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Methodology based on modelling processes and the characterisation of natural flows for risk assessment and water management under the influence of climate change

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Abstract. Climate change and its possible effects on water resources has become an increasingly near threat. Therefore, the study of these impacts in highly regulated systems and those suffering extreme events is essential to deal with them effectively.

This paper responds to the need of an effective methodology that integrates the climate change projections into water planning and management to guide complex basin decision-making through drought risk and management assessments.

In this study is presented an adaptive method based on a model chain and correction processes, where the main outcomes are the impacts on future natural inflows, a drought risk indicator and the simulation of the future water storage of the water resources system (WRS) under consideration. The proposed methodology was applied in the Júcar River Basin (JRB) due to its complexity and the multiannual drought events it goes through. The results shown a decreasing tendency of future inflows to the basin, and the drought risk indicator shows a high probability (≈ 80%) of being under 50% of total capacity of the WRS in the near future, but the uncertainty is considerable from the middle century onwards, indicating that an improvement in the skill of climate projections is required.

Thus, this paper also highlights the difficulties of developing this type of methods, since the conclusions on climate change impact assessment depend on partial decisions taken during the methodological processes. However, the main results call for action in the JRB and the tool developed can be considered as a feasible option to facilitate and support decision-making in future water planning and management.

1. Introduction

The studies related to the possible effects of climate change on social, environmental and economic frameworks have increased exponentially in recent decades. The main reason of this increasing is the need to improve the adaptability of society and the possibility to manage risks, which were recognized by governments, scientists, and decision makers at the World Climate Conference in 2009 and led to the creation of the Global Framework for Climate Services (GFCS) (Hewitt et al., 2013).

In fact, climate services have evolved over time to reach the wide variety of data that is available today, at global, continental or national level. Normally, seasonal forecasts and climate projections are freely accessible through Internet portals.

One of the most known climate service is CORDEX (Coordinated Regional Climate Downscaling Experiment, https://www.cordex.org/), an international database that provides climate projections from all over the world and also has sectoral domains, as the EURO-CORDEX domain for Europe (https://euro-cordex.net/).

However, the massive amount of data provided by these portals need an advanced knowledge to their extraction. In this sense, some portals at continent level facilitate the process of selection of models and variables filtering them according the needs of the user (meteorological and hydrological variables, indicators, graphs, tables, etc.). For example, SWICCA (Service for Water Indicators in Climate Change Adaptation, http://swicca.eu/) is a European portal that filtered climate projections (coming from CORDEX) by the best fitting across Europe and provides a summary of their impacts in graphics, tables and maps for different space and time scales. SWICCA is a Copernicus project that offers readily available climate-impact data to speed up the workflow in climate-change adaptation of water management across Europe.

Then, each country has their own regionalised dataset, as that provided by AEMET (State Meteorological Agency in Spain), which come from the global models used in the 5th Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC, 2014). In fact, these data were used in the report developed by CEDEX (2017) about the assessment of the climate change impact on water resources and droughts in Spain, which is a reference study at national level, since it is based on the main basins of this country. The general conclusion was the future decrease of water resources and the increase in the number of droughts and their intensity in most Spanish basins.

Based on van den Hurk et al. (2016), climate services are essential to boost innovation in the water sector and increase its capacity to adapt to climate change. Hence, this big offer presents the opportunity to develop new methodologies or improve the current ones incorporating climate projections in water management by developing tools to extract useful information adapted to specific sectoral needs (Hewitt et al., 2013). However, the process of developing new methods is not easy, especially if it is for a long-term range, since anticipate responses to extreme events in a solid decision-making context for a distant future is challenging (van den Hurk et al., 2016).

In this sense, there are some issues that have to be addressed, as the correct way to handle the projections, taking into account their inherent uncertainty that normally determines its use in practice (Lemos and Rood, 2010). Some authors recommend working with the ensemble, since increasing the number of ensemble members reduce the sampling uncertainty (Collados-Lara et al., 2018; Thompson et al., 2017). On the other hand, working only with one ensemble member more fitted to the historical data in the reference period is not advisable, since the results can lead to erroneous conclusions due to the extreme values (Collados-Lara et al., 2018). Another option is differentiating between the Representative Concentration Pathways (RCP) implied in the study (Barranco et al., 2018; Marcos-Garcia et al., 2017) in order to consider the impacts related to the emission scenarios.

In addition, van den Hurk et al., 2018 ensure that there is a gap between the spatial and temporal scales of the models versus the scales needed in applications and also highlight the need of tailoring climate results to real-world applications.

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These issues, among many others, may be the reason of so little climate action is taking place despite the wider knowledge of climate change (Naustdalslid, 2011). In fact, our study was focused in the east of Spain, where the inclusion of the assessment of possible effects of climate change in the River Basin Management Plans (RBMP) is mandatory, but they are not yet considered in the decision-making. Here, there is a lack of methodology to incorporate climate projections in the RBMP, where climate change effects were assessed by reducing the natural hydrological resources of the basin in a certain percentage for the future hydrological cycles of management (6 to 18 years), based on the results of CEDEX (2010), and then using Decision Support Systems to assess the impact on the water resources system (WRS) (CHJ, 2015).

Thus, the need of an effective methodology that integrates the climate change projections in order to guide the decision-making is notable in this country and probably in many others. For this reason, we propose a methodology inspired on the work of Suárez-Almiñana et al. (2017) to integrate them in the decision process throughout a model chain, where the impacts on future river flows, and on a drought risk indicator made up of the future total water storage in the system are the main outcomes. Other important improvement of this study lies in the characterisation of future flows, where meteorological data are transformed into river flows using a hydrological model strictly adapted to the case study and different processes of bias correction.

In this case, the general methodology was adapted to the Júcar River Basin (JRB), focusing our attention in each step and trying to improve and adjust them as much as possible to the basin, which was selected because it is heavily regulated and has a high hydrological variability (typical of Mediterranean climate) that leads to face recurrent droughts of several years. Furthermore, if we take into account that these events may be more frequent and intense in the future (CEDEX, 2017; Marcos-Garcia et al., 2017), it is expected that scarcity problems will increase and early decision-making guided by a more accurate impact assessment will be needed.

To this end, the following section presents the proposed methodology, which could be generalized for many basins with similar characteristics as the study area. Next, the characteristics of the case study are detailed, as well as the results and the discussion, where all the partial decisions taken during the process are justified. Finally, the conclusion section closes the circle with the main outcomes of this study.

2. Material and methods

In this section, a distinction between the current assessment in the management of water resources and the analysis of risks was made, despite of being intimately related. In the current way, attention should be paid to the climate and its related hydrology to manage the water resources, while in the analysis way the focus is on the climate change and the variation in water resources depending on the future hydrology. Then, the environmental and socioeconomic risks related to this variation and the management of the water resources system are evaluated in a probabilistic way. In the Fig. 1 the differences and relations between these ways can be seen.

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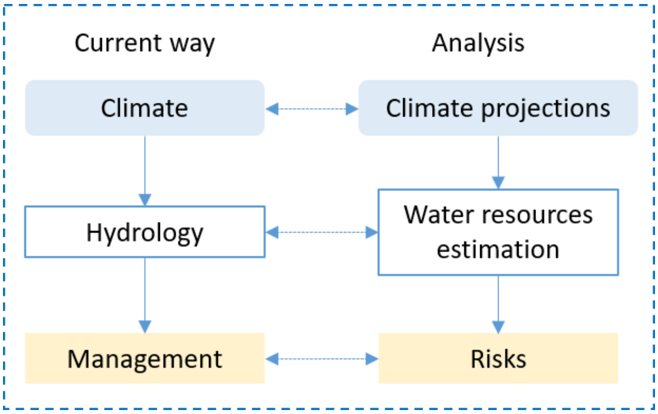

Figure 1. Distinction between management and risk assessments and their relationship.

Thus, as a methodology that integrates climate change projections in water planning and management is needed, we tried to incorporate this analysis part using an improved version of the methodology presented by Suárez-Almiñana et al. (2017), which consists in the integration of climate projections into a model chain to assess the risk of drought throughout a probabilistic indicator about the reservoir storage.

The improvement developed in this study lies in the characterization of future natural inflows and the combination of the management and risk assessments. The characterisation of flows is the conversion of meteorological data into river flows using a hydrological model and paying attention to some processes, as the bias correction. Then, these future flows are introduced in a management model to simulate the future water storage of the WRS, while their statistical properties are used in a stochastic and risk assessment models to obtain a drought risk indicator that informs about the probable evolution of the future water resources in the entire WRS, as Fig. 2 shows.

