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Disclosing the effects of climate, land use, and water demand as drivers of hydrological trends in a Mediterranean river basin.

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ABSTRACT

Disclosing the effects of climate, land use, and water demand as drivers of hydrological trends in a Mediterranean river basin.

Mediterranean basins face significant water scarcity which demands examining long-term data to prospect their trends in water availability and quality. This study focuses on The Onyar River (Inner Catalan basins, NE Spain), to explore its historical streamflow changes, the influencing climatic and land-use factors, and the consequential impacts on water quality. We analyse key hydro-climatic variables—streamflow, precipitation, temperature, and evapotranspiration (both PET and AET)— across a 60-year span (1960-2020) and their relationship with recent stream water chemistry data (2007-2020). We compare these patterns to the changes in land use, and to the variations in water demand according to urban use, livestock, and crop production estimates. Our findings highlight a consistent decline in streamflow, most pronounced over the last two decades, accompanied by an increase in PET, and a probable decrease in groundwater recharge. Notably, these changes co-occurred with higher concentrations of river water ammonium and nitrate. We attribute these patterns to changes in land use such as afforestation and intensive fertilization, as well as increased groundwater withdrawal, particularly during irrigation seasons. Additional factors include growing urban water demand and the discharges of treated wastewater back into the river system. This study offers a comprehensive overview of the declining water quantity and quality in the Onyar River, attributing these trends to an interplay of climatic and anthropogenic factors. The findings underscore the need for integrated water resource management strategies to mitigate the implications of these changes.

KEYWORDS: hydrological regime; climate change; land uses; water uses; water chemistry; water scarcity

RESUMEN

Revelando los efectos del clima, los usos del suelo y la demanda de agua como factores determinantes de tendencias hidrológicas en una cuenca mediterránea

Las cuencas mediterráneas se enfrentan a una escasez de agua significativa, lo que requiere el análisis de datos a largo plazo para entender y anticipar tendencias en su cantidad y calidad. Este estudio se centra en el Río Onyar (Cuencas Internas de Cataluña, NE España) y busca explorar los cambios históricos en su caudal, los factores climáticos y de uso *del suelo que influyen en él, así como los impactos de estas tendencias en la calidad del agua. Para ello, analizamos variables hidroclimáticas clave —caudal, precipitación, temperatura y evapotranspiración (ETP y ETR)— a lo largo de un período de 60 años (1960-2020) y su relación con los datos químicos más recientes (2007-2020). Comparamos estos patrones con los cambios en el uso del suelo y con las variaciones en la demanda de agua para uso urbano, ganadero y agrícola. Nuestros hallazgos destacan una disminución constante en el caudal, sobre todo en las últimas dos décadas, junto con un aumento en la ETP y una probable disminución en la recarga subterránea. Estos cambios coinciden con mayores concentraciones de amonio y nitrato. Atribuimos estos patrones a cambios en el uso del suelo, como la reforestación y la fertilización intensiva, así como al aumento de la extracción de agua subterránea, especialmente durante las temporadas de riego. Factores adicionales incluyen la demanda creciente de agua para usos urbanos y las descargas de aguas residuales tratadas. Este estudio ofrece una visión completa del deterioro de la cantidad y calidad del agua en el Río Onyar, atribuyendo estas tendencias a una interacción de factores climáticos y antropogénicos. Los hallazgos subrayan la necesidad de adoptar estrategias de gestión integrada de recursos hídricos para mitigar las implicaciones de estos cambios.*

PALABRAS CLAVES: régimen hidrológico; cambio climático; usos del suelo; usos del agua; química del agua; escasez de agua.

INTRODUCTION

Anthropogenic activities such as intensive agricultural or industrial water withdrawals alter the hydrological regimes in river networks (Döll and Zhang, 2010; MedECC, 2020), a phenomenon that is overly exacerbated by climate change in arid or semiarid basins (Cramer et al., 2018; Giorgi, 2006). Further, land abandonment is widespread in the northern Mediterranean and associated to a progressive conversion to forest (García-Ruiz et al., 2011). Headwater catchments are the most affected by afforestation, and this may cause a high impact on streamflow through higher evapotranspiration and vegetation interception processes (Buendia et al., 2016; Delgado et al., 2010). Concomitant to this land use change, water demand has intensified due to population growth and dietary changes and the associated expansion of irrigated lands, crop productivity and livestock production (Lassaletta et al., 2021). As said, climate change may decrease water availability because of enhanced evapotranspiration and reduced rainfall, with significant increases in the duration of drought episodes (Cramer et al., 2018)

Because of the reasons above, many river systems show decreasing water flows (García-Ruiz et al., 2011). In extreme cases, rivers shift from permanent to intermittent having an increasing number of days with low water flow or even with zero flow (Cramer et al., 2018; García et al., 2017; Pachauri et al., 2014). This hydrological alteration may cause changes in the concentrations of nutrients and contaminants, and the dilution capacity of the systems is compromised (Abily et al., 2021). Altered streamflow is also detrimental to river habitat availability (Poff et al., 1997), and interfere in the capacity of the biological communities to adjust and respond to disturbances (Poff et al., 2007). Altogether, climatological and land use changes may contribute to structural water flow alterations, eventually leading to water scarcity (Barceló and Sabater, 2010). These alterations affect not only water availability but also its quality (van Vliet et al., 2017).

Regardless of the general causes associated to changes in water quantity and quality, specific patterns and key influencing factors vary widely. So, without properly elucidating the concerned drivers and stressors, managers and decision-makers may propose misdirected or counter-productive policies (Srinivasan et al., 2015). Unravelling these important factors requires the analysis of the long-term hydrological patterns, with the identification of temporal trajectories and the analysis of the main contributors involved in the observed trends (Bulteau et al., 2022). Assessing the consistency in the patterns of drivers (i.e., climate, land, and water uses) and stressors (i.e., groundwater overexploitation, nutrients and contaminants loads), and their relation to the hydrological regimes, provides the ground for developing a proper interpretation of the hydrological dynamics of the basin.

As a matter of fact, understanding the hydrological dynamics requires of the elaboration of the water balance of a basin. This is a relevant tool for identifying and managing the relationship between water demand and the available resources, both in quantity and quality (Mas-Pla and Menció, 2019; Menció et al., 2010). We here examine the case of the Onyar River basin (NE Catalonia, Spain), a mesoscale mixed forested and agricultural basin in Western Mediterranean. This watershed experiences rising human pressures on its water resources and does not differ from many other basins which have seen their water resources progressively compromised (Sabater et al., 2022). To approach the changes in the water balance of the basin, we compiled available hydrological, climatological, water chemistry and land use data, to address the following issues: a) Is the magnitude of change of the streamflow associated to land use and climatological changes? and b) Does nutrient concentrations and loads show similar trends to streamflow? Our overarching hypothesis is that this basin experiences growing hydrological stress associated to the rising environmental pressures and climatological changes. Since these are not uniform along the year or between years, we expect that long-term changes in water quantity and quality are not homogeneously distributed between seasons or hydrological periods, onto which the different drivers may perform distinct roles.

MATERIALS AND METHODS

Study area

The Onyar River basin has an area of 295 km^2 (Fig.1). The main tributaries gather at the centre of the basin showing a parallel drainage pattern, while in the range areas the drainage pattern is dendritic. The drainage network has Strahler's 5th order in the basin's outlet (Mas-Pla et al., 1985). Maximum heigh is 802 m a.s.l. and minimum 65 m a.s.l, with an average slope of 11.75% ± 9.5 σ. The basin hydrogeologic system consist of an unconfined aquifer of alluvial materials (15-20 m thick) overlying a multilayer leaky aquifer of Neogene sedimentary material, mostly sand and silt (Folch et al., 2011; Menció et al., 2014; Menció and Mas-Pla, 2008).

