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Climate change impacts on the streamflow in Spanish basins monitored under near-natural conditions

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ABSTRACT

Study region: This study is focused on 12 basins in mainland Spain where monthly series longer than 30 years of near-natural streamflow measurements are available. It covers areas with different climate conditions.
Study focus: The potential impact of future climate change scenarios on water resources in the Spanish basins is studied. It takes into account uncertainties in the estimation of local climate conditions, and the propagation of the impact due to the structural uncertainties related with the adopted conceptual-numerical approach. Local climate scenarios are derived from available Regional Climate Model (RCM) simulations after statistical downscaling. The future scenarios have been generated assuming two hypotheses of future warming for two basins in mainland Spain: 1.5 °C and 3 °C. In each of these basins, the local climate scenarios have been propagated by using 4 hydrological models, with sufficient capacity to reproduce the historical dynamic, providing values of above 5 in a 0–9 range for the grading method used.
New hydrological insights: The results show a significant spatial heterogeneity of the impact of climate change on the mean streamflow in Spanish basins. The highest reductions of flow appear in the wetter northern basins. The seasonality of the impact is also significant, with the highest reductions during autumn, and the smallest changes in the summer months. Finally, the highest uncertainties in this climate change impact assessment are due to the RCM projections, with the influence of the hydrological models being significantly smaller.

1. Introduction

The adaptation to climate change constitutes a major human challenge for the coming future that necessitates studies of the potential future climate change impact on water resources systems to be carried out (Misra, 2014). Climate change produces a significant impact on the availability and distribution of water resources in the world, which will be amplified in the future (Blenkinsop and Fowler, 2007; Vörösmarty et al., 2000). One of the areas especially sensitive to these climate changes is the Mediterranean region

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(Cramer et al., 2018), where frequent and intensive droughts occur and which will be exacerbated in the future (Tramblay et al., 2020, Hayes et al., 2011). In particular, in Spain, there are several research studies that have shown the significant potential impact of climate change at different scales of water-resource systems: aquifer (Pulido-Velazquez et al., 2012; Tigabu et al., 2020; Rupérez-Moreno et al., 2017; Pardo-Igúzquiza et al., 2019; Baena-Ruiz et al., 2020); basin (Pulido-Velazquez et al., 2011; Molina-Navarro et al., 2016; Senent-Aparicio et al., 2017, 2019, 2018; Pérez-Sánchez et al., 2020). Those impact studies require the generation of potential local climate change scenarios by using bias correction and downscaling techniques (Collados-Lara et al., 2018a, 2020a) and their propagation using different hydrological (Llopis-Albert and Pulido-Velazquez, 2015; Pulido-Velazquez et al., 2007a, 2007b), agronomical (Pulido-Velazquez et al., 2018a) and/or management models (Pulido-Velazquez et al., 2008, 2006).

Several climate models have been used to simulate the RCP (Representative Concentration Pathway) scenarios published by the Intergovernmental Panel on Climate Change (IPCC) in the IPCC AR5 assessment report. Nevertheless, in order to make this information useful to assess the impact of climate change on specific water resources systems, we need to correct/downscale it by using local information. We have to perform statistical corrections of the climate model simulations to adapt their values in accordance with the observed historical data available in the system (Pulido-Velazquez et al., 2015, 2011). In the literature we can find examples in which these local scenarios are defined for specific future horizons: short term (coming decades; e.g. Collados-Lara et al., 2020a; mid-term e.g. Escriba-Bou et al., 2012) and/or long term horizons (referring to the last decades of this century; Pulido-Velazquez et al., 2015). Other recent research studies refer to a specific level of warming (Collados-Lara et al., 2020b), with the information coming from series of the climate model simulations in which the horizon is identified by using a constraint where a certain warming threshold is reached at a global scale or at a certain region area (eg. Mediterranean region; Tramblay et al., 2020). This "what if approach" is useful for assessing the impact and design of adaptation strategies to climate change and compare them for different scenarios. Note that the targets for climate change adaptation and mitigation have been set at levels of global mean temperature change relative to preindustrial levels (Donnelly et al., 2017).

A rational assessment of adaptation strategies for a sustainable planning and management of water resource systems requires the potential sources of uncertainties to be taken into account (Pulido-Velazquez et al., 2018b). In the literature we can find many classification schemes of sources of uncertainty and quantitative methods and tools for their assessment in integrated models (Matott et al., 2009). The focus of this paper is to visualize the uncertainties related to the statistical correction techniques applied to the climate model simulations (Regional Climate Models [RCM] nested to General Circulation Models [GCM]), and hydrological model structures. We have used three correction techniques under two different approaches (delta change and bias correction) to downscale simulation from nine RCMs. Four lumped conceptual hydrological models have been considered to incorporate model structure uncertainties in the novel methodology for visualizing monthly streamflow projections and uncertainty bounds.

Hydrological models based on model equations have been used to propagate climate scenarios to perform impact studies about the availability of water resources in different systems. They reconstruct computational features of water movement in the hydrological cycle (Abdollahi et al., 2018; Pedro-Monzonís et al., 2015) and predict future ones (Ivezic et al., 2017). These approaches are also known as mass balance models, in which the total inflows in a watershed are equal to total outflows plus changes in storage systems (in reservoirs and aquifers). Taking into account the spatial discretization of the watershed, the hydrological balance models can be classified into distributed, pseudo-distributed and lumped. The parametrization of the former is carried out at the cell level, reaching thus a higher level of detail of the watershed. Furthermore, the development of software tools has greatly increased, providing more detailed distributed results (Senent-Aparicio et al., 2018a), taking into account the heterogeneities of the system. This claimed advantage may become a significant inconvenience when the available information is scarce (Paudel et al., 2011), decreasing its effectiveness (Viney et al., 2005) that lumped conceptual models may be able to overcome (Croke et al., 2004). They aggregate the parameters that describe the hydrological system, namely, the physical processes of the watershed are assumed as homogenous. Moreover, lumped conceptual models are less time consuming, they need less data and definition requirements are much lower, frequently producing better performance compared to complex distributed ones (Vansteenkiste et al., 2014) as well as a higher efficiency in calibration processes (Bomann et al., 2009). Indeed, many studies have confirmed that lumped and distributed models provide similar accuracy (Lobligeois et al., 2014; Smith et al., 2012; Agip et al., 2012; Breuer et al., 2009; Zhang et al., 2004; Koren et al., 2004; Ajami et al., 2004; Reed et al., 2004; Boyle et al., 2001; Refsgaard, and Knudsen, 1996; Shah et al., 1996). Vansteenkiste et al. (2014) and Smith et al. (2012) demonstrated that lumped conceptual models provided better performance than the distributed ones in the assessment of flow at the catchment outlet in Belgium and the Oklahoma region, respectively. In Spain, Martínez-Santos and Andreu (2010) evaluated lumped and distributed models in a semi-arid aquifer recharge obtaining better agreement with the former ones. Likewise, Pérez-Sánchez et al. (2019) carried out a comparative study of six lumped conceptual models in several basins with different climate conditions within Spain, with satisfactory results. Senent-Aparicio et al. (2018b) also used multiple monthly water balance models to evaluate gridded precipitation products in Spain. Some of the latest research studies undertaken using lumped conceptual models have assessed catchment discharge (Kumar et al., 2015; Van Esse et al. 2013; Velázquez et al. 2010), have analyzed transferability within different climate conditions (Broderick et al., 2016; Bourgin et al., 2015) or have evaluated the impact of climate change (Haque et al., 2015; Jiang et al., 2007).

In this study we propose a novel study of the potential impact of future climate change on water resources in Spanish basins where near natural streamflow measurements are available. The main objective is to assess the impact of climate change on the water balance of the selected basins. We also aim to quantify the uncertainty of this impact. We have considered different statistical correction techniques of climate models with two approaches (delta change and bias correction), nine RCMs and four hydrological model structures. It has allowed us to assess monthly streamflow projections and uncertainty bounds. The selected drainage basins are located at the headwaters of the rivers analyzed. They are considered to be in a natural regime since upstream of the gauging stations there are no significant anthropic alterations (dams, dykes, pumping, etc.) that could modify the natural flow regime of these rivers. The study covers different climate conditions, taking into account the uncertainties in the estimation related with the local climate conditions, and the propagation of the impact due to the structural uncertainties related with the adopted conceptual-numerical approach. We have used different hypotheses and statistical techniques to define multiple local future scenarios in each basin, where the impact is propagated by using different hydrological models with the ability to reproduce the historical natural dynamic. We have also analyzed the spatial heterogeneity of the impact of climate changes based on the hydrological results in different Spanish basins. The generated series may also be useful in future studies to analyze the impact of climate change on drought (Collados-Lara et al., 2021a), which may be very relevant for identifying and analyzing potential adaptation strategies to minimize future issues related with the supply of water demands and/or environmental impact.

2. Materials: description of the study area and the available information

The natural flow regime may be modified through different pressures such as dams, the extraction of surface water, aquifer overexploitation and land-cover and land-use (LCLU) changes where the impact may be exacerbated by the effects of climate change. Streamflow data from gauging stations of unaltered basins provide relevant information about natural regime streamflow that, in addition to watershed attributes, allow the modeling of the hydrologic cycle and its use to predict the influence of anthropogenic or climate alterations. Thus, to ensure the validity of the results carried in this study, the 12 selected catchments (Fig. 1) are situated in natural regimes.