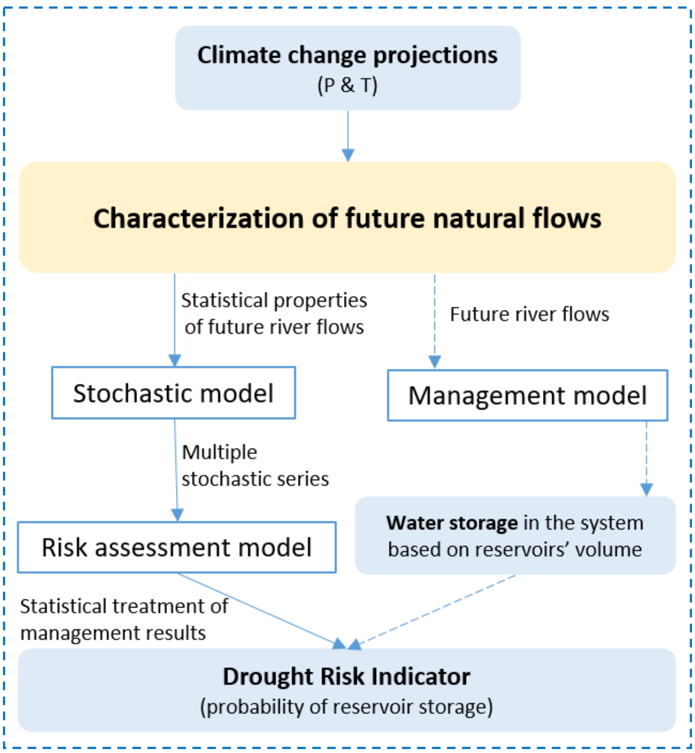

Figure 2. Methodology for the integration of climate change projections in the risk and management assessments with the aim of obtaining a drought risk indicator to support decision-making.

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The steps of this methodology are detailed in the next sections.

2.1 Climate change projections

The starting point of this methodology are the climate projections. The selection of projections and their associated variables depends on the purposes of the study and the tools available to treat them. It is also important to consider that the final results will depend to a large extent on them. Thus, this first step may be the key for the rest of the process.

Input data in the framework of water resources can be meteorological, hydrological or many types of indicators, depending on the final purposes. In this case, it was decided to start with meteorological variables instead of flows, despite the fact that the process may be simpler and shorter using hydrological variables. According to our experience, pan-European models do not have yet the capacity of representing the hydrologic characteristics of complex basins (Suárez-Almiñana et al., 2017). This may be due to the wide scale of European hydrological models, where the tight relationship between rivers and aquifers summed to the high anthropization of rivers typical of dry areas are not well represented (Suárez-Almiñana et al., 2017) unless the hydrological model is well tailored to the basin. In this way, the proposed methodology may be used in other basins by using meteorological variables.

Thus, the meteorological data provided by SWICCA was selected for this study. As it was commented in the introduction section, SWICCA is the result of a Copernicus project that had the aim of having available data related to water resources for Europe and it is managed by the Swedish Meteorological and Hydrological Institute (SMHI). Hence, it allows to download data related to water quantity and quality, precipitation (P), temperature (T), air and socioeconomics in a user-friendly format (.xlsx). Moreover, they made a good selection of RCMs for Europe and there is a huge variety of available data at different temporal and spatial scales.

2.2 Characterization of natural inflows

The characterization of flows means to convert meteorological variables into natural flows throughout a hydrological model that strictly represents the characteristics of the area of application. Thus, the hydrological model has to be well calibrated and, if the series from the reference period (either meteorological or hydrological) are not fitted to the observed values (historical local data), they may need a bias correction. In this sense, we proposed two alternatives for this characterisation (A and B) that are shown in Fig. 3. The main difference between A and B options is the correction of meteorological variables before their inclusion into the hydrological model or the correction of flows after the hydrological model run with raw meteorological variables.

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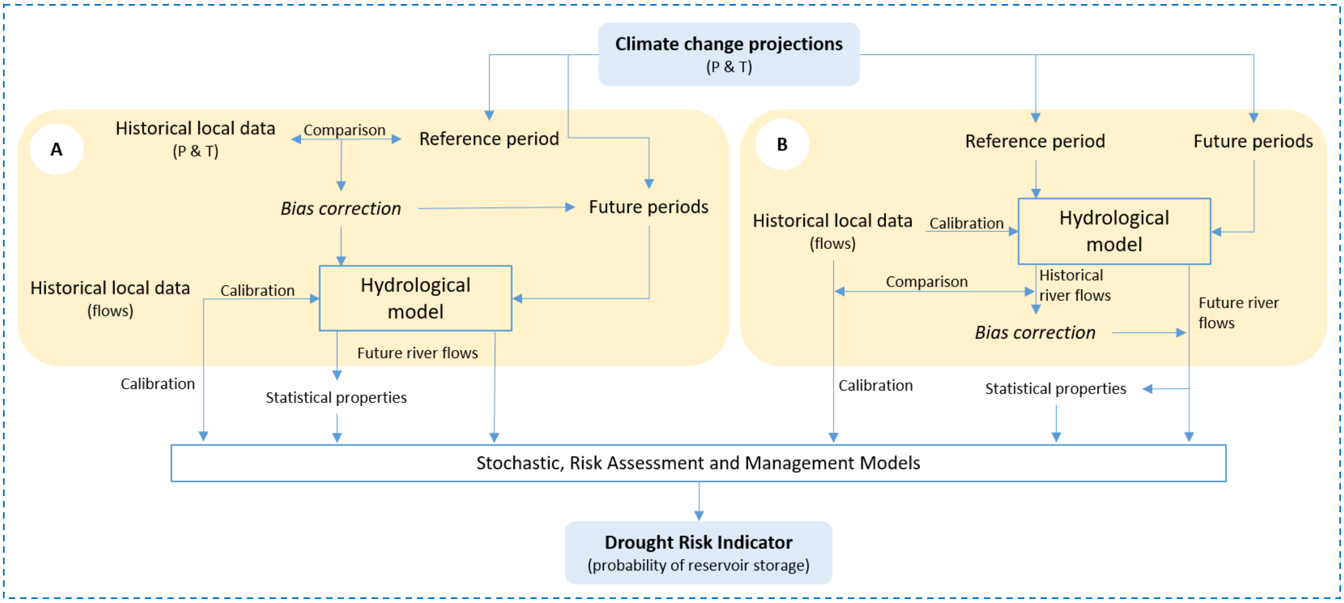

Figure 3. Detailed workflow for characterising natural flows using a bias correction before (A) and after (B) the use of the hydrological model.

In alternative A, the P and T of the reference period are bias corrected using historical local data. Then, this correction is extended to future periods and they are introduced into the hydrological model, which was previously calibrated using historical flow data. However, in B option raw P and T of the reference and future periods are introduced into the hydrological model. Afterwards, the hydrological outputs of the reference period are corrected using historical flow data and the correction is extended to the future periods.

Once future flows were extracted from A and/or B alternatives, their values and statistical properties will be used in the rest of the model chain (stochastic, risk assessment and management models).

2.2.1 Hydrological model

The hydrological model is used to evaluate the amount of water resources produced in a certain basin. In this case we resorted to the module EVALHID (Paredes-Arquiola et al., 2012) of the AQUATOOL Decision Support System Shell (DSSS) (Andreu et al., 2009, 1996). This software is used at national and international level due to its user-friendly interface and the several modules that has integrated related water resources problems, as quality and management among others. These modules are interconnected between them, an important issue to be considered in this study because the outputs of one model are the inputs of the others, as is expected in a model chain.

Thus, EVALHID has available several rainfall-runoff models with different structural complexities and parametrization, but all of them have been aggregated with semi distributed applications at the sub-basin scale (García-Romero et al., 2019; Hernández Bedolla et al., 2019; Suárez-Almiñana et al., 2017).

As input data, P and potential evapotranspiration (PET) are needed, so T has to be converted to PET before running these type of models. In addition, its calibration is essential in order to represent the characteristics of the basin. To do that, historical local flow data are needed.

2.3 Management and water allocation model

In this case, the module SIMGES (Andreu et al., 2007) of AQUATOOL DSSS was used to simulate the future management with the river flows from the previous step. Here, the schematic of the WRS can be drawn and the databases for the definition of its elements (as reservoirs, contributions, demands, returns, aquifers, channels, environmental flows, etc.) can be filled along with the operation rules and the water use priorities in using a friendly graphical interactive interface. All these aspects of the system are used to simulate the water allocation throughout an optimization algorithm for deficits minimization and maximum adaptation to the reservoir objective volume curves.

2.4 Stochastic model

Other module of AQUATOOL DSSS is MASHWIN (Ochoa-Rivera, 2008, 2002), which allows to create stochastic models in order to generate multiple and equiprobable synthetic series of flows conserving the statistical properties of the flows you want to use as a basis for the generation, in this case flows from future periods. Here are also needed the historical local flows in order to calibrate and validate it. This module is a complement for the risk assessment model, since it needs a high number of flow series to perform the assessment.

2.5 Risk assessment model

The risk assessment model is integrated in the SIMRISK module (Sánchez-Quispe et al., 2001; Haro-Monteagudo, 2014; Haro-Monteagudo et al., 2017) and needs the previous step to carry out the analysis. This model simulates the management for each generated series and then all these results are treated statistically and aggregated to provide probability distributions for reservoirs storage, among other results, as deficits on consumptive demands.
This tool can be used at short, medium and long term and its purpose is to inform the decision makers about the probable state of the water resources of the WRS. In this way, they can propose and test different alternatives of management or mitigation measures to minimize possible impacts and choose the most effective ones to try to reduce the impacts (Haro-Monteagudo, 2014).