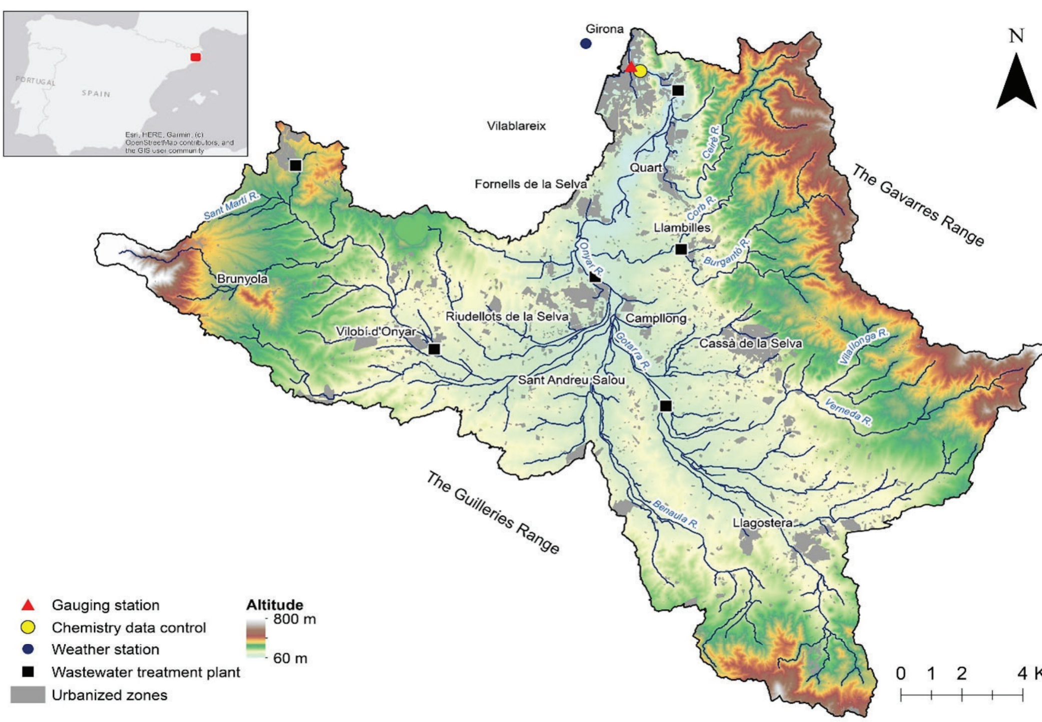

Figure 1. Study area. *Area de estudio.*

The basin receives a mean annual precipitation of 764 ± 210 σ mm, and its mean annual temperature is 14.0 ± 0.7 σ °C. There is no snow contribution. Winter and summer mean monthly temperatures are not extreme (7.8°C vs 21.6°C, average from 1960-2020, respectively), yet rainfall is unequally distributed between periods, lower in summer and higher in autumn (51.3 mm/month vs 79.9 mm/month, average from 1960-2020). Average daily streamflow is 1.6 ± 9.7 σ m^3/s (average from 1960-2020), with minimum values observed in summer (0.4 ± 2.1 σ m^3/s) and maximum records in winter (2.2 ± 12.2 σ m^3/s).

The basin is mostly forested at the upper hillsides and top of the surrounding ranges, with large areas dedicated to crops and pastures in the foothills and plains in the central part of the basin. It shows a moderate urban development, mostly consisting of scattered villages. Although there is no relevant irrigation or hydraulic infrastructure in the basin (reservoirs, dams, canals, or others), it is submitted to severe human pressures affecting water quality, streamflow, and overall ecosystem functions (Menció and Mas-Pla, 2010). The alluvial as well as the Neogene sedimentary aquifers are both affected by intense groundwater exploitation for agricultural supply, mostly from May to October (Menció and Boix, 2018). Groundwater nitrate pollution originates from fertilization practices as diffuse pollution and point source inputs as treated wastewater discharges and untreated sewage from isolated housing areas (Menció et al., 2014). Indeed, pig and cattle farming are important economic activities at the middle areas of the basin. A total of 15 761 heads of cattle and 36 437 pigs were registered in the last agrarian census (2020). Finally, ca. 7600 ha are dedicated to herbaceous crops for animal fodder and industrial usages, like annual ryegrass (25.3%), barley (22.1%), wheat (16.1%), rapeseed (11.6%), and corn silage (7.7% of the crop area), whereas other 17.2% is devoted to other crops as orchards.

Databases

Hydrology

We used the Catalan Water Agency (ACA, 2022a) database which assembled the hydrological records at the basin's outlet (485781, 4646867 UTM; Fig. 1). Mean daily discharge (Q) was available from October 1960 to September 2021, though records were missing for the hydrological year of 1965 and the period 1972-1975. We then excluded these hydrological years from the analysis, which finally assembled 55 hydrological years and 20,104 daily records. The hydrological year 1971 had a continuous gap of 52 days that was filled using the corresponding mean values for each day from the whole series. Eleven small gaps in the data series (<5 days) were also completed by using the mean obtained after the daily discharge recorded before and after the gap (Table S1, supplementary information, available at https://www.limnetica.net/en/limnetica).

Climate

Monthly precipitation (P), temperature (T), potential (PET) and actual evapotranspiration (AET) for the period 1950-2020 were obtained from the Integrated System for Rainfall–Runoff Modelling (SIMPA) that evaluates water resources in a natural regime (data accessible in: https://www.miteco.gob.es/es/agua/temas/evaluacion-de-los-recursos-hidricos/evaluacion-recursos-hidricos-regimen-natural/)(Estrela and Quintas, 1996). It includes all the meteorological data available in the Iberian Peninsula and interpolates it to generate raster-type data (i.e., 1 km^2 resolution) at a monthly frequency. The model calculates PET through a combination of Hargreaves and Penman–Monteith methods and uses a factor that accounts for the vegetation effect. AET is calculated considering the available water in the soil after the rainfall and the PET (CEDEX, 2020)(CEDEX, 2020). The original data set was clipped to the study area boundaries to obtain median values.

Land use land cover

We estimated the land use and land cover (LULC) changes by comparing the different editions of the "Land Use/Land Cover Maps of Catalonia" (MUCSC) (ICGC and Grumets CREAF-UAB, 2020). This is a high-resolution cartography (30 m × 30 m) that accounts for the main types of land uses. Cartographies were available for the years 1987, 1992, 1997, 2002, 2007, 2012 and 2017 (González-Guerrero & Pons, 2020). Although the categories changed over editions, there was always backwards compatibility. To simplify the land use classification, we established five distinct categories: 1) "Irrigated crops" encompassing both irrigated herb crops and fruit trees; 2) "Non-irrigated crops" which includes rainfed herb crops and trees; 3) "Forest" which comprises sclerophyll, deciduous, and coniferous forest; 4) "Scrublands and meadows" which includes forests, mountain and lowland meadows, and shrubs; 5) "Urban zones" encompassing urbanization, urban areas, and industrial areas; we then calculated the area (ha) occupied by each category in different map editions. Additionally, to determine the primary processes of change between 1987 and 2017 and their specific locations, we calculated the landscape transition matrix and generated a map with results (Fig. S1 and Table S3, supplementary information, available at https://www.limnetica.net/en/limnetica).