2.1. Location, climate and geological context

Spain presents a wide variety of climates due to both geographic and atmospheric features. The Iberian Peninsula, with an average altitude of 600 m above sea level (m.a.s.l.), has several mountainous terrains that are higher than 1000 m.a.s.l., which causes an average vertical temperature gradient of 0.65 °C every 100 m, although in some higher alpine regions the theoretical climate gradient may change locally in a significant way (Collados-Lara et al., 2021b, 2018b). Furthermore, the west-east mountain disposal encourages the entry of the Atlantic air masses but blocks Meridian air masses (north-south). Moreover, the linear coasts, with few inbounds and coasted parallel reliefs contribute to most peninsular areas being isolated from the sea. Thus, the inland regions show a marked continental climate with high variations of temperature between the summer and the winter whilst the coastal areas have only slight temperature variations. All of these features mean that the Iberian Peninsula has a large disparity of climates within the mild one. The 12 studied watersheds cover a major part of the Iberian Peninsula (Fig. 1), ranging from 29 to 837 km^2 of area and their altitudes vary

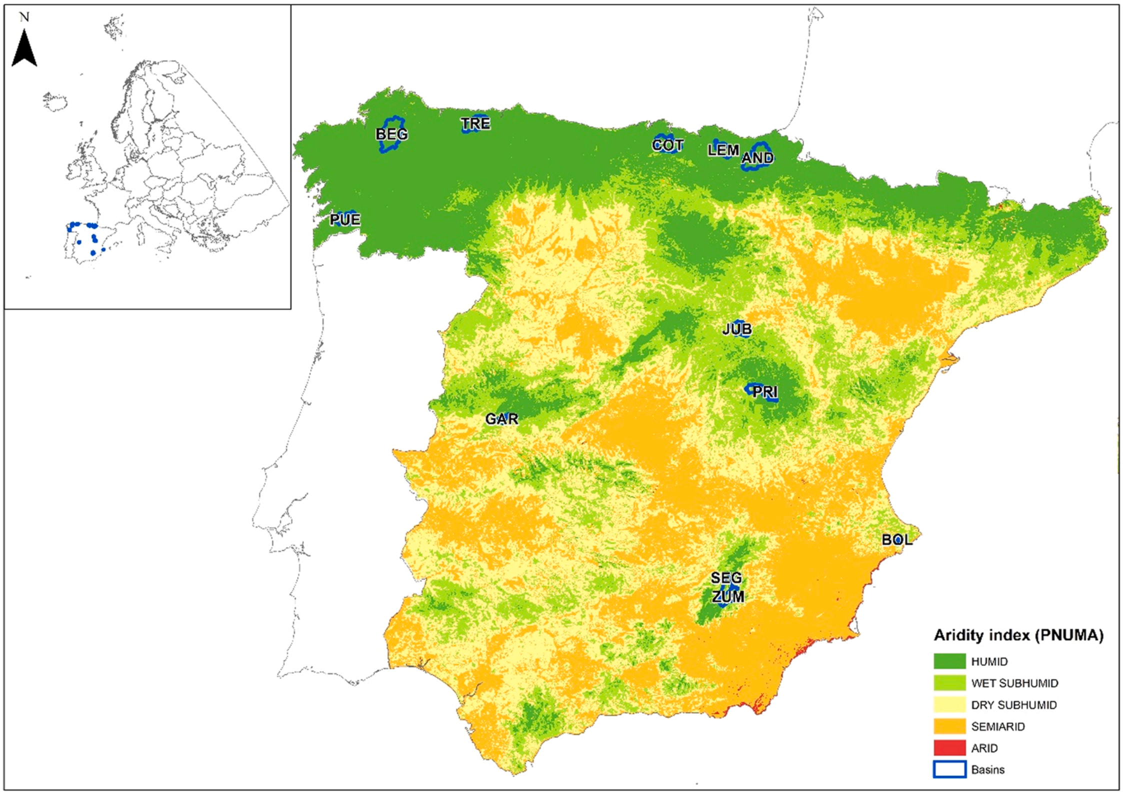

Fig. 1. Location of the basins and the aridity index (climatic context).

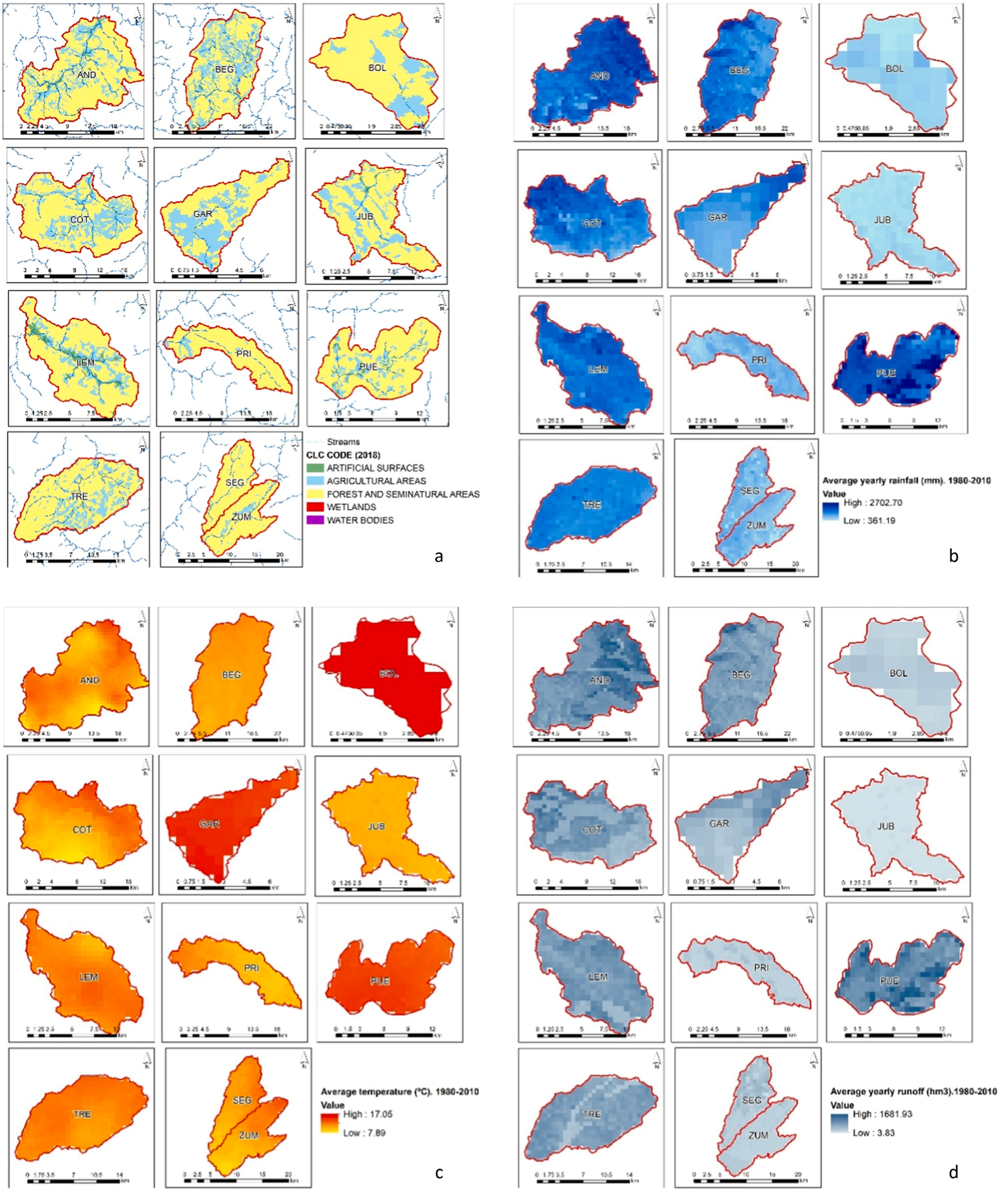

Fig. 2. Map of land use and drainage net (a), yearly mean precipitation (b), temperature (c) and streamflow (d) series for each basin (period 1980–2010).

from 342 to 1550 m.a.s.l. They represent the most common climates in the peninsula according to Köppen's classification (Köppen, 1884, 1918; Köppen and Geiger, 1936): Csb. (warm-summer Mediterranean), Csa. (hot-summer Mediterranean climate), Cfb. (temperate oceanic), and UNEP aridity index (UNEP, 1997). According the UNEP aridity index (AI_U), measured as the ratio between the average annual precipitation (P) and the potential evapotranspiration (PET), all of the studied basins located in the north of Spain (PUE, BEG, TRE, COT, LEM and AND) are classified as humid ($AI_U > 1.00$), as well as PRI, in the center of Spain. The GAR, SEG and ZUM catchments are classified as humid sub-humid ($1.00 < AI_U < 0.65$) due to their altitude above 700 m.a.s.l. and the remaining two, BOL and JUB, may be considered as dry sub-humid ($0.50 < AI_U < 0.65$). No arid basin was taken into account in this study due to the unsatisfactory performance shown for the lumped conceptual models used (Pérez-Sánchez et al., 2019).

The 12 basins are located in the main lithology groups of the Iberian Peninsula: siliceous and calcareous. The BEG, PUE and TRE basins in north-east and the GAR in the west belong to the former group where granite, gneiss, quartz, marble and slate are the main materials. The BOL, JUB, SEG Y ZUM basins in the east and LEM, AND, PRI and COT in the north are predominantly calcareous with limestone, casts and loam rocks. The snowmelt does not have a significant influence on the water resources in the selected basins. Eight of the basins (PUE, BEG, TRE, COT, LEM, AND, GAR) have a mean elevation below 700 m a.s.l., and, therefore, snow rarely appears. The SEG (1418 m a.s.l.) and ZUM (1543 m a.s.l.) are located in southern Spain, where the snow at these altitudes is not significant due to the warm climate. Finally, JUB and PRI, located in central Spain, also have a moderate elevation (1150 and 1256 m.a.s.l., respectively) and the influence of snow melt is not significant.

2.2. Historical climate and hydrological data

Temperature and precipitation data series in the historical studied period 1980–2010 have been obtained from the CEDEX (Centre of Studies and Experimentation of Civil Work) for the Spanish government (Álvarez et al., 2004) at a spatial resolution of 500 × 500 m (Estrela and Quintas, 1996). The average temperatures range from 11 to 15 °C, with a positive gradient to the south (Fig. 2a). Precipitation disparities are much higher (Fig. 2b), varying between 1563 mm in the AND basin and 510 mm in the JUB basin, with a marked rainfall gradient from the northwest to the southeast.

Potential evapotranspiration was calculated by using the Hargreaves method (Hargreaves and Samani, 1985). This simple approach only requires minimum, maximum and mean temperature, and solar radiation. We have used the solution proposed by Samani (2000), which uses tabulated values (depending on the latitude) to calculate the solar radiation.

Streamflow data come from the gauging stations of the official Spanish network. The average of completed data series in the period 1980–2010 for the studied basins is higher than 97%. The basins located in the north of Spain show the highest values, around 70 Mm^3/year, whilst basins with the most severe climates such as BOL have a monthly average streamflow lower than 1 Mm^3/year (Fig. 2d).

