europe

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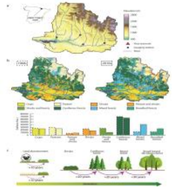
Summary

In the frame of the studies developed in the AXIS-2018 CROSSDRO project, the results obtained at different spatial scales (hydrological basin, Spain and European continent) suggest that vegetation changes may strongly determine the trends in the frequency and severity of hydrological droughts in Europe: (i) At the basin scale we analysed the impact of vegetation changes on blue water generation in a central Spanish Pyrenees basin undergoing intense afforestation. The results showed that vegetation change is a key driver of large decreases in blue water availability. The effect of vegetation increase is amplified during dry years, and mainly during the dry season, with streamflow reductions of more than 50%. This pattern can be attributed primarily to increased plant water consumption. (ii) in Spain we analysed in headwater catchments that are not affected by human perturbations the extent to which vegetation can reinforce trends in hydrological drought severity in comparison to the evolution of climatic drought severity. Results showed that the trends toward higher frequency, duration and severity of hydrological droughts are more marked than the observed trends in climatic droughts, which can be associated to the dominant increase in vegetation coverage and activity in the study domain. Moreover, the spatial differences observed between the trends of climatic and hydrological droughts show some relationship with the patterns of forest succession observed in recent decades. (iii) At the European scale we have found important differences in the trends in hydrological drought severity over the last decades and the analysis suggest that the strong decrease of streamflow in southern Europe cannot be associated with the climate dynamic. In fact, a negative trend related to non-climate factors clearly emerge. This negative trend is reinforced in the dry precipitation years. The results suggest that changes in vegetation activity and land cover have the main role on negative streamflow trends in Southern Europe, particularly during dry years, in which water requirements by vegetation would affect the partition of the available resource between green and blue water.

Our results stress the relevance of land transformation processes on trends in water resources availability, particularly during periods of meteorological droughts in which competence between vegetation water consumption and streamflow production is much more relevant. Thus, the current recommendations for landscape rewilding and nature-based solutions to mitigate climate change, with focus on carbon sequestration, could have important hydrological effects, reducing the availability of water resources and particularly increasing the frequency and severity of hydrological droughts. With aridity expected to rise in Europe over the next few decades, interactions between climate and land management practices appear to be amplifying future hydrological drought risk in the region.

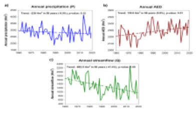
Evidences in the Central Spanish Pyrenees

Unraveling the interaction between vegetation and climate variability, as well as their impact on the partitioning of precipitation into blue and green water, is a high-priority research topic. While an increase in green water consumption has been linked to greening, it is unclear how water availability and seasonality affect the dependency between vegetation changes and precipitation partitioning.There is little understanding of the interaction between vegetation changes and the interannual and intraannual variability of climate conditions to explain anomalies and long-term streamflow trends. We hypothesize that dominant re-vegetation changes in mountain Mediterranean areas of southern Europe have been the primary cause of the large decline in streamflow observed in recent decades. Nevertheless, the role of these vegetation changes in the partition of precipitation between blue and green water is dependent on interannual climate variability, with the role being stronger during dry years when the system has less available water. Here, we analyse the influence of vegetation changes on blue water generation in a humid natural basin (the upper Aragón basin,) over the last six decades (1962-2019). This basin, located in the Spanish Pyrenees (2181 km2), is characterized by intense secondary succession toward more mature vegetation communities, representing a "typical" example of recent observed vegetation changes in mountainous areas of southern Europe.



a) Physiography and main river network in the upper Aragón basin, b) land cover changes distribution and changes between the decades of 1960s and 2010s and c) dominant process of vegetation succession phases and lapse times in the study domain.

Annual precipitation in the basin shows high variability, with a non-significant decrease of 8% in annual totals observed between 1962 and 2019. Over the same time period, AED increased by 5.7%, which is statistically significant at the 95% level (p<0.05). From 1962 to 2019, the annual streamflow in the catchment decreased by more than 40%. After removing the role of precipitation, the non-climate-related streamflow decline would range between 321 Hm3 (if AED increase is fully representing an increase in E) and 452.8 Hm3 (assuming E changes are not driven by AED). These numbers represent between 46% and 65% of total streamflow decline, which would be explained primarily by the basin's secondary succession process.