Water use and demand

In most of the basin, water demand is satisfied by groundwater exploitation plus the contribution of the district transfer network of the Ter River (nearby basin). Urban water demands were estimated after historical population records from the National Institute of Statistics (INE, 2022), after assuming an urban consumption per person of 278±30 l person^{-1} day^{-1}(Menció et al., 2010). The incoming water from the Ter basin was subtracted from the total urban water demand. The estimation of agricultural water demand was based on the irrigated crop area obtained from the LULC maps, along with the mean agricultural water supply reported by the ACA for each municipality within the Onyar River basin (X. Carreras, ACA, 2022 personal communication). To account for median water losses during groundwater extraction, transfer, and irrigation practices in the basin, an efficiency coefficient of 0.56 was applied. Finally, water demand for livestock production was estimated after the available farming censuses and the assumed consumption of each type of livestock according to the Management plan for the river basin district of Catalonia for the period 2022–2027 (ACA, 2022b). Specifically, we used the simplified standard allocations for pigs, cattle, sheep, and goats of 10, 40, 4.5 and 3.45 l head^{-1}day^{-1}, respectively.

Water chemistry

The chemical data at the gauging station located at the basin's outlet (Fig.1) were obtained from the ACA web page (ACA, 2022a). We used monthly data on total organic carbon (TOC), ammonium (NH_4^+), nitrate (NO_3^-) and phosphate (PO_4^{3-}) concentrations from 2007 to 2022 (data, n=174). We computed loads (kg/day) of each nutrient form by multiplying the concentration value (kg/l) by the corresponding mean daily flow (l/day).

Data analysis

Time series trends detection

Mann Kendall test was used to evaluate the statistical significance of trends in mean annual values of discharge and climatic variables. The statistical significance of trends was defined using a significance level of α= 0.05 for Kendall's p-value. Determination of the trend magnitudes was achieved using Sen's slope method (Sen, 1968). Additionally, we used Pettitt's test to determine the existence of change points in the hydrological series (Pettitt, 1979).The seasonal Mann Kendall, a modification of the Mann Kendall test trend that estimates the Kendall statistic as a summary for each period (defined as season; Hirsch et al., 1982), was used for the analysis of nutrients (NH_4^+, NO_3^-, PO_4^{3-}) and TOC time series. All statistical analysis and plots were performed using R 4.1.1 environment (R© Development Core Team, 2021), using the packages EnvStats© (Millard, 2013), lfstat© (Laaha and Koffler, 2022) and the tidyverse© library (Wickham et al., 2019).

Assessment of hydrological regime changes

We computed Flow Duration Curves (FDC) to track changes in the stream discharge magnitude and frequency for each decade. FDC is a cumulative frequency curve that shows the percent of time at which specified streamflow rates are equalled or exceeded. The flow characteristics of a stream are integrated into a single curve, regardless of the order in which the discharges occur (Searcy, 1959; Shaw et al., 2014). This allows to visually recognize changes in the flow frequency distribution and explore variations regarding seasonality.

To determine changes in flow duration and variability over time, we also calculated the Flow Standard Deviation (FSD), as

$$FSD = \left|[(Q_{84} - Q_{16}) + (Q_{95} - Q_{5})]/Q_{50}\right|$$

where Q_i corresponds to the i-th percentile i.e., the discharges equalled or exceeded i% of the time (Batalla et al., 2004). We calculated the interquartile range (IQR) and the standard deviation (σ), as other variability measures. All statistics summarizing what was observed in the FDCs and the measures of variability calculated are included in Table S2 (supplementary information, available at https://www.limnetica.net/en/limnetica).

In addition, we computed the runoff coefficient as the ratio between the annual discharge volume, R, and precipitation (P) for each 5-year period. The R/P ratio estimates the proportion of rainfall that becomes streamflow within the basin. Because just a fraction of rainfall becomes streamflow, (1 - R/P) represents all the other components involved in the water balance, mainly actual evapotranspiration (AET), and the portion of the groundwater recharge that does not exit the catchment as baseflow, i.e., recharge in the range areas that feeds the regional aquifer system in igneous and metamorphic rocks as well as in the Neogene sedimentary formations. Groundwater recharge (GW), defined as the monthly infiltration to the aquifer (mm), was also estimated from the SIMPA gridded datasets to analyse the changes of the ratios of the water budget components with respect to precipitation (i.e., R/P, AET/P and GW/P) over time.

RESULTS

Long-term trends of stream hydrology

Significant changes in daily discharge were observed throughout the study period (Fig. 2, Table 1). The Pettit test indicated a high probability of a change point at the beginning of the hydrological year of 2000 (U=24556, p-value<0.001). The mean values showed a notable reduction of ca. 48% if we compare 1960-1999 and 2000-2020, decreasing from 1.99 to 1.03 m^3/s. Similarly, the median values experienced a decrease of ca. 54% (from 0.49 to 0.23 m^3/s; Fig. 2b). Besides

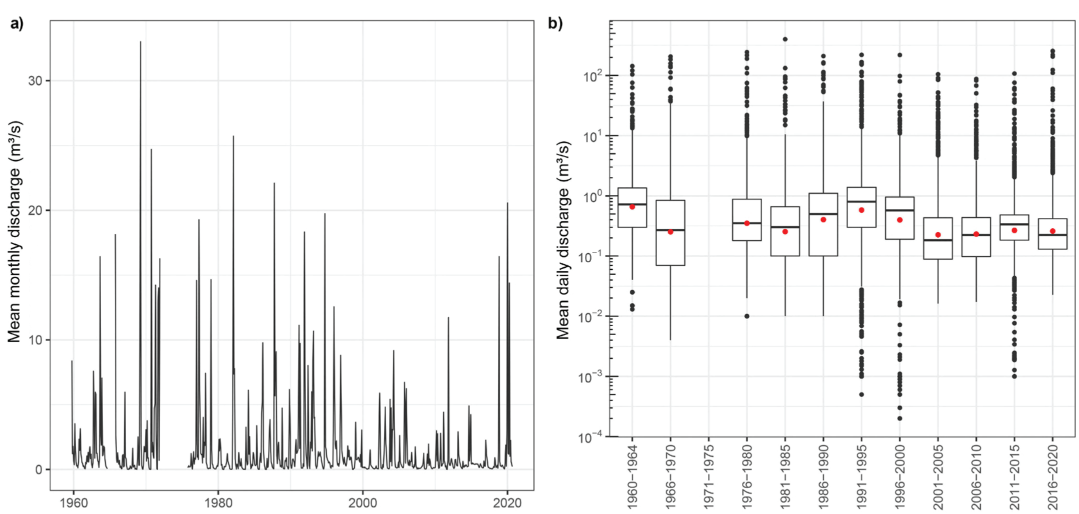

Figure 2. a) Hydrograph of the mean monthly flow (m^3/s), and b) boxplots for mean daily discharge values for each of the 5-year periods. *a) Hidrograma del caudal medio mensual (m^3/s), y b) diagramas de caja de los valores de descarga diaria media para cada uno de los períodos de 5 años.*

Table 1. Mann-Kendall results for annual mean values of water flow and climatic variables. PET stands for potential evapotranspiration, AET stands for real evapotranspiration, R for runoff and GW for groundwater recharge. Resultados de Mann-Kendall para valores medios anuales del caudal y de las variables climáticas. PET representa la evapotranspira*ción potencial, AET representa la evapotranspiración real, R es escorrentía y GW es la recarga del acuífero.*

