A multivariate-driven approach disentangling the reduction of near-natural Iberian water resource post-1980

Amar Halifa-Marín[1], Miguel A. Torres-Vázquez[1], Enrique Pravia-Sarabia[1], Marc Lemus-Canovas[2], Pedro Jiménez-Guerrero[1], Juan Pedro Montávez[1]

[1] Regional Atmospheric Modelling (MAR) Group, Regional Campus of International Excellence Campus Mare Nostrum (CEIR), University of Murcia, 30100 Murcia, Spain.
[2] Andorra Research + Innovation, Rocafort 21-23, AD600, Sant Julià De Lòria, Andorra

Correspondence to: Pedro Jiménez-Guerrero (pedro.jimenezguerrero@um.es)

Abstract

Whereas the literature still debates how several human/natural factors contributed to the recent streamflow decline in the Iberian Peninsula, a continuing decrease of Winter Precipitation (WP) has been noticed in this area since 1980s related to large-scale atmospheric drivers. This contribution assesses its potential propagation into the water resource variability. For this purpose, the novel dataset of Near Natural Water Inflows to Reservoirs of Spain (NENWIRES) was created. The results highlight that those higher decreases of Winter Water Inflows (WWI) are always found related to WP reductions. Whereas WP declining was strongly provoked by the enhancement of NAOi during the study period, the WWI reductions could not be essentially linked to its behaviour in several NENWIRES catchments. Instead, the intensification of drought conditions and forest extension promoted WWI reductions over the target area. In fact, these mechanisms allowed to understand why WWI reductions were generally higher than WP weakening. Summarizing, most humid catchments registered a WWI decline mainly promoted by the NAOi enhancement, while the extension of forest and evapotranspiration rises seem to explain the WWI losses in the semiarid environments. This contribution sheds light on the recent debate about magnitude/drivers of water resource decline over southern European regions.

1 Introduction

The Mediterranean region shows the strongest pattern of significant water resource decline worldwide, whereas water planning in this area thus faces the challenge of securing the sustainability of natural and human systems. For some authors, this streamflow declining mostly is consequence of climate change (Gudmundsson et al., 2021), given the strong temperature rise and precipitation reductions. While Vicente-Serrano et al. (2019) concluded that climate trends cannot fully explain the large reductions of streamflow in southwest Europe, where land use changes and water demand from irrigation playing an important additional role. So, a best improvement of the knowledge about the variability of water resources and the contribution of their drivers is strongly necessary, given that freshwater scarcity poses one of the most incipient risks in the region (Tramblay et al., 2020). Therefore, current studies need to shed light on the water resource records/modelling based on multivariate approaches (Teuling et al., 2019, Massei et al., 2020).

Focusing on the Iberian Peninsula (IP), the scientific literature generally reports a streamflow decline over the last decades (Lorenzo-Lacruz et al., 2012 and references therein). Nevertheless, the role of physical/anthropogenic factors driving these reductions are still under debate. On the one hand, the decrease of recent Winter Precipitation (WP) has been robustly reported (e.g. de Luis et al., 2010; Lorenzo-Lacruz et al., 2013). That decrease was reasonably associated to the variability of the North Atlantic Oscillation index (NAOi) (e.g. Trigo et al., 2004). Nonetheless, Guerreiro et al. (2014) also pointed out abrupt WP decreases within the Tagus Basin since the late(early) 1970s(1980s). Other works also quantified the same drastic reduction of WP in the adjoining watersheds, Jucar and Guadalquivir (Gómez-Martínez et al., 2018, Halifa-Marín et al., 2021). All these authors discussed 1) whether WP losses have shown a continuing or an abrupt decline, and 3) the relationship of WP reduction with the NAOi enhancement noticed during the last decades (e.g. Luo & Gong, 2006, Wang et al., 2014). The lack of knowledge within this topic does not only concern the IP region. An strong increase of streamflow was also reported in central/northern Europe at annual/wintertime scales during the same period (Stahl et al., 2010, Hannaford et al., 2013, Vicente-Serrano et al., 2019). However, while those authors generally accepted the potential links between NAOi and the changes in wintertime streamflow over Europe, they highlighted the importance of carrying out long record analyses in southern Europe, where data are sparse.

They suggested that more long-term series are needed to determine whether recent tendencies towards a decreased runoff in that region are found in longer records and whether this fact is related to the atmospheric circulation. Despite the scarcity of long-term hydrological records, in this line, Peña-Angulo et al. (2020) recently concluded no clear trend in precipitation records of the Iberian Peninsula since 1850, given that they quantified quite similar negative trends in several periods. This finding suggests that the actual declining of water resource could have precedents, despite similar NAO enhancement has not been noticed (i.e., in the same magnitude for second half of 20th Century).

On the other hand, several contributions. have concluded that the streamflow decline was exacerbated by the temperature/evapotranspiration rise in the IP (e.g. Vicente-Serrano et al., 2014). Similar conclusions were obtained for the Mediterranean basin (García-Ruiz et al., 2011) and Europe (Teuling et al., 2019). All these works highlighted the role of a warmer climate and reforestation/afforestation processes into the evapotranspiration rise since potential evapotranspiration (ETP) also increases in response to global warming. Peña-Angulo et al. (2021) reported that the human-induced land greening-up processes through the 20th century contributed to the Iberian water resource decline (intensifying the hydrological droughts). In this line, according to Vicente-Serrano et al. (2019), human-induced land cover changes (e.g. afforestation/irrigation) mainly explain the streamflow decline in the IP. Also, the role of other impacts was assessed (e.g. the construction of dams, Lorenzo-Lacruz et al., 2012) as well as the time-lag in the hydrological response caused by the permeability of soils (Lorenzo-Lacruz et al., 2013).

This state-of-art draws noticeable divergences regarding the importance of anthropogenic/physical drivers modulating the Iberian water resource, which inspire a strong need for further scientific knowledge to ensure efficient water management over this target region. Also, uncertainties persist about how the wintertime NAOi variability has conducted the Iberian water resource changes. At the same time as it appears likely that NAOi variability may cause strong decrease of WP in particular periods, several authors have concluded that human perturbations determined the recent streamflow variability instead of climate drivers. In addition, to the extent water planning is concerned here, the occurrence of short term decreases in the water resource might severely affect the sustainability of natural/human systems (more than gradual changes). Likewise, the assessment of water resources needs to focus on near-natural catchments (e.g. Stahl et al., 2010, Hannaford et al., 2013, Vicente-Serrano et al., 2014), in order to reduce the uncertainties added by human-induced perturbations. Because the water resource depends on several factors with opposing effects, changes in the hydrological response should be analyzed at small scales where individual factors can be understood (e.g. Teuling et al., 2019). This approach allows to fully assess the hydrological response to global change forcings and pressures, such as potential changes in atmospheric circulation patterns and/or human perturbations. In addition, the Iberian basins are controlled by quite different climate conditions, which helps to assess these perturbations to a wide variety of hydroclimate areas. Therefore, this contribution aims to 1) characterise recent changes of water resources in near-natural catchments of Spain and 2) disentangle how climate/human drivers have contributed to the magnitude of these changes.

The following list of tasks has been addressed to achieve both objectives: 1) quantify the short term variability and changes of Wintertime Water Inflows (WWI) in selected reservoirs; 2) analyse whether the NAOi plays a leading role in the changes of WWI; 3) address the contribution of meteorological drought conditions to WWI changes; 4) as well as the contribution of forest extension; and 5) provide an identification of the main precursor for WWI variability in the study period. For that, the initial working hypothesis is that the winter climate essentially controls the variability and short-term trends of water resource, while the impact of human perturbations is weaker in this season. However, despite the vegetation is mostly active in the warm season, we expect that it can impact on the water store (e.g. soil moisture conditions and groundwaters) precedent of winter season, which can reduce the run-off and infiltration magnitudes in the ‘wet season’.