Temporal evolution of annual precipitation (a), atmospheric evaporative demand (AED) (b) and streamflow (c) in the upper Aragón basin for 1962–2019. Dashed lines represent the linear trend obtained by means of least-squares. The percentage changes between 1961 and 2019 are obtained from the regression lines. P-values are obtained by means of the modified Mann-Kendall test

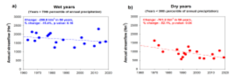
The secondary role of the observed increase in AED in the streamflow reduction is confirmed by the regression analysis. Over the period 1962-2019, regression analysis using precipitation, AED, and time (in years, as a proxy for the effect of secondary succession and general greenness) as predictors of annual streamflow explains 82% of the variability in streamflow. However, AED was removed from our final model because it was not a significant predictor. According to the partial correlation, precipitation has the largest (positive) influence on annual streamflow, while time exhibited a significant (negative) correlation.

	R²	Partial correlations		
		Precipitation	AED	Time
Annual	0.82	0.88	-0.09 (n.s.)	-0.64
Wet season (Nov.-Jun.)	0.87	0.92	-0.06 (n.s.)	-0.63
Dry season (Jul.-Oct.)	0.48	0.31	-0.21	-0.49

Partial correlation coefficients of the linear stepwise regression analysis in which annual and seasonal streamflow was the dependent variable and precipitation, AED and Time (in years) were the independent predictors. R2 represents the percentage of total variance of the independent variable explained by the predictors.

Methods: Daily streamflow data for the basin was provided by the Ebro Basin Management Agency. Climate data were obtained from a high-resolution (1.1 km) weekly gridded dataset for the whole of Spain from 1962 to 2019. The gridded data of air temperature, relative humidity, sunshine duration (as a proxy for solar radiation), and wind speed were used to calculate atmospheric evaporative demand (AED) by means of the FAO-56 Penman-Monteith equation. Land cover maps for the decades of 1960 and 2010 were provided by the Spanish Ministry of Agriculture. We have analyzed the magnitude of the trend in annual P, Q and AED to quantify the magnitude of the annual Q trend that may be associated to climate trends and vegetation changes. Significance of trends in hydrological and climatic variables was analysed by means of a modified Mann–Kendall trend test. To assess the magnitude of change in the different variables, we used a linear regression analysis. To quantify the magnitude of the annual Q trend that may be associated with climate trends and vegetation changes, we analyzed the annual trend magnitude of P, Q and AED. Time was included in the models as a proxy for the progressive evolution of vegetation in the basin as a consequence of secondary succession. The ordinary least square regression method was used to assess trends for wet and dry years and seasons. Herein, wet years (seasons) were defined as those exceeding the 70th percentile of precipitation over the period of record. On the other hand, dry years (seasons) were determined as those with rainfall falling below the 30th percentile.

We found the effect of secondary succession on the partitioning of precipitation to be strongly differential between wet and dry years. Both precipitation and AED show similar non-significant trends during wet and dry years. However, a small (-15.4%) and non-significant decrease in annual streamflow was found in wet years, compared to a larger (-52.1%) and statistically significant decrease during dry years.



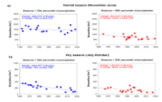
Evolution of annual streamflow during wet (a) and dry (b) precipitation years.

In wet years, green water increase is expected as a consequence of higher water consumption by more dense vegetation coverage but during these years, the abundance of precipitation makes that secondary succession and greenness have less impact on streamflow trend. In contrast, in dry years secondary succession tends to reduce blue water, in favor of increased green water use.

		R²	Partial correlations		
			Precipitation	AED	Time
Annual	Dry years	0.76	0.80	-0.20 (n.s.)	-0.73
	Wet years	0.52	0.69	-0.15 (n.s.)	-0.49
Wet season (Nov.-Jun.)	Dry years	0.66	0.74	-0.00 (n.s.)	-0.63
	Wet years	0.59	0.74	-0.17 (n.s.)	-0.54
Dry season (Jul.-Oct.)	Dry years	0.42	0.55	-0.47	-0.49
	Wet years	0.70	0.18 (n.s.)	-0.19 (n.s)	-0.84

Correlation coefficients of the different regression models for annual and seasonal periods considering a subset of dry and wet years. In all models streamflow was the dependent variable and precipitation, AED and time (in years) were the independent predictors.