3. Case study

We decided to test the suggested methodology in the Júcar River Basin, which is located in the oriental part of the Iberian Peninsuls (Fig.4) and is the main exploitation system of the Júcar River Basin District (JRBD). It has the extension of around 22,187 km^2 and the average volume of water resources generated are around 1,605 hm^3/year (CHJ, 2015). The name of this

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district is due to the Júcar River (512 km long), which main tributaries are the Cabriel, Albaida and Magro rivers that pass through the provinces of Cuenca, Teruel, Albacete and Valencia to flow into the Mediterranean Sea.

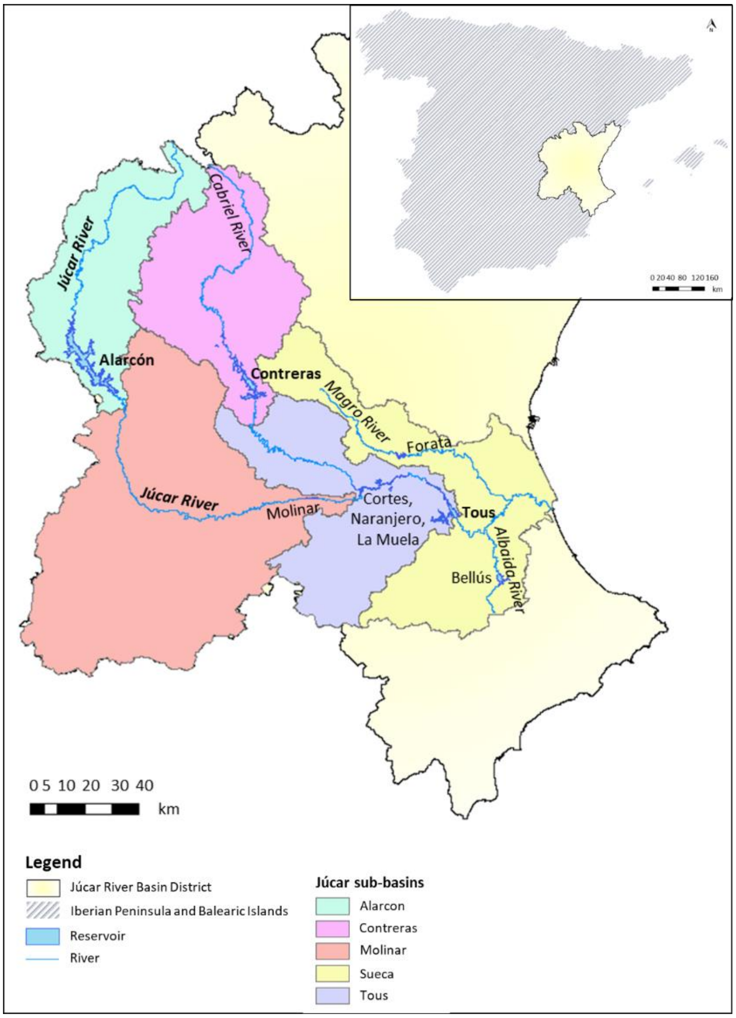

Figure 4. Location of the Júcar River Basin District and the Júcar River Basin (divided in sub-basins) in Spain. Source: Confederación Hidrográfica del Júcar (CHJ, www.chj.es) and Instituto Geológico y Minero de España (IGME, http://www.igme.es/).

As this area is under the influence of the Mediterranean climate, it is characterised by the semi-aridity of the climate. The average P is 475.2 mm/year, the PET is 926.6 mm/year and the annual average T are between 14 - 16.5 °C, reaching the maximum in summer (June, July and August), the dry season.

Moreover, there is a high hydrological variability that lead to recurrent multiannual droughts, as those experimented in the periods 1981-1986, 1992-1995, 2005-2008 and 2013-2018.

In addition to these hydrological features, consumptive demands are high, the irrigated agriculture accounts for nearly 80% of water demand and other sectors (including urban supply) account for 20%.

These conditions forced to adaptation by different management strategies, as water storage infrastructures, conjunctive use of surface and ground waters, and institutional and legal developments. Thus, this water resources system has several reservoirs, the more important ones are Alarcón (1,118 hm^3), Contreras (852 hm^3) and Tous (378 hm^3), as it can be seen in Fig. 4. In the same figure is shown the current division of this basin in five sub-basins, which is based on the position of these reservoirs and the hydrological characteristics of the area.

The inland part of the JRB is a mountainous area and the middle basin is a relatively flat area (high plain) that currently supports the major part of the irrigated agriculture (≈ 100,000 ha). The lower basin lies in the coastal plain, which supports traditionally and relatively recent irrigated areas. In these areas are permeable materials that allow the infiltration of the rainfall to the aquifers of La Mancha Oriental (middle part of the basin) and La Plana de Valencia (lower basin), which permit the water abstraction. In addition, there is an important wetland called l'Albufera de Valencia, which has an extension of 21,120 ha including a vast extension of rice crops in the coastal area.

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Consequently, the ratio between water demands and water resources is tight, meaning scarcity and overexploitation of water resources. The institution in charge of the water management in the JRBD is the Júcar River Basin Authority (JRBA, Confederación Hidrográfica del Júcar – CHJ in Spanish), which is also the responsible of the elaboration of the Júcar River Basin District Management Plan (JRBDMP) (CHJ, 2015) and the Drought Management Plan (PES in Spanish) (CHJ, 2018).

An interesting hydrological feature in the JRBDMP is the so-called "80s effect" (Pérez-Martín et al., 2013; Hernández Bedolla et al., 2019), which consists in a significant decrease of average precipitations and streamflows since the 1980 and onwards. In fact, the JRBDMP is based upon the 1980-2012 series to have a good representation of the current hydrological features of the basin when managing the system.

3.1 Climate projections and historical local data

In this case, meteorological variables (P and T) of 9 Regional Climate Models (RCMs) from the Representative Concentration Pathways (RCPs) 4.5 (stabilization) and 8.5 (high greenhouse gas scenarios) (IPCC, 2014) were downloaded from the SWICCA website at daily and catchment scale (mean area 215 km^2). These data came from the E-HYPE model (Hundecha et al., 2016), which uses global databases and Global Monitoring for the Environment and Security (GMES) satellite products as input data and then is forced by the European Centre for Medium-Range Weather Forecasts (ECMWF) and the SMHI to obtain meteorological, hydrological and other type of outputs for the entire continent (Hundecha et al., 2016; Suárez-Almiñana et al., 2017).

In Table 1, the characteristics of the ensemble members (EM) used in this work are shown. The reference period is 1971-2000 and the future periods are divided into 2011-2040, 2041-2070 and 2071-2100. These data were obtained for the 5 sub-basins depicted in Fig.4.

Table 1. Ensemble member characteristics from SWICCA portal. Modified from: http://swicca.climate.copernicus.eu/wp-content/uploads/2016/10/Metadata_Precipitation_catchment.pdf.

RCP	GCM	RCM	Period	Institute	Name of ensemble members
4.5	EC-EARTH	RCA4	1970-2100	SMHI	SMHI_RCA4_EC-EARTH_rcp45
	EC-EARTH	RACMO22E	1951-2100	KNMI	KNMI_RACMO22E_EC-EARTH_rcp45
	HadGEM2-ES	RCA4	1970-2098	SMHI	SMHI_RCA4_HadGEM2-ES_rcp45
	MPI-ESM-LR	REMO2009	1951-2100	CSC	CSC_REMO2009_MPI-ESM-LR_rcp45
	CM5A	WRF33	1971-2100	IPSL	IPSL-IPSL-CM5A-MR_rcp45
8.5	EC-EARTH	RCA4	1970-2100	SMHI	SMHI_RCA4_EC-EARTH_rcp85
	EC-EARTH	RACMO22E	1951-2100	KNMI	KNMI_RACMO22E_EC-EARTH_rcp85
	HadGEM2-ES	RCA4	1970-2098	SMHI	SMHI_RCA4_HadGEM2-ES_rcp85
	MPI-ESM-LR	REMO2009	1951-2100	CSC	CSC_REMO2009_MPI-ESM-LR_rcp85

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Then, the observed values of P and T variables from the Spain02 v4 dataset (Herrera et al., 2016) were used as historical local data. Spain02 is a gridded dataset of daily time series and 0.11º of spatial resolution that covers the Iberian Peninsula and the Balearic Islands for the period 1971-2010. Currently, this database is used in this area due to its good performance (Pedro-Monzonís et al., 2016; Suárez-Almiñana et al., 2017; Madrigal et al., 2018; García-Romero et al., 2019).

As shown in Fig. 3 (option A), these data are needed to analyse and assess the fitting of climate projections to local scale in the reference period and then proceed to their bias correction, if needed. Thus, four points of each sub-basin (Fig. 4) were taken and averaged in order to obtain a representative time series per sub-basin (Madrigal et al., 2018) for the same reference period provided by the projections.

On the other hand, the conversion of T into potential evapotranspiration (PET) was done in order to use the hydrological model, since it requires both P and PET as inputs. In order to calculate it, the Hargreaves method (Hargreaves and Samani, 1985) was applied. Despite the huge variety of methods to make this calculation with different skills (Milly and Dunne, 2017), the performance of this method for this area is very valuable (Espadafor et al., 2011; Hernández Bedolla et al., 2019) and the data required to perform it can be easily obtained.

Another type of historical local data required in this analysis are flow series, which in this case are in natural regime (as if no anthropogenic modifications of the watercourse were applied) restored from observed data. This dataset is used by the CHJ to report the assessment of water resources in the JRBDMP. Henceforth we will refer to them as natural or observed flows.