2 Data and Methods

2.1 Data Sources

2.1.1 Spanish Near-Natural Water Inflows to Reservoirs

In this study monthly water inflows recharging the Spanish reservoirs network (376 series) have been examined from October 1951 to September 2018, whose series are provided by the state institution responsible for water resource issues (CEDEX, 2021). See Supplementary Material for further information about the water inflow estimation. 36 series (9.6%) were selected, composing the NEar-Natural Water Inflows to REservoirs of Spain (NENWIRES) dataset (See Table SM1 for more details about the reservoirs selected). To identify these 'near-natural' reservoirs were verified that 1) water inflows are not affected by large perturbations, excluding those series impacted by water regulation (e.g. damming) and urban/irrigation extractions; 2) long-term series are prioritized, and water inflows records must cover at least 46 years (70%) through the study period; 3) series must provide continuously records for at least 33 years (50%); and 4) records must not be reconstructed, and homogeneous quality controls have been applied to series. The compiled data thus provides near-natural water inflows records spanning reservoirs in the continental Spain (Fig. 1). In addition, the NENWIRES basins also mention the headwaters of the transboundary basins (Douro, Tagus, Guadiana), so the findings properly considered the variability of water resource in most of IP. Finally, the dimension of NENWIRES catchments is generally small with an average area of 929 km^2, whose boundaries were provided by the IDE (2021). The study of water inflows in near-natural reservoirs, rather than streamflow analysis, draws a more complete picture of the hydrological response in basins. So, water inflows mention the balance between all inputs to the reservoir (i.e. surface and groundwater flows), which includes water losses in the basin, and outputs (e.g. evaporation from the water store). Furthermore, the study focuses on Wintertime Water Inflows (WWI), regarding the records from December to March. This 'extended season' allows to study the contribution of snowfalls (i.e. the early snowmelt). The relevance of wintertime changes of precipitation and water resource resides in 1) it is the wet/recharge season of most reservoirs/aquifers in the IP (Lorenzo-Lacruz et al., 2012), 2) WP shows the strongest significant decline in the region (De Luis et al., 2010); and 3) the 'recent' NAOi enhancement has been reported on wintertime. Whereas WWI generally explains more than 50% of annual records in NENWIRES catchments (See Supplementary Material, Fig. SM1), some series (R3, 9, 20, 21, 25, 33 and 36; the 19%) registered the peak of the hydrograph in spring/autumn (i.e. might be promoted by Mediterranean heavy rainfalls) or late spring and early summer (i.e. would drive by snow accumulation/melt processes). However, those hypotheses are not addressed in this contribution. Likewise, examining the role of the potential ETP/ETR rise at wintertime scale, we merge different mechanisms that are playing a very different role on different seasons. In other words, the vegetation activity is weaker on winter, as well as the temperature is lower. Therefore, these mechanisms could be more relevant for the annual water resource occurring in the warm seasons. Nonetheless, the potential contribution of revegetation to the hydrological response also concerns the WWI variability, given their implications for infiltration and run-off processes. So, we assume that WWI is affected by the intensification of hydrological droughts as a result of water consumption in the scenario of the extension of vegetation cover and warming.

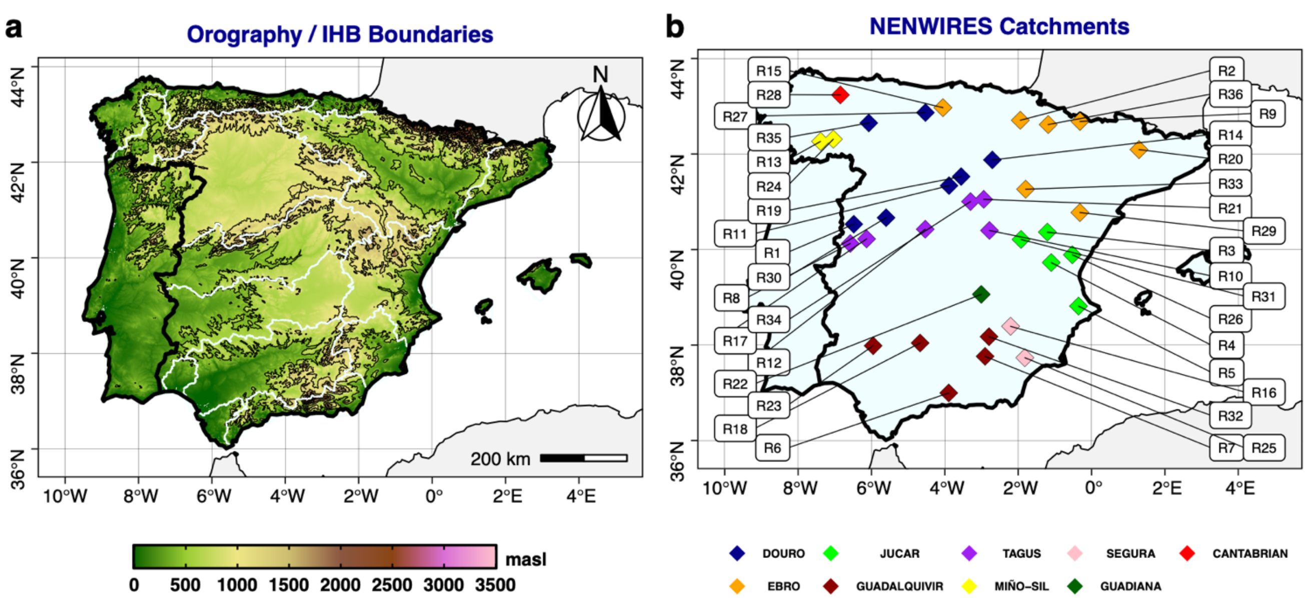

Figure 1. Panels show (a) the orography in the Iberian Peninsula (IP), and (b) the NENWIRES reservoirs grouped by Iberian Hydrological Basins (IHB). In the left panel, light blue contours represent the IHB boundaries in the continental Spain, and black contours mention the altitude above sea level (each 500 meters).

2.1.2 Climate Data

The Spanish Precipitation Gridded Dataset provided by the Spanish Meteorological Agency (AEMET, 2021). This dataset currently covers the period from January 1951 to December 2020 at daily scale, covering the Spanish territory except the Canary Islands. The number of records managed (3,236 rain gauges), and its spatial resolution (~0.05º), motivates the usage of this dataset. They also provide the Temperature Gridded Dataset of Spain, whose interpolation manages 1,800 gauges, providing the daily maximum and minimum temperature. On the other hand, the monthly NAO index (NAOi) was collected from the National Oceanic and Atmospheric Administration (NOAA), which covers the period from January 1950 to nearly real-time (NOAA, 2021). This index is a simplification of a large-scale atmospheric circulation pattern over the North Atlantic, which usefully helps to understand the principal moisture sources reaching the IP (e.g. Trigo et al., 2004). The positive/negative phases of the NAO index are related to lower/higher precipitation in the IP.

2.1.3 Soils Permeability

Hydrological data collected from aquifers is not considered in this contribution. Instead, the interplay between groundwater and WWI is estimated assessing the permeability of soils. The Permeability of Soils Dataset, provided by the Spanish Geological Survey (IGME, 2021), classifies soils into 9 (4) types (groups): 1) A1 and A2 represent alluvial deposits and colluvial soils formed by very permeable porous banks; 2) B1 and B2 represent carbonate bedrock, which are very permeable due to cracking or karstification processes; 3) C1, C2 and C3 represent well-drained volcanic soils, which are not common; and 4) D1 and D2 represent low permeability and impermeable conditions, respectively. This dataset quantifies the percentage of each type of soil in relation to the basin dimension. In this study, these types of soils are classified in 4 groups: A/B1 soils are Very-High Permeable Soils (VHPS); A/B2 soils are High Permeable Soils (HPS); D1 soils are Low Permeable Soils (LPS); and D2 soils are No Permeable Soils (NPS).

2.1.4 Land Cover Changes

The HIstoric Land Dynamics Assessment (HILDA, 2021) model reconstruction of historic land cover/use change (Fuchs et al., 2015) has been used. This dataset is based on multiple harmonized and consistent data streams including remote sensing, national inventories, aerial photographs, statistics, old encyclopedias, and historic maps to reconstruct historic land cover. The spatial resolution reaches 1x1 km, whereas the time coverage ranges from 1900 to 2010 in decadal time steps. The reconstruction provides information for six different land cover/use categories: forest, grassland, cropland, settlements/urban, water bodies and other. Only the changes of forest cover in the NENWIRES catchments have been quantified. The gross land changes were studied, computing the sum of all area gains and losses occurring within an area and period.

2.2 Analysis Procedures

Once we have defined the objectives and tasks in the Introduction section, we clarify here the procedures to obtain the results. In order to address task 1, the trend of magnitudes for WWI throughout the study period was obtained. This trend analysis was conducted using the Sen's slope test with *sens.slope* function (Pohlert et al., 2018). To allow a proportional discussion of trend analysis, slope estimates were standardised (ZSS) as follows (Eq. 1):

$$ZSS_{WWI} = \frac{SS_{WWI}}{\bar{X}_{WWI}}, \qquad \text{(Eq. 1)}$$

where standardised Sen's slope (*ZSS*) is the coefficient between Sen's Slope estimate (*SS*) and the mean WWI for study catchments.

Significant trend estimates are considered with p-value > 0.05, which is required in all statistical procedures of the study. Once the *ZSS* magnitudes were quantified, the potential occurrence/propagation of the post-1980s WP sudden change to WWI was assessed (addressing the aim established in task 1). For that purpose, the most probable change in series was identified through the Pettitt's Homogeneity method, according to *pettitt.test* function (Pohlert, 2018). Likewise, its significance was externally evaluated with the non-parametric Mann-Whitney U test through the *wilcox_test* function (Hothorn et al., 2019). First, the breakpoint (BP) was computed for percentile rank series of average WWI/WP in the dataset. The conversion to percentile series was made by the quantile function (R Core Team, 2021). The average WWI/WP was quantified through the *mean* function (R Core Team, 2021). A similar method was applied to both variables at catchment analysis. Then, the Relative Change (RC) of WWI/WP was quantified after the more frequent significant BP registered in the series, 1979/1980. *RC* was calculated as follows (Eq. 2):

$$RC = \frac{\overline{MS_{P2}} - \overline{MS_{P1}}}{\overline{MS_{P1}}}, \tag{Eq. 2}$$

where *RC* is estimated by subtracting the average (horizontal bars) of WWI/WP during the first period (MS_{P1}) to its average during the last period (MS_{P2}), standardising with the early mean (MS_{P1}). The average was quantified with *mean* function (R Core Team, 2021).