The influence of secondary succession also differs between wet and dry seasons. Although secondary succession contributes to some decrease in blue water generation in the wet season, particularly during dry periods, the main effect is recorded during the warmer dry season (July-October), which is characterized by high vegetation activity, and consequently water consumption

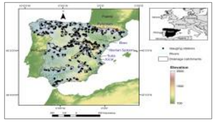


Evolution of annual streamflow during the wet (a) and dry (b) seasons during high and low precipitation periods.

Evidences in the river headwaters of Spain

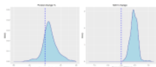
In the Mediterranean region, water resources mostly originate in mountain headwaters. Intense transformation of land cover during the last decades has impacted these areas, mainly by abandonment of traditional agriculture and livestock practices. Specifically, pasture and crop areas have rapidly transformed to shrub and forest lands: a process often accelerated by extensive tree plantations after 1960. In Spain, river streamflow has decreased significantly over the last decades. Analyzing the evolution of the climatic and hydrological droughts on non-regulated basins could also help isolating the possible impacts of land cover changes on the propagation of the climatic droughts to hydrological droughts. Using non-regulated basins of Spain as test cases, this study therefore addresses the following questions: i) How trends in hydrological droughts differ from climatic droughts in non-regulated basins of Spain?, ii) What is the role of vegetation changes on the possible trend differences between climatic and hydrological drought?, iii) What spatial patterns emerge in the trend differences between climatic and hydrological drought that can be related to vegetation changes?

Methods: This study employed the monthly streamflow data gauged at the headwaters of the Spanish basins. We collected data from national and local water management agencies, including the Ministry of transport, mobility and urban agenda and Centro de Estudios y Experimentación de Obras Públicas (CEDEX) besides the Catalan, Basque, and Andalusian water management agencies. The dataset in this study initially included a total of 472 monthly streamflow series spanning the Spanish Peninsula and covering the period 1961-2013. Nevertheless, we decided to exclude the series located in the middle and lower course and those impacted by large perturbations related to water management (e.g. damming) and irrigation extractions. To this end, the final dataset included 226 headwaters. We extracted the corresponding meteorological data from a newly developed high-resolution (1x1 km) gridded dataset for Spain. In this study, we employed the meteorological data at a monthly scale for precipitation, air temperature, relative humidity, sunshine duration and wind speed spanning the period from 1961 to 2013. We also used land cover information using two official land cover maps provided by the Ministry of Agriculture of Spain. For quantifying climatic and hydrologic droughts, this study employed two different indices to characterize drought at the basin scale. We calculated the Standardized Precipitation Evapotranspiration Index (SPEI) to assess climatic drought at time scales ranging from 1- to 48-month. On the other hand, the Standardized Streamflow Index (SSI) was used to characterize hydrological droughts. We adopted a threshold of -0.84 to define drought events using SPEI/SSI. This threshold corresponds to a 20% of probability in the standard normal probability distribution and correspondingly a return period of 1 in 5 years, which refers to a moderate drought. Once the drought events were identified, we computed the corresponding series of drought frequency, duration and magnitude. The drought duration was defined as the number of consecutive months with SPEI/SSI values lower than -0.84, while the drought magnitude was computed following the integration of the SPEI/SSI values over the full length of each dry period. Once climatic and hydrologic droughts were quantified, we used statistical methods to assess possible temporal changes. For this purpose, we employed the nonparametric Mann-Kendall statistic to assess the statistical significance of changes in the frequency, duration and magnitude of climatic and hydrologic droughts (1961-2013). To assess the amount of change in the series of drought duration and magnitude, we applied an ordinary linear regression model, in which the series of time is the independent variable, while the drought duration or magnitude is the dependent variable. The slope of the regression indicates the amount of change, with higher slope values suggesting greater changes and vice versa.



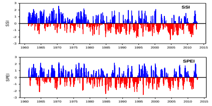
Spatial distribution of the gauging stations and drainage basins selected for this study. The base map shows the elevation (m) and rivers of the Iberian Peninsula.

Changes in land cover types in the study area show an increase in forest area. Overall, results suggest an increase in the forest total surface from 2678.9 km2 (30.7% of the whole domain) to 3458.3 km2 (almost 40%). In the same context., a dominant increase of the Normalized Difference Vegetation Index (NDVI) was evident for all basins.