3.2 Bias correction

If the differences between climate projections and historical local data (either meteorological or hydrological) are notable in the reference period of both alternatives of Fig. 3, a bias correction is advisable to adjust as much as possible the pan-European data to the regional scale.

In this case, the correction of P and T variables was considered in alternative A and the correction of flows was considered in alternative B (Fig.3).

In this sense, one of the most reputed methods in literature is the quantile mapping, maybe because it is relatively simple to apply with good results, both for meteorological and flow variables (Grillakis et al., 2017;Manne et al., 2017; Teutschbein and Seibert, 2012). It is based on the distribution function which tries to keep the mean and standard deviation of the reference series (Collados-Lara et al., 2018). In this case, it is a feasible approach since the observations are of similar spatial resolution as the EMs data (Maraun, 2013).

This process was applied using the R statistical software (https://www.r-project.org/) at the daily (for P and T) and monthly (for flows) timescales by interpolating the empirical quantiles for variables of the reference period based on the package developed by Gudmundsson et al. (2012). First, the correction is made for the climate projections by its comparison with the local data in the reference period, and then this correction is extended to future periods.

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3.3 Modelling chain

In this section, the use of the hydrological, stochastic, risk assessment and management models are described. They belong to the EVALHID, MASHWIN, SIMRISK and SIMGES modules of AQUATOOL DSSS (respectively) and can be accessed from the same interface.

The rainfall-runoff model HBV (Bergström, 1995) was selected in EVALHID module to perform the transformation of P and PET into natural flows due its good performance in this basin at daily scale after a proper calibration. This calibration was made using two optimisation algorithms (García-Romero et al., 2019) and the natural flows from the period 1980-2007, in order to take into account the already mentioned "80s effect".

In option A of Fig. 3 this model was run using bias corrected P and PET series, while in option B it was run using non corrected P and PET and then the output flows were bias corrected before inserting them in the rest of models.

On one hand, the statistical properties (mean and standard deviation) of flow series from each future period were used in the stochastic model (MASHWIN) to generate 1000 synthetic series of 30 years for the entire ensemble. In this case an auto-regressive model of first order AR(1) was enough to generate the series after the time dependence parameter was calibrated using natural flows from 1980-2012 period.

Then, in the risk assessment model (SIMRISK), based on the Monte-Carlo method, the management of the system was simulated for each generated series and the outputs are statistically treated providing probabilistic results. In this case, a drought risk indicator for the whole ensemble and for the three future periods was extracted. This indicator takes into account the sum of the water storages at Alarcon, Contreras and Tous reservoirs, and informs about the probable evolution of the water resources of the water exploitation system.

On the other hand and in order to complement the risk assessment with a more intuitive analysis, the management of the entire future period (2011-2098) was simulated (using previous flow series) to obtain the water storage in the system based on reservoir's volume. As in previous case, the sum of volumes of the main reservoirs was considered.

4. Results

In this section, the ensemble mean and the range covered by all EMs are shown in the figures for all steps. We decided to work with an ensemble of models belonging to the RCPs 4.5 and 8.5 since in this way it is possible to approximate to the most likely future scenario (the RCP 6.0) accorded in the Paris Climate Change Conference 2015 (Barranco et al., 2018). Since the RCP 6.0 is an intermediate scenario of those employed, but no projections are available to us for this scenario, this is a way of approaching it and simplify the process.

4.1 Analysis of meteorological data and their bias correction

Within the climate projections was provided the reference period 1971-2000, but we proposed to reduce it to 1980-2000 in order to consider the "80s effect". As it was reported previously, the data series considered most suitable for working in the

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management of water resources of this basin are those observed from the 1980 onwards. In fact, the current version of the JRBDMP is based upon the period 1980-2012, since the inclusion of previous years can lend to an overestimation of the available water resources in the system for water allocation. Figure 5 shows how the total inflows from the period 1980-2012 and the reference period we proposed (1980-2000) can be considered as equivalent (Suárez-Almiñana et al., in press), while the reference period provided (1971-2000) has higher total inflows, which we want to avoid in order to have a good representation of the current situation of the JRB.

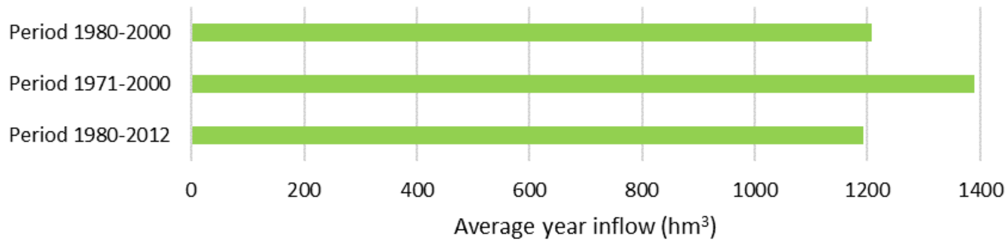

Figure 5. Average year inflows in the Júcar River Basin for different periods. Modified from Suárez-Almiñana et al. (in press).

Thus, we proceed with the proposed reference period (1980-2000) to make the comparison between the P and T series of the EMs and the historical data (Spain02). In this comparison a general overestimation of T on the average year of this period and an underestimation of P in most of the sub-basins was detected (Fig. 6). As these variables were not in the same line, it was decided to apply a bias correction in both variables using the quantile mapping technique already mentioned.

While the overestimation of T disappeared after the application of this technique, the differences between the corrected ensemble of P and the historical data were minimized (Fig. 6), as well as the average, but it is still overestimated in spring and summer. Moreover, Fig. 6 shows how in Molinar and Tous sub-basins the bias correction provided a little difference favouring some months and affecting others, but very subtly in both cases. However, all these differences can be assumed in order to obtain more reliable flows in the next step.

Then, these corrections (P and T) were extended to the future series from 2011 to 2098, since the last period was reduced in 2 years due to the lack of data of two of the EMs (see Table 1).

In addition, the T from the reference and the future periods were converted to PET (using the Hargreaves method) to prepare the data for the hydrological model.

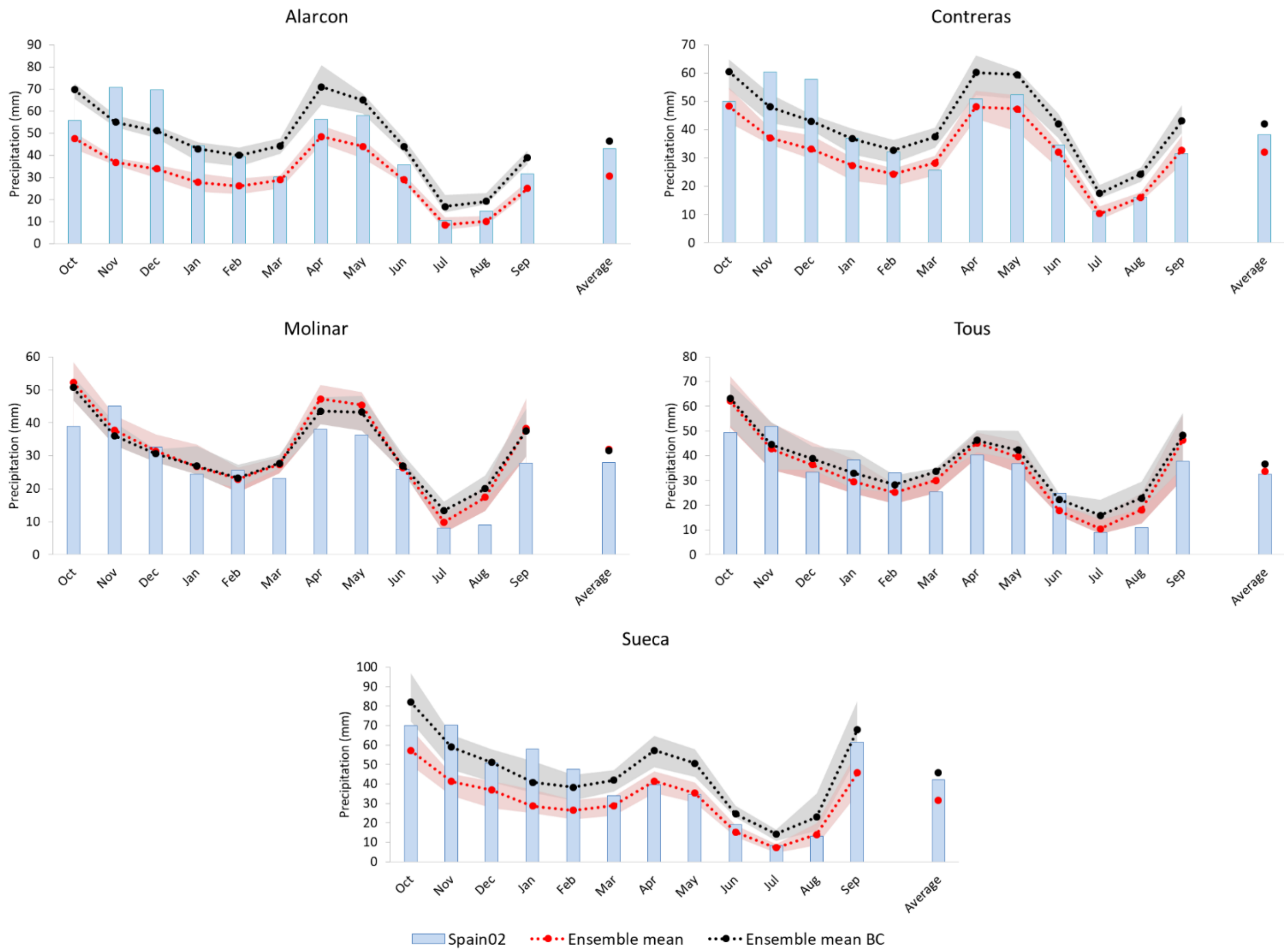

Figure 6. Average year bias corrected precipitation (Ensemble mean BC) compared to the non-corrected precipitation (Ensemble mean) and the historical data (Spain02 data) in the reference period 1980-2000, where the shaded areas represent the entire ensemble.