In order to address the task 2, the break point (BP) in the NAOi series was checked using the aforementioned methods. In addition, the correlation between WP/WWI and NAOi was also calculated. To this end, the *cor.test* function was used under Pearson's method (R Core Team, 2021). Previously, the series were detrended using the *detrend* function (Borchers, 2019). These correlation coefficients were related to the RC of WWI/WP (estimations based on Eq. 2) through the *lm* function (R Core Team, 2021). This function was used to fit linear models (regression) between variables. The function *lm* will be used afterwards in the analysis presented in Section 3. The correlation between WWI and WP was also quantified.

The abovementioned methods allow to identify those basins where WWI changes could not be fully explained with the NAOi/WP variability. So, the role of several factors was analysed (tasks 3/4). Preliminary, the modulation of WWI by the magnitude of the prevailing drought conditions was evaluated. The magnitude of drought conditions is used as an estimation of soil moisture, which impacts the hydrological response (run-off/infiltration processes) in the watersheds. To this end, the wintertime drought intensity based on the previous 6/12 months (from March) is presented in Section 3. It was required the quantification of the Standardised Precipitation-Evapotranspiration Index (SPEI) (Berguería & Vicente-Serrano, 2017), which needs the estimation of potential evapotranspiration (ETP) using the Hargreaves method. SPEI was computed with the *spei/hargreaves* functions. These estimations allow to assess the changes of ETP in relation to the temperature evolution. Likewise, the most probable BP was also detected for the average SPEI series (through the *pettitt.test* function). Finally, the absolute change of SPEI6/12 post-1980 is also shown (RC of SPEI)

The potential time-lag that soil permeability motivates on the hydrological response (i.e. impacts on WWI) was evaluated. The purpose is evaluating the 'extra' WWI registered during the most humid winters, because of higher infiltration processes (i.e. their implications for recharge of aquifers, groundwater flows) during persistent/heavy rainfall events. This analysis is of particular interest to the limestone environments where the high permeability (e.g. soil porosity) guarantees high infiltration rates. So, the deviation between extreme percentiles of WWI/WP is quantified. The QQ-Deviation test (QQD) was calculated as shown in Eq. 3:

$$QQD = \overline{P_{90}(Z_{WWI})} - \overline{P_{90}(Z_{WP})} \,, \qquad \text{(Eq. 3)}$$

where Quantile-Quantile Deviation (QQD) is the difference between standardised WWI/WP anomalies averaged (horizontal bars) to the points over 90th percentile (Z_{WWI}/Z_{WP}). Higher values of QQD thus show a greater water generation whether persistent/heavy rainfalls events occur (most humid winters), whereas lower (below 0) values show the opposite relationship.

In addition, the change of forest cover was assessed. In the NENWIRES catchments, the forest cover also mentions the agricultural abandonment and the human-induced afforestation of pastures. In HILDA dataset, for our study period (1950-2010, a estimation per decade is available (7 time-steps). We thus computed the average of their interdecadal relative changes (DRC) as indicated in Eq. 4:

$$\overline{RC} = \frac{\sum_{i=1}^{n-1} DRC_i}{n-1} \;;\; DRC_i = \frac{DC_{i+1} - DC_i}{DC_i} \,, \qquad \text{(Eq. 4)}$$

where the decadal cover (DC) represents the forest area in each time-step, and the mean RC ($\overline{RC}$) is estimated by the average of interdecadal changes (DRC). Therefore, this method allows us to evaluate the changes of the forest area along the entire study period (shown in Supplementary Material, Fig. SM7).

All those methods were used to disentangle how climate/human drivers contributed to the magnitude of short-term changes (i.e. the post-1980 strong reduction of WWI), and estimate the principal precursor that promoted WWI changes in target catchments. Basically, a clustering methodology was applied through the K-Means algorithm (*kmeans* function, R Core Team, 2021). Once basins were classified, indicators of studied variables were computed (the average) for each cluster.

3 Results and Discussion

3.1 Recent Evolution of Wintertime Iberian Near-Natural Water Inflows

The mean WWI ranged from 5 to 824 hm^3 in the NENWIRES basins (Fig. 2a). Higher records were observed over the western/central sector (400-800 hm^3), and northern/southern areas (250-400 hm^3). The lower WWI were registered in the eastern/southern coast (< 250 hm^3). Meanwhile, the trends ranged from -1.8 to 0.1%/yr (Fig. 3b). 97% of WWI series have decreased in the study period. WWI only increased in one basin, but not significantly. These WWI reductions were significant in most of the catchments (55%), mainly over central and eastern sectors. Also, significant reductions frequently occurred in the most humid basins. The results thus depict significant reductions in the headwater of the Tagus, Ebro, Douro, Segura, Jucar, and Mino basins (as defined in Fig. 1). These results agree with similar quantifications for the IP basins in the literature (e.g. Lorenzo-Lacruz et al., 2012).

3.2 Sudden or Continuing changes of Winter Water Inflows?

This section intends to shed some light to the question raised by Guerreiro et al. (2014) about whether WP gradually or suddenly changed in the IP since early 1980s. The overall negative trends of WWI could obscure a stronger change post-1980, which has been recently noticed for the WP in the several areas of the IP (Gómez-Martínez et al., 2018, Halifa-Marín et al., 2021). Fig. 4 shows that WWI had a significant BP since 1979 in the NENWIRES dataset. The average of WWI was 175.6 hm^3 until 1979, while it shrinks the 30% since 1980. Gómez-Martínez et al. (2018) also identified a significant BP post-1980 on annual streamflow records in the Jucar headwaters. The results presented here suggest that it was provoked by the strong decrease registered in WWI series since 1979. Likewise, the detection of the most probable BP for WWI was also performed at catchment scale. This analysis shows that WWI shift was detected in 1979 (41%), as well as 1978 (17%) and 1980 (14%).

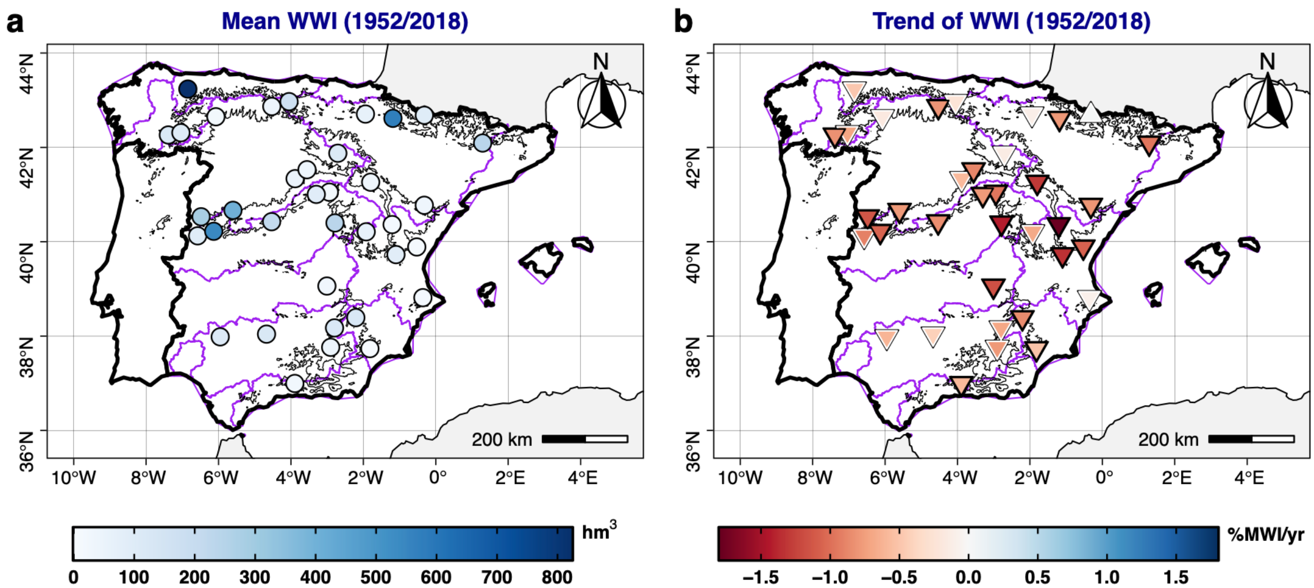

Figure 2. (a) Mean WWI, and (b) its Standardised Sen's slope trend estimates computed after Eq. 1 (Section 2.2). For the trends, symbols represent positive trend (filled triangle/point-up) and negative trend (filled triangle/point-down). In the left panel, significant estimates are indicated with a black outline. Contours of orography (black) and IHB of continental Spain (purple) were also added (see Fig. 1).