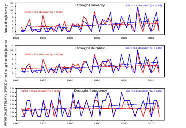
Density plots showing changes in the proportional area of forests (%) and changes in the annual NDVI between 1981 and 2012.

A notable temporal agreement is observed in the occurrence of drought events of SSI and SPEI at 3-month timescale for the period 1961-2013. Nevertheless, changes in hydrological drought were much stronger than climatic drought. In particular, SSI showed a decrease on the order of -0,21 z-unit/decade, while SPEI declined by -0.07 z-unit/decade.



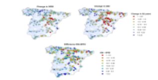
Temporal evolution of the regional series of SSI and 3-month SPEI from 1961 to 2013.

Changes in hydrological droughts were statistically significant (p<0.05), whereas changes in climatic droughts were small and statistically non-significant (p>0.05). Furthermore, in severity and duration a change point in the early 1990's is detected. Before the 1990's, SPEI shows higher values for drought severity and duration, while after the 1990's, SSI shows higher values. This result suggests that hydrological droughts were more reinforced in their severity over the analyzed natural catchments, compared with the severity of climatic drought.

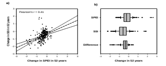


Evolution of the regional series of annual drought severity, duration and frequency . SSI (blue lines) and SPEI (red lines).

Considerable spatial differences exist, where more negative trends were identified considering SSI than SPEI. Specifically, the strongest decrease in SSI was noted in the Mediterranean basins, such as the Ebro, Turia and Júcar basins. The headwaters of these basins originated mainly in the Iberian range and the Pyrenees. In contrast, the basins located in the western portions of the Iberian Peninsula exhibited smaller changes, and even positive changes. This spatial pattern was evident for both SPEI and SSI. Importantly, although negative changes of SSI and SPEI dominated over the majority of the basins Changes in hydrological droughts were more accelerated than climatic droughts, especially in the eastern Spain.



Spatial distribution of the SPEI and SSI changes and their differences between 1961 and 2013. Values above/below (+/-) 0.35 are statistically significant at the 95% level (p<0.05).

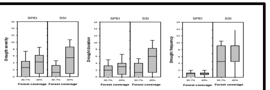


a) Relationship between the magnitude of change in SPEI and SSI for the analysed basins, b) Box-plot showing the the amount of change in SPEI, SSI and their differences.

	Severity (SPEI)	Severity (SSI)	Duration (SPEI)	Duration (SSI)	Frequency (SPEI)	Frequency (SSI)
Significant negative (p < 0.05)	3	12	4	11	6	10
Non-significant negative (p > 0.05)	24	41	22	36	48	55
Non-significant positive (p > 0.05)	171	82	171	86	154	86
Significant positive (p < 0.05)	28	91	29	93	18	75

Number of basins showing positive and negative trends in the severity, duration and frequency of the drought events between 1961 and 2013.

the impacts of changes in vegetation coverage on the evolution of hydrological drought evolution are apparently complex. This complexity is evident in this study, given that the response of hydrological droughts to the evolution of the vegetation coverage is unidirectional over space. Nevertheless, the increase in vegetation coverage corresponded to a more pronounced increase in severity and duration of hydrological droughts, as compared to earlier decades characterized by lower vegetation coverage.



Box-plots showing the differences between the severity, duration, and frequency of drought events during two periods (1962-1986 and 1987-2013), which correspond to different forest coverage (30.7% vs 40%, respectively)

In more mature forests (e.g. coniferous, broadleaf, and mixed forests), the forest succession process seems to have a significant impact on differences in the evolution of hydrological and climatic droughts. As listed, for the coniferous and broadleaf forests, results suggest statistically significant correlations between the difference in the evolution of the drought variables and the average surface of these forests. The differences in the sign of the correlation may highlight the role of the forest succession, as many basins witnessed a dominant replacement of coniferous forest by mixed forests. Interestingly, these basins showed a stronger increase in the severity of hydrological droughts than in climatic droughts.