2.3. Climate model simulation data. Control and future scenarios

We have used results obtained from the simulation of nine climate models (see Table 1) under the Representative Concentration Pathway (RCP) 8.5 emission scenario. It is the most pessimistic scenario included in the fifth assessment report (AR5) (IPCC, 2014) of the Intergovernmental Panel on Climate Change (IPCC). The IPCC is the United Nations body for assessing the science related to climate change. The climate model simulation data were taken from the website of the Coordinated Regional Climate Downscaling Experiment for the European domain (EURO-CORDEX) project (2018). The RCM simulations, which include control (historical simulations) and future results up to2100, are nested to different GCM. These nine climate models were randomly selected assuming that all the RCMs included the EURO-CORDEX project are good enough to generate potential future scenarios. We have also assumed that the nine climate models are enough to assess the uncertainty related to the RCMs.

2.4. Calibrated hydrological balance models

An assessment of four hydrological balance models [ABCD, GR2M, Australian Water Balance Model (AWBM) and GUO-5p] in the historical studied period (1980–2010) was carried out in the twelve basins, and six statistical indices (the Akaike information criterion (AIC), the Bayesian information criterion (BIC), Nash–Sutcliffe model efficiency coefficient (NSE), coefficient of determination (R^2), percent bias (PBIAS) and the relative error between the observed and simulated run-off volumes (REV)) were used to calibrate and validate them and their use in the propagation of the climate scenarios. Pérez-Sánchez et al. (2019) demonstrated that, regardless of the basin area, these lumped conceptual hydrological models performed well in humid and sub-humid watersheds according to Moriasi

Table 1
Climate models considered to generate the potential future local scenarios. The RCMs are nested to the GCMs indicated by the crosses.

GCM RCM	CNRM-CM5	EC-EARTH	MPI-ESM-LR	IPSL-CM5A-MR
CCLM4-8-17	X	X	X	
RCA4	X	X	X	
HIRHAM5		X		
RACMO22E		X		
WRF331F				X

et al. (2007). The more humid the basin is the better the results that are obtained, which indicates the strong influence of climate characteristics. GR2M proved to be the model with the best performance whenever AI_U is higher than 1 with NSE values above 0.75 in a 95% confidence interval. On the contrary, the driest regions did not register satisfactory results but the estimation of total volumes with GUO-5P showed differences below 12% or even lower in dry sub-humid regions. It was also evident that a set of goodness-of-fit measures should be used in order to provide accuracy and robustness to the application of the hydrological model and the use of a specific one largely depends on the aim of the research.

3. Method. Theory/calculation

The proposed methodology is summarized in Fig. 3. The first step of the methodology is the generation of local climate scenarios. We considered two scenarios according to the two considered hypotheses of warming in Spain (1.5 and 3.0 °C). These constraints are used to select the series of the RCM simulations. The outputs of these RCMs are corrected and adapted to the local conditions by using three statistical techniques under two different approaches (delta change and bias correction). The local future meteorological scenarios are propagated with four hydrological balance models. Finally, the impact of climate change was assessed by comparing the historical streamflow in the reference period with the future projections. The different combinations of RCMs, statistical techniques and correction approaches, and hydrological models allow us to quantify the uncertainty of the climate change signal.

3.1. Generation of future local climate change scenarios

The future results have been selected from the RCM simulations under two different hypotheses of future levels of warming in

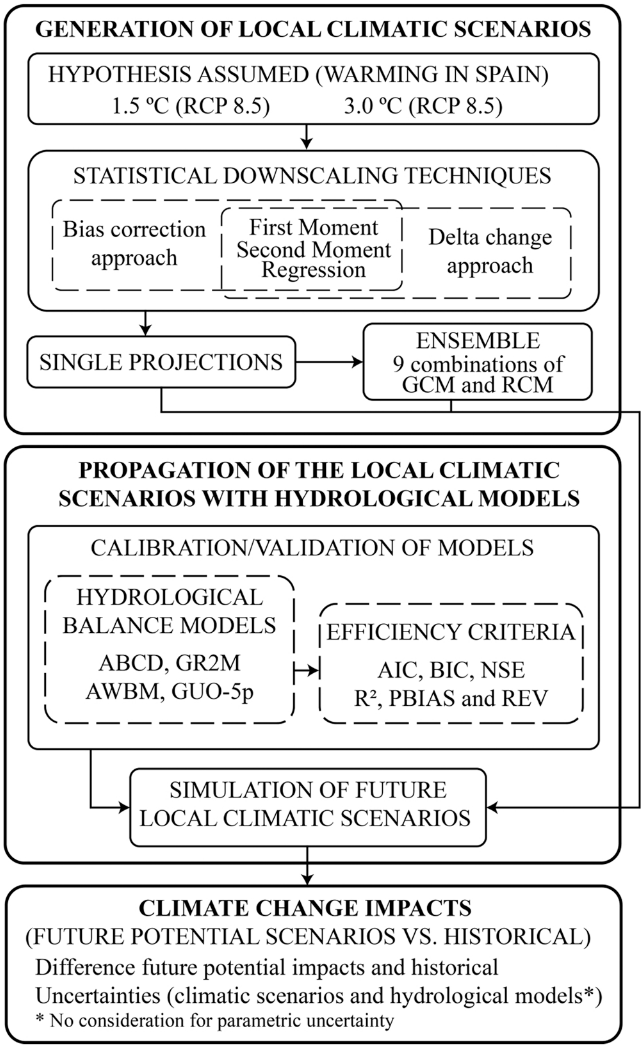

Fig. 3. Flowchart of the methodology.

Spain, 1.5 °C and 3 °C. Spain, due to its location and hydro-meteorological conditions, is one of the most vulnerable countries within the EU. The study covers areas with different climate conditions within Spain. The assessment of the impact of climate change s and its uncertainty under different scenarios (1.5 and 3.0 °C) is a key task to be undertaken before the study of adaptation and mitigation strategies. For each RCM we selected series simulated for two future 30-year periods, which respectively fulfill the hypotheses of 1.5 and 3.0 °C of warming within Spain for the scenario RCP 8.5. Those increments in mean temperature were calculated with respect to the control simulation series of the RCMs for the reference period (1976–2005). We obtained different 30 year future horizons for each RCM but these periods represent the same hypothesis of warming (see Table 2). The historical and control simulation series from RCMs in the reference period (1976–2005) and the future simulations of RCMs for the periods shown in Table 2 were used to generate the potential future scenarios by applying the described statistical downscaling procedure. For the selected RCMs the mean temperature in the reference period varies from 10.5 to 12.6 °C for Spain. The maximum differences between the future horizons for the 1.5 and 3.0 °C warming hypotheses in the different RCMs are for 6 years and 10 years respectively (see Table 2).

The GROUND tool (Collados-Lara et al., 2020b) is used to generate multiple future local climate change scenarios by applying different statistical downscaling techniques: first moment correction, first and second moment correction, and regression. In the first moment correction technique, the transformation function only tries to improve the approximation to the mean values (Pulido-Velazquez et al., 2015). The second moment correction technique also tries to provide a good approximation for the standard deviation (Collados-Lara et al., 2018a). The regression technique defines the transformation function by adjusting a regression model (Chen et al., 2014). These techniques are used under two different conceptual approaches (delta change and bias correction) (Räty et al., 2014). In the delta change approach, the transformation function is obtained by using the future and control RCM simulations. It assumes that the changes described by this transformation function can be directly applied to the historical series to obtain potential future local series. The bias correction approach defines the transformation function from the historical series and control simulation series. The objective is to obtain a corrected control simulation series where the statistics are similar to the historical ones in the reference period. This function can also be applied to correct the future RCM simulations to obtain potential future local series. Different correction techniques or statistical methods can be applied for each approach (delta change and bias correction) (Table 3). The combination of approach and correction technique give rise to six potential scenarios for each available RCM simulation nested to a GCM, which produce a total number of 54 potential future climate change scenarios for each combination of basin, which is the scale used to generate the potential future scenarios, and warming scenarios.

In the case of the bias correction approach we also obtain corrected control simulation for the reference period. The mean annual values of precipitation and temperature of the control simulations before and after correction, and historical series in the reference period (1976–2005) are shown in Appendix G of the Supplementary Material.

3.2. *Propagation of climate scenarios with the selected hydrological balance models*

Four lumped conceptual hydrological models (ABCD, GR2M, AWBM and GUO-5p) defined by using different conceptual approaches (Fig. 4) have been explored. In each of the selected basins, we assessed the ability of these lumped conceptual hydrological models to reproduce the historical dynamic of the resources. This was assessed in accordance with different statistical indices: AIC (Akaike, 1973, 1974), BIC (Fabozzi et al., 2014), NSE (Nash and Sutcliffe, 1970), R^2 (Pearson, 1895), PBIAS (Gupta et al., 1999), and REV (Karpouzos et al. 2011).

We agreed the selection of the four water balance models after a thorough literature review of the performance of these models in different climate regions in Europe. In fact, Pellicer-Martinez and Martinez-Paz (2015) found that the ABCD model had the best performance in southern Spain. Wriedtand and Bouraoiu (2009) used GR2M model and obtained high NSE in the northern half of the Iberian Peninsula and in French and German basins. AWBM performed well in the French Alps reaching a NSE value of 0.79 (Yu and Zhu, 2015). Guo-5p is particularly recommended in humid and semi-humid regions (Guo, 1995). The ABCD 4-parameter model (Thomas Jr., 1981) is an example of simple hydrologic model for simulating streamflow. It consists of two zones: the non-saturated zone (NSZ) and the saturated zone (SZ). Precipitation (P) is divided into evapotranspiration (ET) and drainage into aquifers or rivers and the excess becomes surface run-off (Qs) or drainage run-off (Qg). The GR2M model (Makhlouf and Michel, 1994) was developed by the CEMAGREF (Centre of Agricultural and Environmental Research of France). P is divided into run-off through two equations (production and transfer functions) and is distributed between S and G. The latter is considered to have limited capacity. The AWBM model (Boughton, 2009) has three surface storage tanks (S1, S2 and S3) and the water balance is assessed separately. Qs is

Table 2
30-year future horizons in which the climate model simulations fulfill the warming constraints (1.5 °C and 3 °C) in Spain.