4.2 Characterisation of natural flows

In this section, corrected and non-corrected P and PET were introduced in the HBV model to assess its performance and then generate future river flows for the risk assessment. For both approaches of Fig. 3 (A and B), the simulation of future flows was made using series from 2011 to 2098 and then they were divided into the stipulated future periods. In this way, initial conditions for all periods are conserved and maintained, as well as the tendency of the future flows.

In the case of option A (Fig. 3), this model is run using bias corrected data, however, for option B it is run using raw data and the resulting flows are bias corrected before moving on to the model chain, as depicted in the Fig. 3.

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4.2.1 Option A: HBV model simulation using bias corrected data

First, the output flows from the HBV model using historical data (P & PET from Spain02) of the reference period were compared with the observed flows to assess their performance and validate it for the JRB. This comparison is illustrated in the Fig. 7, which was completed including the output flows from the ensemble (HBV-JRB Ensemble), where the shade area is the range covered by the EMs. There can be seen how both HBV model results (HBV-JRB Spain02 and HBV-JRB Ensemble) are generally close to the observed flow values and its average, setting aside some differences that are likely due to its parametrization in the calibration process and the P overestimation during the spring months (bias corrected data). The estimations of the HBV model are more accurate in the headwaters basins (Alarcon and Contreras), where are placed the main reservoirs and therefore a fact to consider from the point of view of management. In this way, the apparent mismatch in the Sueca sub-basin is not relevant for the purposes of this study since it is located in the final stretch of the river, where is no longer regulation.

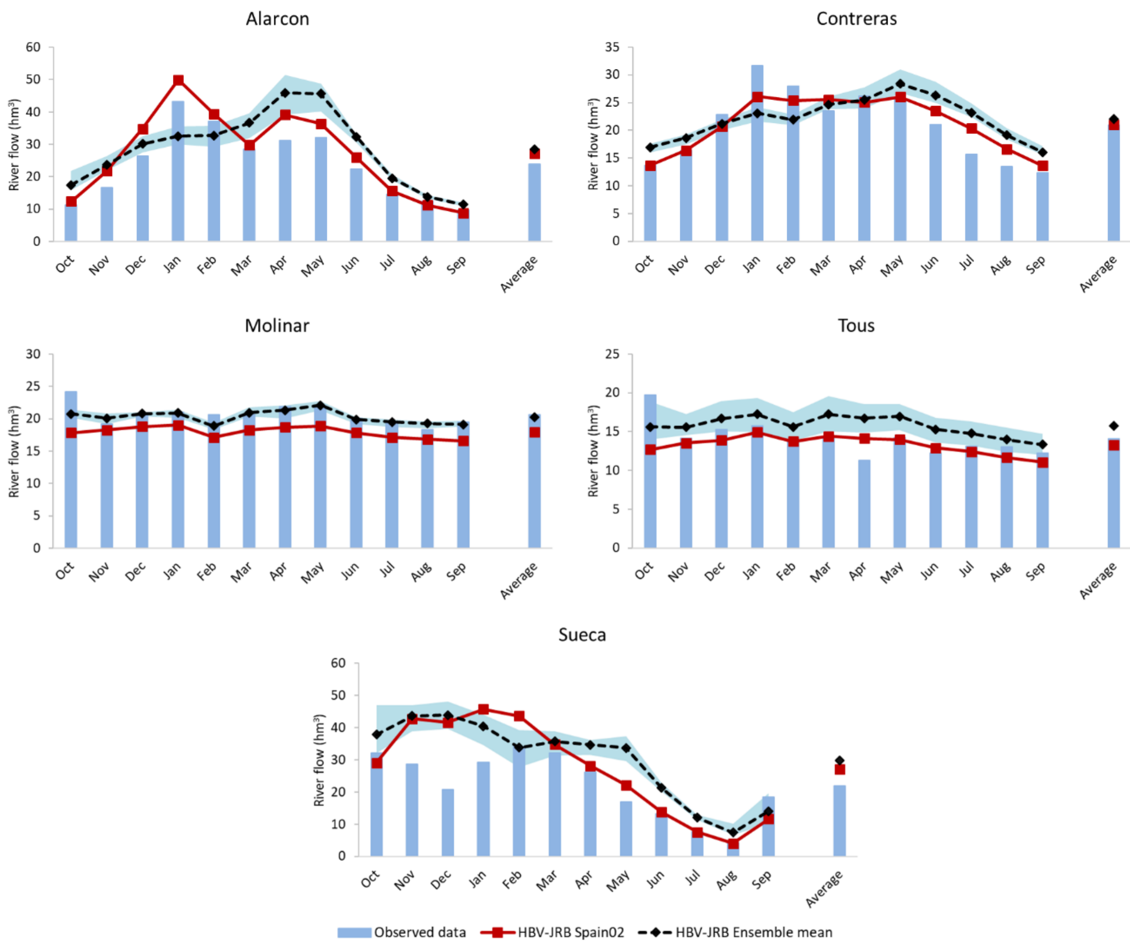

Figure 7. Average year of river flows from the application of the HBV model using historical (HBV-JRB Spain02) and ensemble data (HBV-JRB Ensemble mean and shaded area) compared to the observed flows in the reference period 1980-2000.

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In the Alarcon sub-basin, the HBV-JRB Ensemble is underestimating river flows in January and February (as in Contreras), while it is overestimating them in spring months, which are likely related to the outputs of the bias correction process in these months. In the Molinar and Tous sub-basins, these ensemble flows has higher values than HBV-JRB Spain02 and they are closer to the observed ones. In the case of Tous, both setups underestimate river flows, but these differences are expected because this sub-basin is the most heavily regulated and difficult to simulate with hydrological models, mainly due to its intimate relationship with the underground component. In the Sueca sub-basin, both flow series overestimate observed river flows from November to January and the HBV-JRB Ensemble also overestimates spring flows, which may be due to the overestimation in corrected P.

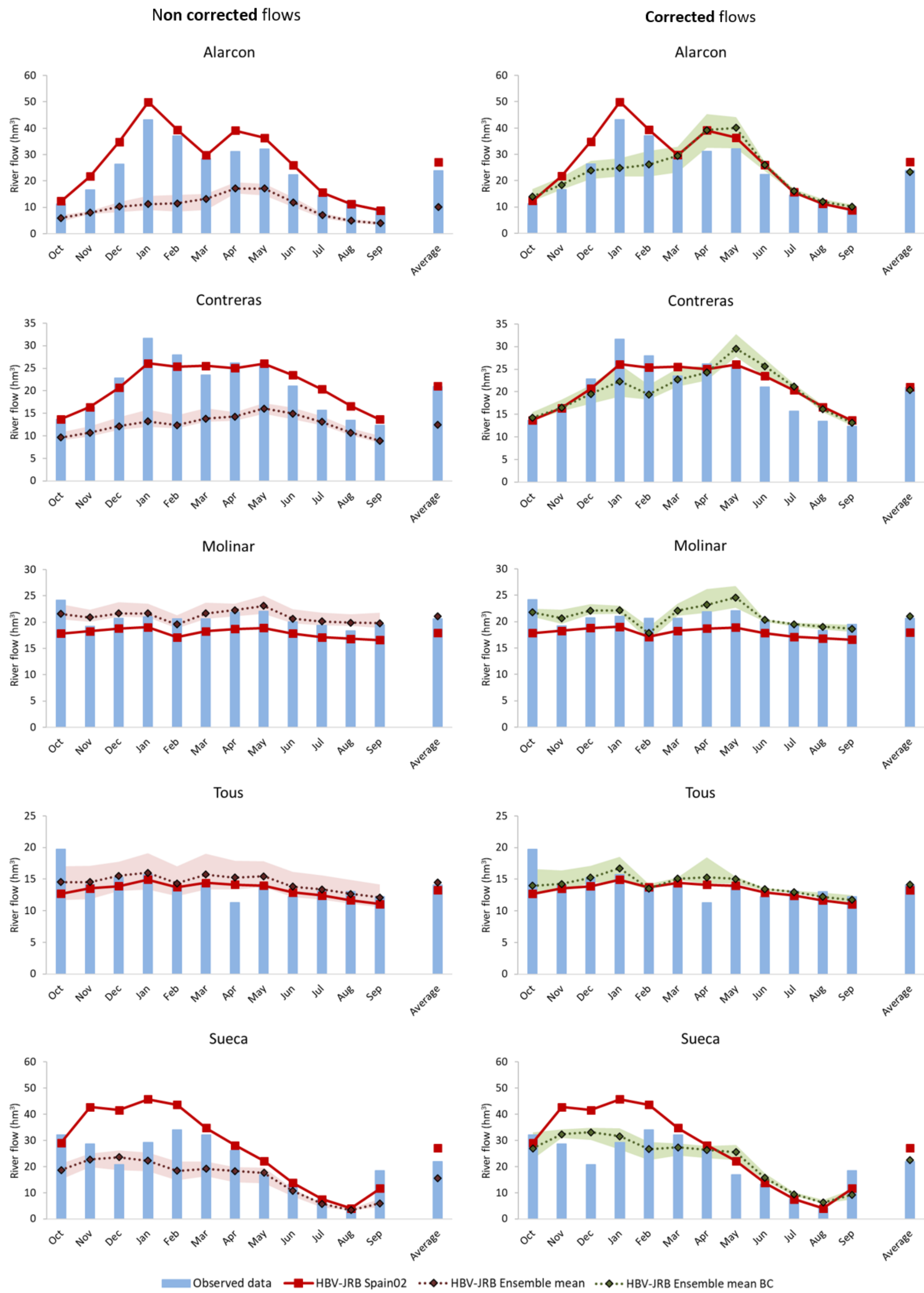
Despite these differences, the performance of HBV model can be considered as acceptable and quite good due the huge complexity of this basin. Thus, it was a good option to continue with the study and future flows were simulated with it.