3.3 Abrupt changes or trend of Wintertime Water Inflows?

This section intends to shed some light to the question raised by Guerreiro et al. (2014) about whether WP gradually or suddenly changed in the IP since early 1980s. The overall negative trends of WWI could obscure an strong change post-1980 (noticed in the literature). Fig. 3 (bottom) shows that average WWI had a significant BP since 1979 in the NENWIRES dataset. The average of WWI was 175.6 hm^3 until 1979, while it shrinks the 30% since 1980. The detection of the most probable BP for WWI was also performed at catchment scale (Supplementary Material, Fig. SM2a). This analysis shows that WWI shift was detected in 1979 (41%), as well as 1978 (17%) and 1980 (14%). Despite 55% of these detections were significant (Fig. SM2). We found a significant BP in the headwater of Jucar, Tagus, Segura, Guadalquivir, and Douro basins. Gómez-Martínez et al. (2018) also identified a significant BP post-1980 on annual/winter streamflow records in the Jucar headwaters, while Guerreiro et al. (2014) and Halifa-Marín et al. (2021) noticed the BP of WP in the western/southern IP (i.e. Tagus and Guadalquivir basins).

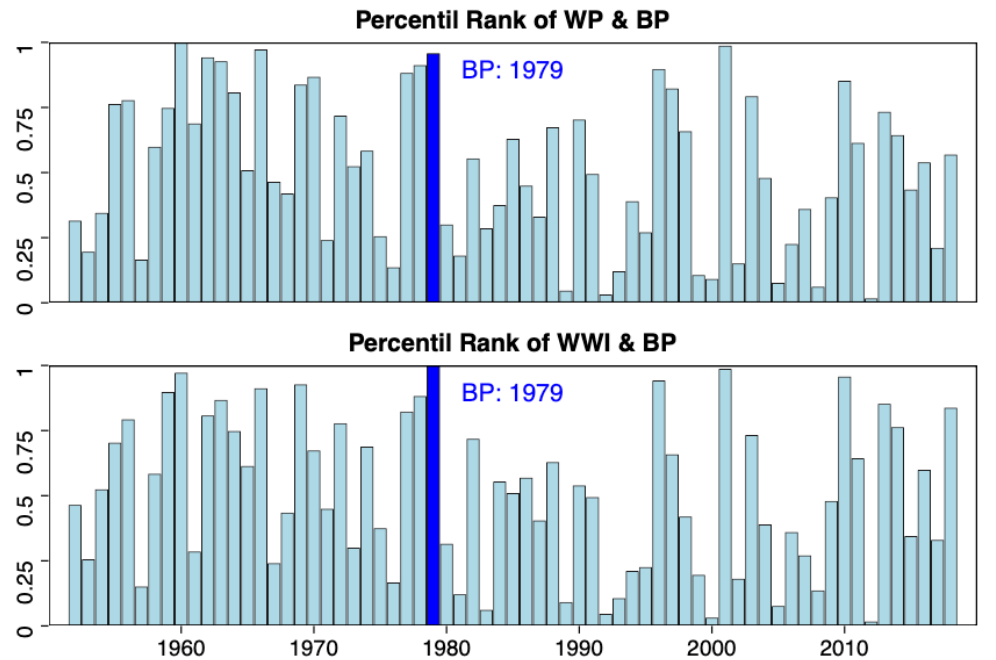

Figure 3. Percentile rank of average Wintertime Precipitation (WP, top) and Wintertime Water Inflows (WWI, bottom) in the NENWIRES dataset, during the period 1952/2018. Bars represent negative (red) and positive (blue) values. Vertical dark blue lines represent the most probable BP detected through the Pettitt's Homogeneity Test (Section 2.2).

3.4 Does Precipitation Control the Change of Wintertime Water Inflows?

A similar BP analysis was conducted for WP records. The BP detected for average WP was found in 1979 (Fig. 3, top), matching the estimation for average WWI. Meanwhile, the average WP decreased by -21% since 1979, a lower reduction than the average WWI change (~30%). Furthermore, a high correlation was found between both average series (0.87). For WP, the analysis at basin scale shows that 75% of precipitation series have a BP in 1979, significant for 58%, generally in the southern/western IP (Fig.

SM2b). But the BP detection differed for eastern/northern IP. These results agree with the conclusions of previous studies (Guerreiro et al., 2014, Gómez-Martínez et al., 2018, Halifa-Marín et al., 2021. In conclusion, it seems very likely that the reduction of precipitation provoked the WWI decrease. However, the average WP decrease was more important than the corresponding decrease of average WWI. After characterising the BP of WWI/WP, the RC was quantified at basin scale for both variables since 1979/1980 (Fig. 4).

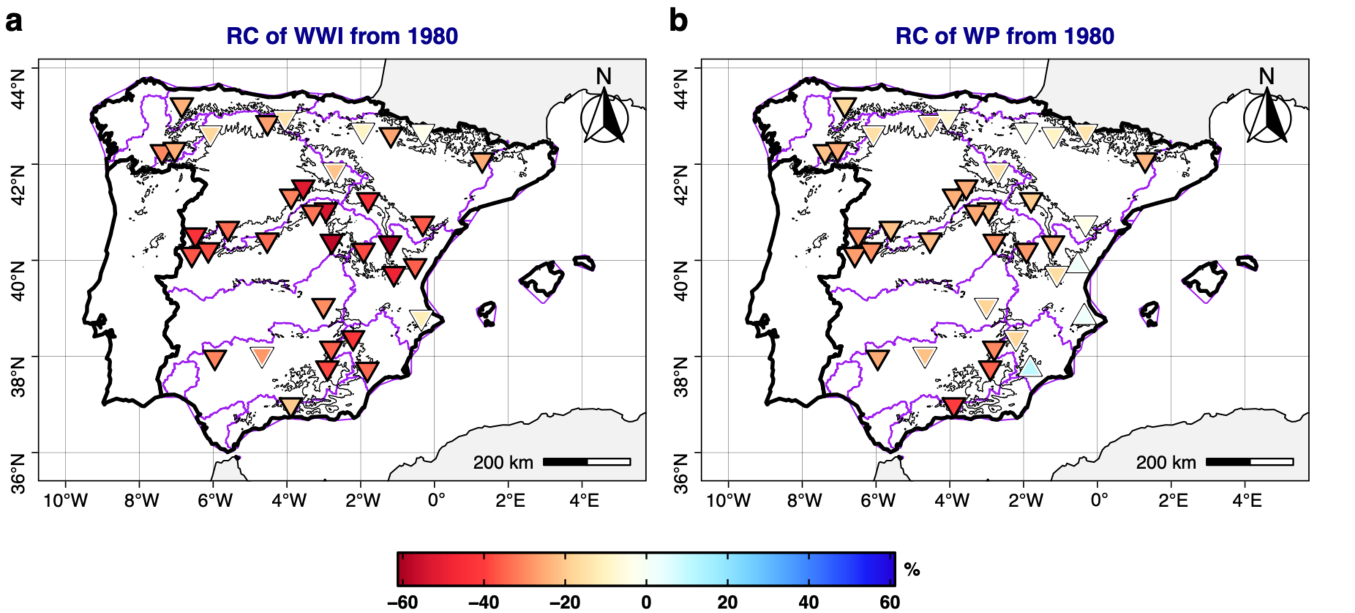

Figure 4. (a) Relative Change (RC) of WWI since 1979/1980; and (b) Id. for WP. The RC is computed as Eq. 2 (Section 2.2). Basically, the RC analysis compares the mean during the period 1980-2018 with the mean during the former (1952-1979). Symbols represent positive RC (filled triangle point-up) and negative RC (filled triangle point down), being marked with a black outline the significant estimates. Contours of orography (black) and IHB of continental Spain (purple) were also added (see Fig. 1).

So, the RC of WP ranged from -40% to 10% (Fig. 4a). 61% of catchments registered a significant RC of WP. A significant RC was observed in the central areas and western/southern IP. Conversely, a positive RC of WP was estimated over the eastern IP. For WWI, all catchments registered losses (Fig. 4b). The RC of WWI ranged from -60% to -3%. Major WWI decreases were observed in the headwater of Tagus, Jucar, and Segura basins (central-eastern IP, see Fig. 1). The magnitude of WWI losses is generally higher than the WP reductions. That is, WWI also decreased where WP increased post-1980. This converse pattern suggests a poor or moderate relationship between WP and WWI in several NENWIRES basins. Vicente-Serrano et al. (2019) have already evidenced the poor relationship between climate and streamflow in basins of southern Spain. The results presented here match these conclusions, given that increases(decreases) of RC were found for WP(WWI) over southern IP. Questions arise, however, about why an abrupt decrease of WP has been registered. Hence, once could wonder about the role that NAOi plays into WP changes. This question is analysed in the following subsection.