RCM	Nested to GCM	Mean temperature 1976–2005	Future horizon for 1.5 °C warming	Future horizon for 3.0 °C warming
CCLM4-8-17	CNRM-CM5	11.6	2030–2059	2060–2089
CCLM4-8-17	EC-EARTH	11.9	2028–2057	2056–2085
CCLM4-8-17	MPI-ESM-LR	12.6	2025–2054	2056–2085
HIRHAM5	EC-EARTH	11.9	2034–2063	2064–2093
RACMO22E	EC-EARTH	10.5	2027–2056	2058–2087
RCA4	CNRM-CM5	11.1	2031–2060	2062–2091
RCA4	EC-EARTH	11.0	2027–2056	2056–2085
RCA4	MPI-ESM-LR	12.2	2027–2056	2056–2085
WRF331F	IPSL-CM5A-MR	11.7	2027–2056	2054–2083

Table 3
Approaches and statistical methods used to obtain the transformation function to generate local climate change scenarios.

Transformation function to correct RCMs				
Information used/approach		Statistical method/Correction techniques		
Delta change	Bias correction	First moment correction	First and second moment correction	Regression
Using control and future simulation series	Using historical and control simulation series	Correction of the mean values	Correction of the mean and standard deviation values	Fit of a regression model (linear, quadratic)

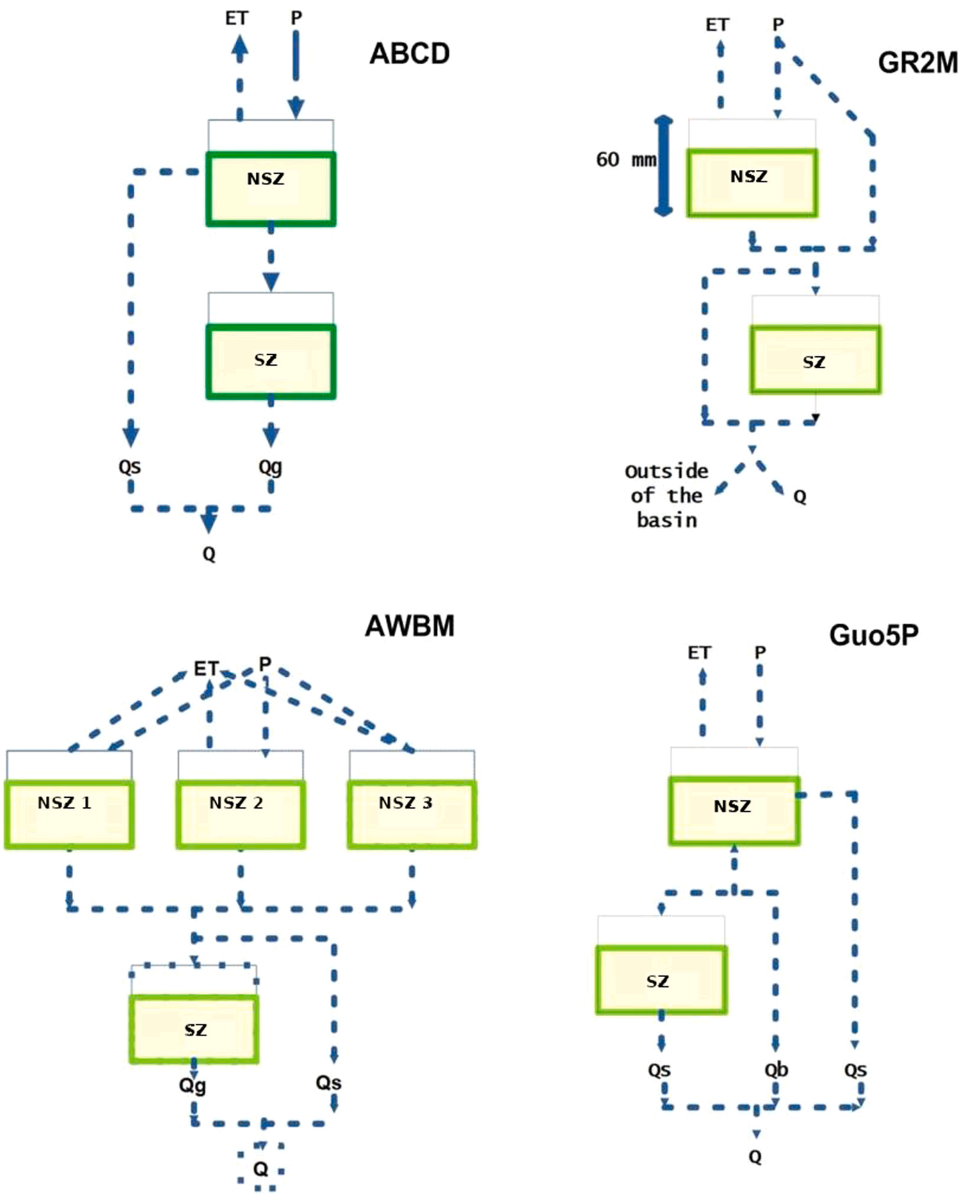

Fig. 4. Conceptual approach used by the different hydrological models.

obtained from one part of the surplus of the tanks, whilst the other part is drained to G, which is converted into Qg. GUO-5p (Xiong and Guo, 1999) is particularly used in humid and sub-humid regions. Q is obtained adding Qs, Qg and the subsurface run-off (Qb). The 4 models considered are satisfactory (ABCD, GR2M, AWBM, GUO-5p) in all the basins, in accordance with the widely used criteria proposed by Moriasi et al. (2007) (based on the NSE, R2, and PBIAS values), and we also carried out an uncertainty analysis of their

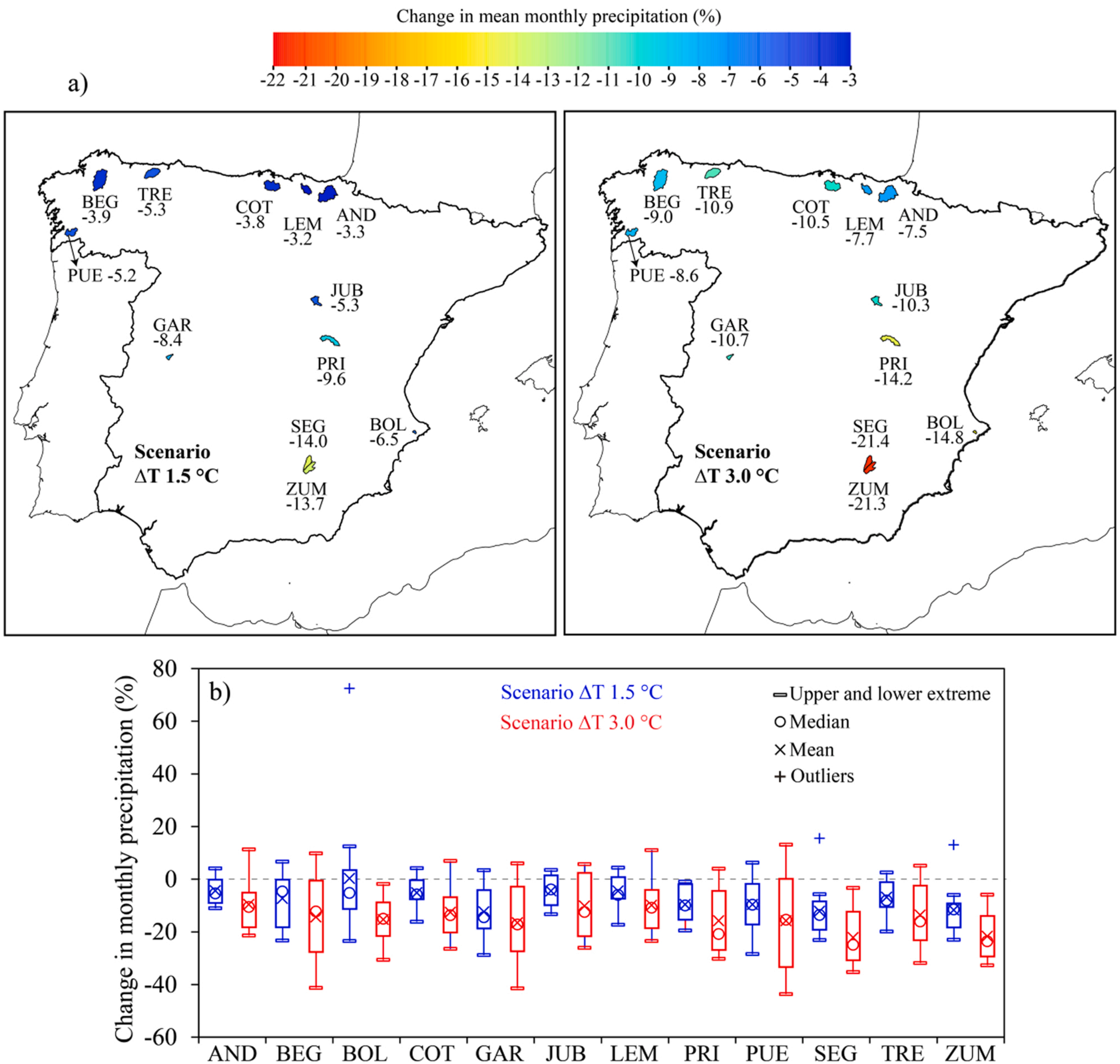

Fig. 5. Average change (%) in monthly precipitation in each basin for the scenarios 1.5 and 3.0 °C global warming in Spain) (a); box whisker of the changes (%) in monthly precipitation for the warming scenarios 1.5 °C (blue) and 3 °C (red) (b). The comparison is done with the historical field data for the reference period 1976–2005.