	Severity	Duration	Frequency
Crop surface	-0.09	-0.07	-0.04
Pasture surface	0.09	0.07	-0.03
Shrub surface	0.07	0.06	0.02
Coniferous For. Surface	0.16*	0.17*	0.10
Broadleaf For. Surface	0.05	0.04	-0.02
Mixed For. Surface	0.18*	0.19*	0.09
Average NDVI	0.11	0.10	-0.01
Difference crop surface	-0.06	-0.05	0.00
Difference pasture surface	-0.02	-0.04	-0.01
Difference shrub surface	-0.03	-0.03	0.07
Difference conif. For. Surface	-0.14*	-0.14*	-0.12
Difference broad. For surface	-0.04	-0.06	-0.12
Difference mixed For. Surface	0.16*	0.16*	0.08
NDVI change	0.08	0.07	0.02

Pearson's r correlation coefficients between the spatial patterns of the difference of change between hydrologic and climatic droughts, the surface (%) of different land cover types in 2010s, the average annual trend magnitude of NDVI, changes (%) in the surface of each land cover type between the 1970s and 2010s.

To account for the possible role of the dominant forest types, we employed a linear regression model, in which differences in the severity and duration between hydrologic and climatic droughts served as dependent variable. Results revealed that the observed changes in the total surface covered by mixed forests was the most significant variable contributing to the the spatial variability of of the magnitude of changes between hydrological and climatic droughts..

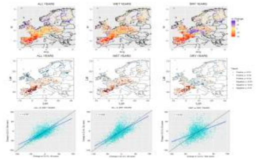
	Drought Severity	Drought Duration
Change NDVI	0.29	0.11
Change crop area	0.08	0.01
Change pasture area	0.47	0.35
Change shrub area	-0.17	-0.33
Change conif. Forest area	-0.43	-0.36
Change broadleaf forest area	0.51	0.27
Change mixed forest area	1.09	1.12

Beta standardized coefficients obtained from two linear regression models, considering the difference of change between hydrological and climatic drought severity and duration for each basin, changes in the different land cover types, and annual NDVI changes as input variables.

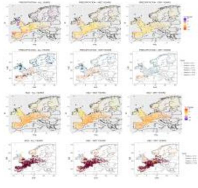
Evidences at the European level

This study analyses the evolution of annual streamflow across Europe between 1962 and 2017, focusing on the connection of streamflow trends with climate dynamics and physiographic and land cover characteristics and changes. The spatial pattern of trends in streamflow shows strong agreement with the spatial patterns of climate trends, suggesting a climate attribution of these trends. However, analysing temporal evolution at the basin scale shows that the strong decrease of streamflow in southern Europe cannot be directly associated with climate dynamic. In fact, a negative trend related to non-climate factors clearly emerges. This negative trend is reinforced if we focus on the dry precipitation years.

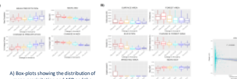
The strong decrease of streamflow in southern Europe is not explained by the evolution of precipitation during the studied period, which shows small decrease that is dominantly non-significant statistically. Thus, the difference between the magnitude of change in streamflow, and the magnitude of change in precipitation is very important in South Europe. The decrease of streamflow has been very important in the majority of the basins of southern Europe, with statistically significant trends and reductions of streamflow of more than 50% between 1962 and 2017. On the contrary, the reduction of precipitation is small in these areas (approximately 5%) and in most basins non-statistically significant. Therefore, the strong decrease of streamflow in southern Europe cannot be clearly attributed to the recent dynamic of precipitation alone.



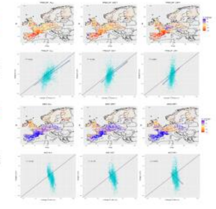
Top: Magnitude of change of streamflow (Q) in percent (1962 = 100) between 1962 and 2017 considering all, wet and dry years. Middle: Statistical significance of streamflow changes considering all, wet and dry years. Bottom: Spatial relationship between the magnitude of the annual streamflow changes for all, wet and dry years.



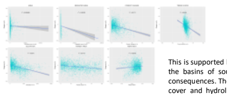
First row: Magnitude of change of precipitation in percent (1962 = 100) between 1962 and 2017 considering all, wet and dry years. Second row: Statistical significance of precipitation changes considering all, wet and dry years. Third row: same that first row but for AED. Fourth row: same as third row but for AED.



A) Box-plots showing the distribution of mean precipitation and AED and the magnitude of change in precipitation and AED as a function of the statistical significance of changes in annual streamflow. B) Same that A) showing the distribution of values for different basin physiographic and land cover characteristics as a function of the statistical significance of changes in annual streamflow.