	Z-trend	*p*-value[a]	Tau	Sen's slope	Intercept
Daily discharge (m^3/s)	*-16.91*	*<0.01*	*-0.08*	*-<0.01*	*8.11*
Mean monthly temperature (ºC)	*4.29*	*<0.01*	*0.10*	*0.02*	*-20.40*
Monthly acc. precipitation (mm)	*-2.71*	*<0.01*	*-0.06*	*-0.17*	*347.70*
Mean monthly PET (mm)	*5.77*	*<0.01*	*0.13*	*0.09*	*-127.54*
Mean monthly AET (mm)	0.45	0.65	0.01	0.01	-29.99
R/P	-1.56	0.11	-0.14	-<0.01	2.69
AET/P	*1.96*	*0.05*	*0.17*	*<0.01*	*-4.31*
GW/P	*-2.77*	*<0.01*	*-0.24*	*-<0.01*	*1.28*

[a] Statistically significant results *(p*<0.05) are highlighted in italics. *Los resultados estadísticamente significativos (*p*<0.05) se resaltan en itálica.*

this decrease in the central tendency measures, as indicated by measures such as IQR and FSD (refer to Table S2), flood peaks (i.e., values exceeding Q_2=10.5 m^3/s), also became less frequent in the last two decades. On average, there were 77.5 days per decade with Q values exceeding Q_2 during the 1960-1999 period, which reduced to 50 days per decade in the 2000-2020 period. The decrease in the value of Q_5 since 2000 indicates a diminishing magnitude of the largest flows.

The FDC plots also illustrate the significant and progressive shift of the daily water flow distribution in the last two decades (Fig.3a). High and frequent flows, related to discharge magnitudes with an exceedance below 10% and 80% respectively, have decreased since 1960, whereas low flows (magnitudes between exceedance percentages 80-95%) have increased. This reduction of flow variability is shown by the progressive flattening of the FDCs. The temporal variations exhibited non-uniform patterns across seasons, as evident from the seasonal FDCs (Fig.3b). Daily flow variability decreased in all seasons, except for spring. Winter low flows remained unchanged, while high and mean flows decreased. Conversely, summer and autumn experienced an increase in flows with exceedance percentages above ≈80%, indicating higher discharge values during low flow periods. Notably, between 1960 and 1990, summer and autumn recorded zero discharge values with an exceedance above 95%, indicating complete drying of the river outlet (Tables S1 and S2).

Changes in climate, land use and water demand

Temperature and PET increased significantly since the 1950s (Fig. 4, Table 1). Temperature increase was pronouncedly higher after the 1970's, when rose about 1.98°C up to 2020, with a clear upward tendency. Precipitation indicated a negative significant trend (Table 1), evident in the five-year moving average (Fig. 4b), which decreased after the mid-90s by an average rate of 10 mm/month. Extreme events accounted for the existence of some outliers above the 90-th percentile in each 5-year period, though these were less frequent and with lower magnitudes in the last five-year period (Fig. 4d). AET has a non-significant trend (Fig. 4f).

The runoff coefficient R/P exhibited a decreasing trend over the study period, reaching its minimum between 2005 and 2015 (Fig. 5a). During humid periods, larger runoff coefficients were observed (Fig. 5b). However, it is important to note that some variability can be expected between R/P and P (e.g., 1986-1990). While runoff gen-

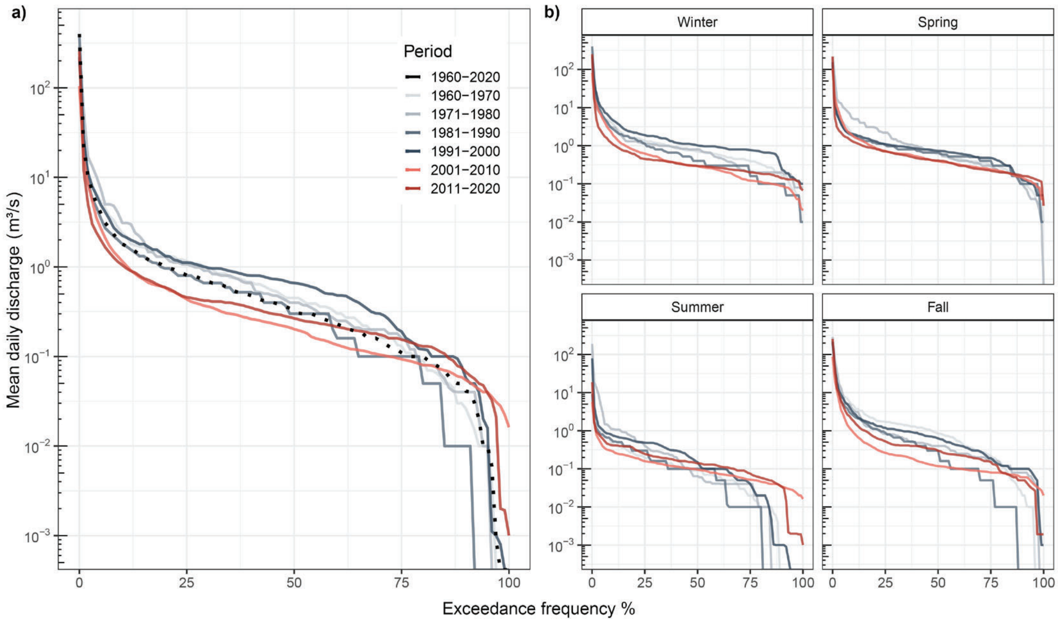

Figure 3. Flow Duration Curves (FDC) for the whole year a), and seasons b) for the Onyar River in Girona by decades (1960-2020). *Curvas de Caudales Clasificados (CCC) para todo el año a), y para cada estación b) en el Río Onyar en Girona por décadas (1960-2020).*