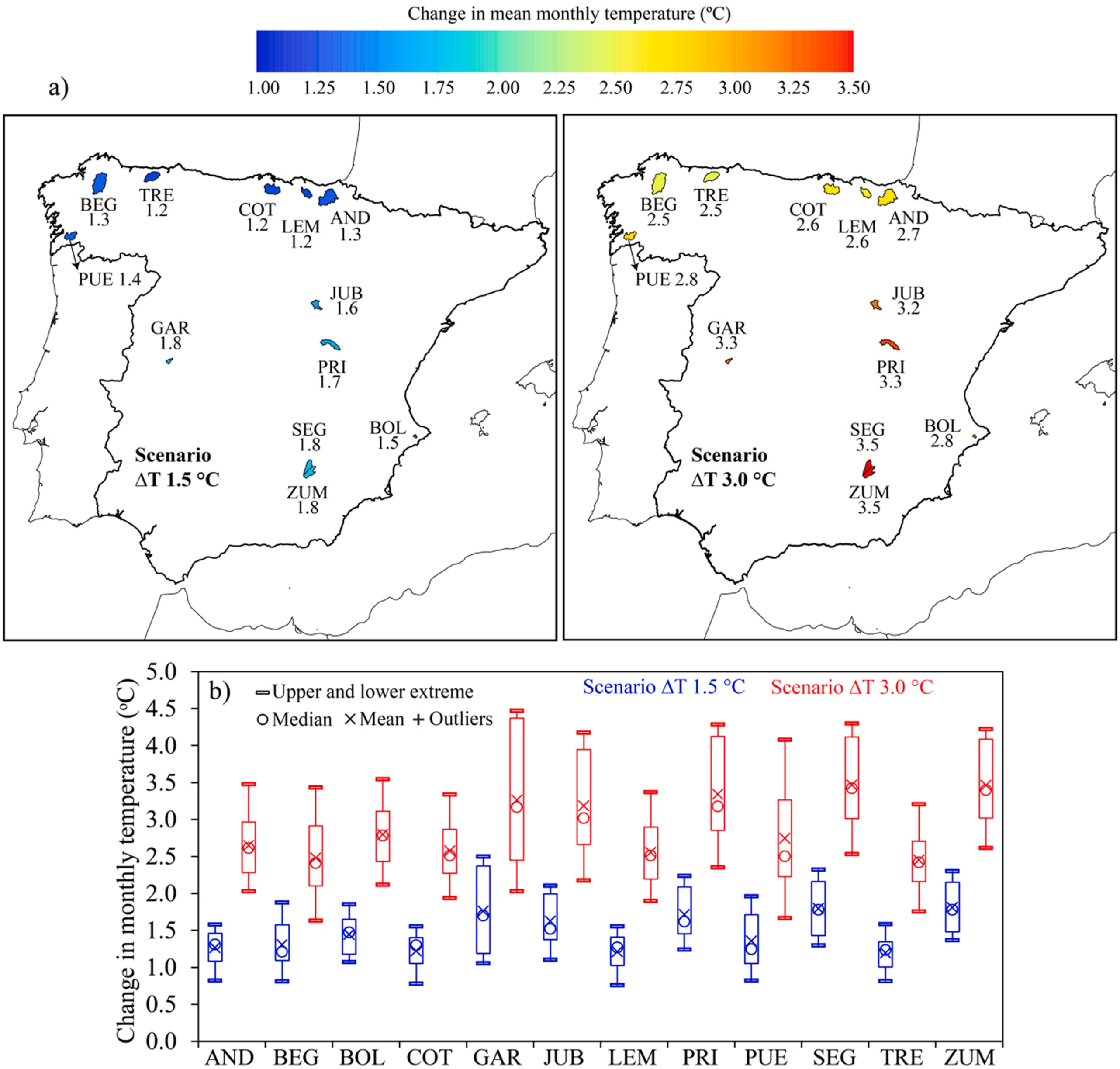

Fig. 6. Changes in mean monthly temperatures in each basin for the scenarios 1.5 and 3.0 °C global warming in Spain (a); box whisker of the changes in monthly mean temperature for the warming scenarios 1.5 °C (blue) and 3 °C (red) (b). The comparison is done with the historical field data for the reference period 1976–2005.

results.

The hydrological balance models were used to simulate the generated future local climate scenarios. For each future projection, the hydrological impact is assessed by comparing the output of the hydrological balance models obtained by simulating the observed historical climate in the reference period with the output generated with the future climate series. It is the only way to perform these analyses when the delta change approach is applied, because it does not generate corrected simulation series for the reference period. For this reason, in order to make the impact assessment comparable in both approaches (delta change and bias correction), we have also compared the future simulated flows with the historical simulated series. Nevertheless, the differences between observed climate series and the corrected climate simulation for the reference period in the bias correction approaches are minimal (see Appendix G).

3.3. Analyses of climate change impacts and its uncertainties

We used the propagation of the future potential local scenarios by using the hydrological models to analyze the hydrological impact of climate change, taking into account the differences between the potential future hydrology and the historical ones. The uncertainty of the impact of climate change was analyzed taking into account the component due to the considered potential local scenarios and due to the applied hydrological models (structural uncertainty). It was studied taking into account the variability of climate change impact results introduced by the scenarios and by their propagation. We have used box whisker plots to summarize the impacts and their uncertainty. It shows the mean and median values, the upper and lower extremes, and outliers. The lower extremes are defined as Q1–1.5ICR and the upper extreme as Q3 + 1.5ICR, where Q1 and Q3 are the first and third quartile and ICR is the interquartile range, which is calculated as the difference between Q3 and Q1. The values below or above the extreme values are considered outliers.

4. Results and discussion

4.1. Local climate change scenarios

From the selected simulations (Tables 1 and 2), we obtained the average change in monthly precipitation (in %, see Fig. 5) and temperature (in °C, see Fig. 6) within each basin. In general, the highest changes will appear in the southern basins. The reduction in the precipitation moves from 3.2% (LEM basin) to a maximum around 21.5% (21.4% in SEG basin and 21.3% in ZUM) in the scenario of 3.0 °C. In this 3 °C global warming scenario, the increase in temperature goes from 2.5 °C (BEG and TRE basins) to 3.5 °C (SEG and ZUM basins). The box whiskers of the monthly changes in precipitation and temperature Fig. 7 show the highest interquartile differences in the 3 °C warming scenario in both variables (temperature and precipitation) in all the basins. The highest interquartile ranges in these 3 °C scenarios appear in the basins located in the humid western area (PUE, BEG, TRE and GAR).

We have also analyzed the global seasonality of the changes in precipitation and temperature that correspond to the selected RCM simulations (Figs. 8 and 9). In the 3 °C warming scenario, all the months show a reduction of mean precipitation, with the exception of February (see Fig. 8). The percentages of reduction increase during the summer months. This is consistent with previous studies, which projected a future decrease in summer precipitation over southern Europe (Matte et al., 2019). The highest standard deviations of the monthly changes are also expected during the summer months.

The monthly mean changes in temperature are also higher in the 3 °C warming scenario, with the maximum during the summer, but also with significant increases in the autumn (see Fig. 8). The highest standard deviations of the monthly changes are also observed during the summer and autumn.

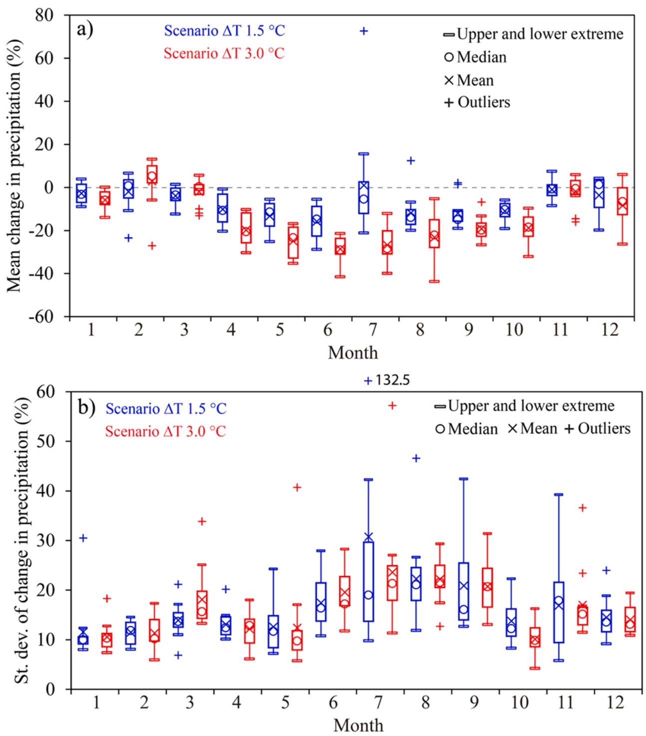

Fig. 7. Box whiskers to summarize the monthly mean (a) and standard deviation (b) of the change (%) in precipitation within the mean year for the 2 hypotheses: 1.5 °C (in blue) and 3 °C (in red) of global warming in Spain. Results derived from all the projections (54 projections) for each basin.

In this paper we have considered different sources of uncertainty in the generation of local climate change scenarios: climate model simulations (including both different GCMs and RCMS nested to them), and downscaling techniques (including different statistical correction methods [first moment, second moment, and regression] under the delta change and the bias correction assumption (Section 4.3)). As an example, we show the multiple series generated in one of the basins (SEG) taking into account the cited sources of uncertainties (Fig. 9). The uncertainty related to the precipitation in the potential scenarios is higher than the uncertainty related to temperature.

We have also represented the ensemble series. In the literature we can find many examples in which the assessment of future impact is limited to the propagation of some ensemble scenarios (Pulido-Velazquez et al., 2018a; Escriva-Bou et al., 2017). These ensemble scenarios are more representative of the potentially expected future conditions than the individual ones (Pulido-Velazquez et al., 2015; AEMeT, 2009). Nevertheless, their use rather than the use of the simulation of multiple individual scenarios will produce a loss of information about the uncertainty of the impact of future climate conditions. In the SEG basin, for the warming scenarios 1.5 and 3.0 ℃, the mean reduction of mean monthly precipitation are respectively 10.3 and 15.7 mm and the increment of temperature is1.8 and 3.5 ℃ respectively (see Fig. 9).