3.5 NAOi Variability Causing the Post-1980 Decrease of Precipitation

The previous results have shown that WP/WWI strongly decreased since early 1980s. The scientific literature has already warned about the WP decreases in several Iberian basins, which were preliminary associated to the NAOi enhancement (e.g. Trigo et al, 2004, Guerreiro et al., 2014, Gómez-Martínez et al., 2018, Halifa-Marín et al., 2021). So, a significant BP post-1980 in NAOi series was detected in this contribution (Supplementary Material, Fig. SM3a). Average NAOi changed from -0.35 (1952/1979) to 0.38 (1980/2018). Almost identical composites of SLP/Z500/U/V-W between NAOi-/NAOi+ phases and before/after 1980 were obtained (Supplementary Material, Fig. SM3b-c), which confirms that winters post-1980 generally presented NAOi+ phases. A higher frequency of NAOi+ would explain the WP declining over the IP, and its propagation in WWI records. In fact, WP/WWI (Fig. 3) and NAOi (Supplementary Material, Fig. SM3a) have shown a significant BP since 1979/1980. Changes post-1980 in these variables are physically coherent with the variability of NAO. Also, WP/WWI highly correlated with the NAOi in the NENWIRES catchments (Fig. 5). The correlation WP/NAOi ranged from -0.75 to -0.1. Generally, these correlations were significant except in the case of eastern/northern IP (see Apendix A, Fig. SM4). Higher correlations were found in those basins where BPs of WP were detected in 1979 (Fig. 7b). A strong relationship between the NAOi/WP correlation and RC of WP was also found. A significant adjusted $R^2 = 0.82$ was quantified through linear regression between both variables, attributing those larger decreases of WP to the NAOi post-1980 enhancement. Meanwhile, focusing on WWI/NAOi links, non-significant positive correlations were observed over the eastern IP (Supplementary Material,

Fig. SM4). In this case, correlation coefficients ranged from -0.6 to 0.2 (Fig. 5a). The NAOi/WP correlation was clearly more intense than NAOi/WWI. Likewise, linear regression between WWI/NAOi correlation and RC of WWI shows a poor relationship. Therefore, the Iberian WWI abrupt reductions, understandably, depends on NAOi enhancement post-1980, whereas their magnitudes might not be essentially provoked by the WP declining. Likewise, NAOi shift was the principal precursor of WP decreases, especially in areas severely affected by Atlantic fronts (e.g. precipitation events coming from Atlantic Ocean, where NAOi influence is crucial to the precipitation regime).

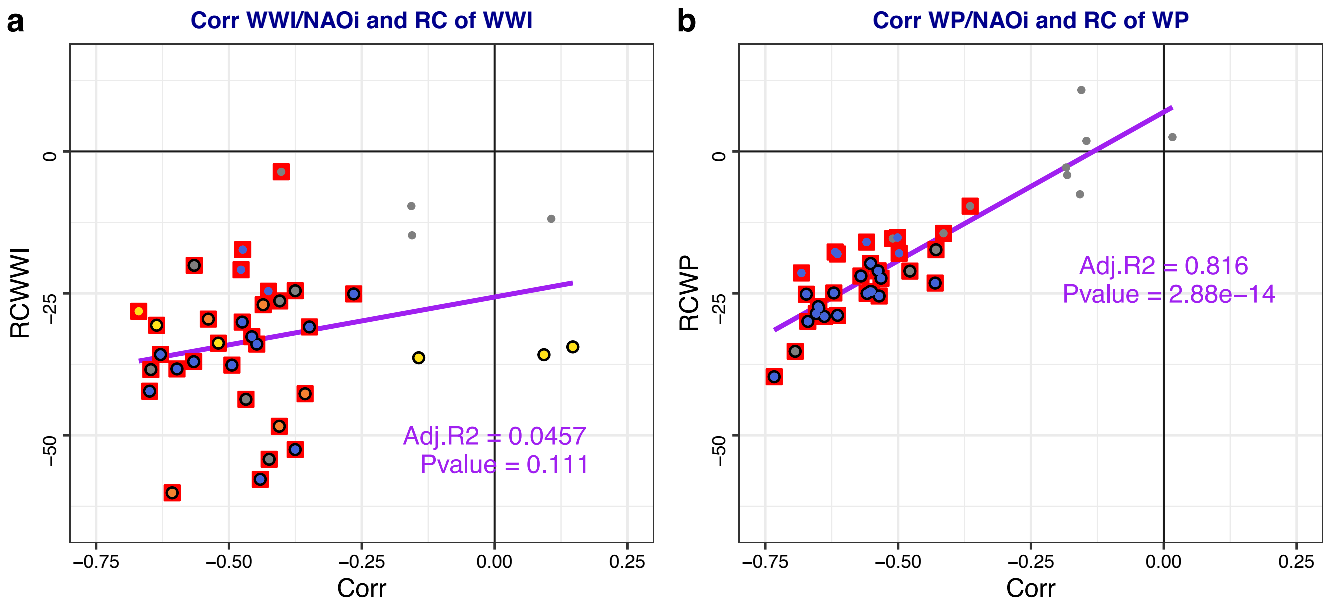

Figure 5. Correlation between WWI (a) and WP (b) with NAOi (X axis) in relation to the RC of each variable (Y axis). Red squares show the significant correlation values. Black circles show the significant RC of each variable. Painted spheres show the BP detected through the same rules (colour palette) used in the Fig. SM2 (Supplementary Material). Purple line/text shows the linear regression coefficients.

3.6 Propagation of Prevailing Drought Conditions into Winter Water Inflows

At this point, it has been depicted that several series were not driven by NAOi/WP changes (WWI declining shows inverse/higher magnitude than WP reductions). Moreover, Vicente-Serrano et al. (2019) inferred that human-induced factors are sometimes more important that climate for understanding streamflow trends in Spain (e.g. irrigation), and Peña-Angulo et al. (2021) conclude that changes in vegetation have a strong impact on the relationship between climatic and hydrological drought over time. Henceforth, their conclusions advice to assess the contribution of other factors to the WWI changes. The SPEI6/12 index was used to understand how the drought conditions might impact on WWI records (Section 2.2). The average of wintertime SPEI6/12 is shown in Fig. SM5 (Supplementary Material). The BP was detected in 1980 (SPEI12) and 1970 (SPEI6). Clearly negative estimations turn more frequent in both series since its BP was detected. For SPEI12, the BP detection agreed with the BP of WWI/WP series. The average SPEI12 changed from 0.37 to -0.27 since 1980. Also, drought conditions prevailed in 70% (25) of post-1980 winters. In those basins where SPEI12 decreases (increase of meteorological droughts conditions), WP events probably need to supply the water stress of vegetation and lower water reserves in aquifers, where WP decline was also. SPEI weakening also refer to the temperature/ETP rise. The decrease of SPEI12 estimations in headwaters of Spain already has been mentioned by the literature (Vicente-Serrano et al., 2014; Peña-Angulo et al., 2021). The mechanisms that could promote the droughts intensification are the decrease of cloud cover, insolation and maximum temperature rise due to NAOi enhancement. But further work is needed to verify this assertion. In fact, an increase of maximum temperature (~0.9ºC) from 1980 is generally reported in the NENWIRES catchments (Supplementary Material, Fig. SM6).

On the other hand, the potential impacts on the recharge/reserve in groundwaters due to the increase of meteorological droughts (SPEI12) have been addressed. Continental Spain shows a wide variety of soils, with permeable(impermeable) soils prevailing over central/eastern(western) IP (Supplementary Material, Fig. SM7). The permeable soils exceeded 80% in southeastern catchments, where limestone soils are abundant. Conversely, impermeable soils reached 100% over the western IP. Therefore, the relationship between soil permeability and WP/WWI correlation was assessed (Fig. 6a). These correlation coefficients ranged from 0.3 to 0.9. Generally, WP/WWI are highly correlated (0.8-0.9) where impermeable soils prevail. It is well-known that correlation between WP and WWI is more intense within impermeable basins because the run-off response is instantaneous (Lorenzo-Lacruz et al., 2013 and references therein). Conversely, some permeable watersheds have registered poor correlation between WP and WWI. After

WP/WWI correlation was estimated, the QQ-Deviation (QQD) (Eq. 3, Fig. 6) was quantified (the reader is referred to Section 2.2 for further information about QQD quantification). A significant adjusted R^2 above 0.35 is found in the linear regression analysis between QQD and WWI/WP correlation. So, the role of permeable soils to generate higher WWI was mostly proved during humid winters (Fig. 6a). Whereas QQD showed negative estimates over the northern/western IP (impermeable soils), positive estimates have been found in the high-permeable catchments (eastern/southern IP).