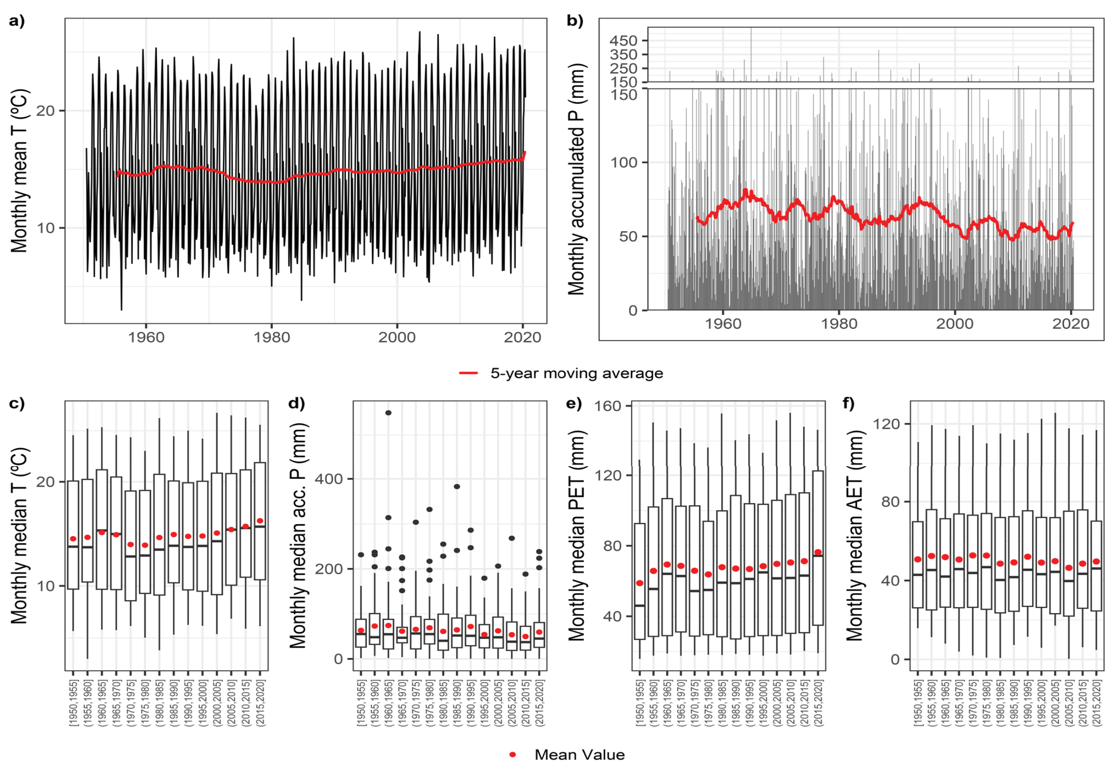

Figure 4. Temporal trends of climatic variables in the Onyar River Basin. *Tendencias temporales de las variables climáticas en la cuenca del Río Onyar.*

eration is influenced by the overall hydrological state of the basin, a central element of this dynamic is the constant interaction between surface water and groundwater. Groundwater exploitation can significantly alter this relationship, affecting baseflow and the runoff coefficient. High discharge events are commonly linked to single or multiple heavy rainfall occurrences, while low flows tend to prevail during the rest of the year, especially in the summer months, masking the average response of the basin represented by the runoff coefficient.

Although the overall decreasing trend of R/P from 1960 to 2020 is not statistically significant (Table 1, Fig. 5b), the most significant changes have occurred in the last two decades. The decreasing rate of R/P with diminishing P in recent years suggests that, under an extreme scenario, stream discharge would become negligible for annual rainfall values around 300-400 mm (Fig.5b). With the decreasing trend in the runoff coefficient (R/P), there is a concurrent increase in the proportion of precipitation that is converted to actual evapotranspiration (AET/P). This shift indicates a changing pattern in how precipitation is distributed within the hydrological cycle, with a larger fraction being lost to evapotranspiration. Additionally, this change might be accompanied by a potential decline in the groundwater recharge rate (GW/P) (Table 1, Fig.5c). Proportions of each ratio using the mean monthly values of each variable are $R/P = 0.19 \pm 0.16\sigma$, $AET/P = 0.83 \pm 0.16\sigma$, and $GW/P = 0.04 \pm 0.03\sigma$.

Changes in LULC have been extensive in the basin since 1987 (Table 2). The forested area has shown a consistent and steady increase, except for a momentary decrease observed in 2012. Additionally, both the area of irrigated crops and urbanized areas have experienced growth over time. However, in the case of crops, there seems to be a decreasing trend since 2007, while urbanized areas have stabilized since then. Non-irrigated crops, on the other hand, witnessed a decline between 1987 and 2007, followed by an increase thereafter. Scrublands and meadows have exhibited a decreasing pattern.

The most important LULC changes between 1987 and 2017 were afforestation, changes in agricultural practices (increase in irrigated crops), and the increase in urban and industrial areas (Fig.6). Afforestation (15%) and scrubland areas increase (6%), is the major change (Fig.S1, Table S3 (supplementary information, available at https://www.limnetica.net/en/limnetica), affecting the basin headwaters (especially the Gavarres massif, Fig. 1). Agricultural land has evolved from rainfed crops into forests or scrubland or become urbanized (3%). A fraction of crops changed from irrigated to rainfed (4%), though the major changes has taken the reverse path, transformed into irrigated crops (7%). Transformation to irrigation has occurred mostly in the alluvial areas along the main course of the Onyar River and tributaries. Finally, a 6% of the land has change to urban and industrial areas, mostly affecting the middle and lower zones of the basin.

The annual water demand for human uses in the basin has increased from 17.58 hm^3 in 1980 to 20.71 hm^3 in 2020.The increase corresponds to agricultural uses, being an 89% of the total use in

Table 2. Area of the main land use and land cover changes (in ha) in the Onyar basin, in different periods. *Área de los principales cambios en el uso y cobertura del suelo (en ha) en la cuenca del Río Onyar, para diferentes periodos.*

	1987	1992	1997	2002	2007	2012	2017
Forest	9887	10 256	11 126	11 382	11 826	10 361	12 599
Irrigated crops	2508	1627	2586	2642	4427	3483	3003
Non-irrigated crops	11 523	12 781	10 840	10 198	7197	8735	9118
Scrublands and meadows	4822	3965	3583	3628	3893	4875	2728
Urbanized zones	1134	1394	1758	1921	2619	2614	2526

[a] Data available at https://agricultura.gencat.cat/ca/detalls/Article/Usos-i-cobertes-del-sol-de-Catalunya (ICGC and Grumets CREAF-UAB, 2020)

2020, yet this percentage has been quite steady over time (Table 3). Irrigation and livestock demand is mainly from groundwater resources, while urban supply complements groundwater extractions water from the Ter River transfer since the late 1990s. As result of groundwater exploitation, the water table decreases during the irrigation season (Fig. S2, supplementary information, available at https://www.limnetica.net/en/limnetica; (ACA, 2022b) and the river channel