4.2. Propagation of climate scenarios with the selected hydrological balance models

The hydrological models ABCD, GR2M, AWBM and GUO-5p that are satisfactory (Table 4), will be employed to simulate the generated future local climate scenarios in each basin. We assume that the parameters of the hydrological models, which are calibrated and validated in the historical period to propagate the impact of climate change on hydrology, will stay invariant in the future. Therefore, we do not consider a potential retroaction of LCLU due to climate change. Under this assumption those models with a good performance in the historical period will be also be good for simulating the hydrological impact in future climate scenarios. According to Moriasi et al., (2007) a model gives a very good performance if the classification sum value is above 7, good if it is between 5 and 7 and satisfactory when it is above 3. An unsatisfactory model does not reach 3 values. A detailed explanation of the goodness-of-fit tests used is shown in the Supplementary Material. The best performances are reached in humid watersheds for all the models, though there are marked changes between results in calibration can be observed (1980–1995) and validation (1995–2010) stages depending on the hydrological model selected. Each basin has, at least one model with satisfactory results but the GAR, JUB and ZUM provide lowest value in the ABCD or/and AWBM models. GR2M provides better results in nearly all the watersheds than previous models but GUO-5P has greater stability, on average, with the highest grading (9.0) in several basins, both humid and semi-arid ones. Following the recommendations of Arnold et al. (2012), the selected calibration period includes dry and wet periods to ensure that it reflects the range of conditions under which the model is expected to operate.

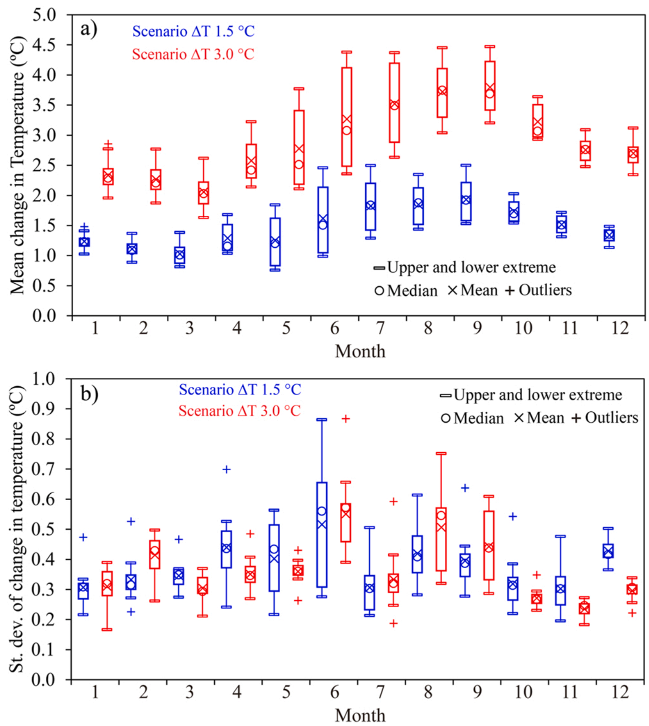

Fig. 8. Box whiskers to summarize the mean (a) and standard deviation (b) of the monthly change (absolute) in temperature within the mean year for the 2 hypotheses: 1.5 ℃ (in blue and 3 ℃ (in red) of global warming in continental Spain. Results derived from all the projections (54 projections) for each basin.

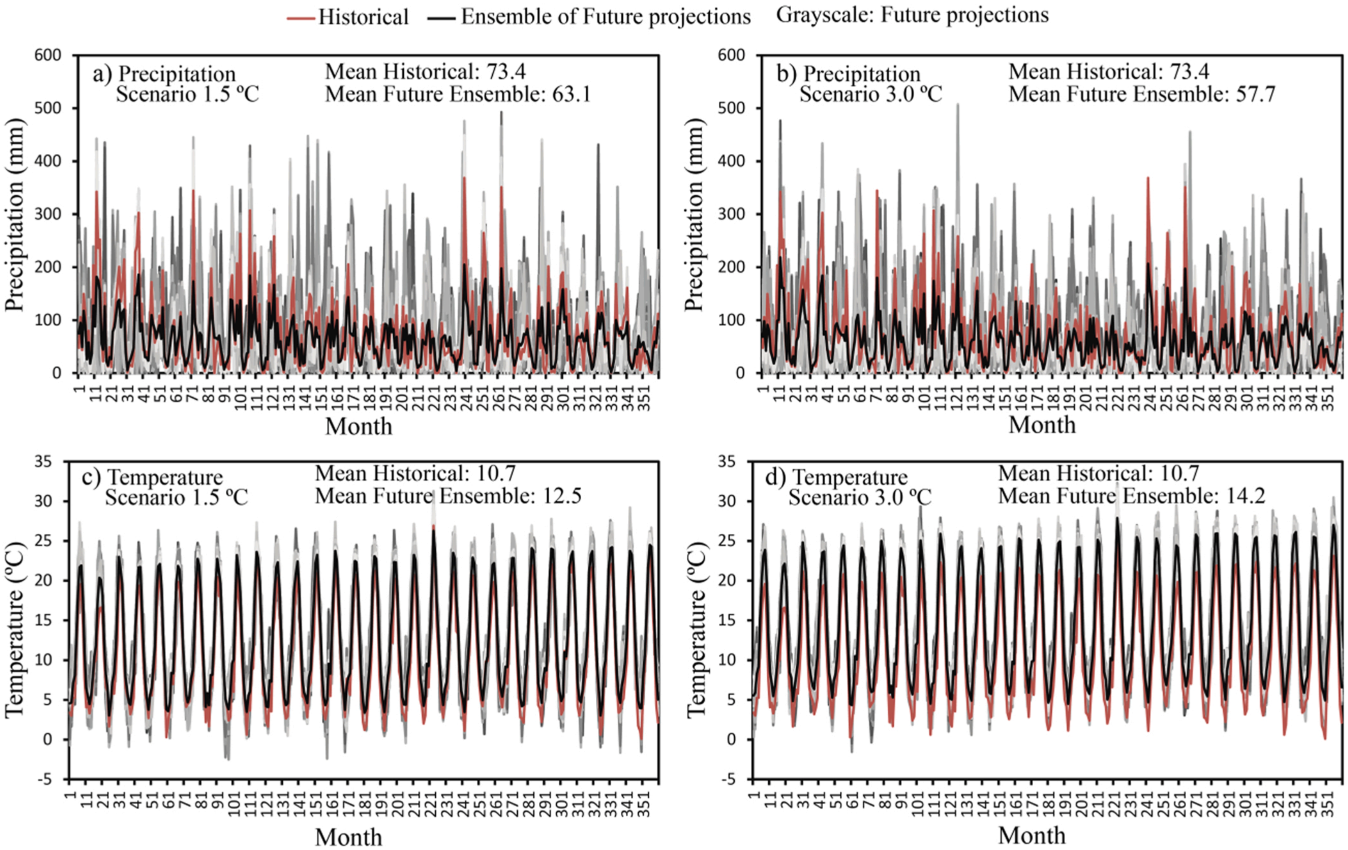

Fig. 9. Multiple monthly climate series generated and their ensemble in the SEG basin for the 2 hypotheses: 1.5 °C [precipitation (a) and temperature(c)] and 3 °C [precipitation (b) and temperature (d)] of global warming in Spain.

Table 4
Summary of performance of the selected water models according to Moriasi et al. (2007) in calibration (1980–1995) and validation (1995–2010) periods.

	Area (km^2)	AI_U	Geology	ABCD		AWBM		GR2M		GUO5P		Average	
				Calib.	Valid.	Calib.	Valid.	Calib.	Valid.	Calib.	Valid.	Calib.	Valid.
AND	778.49	2.15	Limestone	5.00	8.00	4.00	6.00	2.00	8.00	5.00	9.00	4.00	7.75
BEG	836.89	2.07	Siliceous	8.00	7.00	4.00	5.00	9.00	5.00	9.00	5.00	7.50	5.50
BOL	29.23	0.54	Limestone	2.00	4.00	6.00	7.00	4.00	2.00	7.00	7.00	4.75	5.00
COT	488.22	1.65	Limestone	9.00	2.00	7.00	4.00	9.00	5.00	9.00	5.00	8.50	4.00
GAR	69.92	1.02	Limestone	7.00	5.00	0.00	3.00	7.00	2.00	1.00	4.00	3.75	3.50
JUB	207.66	0.65	Limestone	0.00	5.00	9.00	4.00	7.00	9.00	9.00	7.00	6.25	6.25
LEM	252.58	1.96	Limestone	8.00	7.00	7.00	9.00	6.00	7.00	6.00	9.00	6.75	8.00
PRI	328.16	1.19	Limestone	5.00	7.00	7.00	8.00	9.00	7.00	7.00	9.00	7.00	7.75
PUE	263.85	2.20	Siliceous	4.00	4.00	2.00	5.00	9.00	4.00	3.00	4.00	4.50	4.25
SEG	232.89	0.88	Limestone	3.00	5.00	5.00	2.00	9.00	6.00	9.00	9.00	6.50	5.50
TRE	413.54	1.84	Siliceous	2.00	8.00	5.00	2.00	9.00	2.00	9.00	8.00	6.25	5.00
ZUM	266.03	0.79	Limestone	3.00	0.00	5.00	0.00	7.00	4.00	9.00	6.00	6.00	2.50
Average				5.50	5.17	5.50	4.58	6.63	5.08	6.63	6.83	–	–