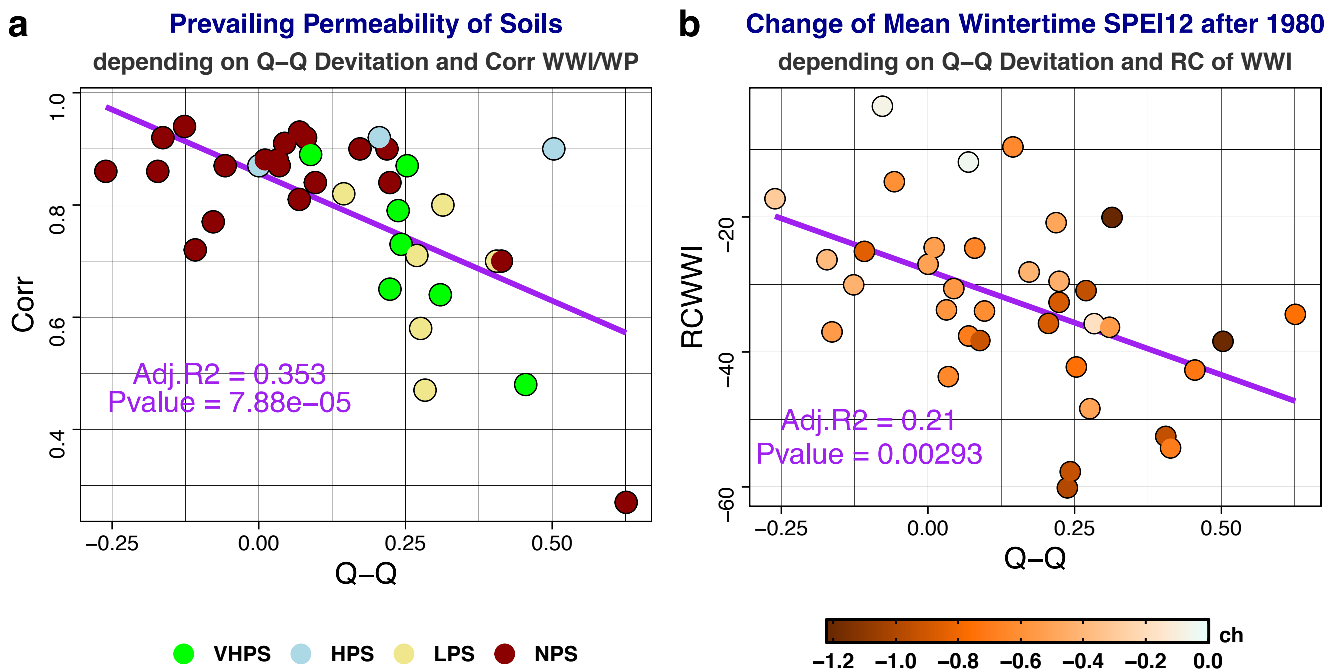

Figure 6. (a) Symbols represent the relationship between Q-Q Deviation (X-axis) and Correlation estimated for WWI and WP (Y-axis), whereas are painted through the prevailing type of soils in the catchments (permeability characteristics). Types of soils depending on its permeability conditions are defined in Methods (Section 2.1.3). (b) Symbols represent links between Q-Q Deviation (X-axis) and RC of WWI (Y-axis), which are painted through the absolute change of Mean Wintertime SPEI12 before/after 1980. The purple line shows the linear regression between X-Y variables, which Adj. R^2 and p-value are also mentioned.

The spatial pattern of QQD and WWI/WP correlation are shown in Fig. SM7 (Supplementary Material). These results can be summarized as follows: 1) porous watershed can infiltrate a larger volume of water; 2) Iberian extreme events of WP are characterized by the persistence of rainy days, even for several weeks, causing by the blockings in northern Europe/Atlantic; 3) which allows the water accumulation into aquifers; 4) generating an underground baseline flow joint to the surface run-off. The response between WP and WWI anomalies is higher in relation to common/dry winters. This time-lag effect probably depends on the hydrological response, water yield and the capacity of aquifers to store water. A significant adjusted R^2 above 0.2 between QQD and RC of WWI is found (Fig. 6b). The same panel shows that the intensification post-1980 of prevailing drought conditions (SPEI12) was higher in those basins which registered higher RCs of WWI decreases and a higher QQD. These results suggest that those basins, where the groundwater reserve highly contributes to WWI, have been affected by the increase of droughts conditions in the previous months of wintertime (see the RC of water inflows and precipitation computed for warm seasons in Supplementary Material, Fig. SM8). There, higher reductions post-1980 of WWI than WP are physically consistent because the implications of drought intensification for the hydrological response, especially under permeable conditions (where WWI also depends on groundwater reserve/flow). Future works should be devoted to further research on this assertion. In brief, the results presented here suggest that changes of infiltration have influenced the WWI reductions, given that prevailing soil moisture content has decreased as a result of precipitation losses at annual scale (i.e. the previous seasons).

3.7 Does Land Greening-up Amplify the Water Inflows Decline?

In the NENWIRES catchments, the extension of forest cover was generally registered from 1950 to 2010 (Supplementary Material, Fig. SM9b). The RC of forest cover ranged from -12% to 15%. Forest areas extended in 67% of the catchments through the study period (greening-up), whereas its cover mainly did not extent over the northern/southeastern IP. It should be noted that this study concerns the ‘extension’ of forest cover, but its density is not evaluated. This can motivate the disagreement with previous studies which also found the extension of forest cover in northern IP (e.g. García-Ruiz et al., 2011). In addition, the greening-up was limited where forest already exceeded 80% of watershed dimension in 1950

(Supplementary Material, Fig. SM9a). Several basins already had a large forest cover in 1950, especially in the northern IP. So, gains of forest cover mostly occurred in the semiarid basins during the study period (Fig. 7a,b), where lower mean WP is recorded. Meanwhile the most humid basins generally registered stability or slight reduction of forest cover. The fact that higher dimension of forest cover impacts on ETR and run-off is shown by previous works (e.g. Teuling et al., 2019). So, it is reasonable to assume that the greening-up has contributed to increase the reduction of WWI in NENWIRES catchments, especially in semiarid environments. This assertion agrees with the results of Peña-Angulo et al. (2021), who confirmed the implications of forest extension in the occurrence of hydrological droughts more intense than simultaneous meteorological droughts. Those authors do not discriminate between basins based on their precipitation regime. Therefore, the results shown here warn of the potential ET gains as a consequence of the greening-up (e.g. extension of forest), which coexists with the temperature rise.

One of the main results of this contribution is that a higher magnitude of WWI reductions is found in relation to WP losses, leading to the assumption that WP was not the only cause for the WWI decline. So, this study evaluated how several causes have contributed to post-1980 sudden losses of Iberian WWI. To understand how each of them modulates the WWI changes, a K-Means clustering was conducted. The clustering shows catchments where WWI changes are explained by similar mechanisms/factors (Fig. 7f, Supplementary Material Fig. 10b). 4 clusters that differed in contribution of each precursor are identified (Supplementary Material, Table A2). Cluster 1 (C1) consist of 11.1% of dataset, which are well differentiated from other NENWIRES basins. These basins 1) registered the lower mean WP (164.7 mm/yr); 2) had the most important extension of forest cover; 3) registered a very poor correlation of WWI with NAOi, 4) presented a lower intensification of droughts (SPEI12 decrease); 5) had high permeable soils and 6) showed a higher magnitude of WWI reductions in relation to WP losses (-32.4%). It seems that the WP losses and forest extension drove the higher magnitude of WWI reductions in those basins. The ETP is assumed to increase due to forest extension, while SPEI12 quantifications did not intensify since 1980. So, although the WP does not change significantly, WWI reduced by -29.6% because the rise of outputs affecting the water yield.