4.2.2 Option B: HBV model simulation using raw data and bias correction of flows

In this section, the raw P and PET of the reference period were introduced in the HBV model in order to extract the non-corrected flows and evaluate if previous correction was worth it or not.

Looking at Fig. 8 it is evident that a bias correction is needed on P and T or on river flows, since they are not representing the current situation of the basin. The raw flows of the reference period are highly underestimated in Alarcon and Contreras and if this is extended to future flows, the conclusions on the impacts of climate change can be misleading and have a severe and false view of the future. Thus, in this part was decided to correct raw flows and see the differences between correcting data before and after the hydrological model from this point onwards.

The flows were also corrected using the quantile mapping method and the improvement was notable, particularly in the average fitting. Despite this, there are some mismatches in accordance to previous correction. There are some underestimation in January and February in Alarcon and Contreras and spring moths are also overestimated. However, in Tous and Molinar they are more or less in line to observed flows and in Sueca the months of December and May are overestimated, but in general can be considered a good option, as in the case of A approach. Thus, this correction was extended to future flows.



390 **Figure 8. Average year of river flows from the application of the HBV model using historical (HBV-JRB Spain02) and raw ensemble data (HBV-JRB Ensemble mean and shaded area) compared to the observed and corrected (HBV-JRB Ensemble mean BC and shaded area) flows in the reference period 1980-2000.**

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4.2.3 Impact of future river flows

The ensemble of future flows from each sub-basin, period and approach (A and B) were compared with their respective ensemble baselines (1980-2000) to evaluate the impact of climate change on future flows. In this case, the average change rates of future periods were obtained, not counting the increment or reduction of previous periods.

The Fig. 9 shows the impacts per sub-basin, period and approach, as well as the mean values for the whole JRB.

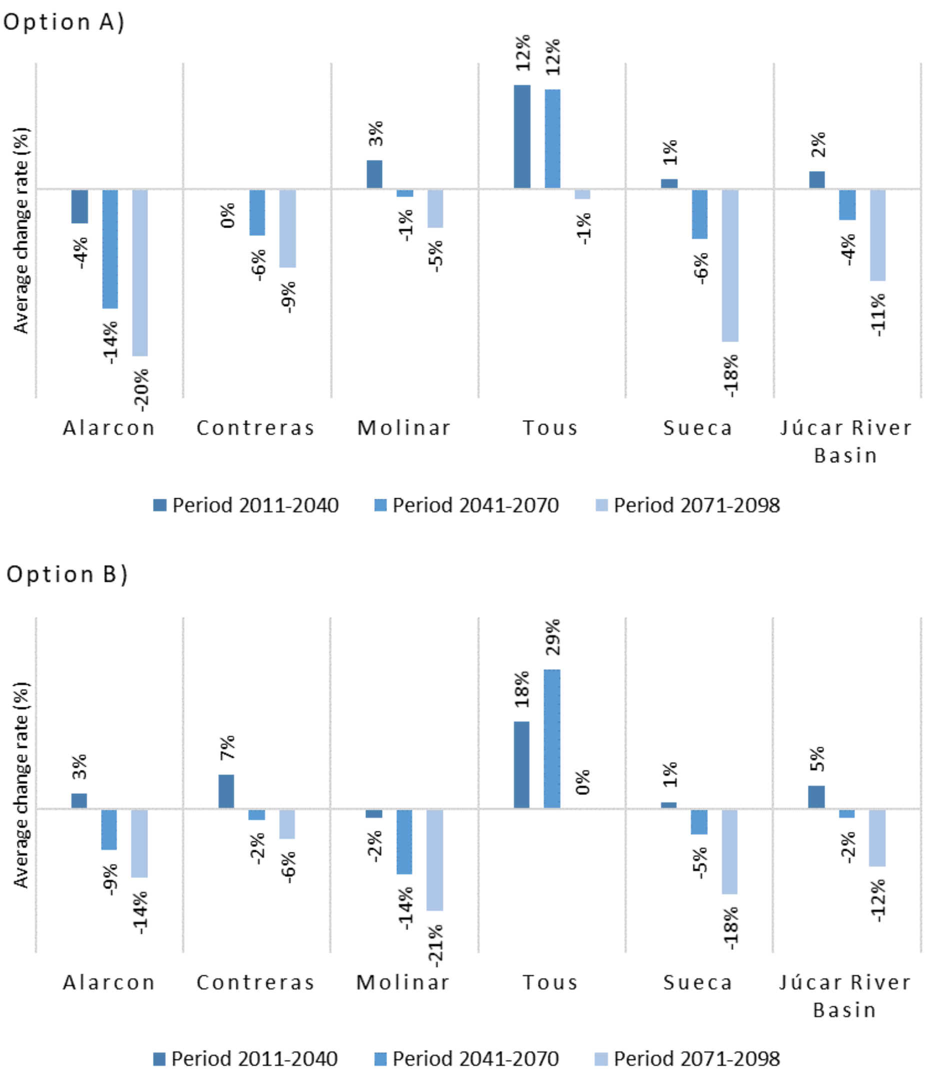

Figure 9. Average change rates per sub-basin and the whole JRB for future periods (2011-2040, 2041-2070 and 2071-2098), distinguishing between A (top) and B (bottom) options.

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As was expected, simulated river flows has a decreasing tendency over the years, but change rates differ from sub-basins and approach. If we compare both results, the reductions in the headwaters (Alarcon and Contreras) are important, but more drastic in the A approach, where they can be reduced in average -20% for the last future period in Alarcon. However, Molinar has a drastic decrease in the B approach (until -21% at the end of the century), while this tendency is less marked in the A approach. Then, the behaviour of flows in Tous is remarkable (in both cases), since there is a large flow increase in the near and medium futures that then decreases for the last period. This sub-basin is highly influenced by the underground component and increasing contributions to this basin are been observed in recent years (Hernández Bedolla et al., 2019), so this may be the reason of these increases that may continue and be translated into more contributions to this sub-basin until the second period.

However, Sueca has very similar decreases in both cases reaching -18% in the las future period. The same happens if we look at the JRB as a whole, the differences between using A or B approaches are minimal.

Hence, we can say that there are important decreases in the headwaters, which may be a great challenge for the future management because there is where the main reservoirs are located. Moreover, there are sharp reductions in the final section of the river (Sueca), where most of the irrigation is located, which may lead to increased demand and pressure on irrigation campaigns.

4.3 Drought risk indicator

The statistical properties (mean and standard deviation) of future flows obtained in the previous section (options A and B) were used to modify and adapt the stochastic model (MASHWIN) for the generation of future series, since it was calibrated for the historical series. Then the outputs from this model were integrated in the risk assessment model (SIMRISK), where the drought risk indicator was extracted.

The adaptation of the AR(1) was made modifying the mean and the standard deviation by those of the future flows. Thus, based on these future statistical properties, the model generated 1,000 synthetic series for each EM and future period, maintaining the mean and the variance from input series. Then, SIMRISK simulate the management for each one of the generated series and the management results were treated statistically to provide probabilities of reservoir storages, which were transformed in the drought risk indicator for the entire system.

In the Fig. 10 is depicted the resulting ensemble indicator (mean probabilities of all EMs) for each future period and approach. It informs about the evolution of the reservoir storage of the system, which has a total capacity of 1,796 hm^3 that was divided in 10 equal intervals. Then, the probability of being in each interval was displayed for each period.

The probabilities of both alternatives are very similar in all future periods. In both options, the probabilities of being under the 50% of total capacity (898 hm^3, medium green colour) is about the 80% in the near future (period 2011-2040), but these probabilities are around 70% and 60% in the medium (period 2041-2070) and far future (period 2071-2098) respectively, a little higher for B approach. This may lead to the conclusion that the probabilities of being at lower intervals are decreasing over the periods despite flow reductions, but this is due that as time passes there is a greater probability of falling in any interval (≈10%), as seen from the second period onwards. This indicates a high uncertainty for the future, since there is a large variation in future simulated storage volumes.