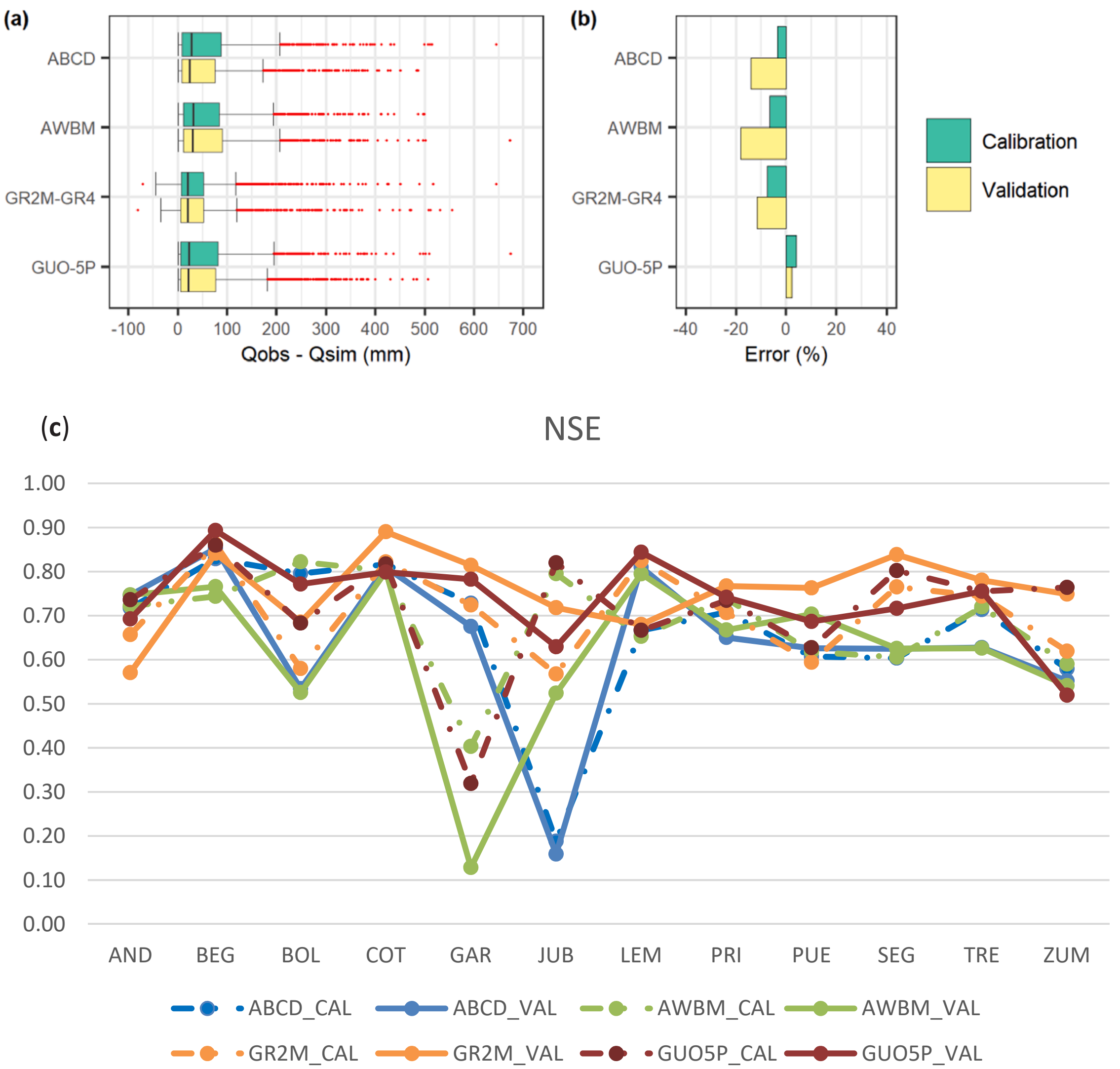

Fig. 10. Uncertainty analysis of the simulated values depending on the hydrological model (10a and 10b) and the studied basin (10c).

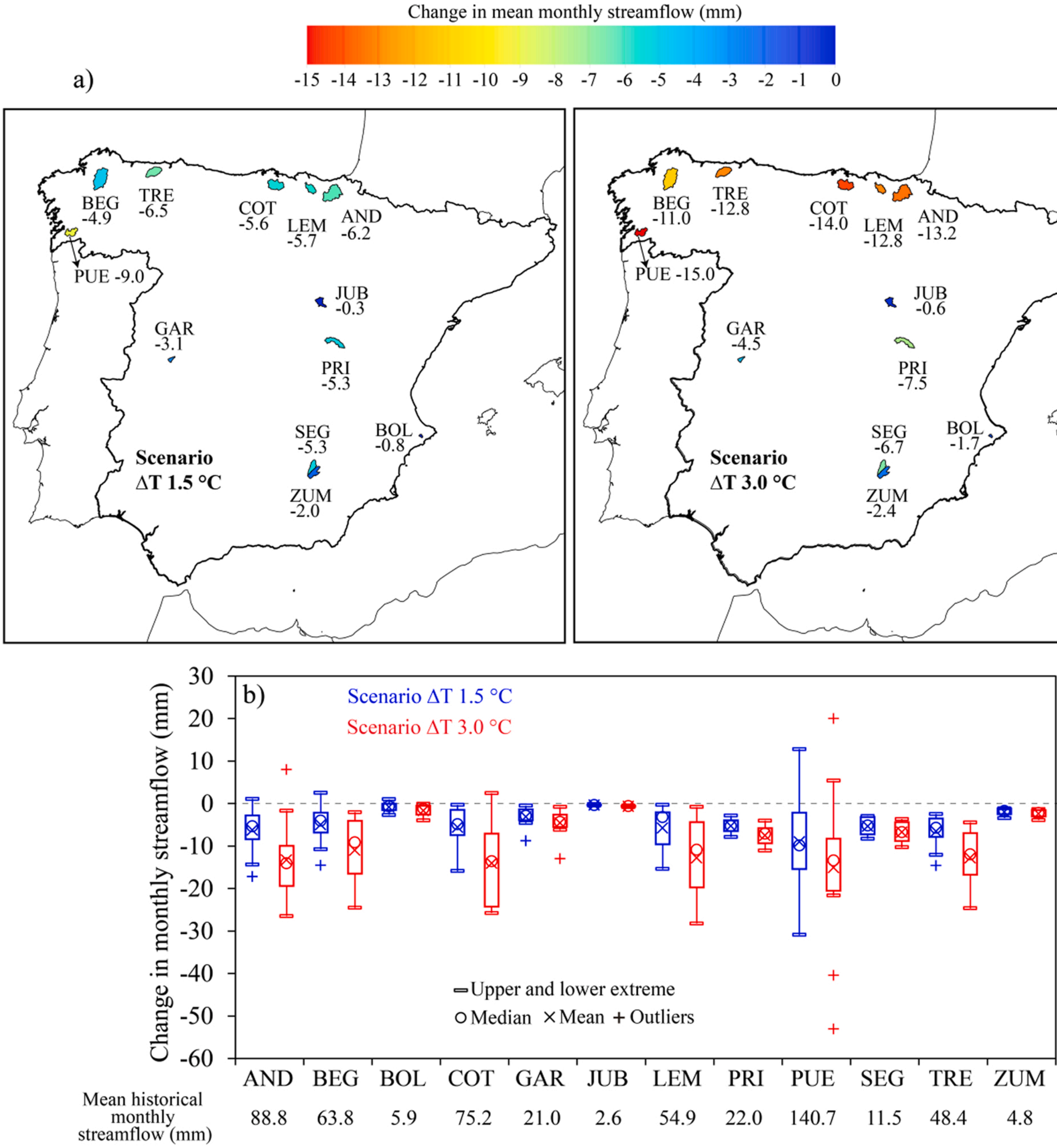

Fig. 11. Average changes in monthly streamflow values (mm) for each basin for the 1.5 and 3.0 °C warming scenarios in Spain (a); box whisker of the monthly changes in streamflow for the scenarios 1.5 °C (blue) and 3 °C (red) (b).

Furthermore, an uncertainty analysis has been carried out with the values obtained differentiating between models and basins (Fig. 10). The box-whiskers in Fig. 10a assess the error in simulated streamflow concerning the hydrological model. The results highlight the wide climatological variability in Spain. Although the median and length of boxes are pretty similar for all the models except the GR2M, the numerous outliers have some sort of normality effect as their extension in graphics is even greater than 50% of the sample. These outliers can be explained because the models do not adequately represent the peak flows, as can be seen in the Supplementary Material, so the highest maximums of streamflow observed exceed simulated streamflow peaks. In spite of these outliers, total error in predicting streamflow (Fig. 10b) in calibration and validation periods is below 20% in the four models and it is usually negative (except fortheGUO5p model), indicating a general over prediction. Furthermore, the GR2M model shrinks its length by nearly 50% compared to the others and it is the only one that appears to show some over prediction, though often much lower than the examples on the opposite side.

Fig. 10c represents the variation of NSE, both in calibration and validation, for all the studied basins. GAR and JUB show, in general, the worst results due to their aridity, reaching values of below 0.15 with the ABCD and AWBM models. Only the GR2M provides satisfactory results in both stages of all the basins, with NSE values over 0.55. GUO5P shows similar homogeneity with an average NSE of 0.73, despite the 0.30 value in the GAR basin for calibration. No significant differences were found between the calibration and validation periods.

The results of these simulations will be used to analyze the hydrological impact of climate change and its uncertainties, taking into account the differences between the potential future hydrology and the historical ones.

4.3. Analyses of climate change impact and its uncertainties

The use of different hydrological models to propagate the scenarios will allow us to consider in climate change impact assessment, the structural uncertainty coming from different conceptual hydrological models in addition to the uncertainty coming from the local climate scenarios (Mattots et al., 2019).

In this section we have analyzed the changes of future potential streamflow in mm compared to the historical values. These mm units have allowed us to compare values without the influence of the basin size. We have analyzed the variability by basin, months of the year, RCMs, and hydrological model used. Note that the influence of the correction approach or the statistical technique applied to RCMs is low. For example, considering the AND basin, the hydrological model ABCD and the scenario 1.5 °C the variation coefficient of the mean streamflow for each RCM with respect to the correction approach/technique applied varies from 0.6% to 1.9%. For the rest of cases these values are similar.

Fig. 11 summarises the monthly impact on the different basins that show a significant spatial heterogeneity. As previous studies in Spain have already indicated, the magnitude of this impact will depend on the level of warming and the geographical characteristics of each basin (Rasilla et al., 2013). The mean monthly historical streamflow in the basin covers a wide range of values, between 2.6 mm in the JUB basin and 140.7 mm in the PUE basin (Fig. 11b). The highest reductions in mm appear in the wetter basins located in northern Spain (see Fig. 11b), with a maximum of 15.0 mm in the PUE basin for the 3.0 °C warming scenario, with the minimum reduction being obtained in the southern basin (2.4 mm in ZUM). The variability of the potential changes (in mm) is also clearly higher in the northern basins, especially for the 3.0 °C scenario. However, the southern basins show the higher relative changes (in %) as we have also shown for precipitation and temperature.