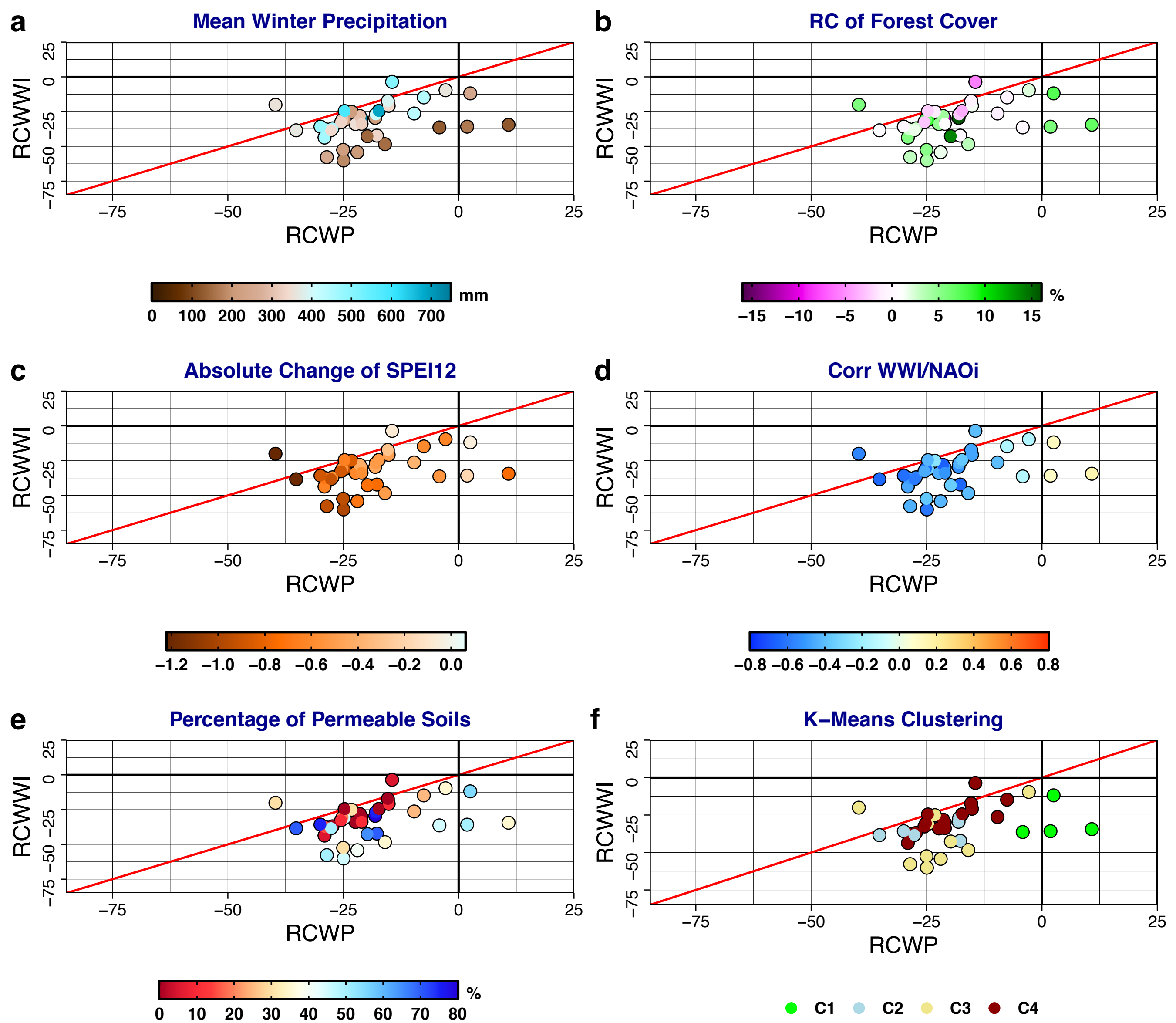

Figure 7. Scatter plot of relative changes of WP (X axis) and WWI (Y axes). Symbols are filled by the magnitude of several variables: (a) mean WP; (b) RC of forest cover computed after Eq. 6; (c) absolute change of SPEI12, (d) correlation between WWI and NAOi; (e) percentage of permeable soils; and (f) K-Means clustering depending on abovementioned variables.

However, hydrological modelling is needed to confirm this assertion. Cluster 2 (C2) covers the 16.7% of basins where 1) mean WP is 355.2 mm/yr; 2) permeable soils are abundant (70.1%); 3) WWI highly correlated with NAOi; 4) SPEI12 severely decreased; 5) forest cover extended 2.5%; and 6) WWI reduced more than WP (-10.8%). WWI changes are seemingly provoked by NAOi enhancement, whereas the magnitude of reduction was intensified by the amplification of permanent meteorological droughts since 1980, which affected to the groundwater reserves, given that C2 consist of, generally, permeable soils. Clearly, the extension of forest also contributes to reduce WWI, as suggested for C1 basins, but in the case of C2, forest extension was less important. Likewise, Cluster 3 (C3) includes 27.7% of catchments where 1) mean WP is 232.4 mm/yr; 2) permeable soils are less frequent (40.5%); 3) WWI correlated with NAOi (-0.4); 4) SPEI12 decreased -0.9 since 1980; 5) the extension of forest cover was important (4.7%); and 6) WWI reduced more than WP (-17.5%). In this group of basins, the higher reduction of WWI is driven by the same processes as for C2, but C3 registered higher intensification of SPEI12 (duration of meteorological droughts) and extension of forest. Oppositely, the influence of NAOi is less important for C3. Also, the RC of WP was weaker. Finally, Cluster 4 (C4) covers 44.4% of basins. Most humid basins are grouped into C4, where 1) mean WP is 445.2 mm/yr; 2) soils are mainly not permeable; 3) WWI highly correlated with NAOi (-0.5); 4) SPEI12 decreased -0.5; 5) forest cover does not change (-0.1); and 6) WWI changed more than WP (-7.1), however the magnitude of change was almost similar for both variables. Clearly, in the C4 basins, WWI changes were driven by NAOi enhancement and amplification of meteorological droughts. Likewise, given that C4 basin are generally impermeable, the groundwater reserve cannot supply the decrease of surface run-off during dry events.

4. Final Remarks

This contribution focused mainly on disentangling the WWI reduction post-1980, echoing the call made in Halifa-Marín et al. (2021), for assessing the potential propagation of short-term changes in WP records into the water resource variability. Therefore, the main findings of this contribution can be summarized as:

1) The NENWIRES dataset was created to analyze the recent evolution of near-natural Iberian water inflows draining to reservoirs in headwater catchments (NENWIRES). We identify a significant

reduction of the WWI, that is related to a sudden change after 1980 for most of basins. This change agrees with the BP reported for WP by other authors and confirmed in this contribution. This allows to analyze the changes reported here as the differences between two periods (1952/1979-1980/2018).

2) The decrease of WP is the main driver of the decline of WWI. However, a higher magnitude of WWI losses rather than WP reductions has been generally quantified. These extra water losses would depend on the extension of vegetation, and moisture content of soils (e.g. its permeability characteristics), which, in turn, also differed between the variety of climate conditions (e.g. precipitation regime).

3) A strong reduction of WWI has been observed in a set of semiarid catchments, where WP slightly increased, and where the NAOi does not exert an important influence. Those basins (grouped in the C1 cluster) are characterized by permeable soils, which are affected by the most important extension of vegetation. So, it is assumed that this greening-up in semiarid environments, where water storage of soils is abundant, has provoked significant evapotranspiration rises. Consequently, those water losses have decreased the WWI records. Similar assertions are concluded for catchments classified in the C3 cluster, where, however, WP is promoted by the NAOi influence, although they also are semiarid environments. C3 catchments registered the higher decreases of WWI.

4) Another set of most humid catchments (C4 cluster) is characterized by impermeable soils, and unchanged vegetation cover. There, the magnitude of WWI and WP reductions is almost similar. Meanwhile, the WP of catchments grouped into C2 cluster is characterized by a strong influence of the NAOi, and the extension of vegetation. Then, higher reductions of WWI are observed in relation to C4 catchments.

These assertions allow to conclude that a higher mean precipitation (i.e. winter/annual) induces a minor role of evapotranspiration/infiltration losses into water resource changes. Nonetheless, water generation in semiarid catchments is widely affected by those losses, which can play the main role, as important as the decrease of precipitation.

Last, the conclusions to this contribution confirm that the initial hypothesis was not accurate, since WWI changes essentially do not depend on climate in the set of NENWIRES catchments. Short-term changes (i.e. sudden decreases of water resource) do not impact on water planning in the same way as gradual changes, so that policies adapted to this mode of climate variability is recommended. The findings presented here thus encourage the need to develop a deeper knowledge about NAOi predictability under a warmer climate and conduct high-resolution modelling considering the water losses because of vegetation extension and moisture-soil content, especially in semiarid environments where the availability of freshwater is crucial. Likewise, the accuracy of the caveats presented here depends on the intrinsic uncertainties in datasets used. In addition, a source of error in the BP estimation could be caused by missing values in several WWI series, however, we identified a significant BP from 1978/1980 in case of full series and series with some missing values, whose finding shows a robust geographical pattern. As Peña-Angulo et al. (2020) concluded for the precipitation, other short-term changes of water resource (e.g. due to abrupt decreases/increases of precipitation) could be registered since 1850, which do not reduce the interest of understand the post-1980s drop of hydroclimate series in the IP, even if it is mostly conducted by internal variability of climate system. Indeed, this do not clarify the interplay of these short-term changes with the warmer climate forcings.

Data availability. All data sets used in the current study are publicly available from the indicated references or sources (See assets in the doi of manuscript). Also, we will be pleased to send the NENWIRES dataset under request.

Author contributions. A.H-M conceived the original idea and designed the overall study. A.H-M, E.P-S and M.T-V developed the NENWIRES dataset. A.H-M, and JP.M performed the analysis. All co-authors

contributed to the interpretation of the results. A.H-M led the writing of the paper, with contributions of P.J-G and JP.M.

Competing interests. The authors declare that they have no conflict of interest.

Acknowledgements. The authors thank the reviewers and the editor of the manuscript for their valuable contributions and fruitful discussions.

Funding. The authors acknowledge the ECCE project (PID2020-115693RB-I00) of *Ministerio de Ciencia e Innovación/Agencia Estatal de Investigación* (MCIN/AEI/10.13039/501100011033/). A.H-M thanks his predoctoral contract FPU18/00824 to the *Ministerio de Ciencia, Innovación y Universidades* of Spain. E.P-S thanks for his predoctoral contract to the ACEX project. M.L-C thanks his predoctoral contract FPU17/02166 to the *Ministerio de Ciencia, Innovación y Universidades* of Spain.

Review statement. This paper was edited by Erwin Zehe and reviewed by A.J. Teuling, S.M. Vicente-Serrano and one anonymous referee. The authors acknowledge their contributions in the final version of this manuscript.

References

AEMET, Precipitation/Temperature Gridded Dataset, available at: http://www.aemet.es/es/serviciosclimaticos/cambio_climat/datos_diarios?w=2, last access: 20 October 2021.