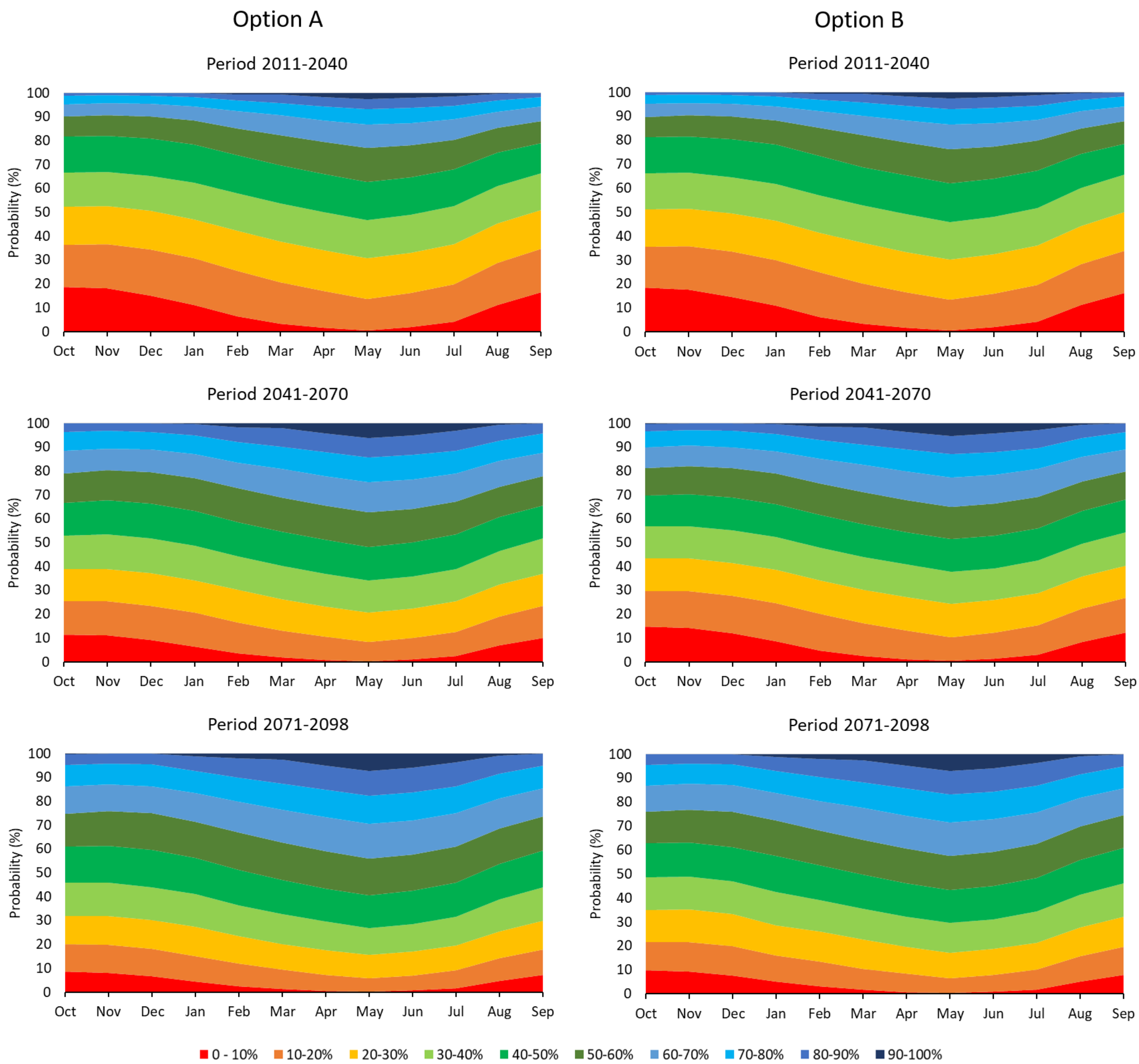

Figure 10. Drought risk indicator of the ensemble mean coming from options A (left) and B (right) for each future period (2011-2040, 2041-2070 and 2071-2098), where the different colours of the legend correspond to the 10 equal intervals in which was divided the total capacity of the system.

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Looking at these results, we decided to pay attention on the exceedance probabilities of September (Fig. 11) as it is the final state of the system for each future period coinciding with the end of the irrigation season and the hydrological year.

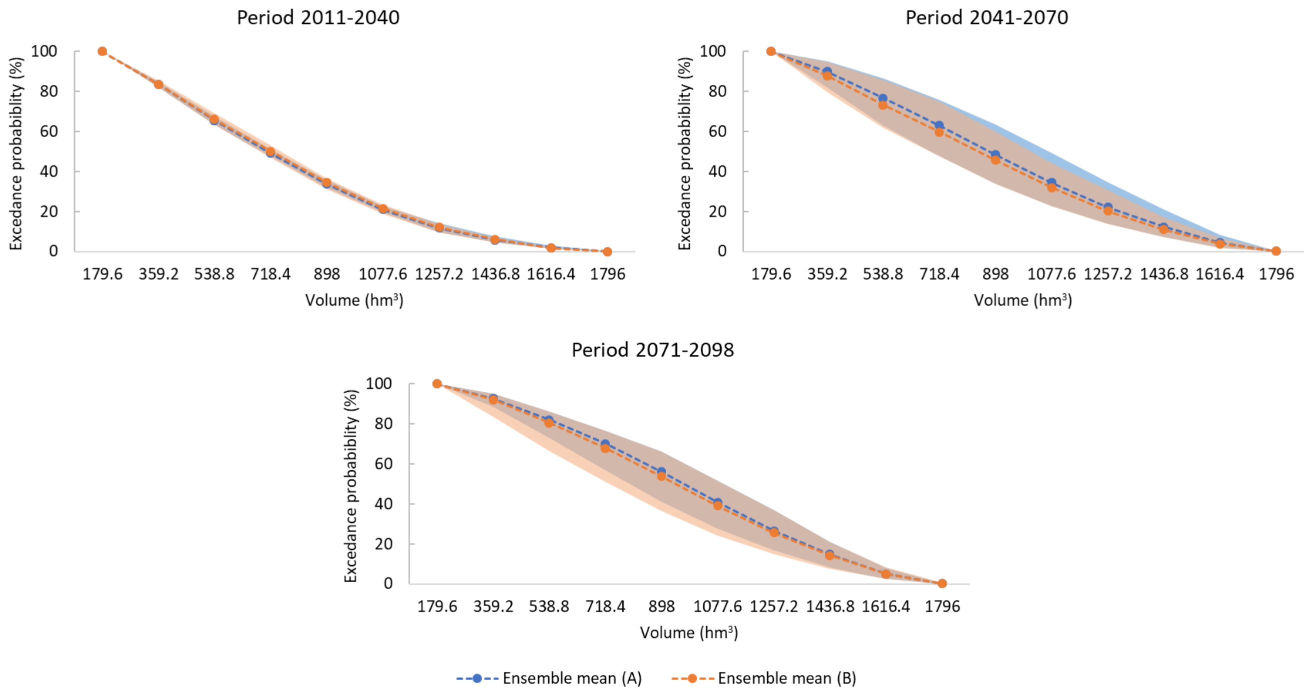

Figure 11. Exceedance probability of the ensembles (shaded areas) coming from options A and B in September for the future periods (2011-2040, 2041-2070 and 2071-2098).

In the first period, the range of exceedance probabilities covered by the ensemble members is very tight, coinciding with the entire ensemble of both approaches, while in the other periods this range is wider (more dispersion of the EMs), where the ensemble A shows higher probabilities of exceeding higher storage volumes. For example, in the near future the probabilities of exceeding the 50% of total capacity (898 hm^3) are as average 34% in both approaches, while in the second period these probabilities are 48% for the ensemble A and 46% for the ensemble B, but ranges are between 34-63% and 34-60% respectively. In the same way, the probabilities of exceeding 898 hm^3 for the far future are as average 56% for the ensemble A and 54% for the B, with ranges between 41-66% and 36-66% respectively. Hence, the dispersion and uncertainty beyond the first period is considerable.

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4.4 Future water storage in the system

The future output flows from the Sect. 4.2 (both options A and B) were inserted in the management model (SIMGES) to simulate the water allocation for the entire future period (2011-2098). In this way, the future tendencies and the continuous evolution of storage values can be better observed to complement the results of previous section.

In Fig. 12 is represented the average volumes of the ensemble (lines) and the range of volumes covered by all EMs (shaded areas) in the total storage of the system (1796 hm^3).