Fig. 12 summarises the results within the 12 basins derived from all the projections (54 projections), and rainfall-recharge models (4 propagations) in terms of monthly changes in a mean year. In general, the higher mean reductions and variability of the monthly streamflow values are associated to the warming scenario of 3.0 °C (Fig. 12a). It gives us a global idea of the temporal distribution and/

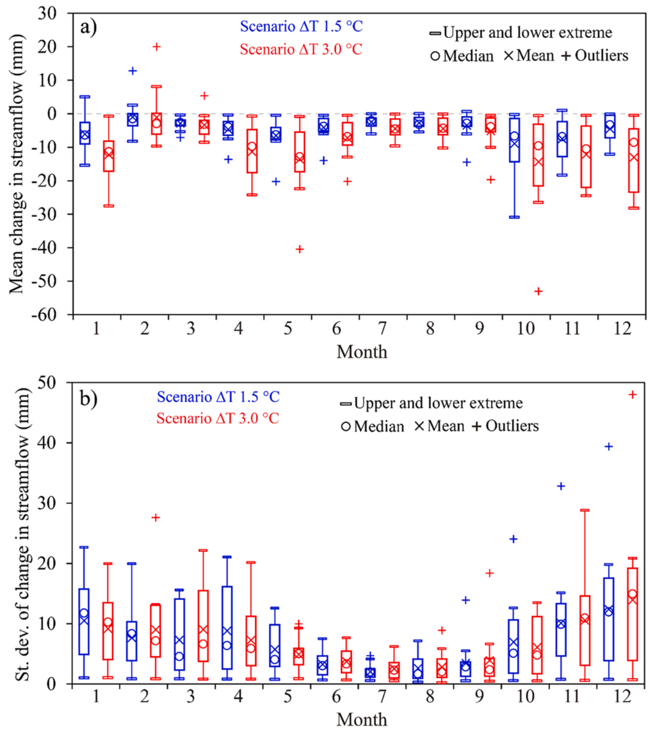

Fig. 12. Monthly Box whiskers to summarize (including results in the 12 basins) monthly mean (a) and standard deviation (b) of the absolute change in the streamflow within the mean year for the warming scenarios 1.5 °C (blue) and 3 °C (red).

or seasonality of the impact of climate change. The maximum streamflow reductions appear in autumn. It contributes to a more pronounced low water level period in the summer as indicated in previous studies in Spain (Rasilla et al., 2013; Morán-Tejeda et al., 2014). Significant reductions are also observed during the spring, with the smallest changes occurring in the summer months. The highest values of changes in standard deviation are also obtained during the autumn months and the smallest in the summer months (Fig. 12b).

The estimated impact will depend on the combined influence of the different selected RCMs, the approach (delta change or bias correction) and correction techniques applied to generate the local climate models and the hydrological models used to propagate the impact to the streamflow. Previous studies have shown that the variability in the climate variable due to RCMs is higher than the variability due to correction approaches (Collados-Lara et al., 2018a; Pardo-Igúzquiza et al., 2019). In this study we have also tried to analyze the impact on the streamflow introduced by the selected RCMs (Fig. 13) and hydrological models (Fig. 14) for the two considered warming scenarios (3 °C and 1.5 °C). The discussion will be focused on the 3 °C scenarios, in which the highest impact will be observed in all the cases.

Fig. 13 summarises the impact obtained for the 12 basins derived from all the correction techniques and rainfall-recharge models (4 propagations) when we fix a RCM model. The differences between the estimated mean impacts depending on the selected RCM are significant, with values that move from − 4.4 mm (RCM5) to − 10.7 mm (RCM 4), in the most pessimistic scenario (the 3 °C warming scenario). The interquartile range also shows significant differences, with the smallest range of 3.7 mm (RCM 5) and the greatest of a maximum of 10.3 mm (RCM 1).

These differences on the estimated impact depending on the hydrological models are significantly smaller, they move from − 8.0 to 9.1 mm for the warming scenario of 3.0 °C (Fig. 14). The changes in the interquartile ranges are also significantly smaller, and move from 6.5 mm in the smallest (GR2M-GR4) to 8.9 mm in the greatest (ABCD).

Similar methodologies and consistent results were obtained in the assessment of climate change impact on precipitation (Matte et al., 2019) and streamflow (Rasilla et al., 2013; Morán-Tejeda et al., 2014) in previous studies in Spanish basins. The main novelty of this paper is that we also assess the uncertainty of the potential impact coming from different sources. We have considered different statistical correction techniques of climate model simulations with two approaches (delta change and bias correction), results from nine RCM models and four hydrological model structures. It has allowed us to assess monthly streamflow changes and uncertainty bounds for the two selected warming scenarios.

The uncertainty analysis showed that the highest variability and uncertainties related to climate change impact assessment on streamflow are due to the RCM projections, with the influence of the employed downscaling techniques and hydrological models used being significantly smaller.

5. Conclusions

In this study we have analyzed the impact of climate change on water resources in 12 Spanish basins, in which sufficiently long monthly historical streamflow measurements (monthly series longer than 30 years) are available to calibrate rainfall-runoff models for near-natural conditions. The 12 basins have been selected to cover different climate conditions identified in Spain with an aridity index of above 0.5. Local climate scenarios have been generated in accordance with the available RCM simulations in agreement with the fifth RCP scenarios defined by the IPCC. The future scenarios have been generated from the RCM simulations by assuming two hypotheses of future level of warming in Spain: 1.5 °C and 3 °C. In each of these basins, the local climate scenarios have been propagated by using 4 hydrological models (ABCD, GR2M, AWBM and GUO-5p), with a sufficient ability to reproduce the historical dynamic in accordance with different statistical indices (AIC, BIC, NSE, R2, PBIAS, and REV). The results have allowed us to assess the future potential impact on water resources, taking into account different sources of uncertainties related with local scenarios and conceptual hydrological models applied to propagate them (structural uncertainty). The impact of climate change on streamflow shows a significant spatial heterogeneity, with the highest reduction (in mm) of flow in the wetter northern basins. The seasonality of the impact is also significant, with the highest absolute reductions during autumn, and the smallest changes in absolute values in the summer months. The results also show that the highest variability and uncertainties related to the impact of these climate change s assessments are due to the RCM projections, with the influence of the downscaling techniques and hydrological models used being significantly less.

CRediT authorship contribution statement

D. Pulido-Velazquez: Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Supervision, Project administration, Funding acquisition. **A.J. Collados-Lara**: Methodology, Writing – original draft, Writing – review & editing, Supervision, Software, Data curation, Visualization. **J. Pérez-Sánchez**: Methodology, Writing – original draft, Writing – review & editing, Supervision, Data curation, Visualization. **Francisco José Segura-Méndez**: Methodology, Writing – original draft, Writing – review & editing, Supervision, Software, Data curation, Visualization. **J. Senent-Aparicio**: Methodology, Writing – original draft, Writing – review & editing, Supervision, Data curation, Visualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

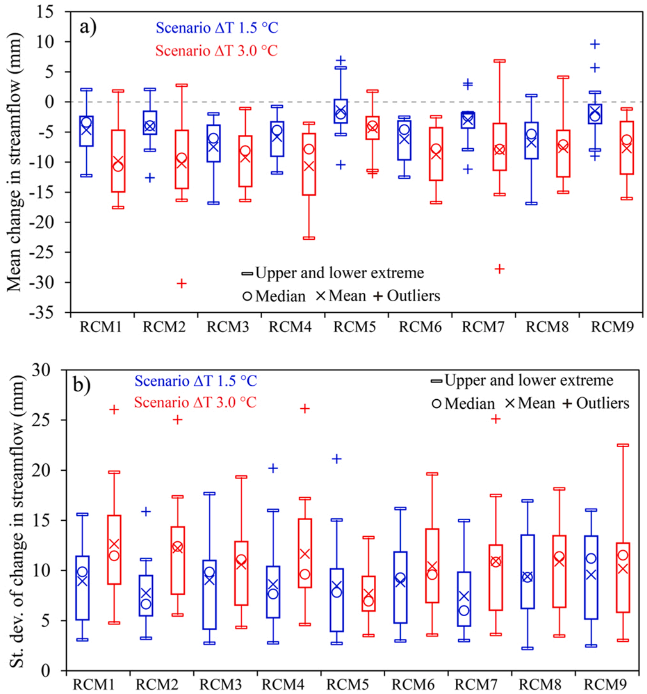

Fig. 13. Box whiskers (for each RCM represented) of the mean (a) and standard deviation (b) of the monthly change (absolute) in streamflow. Hypotheses: 1.5 °C (blue) and 3 °C (red) of warming in Spain.

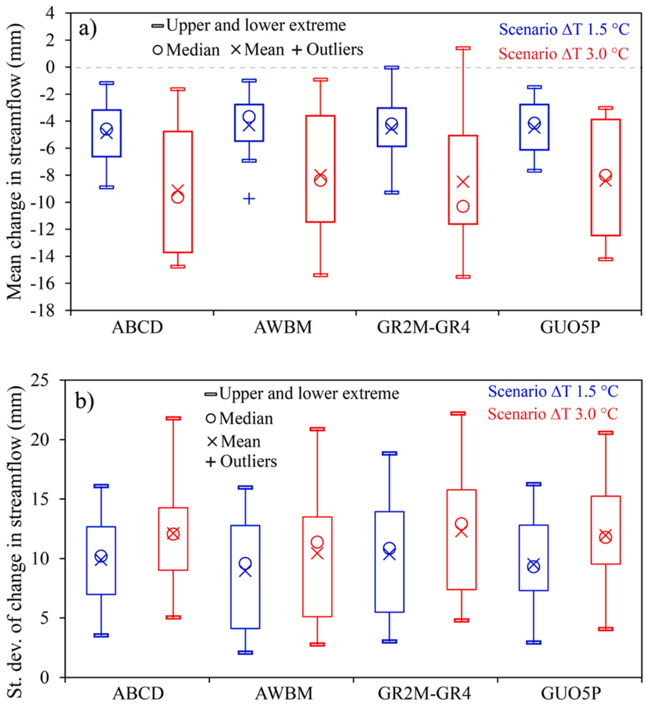

Fig. 14. Box whiskers for each rainfall-recharge model representing the mean (a) and standard deviation (b) of the monthly change (absolute) in the streamflow. Hypotheses: 1.5 °C (blue) and 3 °C (red) of global warming in Spain.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ejrh.2021.100937.

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