Berguería, S., Vicente-Serrano, S.M.: SPEI: Calculation of the Standardised Precipitation-Evapotranspiration Index, R package version 1.7, available at: https://cran.r-project.org/web/packages/SPEI/index.html, last access: 20 October 2021.

Borchers, H.W.: Pracma: Practical Numerical Math Functions, R package version 2.2.9, available at: https://CRAN.R-project.org/package=pracma, last access: 20 October 2021.

CEDEX, Spanish Hydrological Repository, available at: https://ceh.cedex.es/anuarioaforos/demarcaciones.asp, last access: 20 October 2021.

de Luis, M., Brunetti, M., González-Hidalgo, J. C., Longares, L. A., & Martin-Vide, J.: Changes in seasonal precipitation in the Iberian Peninsula during 1946-2005, *Global and Planetary Change*, 74, 27-33, doi:10.1016/j.gloplacha.2010.06.006, 2010.

Fuchs, R., Herold, M., Verburg, P. H., Clevers, J. G. P. W., and Eberle, J.: Gross Changes in Reconstructions of Historic Land Cover/Use for Europe between 1900 and 2010, *Glob. Change Biol.*, 21, 299–313, https://doi.org/10.1111/gcb.12714, 2015.

García-Ruiz, J. M., López-Moreno, J. I., Vicente-Serrano, S. M., Lasanta–Martínez, T., & Beguería, S.: Mediterranean water resources in a global change scenario, *Earth-Science Reviews*, 105(3-4), 121-139, https://doi.org/10.1016/j.earscirev.2011.01.006, 2011.

Gómez-Martínez, G., Pérez-Martín, M. A., Estrela-Monreal, T., & del-Amo, P.: North Atlantic Oscillation as a Cause of the Hydrological Changes in the Mediterranean (Júcar River, Spain), *Water Resources Management*, 32(8), 2717–2734, doi:10.1007/s11269-018-1954-0, 2018.

Gudmundsson, L., Boulange, J., Do, H. X., Gosling, S. N., Grillakis, M. G., Koutroulis, A. G., ... & Zhao, F.: Globally observed trends in mean and extreme river flow attributed to climate change, *Science*, 371(6534), 1159-1162, 2021.

Guerreiro, S. B., Kilsby, C. G., & Serinaldi, F.: Analysis of time variation of rainfall in transnational basins in Iberia: Abrupt changes or trends?, *International Journal of Climatology,* 34, 114-133, doi:10.1002/joc.3669, 2014.

Halifa-Marín, A., Lorente-Plazas, R., Pravia-Sarabia, E., Montávez, J. P., & Jiménez-Guerrero, P. (2021). Atlantic and Mediterranean influence promoting an abrupt change in winter precipitation over the southern Iberian Peninsula, *Atmospheric Research*, 253, 105485, https://doi.org/10.1016/j.atmosres.2021.105485, 2018.

Hannaford, J., Buys, G., Stahl, K., and Tallaksen, L. M.: The influence of decadal-scale variability on trends in long European streamflow records, *Hydrol. Earth Syst. Sci.*, 17, 2717–2733, https://doi.org/10.5194/hess-17-2717-2013, 2013.

HILDA, HIstoric Land Dynamics Assessment Dataset, available at: https://www.wur.nl/en/Research-Results/Chair-groups/Environmental-Sciences/Laboratory-of-Geo-information-Science-and-Remote-Sensing/Models/Hilda.htm, last access: 20 October 2021.

Hothorn, T., Winell, H., Hornik, K., van de Wiel, M.A., Zeileis, A.: Coin: Conditional Inference Procedures in a Permutation Test Framework, R package version 1.3-1, available at: https://CRAN.R-project.org/package=coin, last access: 20 October 2021.

IDE, Spanish Catchment Boundaries Dataset, available at: https://www.miteco.gob.es/es/cartografia-y-sig/ide/descargas/agua/cuencas-y-subcuencas.aspx, last access: 20 October 2021.

IGME, Mid-Resolution Permeability of Soils Dataset, available at: http://mapas.igme.es/Servicios/default.aspx#IGME_Permeabilidad_1M, last access: 20 October 2021.

Lorenzo-Lacruz, J., Vicente-Serrano, S. M., López-Moreno, J. I., Morán-Tejeda, E., and Zabalza, J.: Recent Trends in Iberian Streamflows (1945–2005), J. Hydrol., 414–415, 463–475, https://doi.org/10.1016/j.jhydrol.2011.11.023, 2012.

Lorenzo-Lacruz J, Vicente-Serrano SM, González-Hidalgo JC, López-Moreno JI, Cortesi N.: Hydrological drought response to meteorological drought in the Iberian Peninsula, *Clim Res* 58:117-131, https://doi.org/10.3354/cr01177, 2013.

Luo, D., & Gong, T.: A possible mechanism for the eastward shift of interannual NAO action centers in last three decades, *Geophysical research letters*, 33(24). https://doi.org/10.1029/2006GL027860, 2006.

Massei, N., Kingston, D. G., Hannah, D. M., Vidal, J. P., Dieppois, B., Fossa, M., ... & Laignel, B.: Understanding and predicting large-scale hydrological variability in a changing environment, *Proceedings of the International Association of Hydrological Sciences*, 383, 141-149. https://doi.org/10.5194/piahs-383-141-2020, 2020.

NOAA, The North Atlantic Oscillation Index, available at: https://www.cpc.ncep.noaa.gov/products/precip/CWlink/pna/nao.shtml, last access: 20 October 2021.

Peña-Angulo, D., Vicente-Serrano, S. M., Domínguez-Castro, F., Murphy, C., Reig, F., Tramblay, Y., ... & El Kenawy, A.: Long-term precipitation in Southwestern Europe reveals no clear trend attributable to anthropogenic forcing. Environmental Research Letters, 15(9), 094070, https://doi.org/10.1088/1748-9326/ab9c4f, 2020.

Peña-Angulo, D., Vicente-Serrano, S. M., Domínguez-Castro, F., Noguera, I., Tomas-Burguera, M., López-Moreno, J. I., ... & El Kenawy, A.: Unravelling the role of vegetation on the different trends between climatic and hydrologic drought in headwater catchments of Spain. *Anthropocene*, 36, 100309, https://doi.org/10.1016/j.ancene.2021.100309, 2021.

Pohlert, T.: Trend: Non-parametric Trend Tests and Change-Point Detection, R package version 1.1.1, available at: https://CRAN.R-project.org/package=trend, last access: 20 October 2021.

R Core Team: A language and environment for statistical computing, R Foundation for Statistical Computing, at available at: https://rdrr.io/r/base/base-package.html, last access: 20 October 2021.

Stahl, K., Hisdal, H., Hannaford, J., Tallaksen, L. M., van Lanen, H. A. J., Sauquet, E., Demuth, S., Fendekova, M., and Jódar, J.: Streamflow trends in Europe: evidence from a dataset of near-natural catchments, Hydrol. Earth Syst. Sci., 14, 2367–2382, https://doi.org/10.5194/hess-14-2367-2010, 2010.

Teuling, A. J., de Badts, E. A. G., Jansen, F. A., Fuchs, R., Buitink, J., Hoek van Dijke, A. J., and Sterling, S. M.: Climate change, reforestation/afforestation, and urbanization impacts on evapotranspiration and streamflow in Europe, *Hydrol. Earth Syst. Sci.*, 23, 3631–3652, https://doi.org/10.5194/hess-23-3631-2019, 2019.

Tramblay, Y., Llasat, M.C., Randin, C. et al.: Climate change impacts on water resources in the Mediterranean, *Reg Environ Change*, 20, 83, https://doi.org/10.1007/s10113-020-01665-y, 2020.

Trigo, R. M., Pozo-Vázquez, D., Osborn, T. J., Castro-Díez, Y., Gámiz-Fortis, S., & Esteban-Parra, M. J.: North Atlantic oscillation influence on precipitation, river flow and water resources in the Iberian Peninsula, *International Journal of Climatology*, 24(8), 925–944, doi:10.1002/joc.1048, 2004.

Vicente-Serrano, S. M., Lopez-Moreno, J. I., Beguería, S., Lorenzo-Lacruz, J., Sanchez-Lorenzo, A., García-Ruiz, J. M., ... & Espejo, F.: Evidence of increasing drought severity caused by temperature rise in southern Europe, *Environmental Research Letters*, 9(4), 044001, https://doi.org/10.1088/1748-9326/9/4/044001, 2014.

Vicente-Serrano, S. M., Peña-Gallardo, M., Hannaford, J., Murphy, C., Lorenzo-Lacruz, J., Dominguez-Castro, F., ... & Vidal, J. P.: Climate, irrigation, and land cover change explain streamflow trends in countries bordering the northeast Atlantic, *Geophysical Research Letters*, 46(19), 10821-10833, https://doi.org/10.1029/2019GL084084, 2019.

Wang, Y. H., Magnusdottir, G., Stern, H., Tian, X., & Yu, Y.: Uncertainty estimates of the EOF-derived North Atlantic Oscillation, *Journal of climate*, 27(3), 1290-1301. https://doi.org/10.1175/JCLI-D-13-00230.1, 2014.