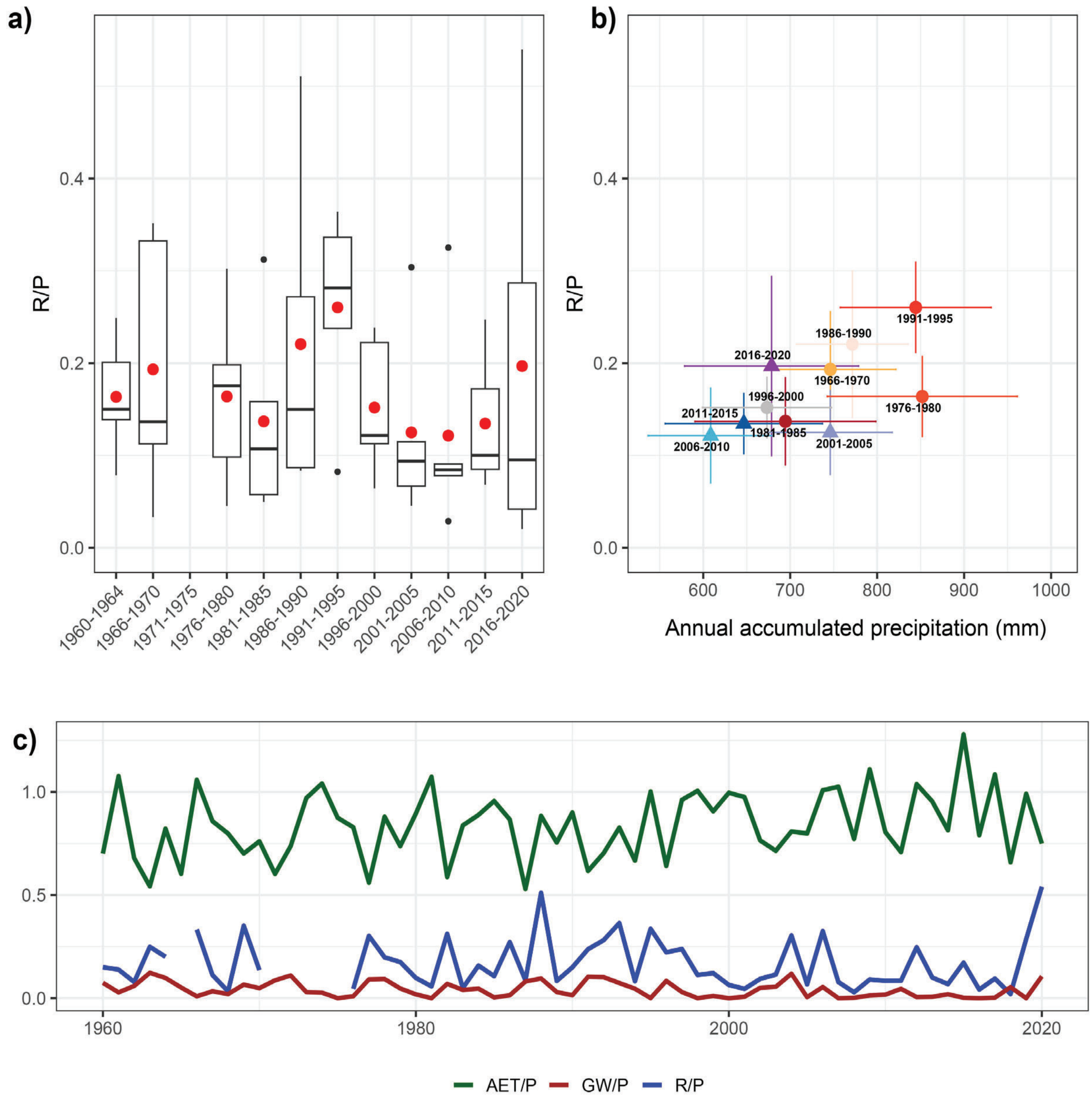

Figure 5. a) Box plots of the annual runoff coefficient R/P for each 5-year period, and b) R/P vs precipitation (P). In b), circles represent periods before 2000, and triangles periods after 2000. Error bars correspond to the standard error. c) Evolution of the different ratios among the water balance major components: R/P, AET/P and GW/P, estimated using the mean annual values of each variable.
a) Diagramas de caja del coeficiente anual de escorrentía (R/P) para cada período de 5 años, y b) R/P frente a la precipitación (P). En b), los círculos representan períodos anteriores al año 2000, y los triángulos períodos posteriores al 2000. Las barras de error corresponden al error estándar. c) Evolución de las diferentes relaciones entre los principales componentes del balance hídrico: R/P, AET/P y GW/P, estimadas utilizando los valores medios anuales de cada variable.

turns to be a losing stream, mostly in the central part of the basin.

Table 3. Estimation of the annual water consumption for the main uses (in hm3; i.e. 1×106 m3). Urban consumption refers to the amount of local resources, plus the contribution of the Ter River transfer system (in parentheses). *Estimación del consumo anual de agua para los principales usos (en hm3; es decir, 1×106 m^3). El consumo urbano se refiere a la cantidad de recursos locales, más la contribución del sistema de transferencia del Río Ter (entre paréntesis).*

	1980	1990	2000	2010	2020
Urban	1.68	1.82	1.60 (0.36)	2.13 (0.59)	1.74 (1.16)
Irrigation	15.53	10.07	16.18	24.49	18.59
Livestock	0.37	0.40	0.46	0.45	0.38
Total	17.58	12.29	18.24	27.07	20.71

Water quality trends

Nutrients have shown specific seasonal patterns throughout the study period (Fig. 7). Both nitrate and ammonium show an important concentration increase (Table 4). Between seasons, winter nitrate concentrations have progressively increased, even though that change does not correspond to the total flushed nitrate load. Most of the higher values of nitrate (above 20 mg/l) occurred in winter and autumn, while summer values were usually below 10mg/l. Regarding ammonium, seasonal patterns in concentrations were similar to nitrate, being the median values in winter and autumn of 0.4 and 0.5 mg/l, which decreased to 0.1 mg/l in summer. Phosphate concentrations were high, and values above 8 mg/l were recorded in autumn-winter of 2015-2016. However, no notable differences in concentrations among seasons were found and phosphate loads did not show any statistically significant trend (Table 4). TOC concentrations showed a lower temporal dispersion and higher consistency among seasons. Most of the low TOC concentrations occurred in summer, especially before 2015. Scattered high values of TOC concentration were distributed along the sampling period. TOC loads were more dispersed, associated to the variability of flow rates.

DISCUSSION

The Onyar River basin has experienced relevant hydrological changes in recent times, and there is evidence of the unequal alteration of discharge between seasons. These changes are founded on large changes in LULC as well as in climatological changes, with implications on the discharge pattern and water quality of surface waters.

Table 4. Seasonal Mann-Kendall results for the chemistry concentrations and loads. *Resultados del análisis estacional de Mann-Kendall para las concentraciones y descargas de nutrientes.*

		Z-trend	*p*-value[a]	Tau	Sen's slope	Intercept
Concentration (mg/l)	NH_4^+	5.16	<0.01	0.27	0.04	-95.23
	NO_3^-	3.62	<0.01	0.19	0.40	-784.93
	PO_4^{3-}	-1.37	0.17	-0.08	-0.08	204.73
	TOC	0.87	0.39	0.05	0.02	6.30
Load (kg/day)	NH_4^+	*5.27*	*<0.01*	*0.28*	*1.11*	*-2205.76*
	NO_3^-	*2.07*	*0.04*	*0.11*	*7.27*	*-20482.61*
	PO_4^{3-}	0.37	0.71	0.02	0.92	-593.48
	TOC	1.53	0.13	0.08	2.75	-7685.71

[a] Statistically significant results (*p*<0.05) are highlight in italics. *Los resultados estadísticamente significativos (*p*<0.05) se resaltan en itálica.*

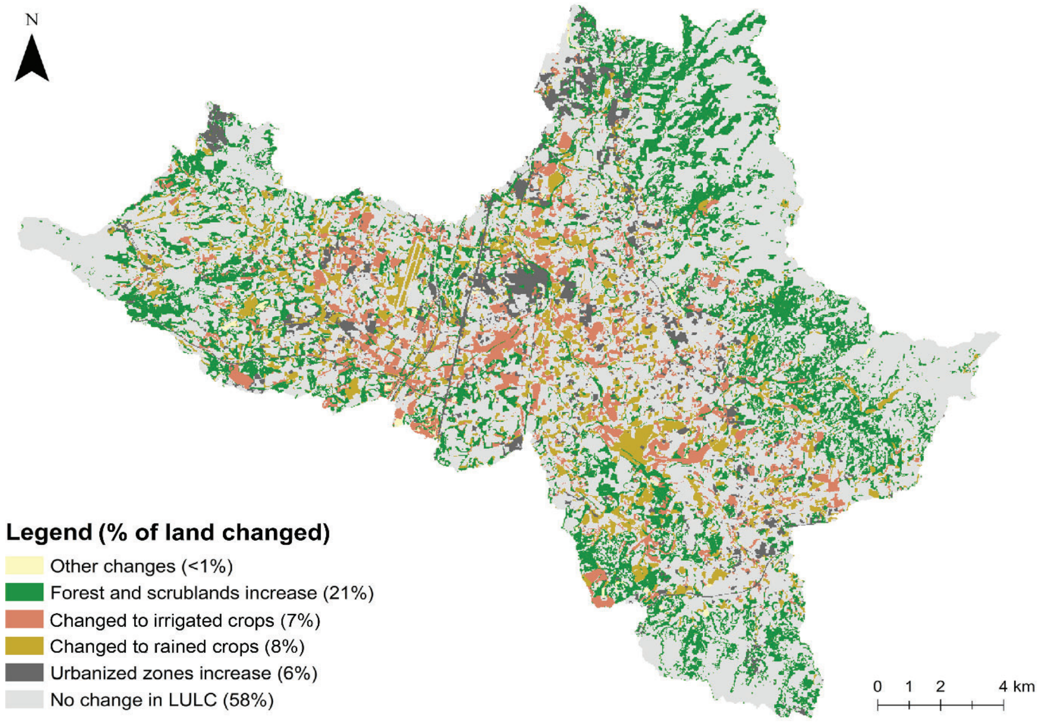

Figure 6. Changes in land use and land cover in the Onyar River basin between 1987 and 2017. Land use data from ICGC (2022). *Cambios en los usos del suelo y la cobertura terrestre en la cuenca del Río Onyar entre 1987 y 2017. Datos de uso del suelo del ICGC (2022).*