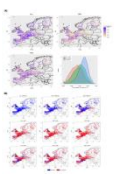
First row: Difference in the magnitude of change in precipitation and streamflow (both in percent) between 1962 and 2017 considering all, wet and dry years. Second row: Spatial relationship between changes in precipitation and streamflow obtained for all, wet and dry years. Third Difference in the magnitude of change in AED and streamflow (both in percent) between 1962 and 2017 for all, wet and dry years. Fourth row: Spatial relationship between changes in AED and streamflow obtained for all, wet and dry years.



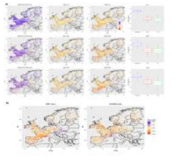
Spatial relationship between different physiographic and land cover characteristics for each basin and changes in annual streamflow between 1962 and 2017.

Methods: The main data used in this study comprise a monthly streamflow dataset containing information of 3224 gauging stations across Europe for the period 1962-2017. The total annual (October-September) streamflow was quantified at each gauging station in Hm3. Climate information was obtained from two different sources. Gridded precipitation data were obtained from the E-obs database 55 at the spatial resolution of 0.1 degrees and the necessary data to calculate the atmospheric evaporative demand (AED): air temperature, solar radiation, wind speed and humidity was obtained from the ERA-5 Reanalysis 56 also at 0.1 degrees of resolution. For comparison with streamflow records, climate variables were also transformed to Hm3. Data on relevant land cover characteristics, including the surface area irrigated lands was obtained from CORINE land cover global dataset (https://land.copernicus.eu/pan-european/corine-land-cover) and summarised for each basin. We first analysed the magnitude of trend in annual streamflow during the period 1962-2017 for complete years and wet and dry years. Herein, wet years were defined as those exceeding the 50th percentile of precipitation over the period of record, while dry years were defined as those falling below the 50th percentile.

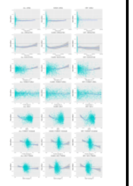
To quantify the magnitude of the annual streamflow trends that may be associated with climate and other variables (e.g., vegetation changes), we used a multiple regression, developed for each basin, with streamflow as the dependent variable and precipitation, AED, and time as the independent variables. Time was included in the models as a proxy for the progressive evolution of vegetation, other land cover changes (e.g. the increase of the irrigation surface) or other factors (e.g., the increase of urban or industrial demands). The forward stepwise selection of predictors was used in the construction of regression models with a threshold of 0.05. We quantified the independent role of each variable (precipitation, AED and time) using the regression Beta coefficient, which varies between -1 and 1. This provides information on the weight that each independent variable has in determining the changes observed in the dependent variable, in this case annual streamflow.



A) Maps: percentage of the variance (R2 coefficients) in annual streamflow explained by each stepwise regression model considering precipitation, AED and time as independent variables for all, wet and dry years. B) Basins in which the three independent variables: precipitation, AED and time are included or not in the stepwise regression models.



A) Spatial distribution of the beta coefficients obtained from the independent regression models. B) Difference between the beta coefficients obtained by means of the stepwise regression models between all and dry years (left) and between all and wet years (right).



AScatterplots and fitted GAM curves relating the spatial distribution of different physiographic and land variables and the percentage of each basin with the beta coefficients of the time variable obtained from the stepwise regression models for all, dry and wet years.

We conclude that climate trends have played only a partial role in explaining the spatial patterns of streamflow trends across Europe in comparison to the effect of non-climate factors.

This is supported by the existence of a dominant non-climatic temporal component, which is included in a high percentage of regression models obtained for the basins of southern Europe. Land cover and water management changes have been very important in the region, with noticeable hydrological consequences. The negative streamflow trends explained by non-climatic factors are more pronounced in dry years. This finding has large implications for land cover and hydrological drought management in where precipitation is projected to decrease during this century since landscape management in the headwaters could reduce the severity of hydrological droughts in the medium and lower reaches of rivers and improve the availability of water for high demand activities such as irrigation during dry periods. Thus, current policies and recommendations for landscape rewilding and nature-based solutions to mitigate climate change with a focus on carbon sequestration in southern Europe could have important and detrimental hydrological effects, reducing the availability of water resources and potentially increasing the frequency and severity of hydrological droughts.