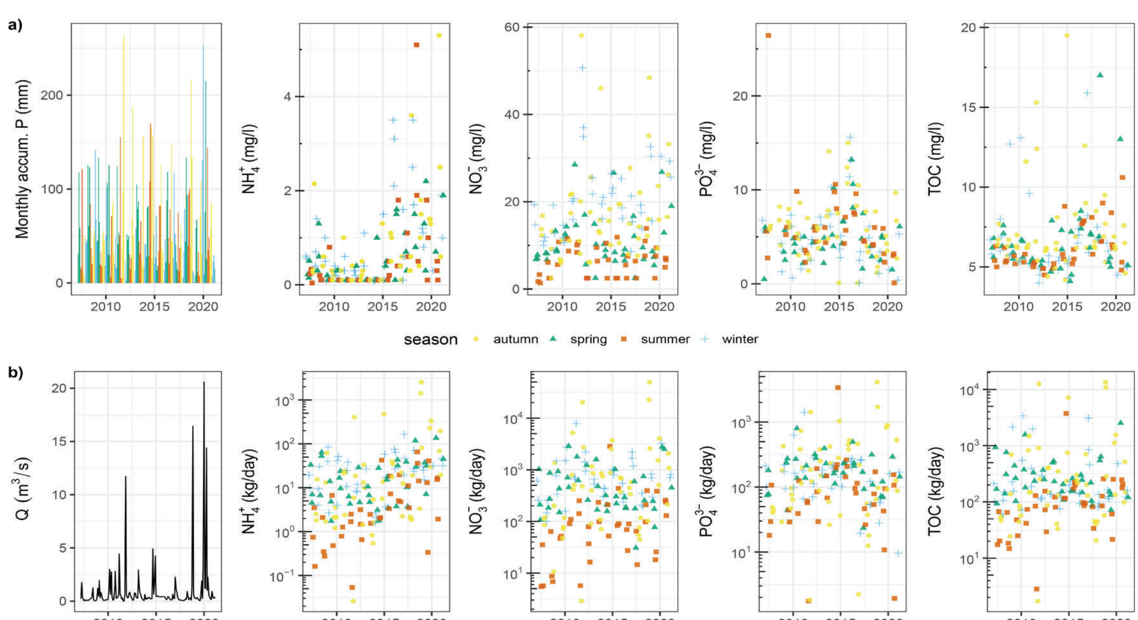

Figure 7. Concentrations (a) and loads (b) of NH_4^+, NO_3^-, PO_4^{3-}, and TOC at the Onyar basin gauging station in Girona from 2007 to 2020. *Concentraciones (a) y descargas (b) de NH_4^+, NO_3^-, PO_4^{3-}, y de TOC en la estación de aforo de Girona desde 2007 hasta 2020.*

Long-term and seasonal changes in streamflow

We observed an increment in the low flow frequency and a general decrease of the high and medium flows in the Onyar, which are consistent with others observed in the Mediterranean region (García-Ruiz et al., 2011; Lorenzo-Lacruz et al., 2012). Despite the differences in basin sizes, the decrease in mean daily flow observed over the past 60 years in the Onyar River largely corresponds with the widely documented decline in streamflow of various Iberian rivers (e.g. the Duero tributaries (Morán-Tejeda et al., 2010), the Tagus (Mezger et al., 2022), and the Ebro (Gallart et al., 2011), etc) This trend is consistent with changes observed in other basins throughout southern Europe (e.g. Croatia (Lutz et al., 2016), France (Folton et al., 2019), Italy (Darvini & Memmola, 2020), and across the entire Mediterranean basin (Masseroni et al., 2021)). Runoff coefficient in the Onyar has decreased by nearly half from 1961-1965 to 2011-2015, reaching values down to 0.13. These low runoff coefficients ($R/P \leq 0.2$) tend to occur under aridity conditions, or in basins located under extreme climatic conditions (Romero et al. 2021). In this study case, human stressors, as stream discharge capture by groundwater withdrawal, must also be considered to explain such a low R/P ratio.

Along with the observed reduction in discharge, water flow variability has also decreased in the Onyar River (Fig. 2b). Rainfall events are presently concentrated in a shorter number of days (Alpert et al., 2002), with the heavy rainfall in January 2020, associated with the Gloria storm, and the widespread floods in October 2018 being notable examples. This increase in rainfall intensity has been reported across the entire Mediterranean basin (García-Ruiz et al., 2011). All these extreme events contribute to the increase in outliers and may account for the apparent momentary recover of the basin's runoff coefficient observed over the past five years (Fig. 5).

While it is not easy to differentiate gradual from abrupt hydrological changes, the analysis of patterns may help to attribute causes and shape management actions (Rougé et al., 2013). We identified a change point around the year 2000, consistent with the observed decrease in the runoff coefficient, which emphasizes that streamflow reduction has been especially acute in the last twenty years. Other basins in the Iberian Peninsula have also experienced change-points in water runoff although timing can vary. For example, The Tagus River had a shift between 1979 and 1982 (Mezger et al., 2022), and runoff in the Noguera Pallaresa (Ebro basin) declined in the 1980s (Buendia et al., 2016). This shows that hydrological shifts are idiosyncratic, likely related to the specific hydrological events occurring in each basin, which in the Onyar River may be attributed to climate change and afforestation.

Of particular interest, due to the Mediterranean character of our study basin, is that shifts in streamflow distribution are season-dependant. Autumn, winter, and summer experienced a larger decrease in medium and high flows, while spring discharge has not substantially varied through the last 60 years. This is related to the baseflow contribution when the water table in the alluvial aquifer is high. While summer flows are low or nearly absent in many Mediterranean river systems (García-Ruiz et al., 2011), this has not been the case in the Onyar River during the last decades (Fig.3). The Onyar is therefore performing as a regulated river (which receive water from reservoirs; Lorenzo-Lacruz et al., 2012), though it is not having relevant dams or weirs. We contend that wastewater inputs may exert a main control on the observed quasi-permanent low discharge all over the summer season as indicated by Menció et al. (2014). In fact, the five wastewater treatment plants (WWTP) currently operating in the basin (Fig.1) were commissioned between 1993 and 2013. Occasionally, summer storms of convective origin are of common occurrence, and may turn into some abnormal increases of summer discharge, consisting of flash floods from mid-August to early September.

Still, the streamflow regime at the basin outlet does not reflect the hydrological conditions in the middle or upper reaches of the basin. Middle reaches usually get dry during summer, performing as losing reaches, because of the intense exploitation of the alluvial aquifer (Menció et al., 2014). The WWTPs inputs infiltrate after few hundred meters from the input location during the summer months, contributing to the hydrological discontinuity of the river (Menció et al., 2014). Regardless the gauging station at the Onyar River is an integrated portrayal of the hydrological regime of the whole river network, the patterns of many tributaries remain unnoticed. This suggests the need of appropriate scales of study to cope with the whole hydrological idiosyncrasy of the basin, as some drivers act locally producing effects only noticed at specific locations.

Consistency of changes in the hydrological regime with drivers' trends

Even though we cannot unequivocally attribute the detected streamflow trends to the changes observed in the main analysed drivers, the relationships between physical and anthropogenic drivers and their effects on the streamflow can be outlined. In this sense, both the change of scrublands and pastures to forested areas (Table 2, Fig. 6), and the groundwater demands have steadily intensified in the last 60 years. Groundwater exploitation, particularly between 1990 and 2010, is related to intensive agricultural practices, especially summer crops irrigation, and livestock production all year long. These changes in land use support the shift in the ratio between stream discharge and groundwater recharge with precipitation (i.e., R/P and GW/P).

Climate change also plays a significant role in the basin's hydrology. Precipitation showed a negative trend, which contributes to the flow decrease and the R/P decline from 1960 to 2020. Additionally, air temperature increased by 1.8°C (Fig. 4), which combined with the increase in forest cover accounts for increased evapotranspiration (Fig. 5).

Afforestation has gradually expanded in the basin, especially in the headwaters. Increases in forest cover have also been observed in mountain and hilly areas all around the north of the Mediterranean region, particularly during the second half of the 20th century. Land abandonment and reduced traditional forest activities and subsistence agriculture have occurred during this period (Lasanta-Martínez et al., 2005; Teuling et al., 2019). A large forest cover increases not only evapotranspiration, but rainfall interception rates and affects soil-water storage (Peña-Angulo et al., 2021), reducing the proportion of runoff. In fact, afforestation is reported as a main cause for the decrease of discharge and hydrological stress intensification in non-disturbed headwater catchments in the Iberian Peninsula (Beguería et al., 2003; Gallart et al., 2011; García-Ruiz et al., 2011; Lorenzo-Lacruz et al., 2012; Peña-Angulo et al., 2021; Salmoral et al., 2015), and so can be stated as an intensification factor of the climatic effects previously mentioned.

The demand for water resources in the basin has experienced significant growth. Like other Mediterranean basins, there has been an increase in irrigation and urban land use in the lowland areas (García-Ruíz et al., 2011). By the 2000s, we identified a sharp rise in livestock production and a high-water demand, particularly for summer crops like corn, which coincided with changes in streamflow. However, water requirements for livestock have stabilized or slightly decreased in the last decade. The exploitation of groundwater resources in the basin has reached a concerning level. The current exploitation index (ratio of abstractions to resources) is about 0.89 in an average year and 1.1 in a dry year (ACA, 2022c). Although groundwater recharge from surrounding mountain ranges compensates the annual water deficit caused by the groundwater exploitation (Menció et al., 2010), our estimates suggest that the demands on groundwater resources are likely to be unsustainable in the mid to long term.

Changes in the hydrological regime and chemistry trends

Increasing trends in NH_4^+ and NO_3^- loads and concentrations in the Onyar River mostly occurred in winter when the stream water chemical quality is the most detrimental. Conversely, the lowest loads of PO_4^{3-}, NH_4^+ and NO_3^- were recorded in summer. Similar shifts in long-term trends regarding nutrient concentrations have been reported in European rivers (Vigiak et al., 2023). For example, we observed that PO_4^{-3} concentration shows a slight decreasing trend, possibly related to the wastewater treatments focused on PO_4^{-3} reduction (Aguilera et al., 2015). Moreover,

NO_3^- and NH_4^+ showed increasing trends, likely because of the increase in the use of N fertilizers and the expanded number of irrigated lands, crop productivity, and livestock production (Einarsson et al., 2021; Lassaletta et al., 2021).

Nutrient patterns seem to be largely explained by the interaction between several components of the hydrologic cycle. On the one hand, higher values of ammonium (Fig. 7) could be attributed to the contribution of urban wastewater treatment plants or food-processing industries, while the increase of nitrate in autumn and winter is likely associated with high water table levels in the alluvial aquifer, indicating a nitrate contribution from groundwater wherever the Onyar performs as a gaining stream. Mean nitrate concentrations of 114 and 116 mg/l in the alluvial aquifer have been reported (Menció et al., 2012; Menció and Boix, 2018). Therefore, the seasonal patterns of NO_3^- and NH_4^+ can be related both to the complex river-aquifer relationship and to the differences in the intra-annual N exports in rainfed and irrigated crops (Lassaletta et al., 2012). High concentrations of N-compounds during autumn, winter and, perhaps, early spring coincide when plant nitrogen uptake is lower and groundwater baseflow contribution to stream flow is higher. Finally, the low phosphate concentrations observed in the alluvial aquifer, typically below 0.04 mg/l (Menció & Boix 2018), are one-tenth of the values found in surface waters. Such a significant difference suggest that phosphorus inputs mainly originate from other local sources (i.e., industrial activity and WWTP) and could be associated with flood events and sediment transport (Aguilera et al., 2015).

Implications and future directions

Our research highlights that the hydrological resilience of the Onyar River Basin is compromised regarding the current and prospected future uses. Although water demand for irrigation and livestock has apparently decreased in the last few years, the projected availability of water resources indicates that water scarcity will persist and likely increase (ACA, 2022c). Precipitation predictions suggest a decrease by 2050, while temperature and evapotranspiration will continue to rise (MedECC, 2020).

Water quality (particularly nitrates) remains threatened due to human activities that act as stressors of the basin hydrological regime. Inputs from WWTPs and groundwater flow seasonal recharge of streams are the origin of the occurrence of these nutrients, pointing out that a recurring increase in discharge correspond to a loss of stream water quality.

The Onyar River mirrors the processes occurring in other Mediterranean basins elsewhere. Ascertaining the cause-effects relationships for management purposes requires understanding critical aspects such as 1) the existence of stream reaches deprived of baseflow contribution due to groundwater exploitation, 2) WWTP inputs that locally add water to the streambed, yet with a low water quality, and 3) the consideration of the positive contribution of large regional hydrogeological systems. These aspects should determine which long-term strategies can be adopted to overcome present water scarcity, chemical degradation, and its expected impairment. Nevertheless, considering the sparsity of monitoring points within the basin that fails to provide local information of each of the hydrological impacts, a future basin instrumentation and models that reproduce the stream water regime in detail across the whole catchment will largely improve our management capability and the success on adapting to future hydrological scenarios.

CONCLUSIONS

Our study on the Onyar River basin has revealed significant hydrological changes over recent years, showing the complex interplay of natural and anthropogenic factors impacting both water quantity and quality. Based on our key findings, we conclude:

- The Onyar River has experienced a marked decrease in high and medium flows, along with an increase in low flow frequency. This pattern, which aligns with broader trends in the Mediterranean region, has been particularly evident in the last two decades. Concurrently, the runoff coefficient has decreased, indicative of these hydrological alterations.

- Seasonal shifts in streamflow have been observed in the basin, with autumn, winter and summer experiencing notable decreases in flow. These changes are linked to reduced precipitation and increased evaporation, as well as to human activities, including intensified irrigated agriculture and groundwater exploitation.

- Trends in water chemistry, particularly regarding nutrient loads, indicate a deterioration in water quality, especially during winter. The interplay between different components of the hydrological cycle, such as WWTP inputs and groundwater contributions, are key to understanding these trends.

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