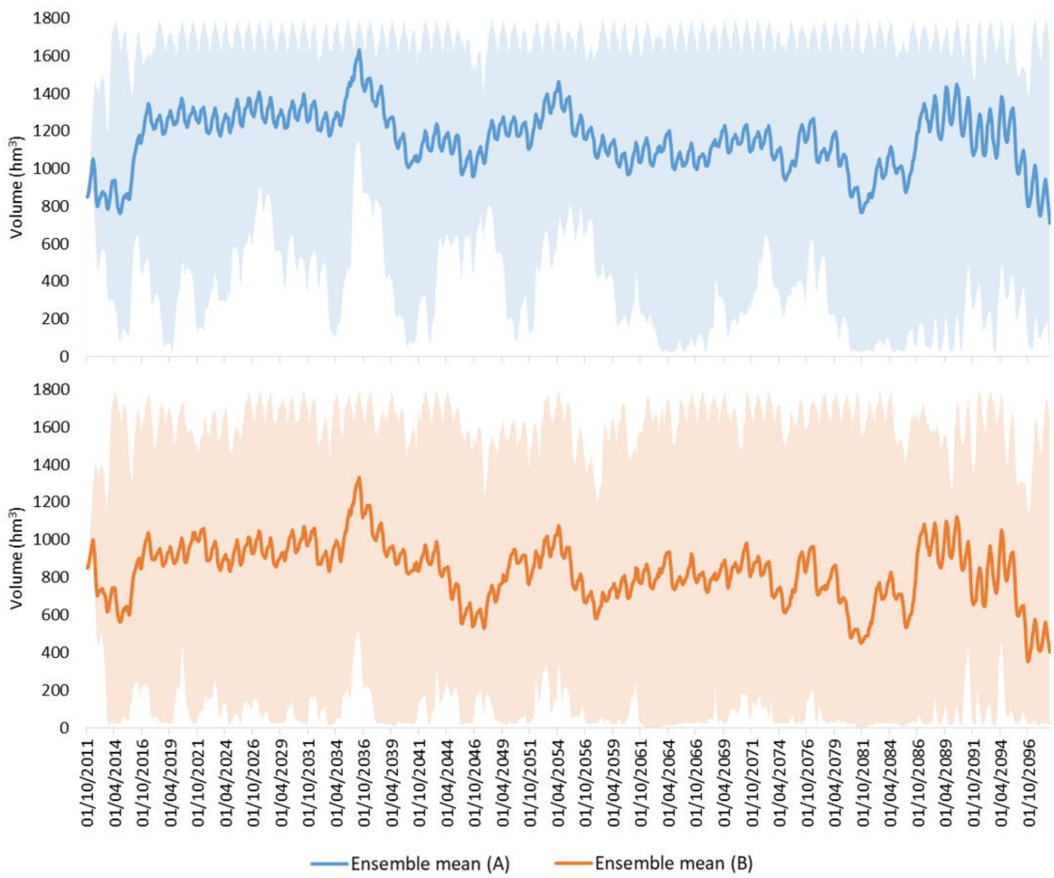

Figure 12. Evolution of the water storage in the Júcar River Water Resources System for the ensemble (shaded area) of A (up) and B (down) options in the future period 2011-2098.

In general, the option B (Fig. 12, bottom) presents lower average values than option A (Fig. 12, up), which may result in worst climate change impacts from the middle century onwards. However, the shaded area of the ensemble occupies practically the entire volume under consideration, indicating a huge uncertainty for the future and coinciding with the statement made in previous section. However, the dispersion (shaded area) of the option A is less intense, mainly due to the minimum values of the EMs, which are higher than in the option B, especially until mid-century. Therefore, the conditions

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presented in option A provide a more favourable average, but still not reliable due to the large dispersion of results, as in the case of option B.

5. Discussion

This work has highlighted all the points that need attention in order to integrate climate projections into decision-making processes. The methodology is easy to follow but has to be adapted to the features of the case study, so a high level of knowledge of the WRS in question is an important requirement to use and understand it (Haro-Monteagudo et al., 2017). In this case, which is a Mediterranean basin with water scarcity problems and long periods of drought, the more attention we pay to each step, the better the results. In spite of this, the indicators did not provide conclusive results due to the great dispersion of climatic projections, especially in the last two periods. It is therefore necessary to discuss the process step by step to estimate possible mistakes and improvements.

First, the data from SWICCA were selected because there was made a pre-processing of filtering the models that best fit in the European area. Despite this, in the literature it is stated that for the Mediterranean area it is very difficult to find reliable data or with enough skill to work with them with confidence (Barranco et al., 2018; Collados-Lara et al., 2018), especially if these are hydrological data (Suárez-Almiñana et al., 2017).

Looking al Fig. 6 and Fig. 8, where raw and corrected P and flows are shown, there is no doubt that the application of some kind of bias correction was necessary. Working with the raw data would lead to unfavourable results for the future, since the underestimation of flows in the headwaters (where the major reservoirs are located) are notable, this fact may also lead to alarming conclusions about the future hydrology in this basin. Therefore, the quantile mapping technique was applied in both cases (P and flows). This technique is highly recommended in the literature (Grillakis et al., 2017; Collados-Lara et al., 2018; Manne et al., 2017; Teutschbein and Seibert, 2012), but after having tried other simpler techniques such as month-specific correction factors (Suárez-Almiñana et al., 2017), the differences between their performances are not significant, although the fitting is improved especially in the annual average. It seems that the currently available methods of correction may not provide a fully satisfactory correction of P and flows. A future consideration might be the application of a seasonal correction, which may be more relevant for water management and especially in this area totally conditioned by the irrigation seasons. However, some authors say that in some cases, the RCMs are not able to reproduce drought statistics from the observed series (Collados-Lara et al., 2018; Cook et al., 2008; Seager et al., 2008), so a correction focussed on drought statistics is also a feasible solution to try to leave out the mismatches between reference periods.

On the other hand, we believe that the reduction of the reference period is a good choice to start with data more in line to the current situation of the basin. This fact has also been demonstrated in Suárez-Almiñana et al., (in press), where the uncertainty about the impact of future flows on this basin was minimized.

Regarding the future impacts on flows, the average change rate of the ensemble was shown in an attempt to represent the RCP 6.0, which is the most probable scenario for the future (as was reported previously), as well as to try to reduce the

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uncertainty considering all EMs (Collados-Lara et al., 2018). However, the main differences between RCPs are only notable in the far future, where the range covered by them is between -7% (RCP 4.5) and -17% (RCP 8.5) for the A approach, and from -5% (RCP 4.5) to -21% (RCP 8.5) for option B.

The trends for future flows were decreasing in both options (A and B), which is consistent with several studies conducted in this area (Barranco et al., 2018; CEDEX, 2017; Marcos-Garcia et al., 2017). But the behaviour of Tous is remarkable, which increases flows until the second period. As mentioned above, this may be conditioned by its relationship with the aquifer and the increase in contributions observed in recent years (Hernández Bedolla et al., 2019). This increase in contributions seems to be captured by the models, since rainfall increases by an average of 2% in the first period and maintains the average of the reference period until the second period, after which it sinks by -6%. This increase in rainfall combined with the increasing contributions from the groundwater (contemplated in the hydrological model) and the reference period scarce in water resources may lead to that percentage increments in both cases (A and B). In any case, the variability of changes between sub-basins is not an isolated case (Folton et al., 2019).

However, if we focus on the average changes concerning the whole basin of Fig. 9 (between 2% (A) and 5% (B) for the first period, from -4% (A) to -2% (B) in the second period and from -11(A) to -12 (B) in the last period), may seem rather low when compared to the benchmark study of the CEDEX (2017). This study estimates average reductions (RCPs 4.5 and 8.5) of -7%, -18% and -28% for the entire JRBD, although it is indicated that change rates can be applied to all its points (Barranco et al., 2018). The principal reasons of these differences may lead in the reference period, which in that study is 1960-2000, and the not correction of data despite the fact that precipitation on the Mediterranean side was underestimated (Barranco et al., 2018). Thus, there was not considered the “80s effect” and the data before the 1980 may lead to a much more favourable scenario in terms of availability of water resources than the current one, therefore the decreases are more drastic in the future. These simple premises may explain why the change rates of this work are lower than those provided by the CEDEX (2017) and therefore the results tend to be more “optimistic” regarding the water resources of the future.

Then, it was decided to continue with the statistical characteristics of future flows to obtain the drought risk indicators, however this negative trend observed in flows was not equally evident in the indicators (options A and B), which are very similar to each other (Fig.10). Only in the first period can be seen a complicated scenario in which the probabilities of being below 50% of the total storage capacity of the system are 80%, however, in the rest of the periods the probabilities of being in any of the intervals is practically the same (≈10%). The reason for this is most clearly seen in the probabilities of exceedance capacity (Fig. 11), where the range of probabilities covered by the ensemble is very wide, indicating that their dispersion from the second period onwards is very high and no conclusions can be drawn from them.

The results from the simulation of the future water management supports the dispersion theories extracted from the evaluation of the indicators and the exceedance probabilities, since in Fig. 12 the ensemble is occupying practically the entire volume under consideration in both options (larger in option B), indicating that anything could happen and confirming that the uncertainty of climate projections is considerable. In addition, looking at Fig. 12 it seems that the bias correction of river flows provide more dispersion to results despite conserving the mean of the average year in the reference period (Fig. 8).

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In this way, the results obtained on the risk assessment branch (Fig. 2) can be better understood, as well as why it is better to work in terms of probabilities when the future is so uncertain. Furthermore, the fact of choosing the dammed volumes and their evolution as a reference is motivated by the great influence that these volumes have on the Jucar River Basin drought indicator system (CHJ, 2018), representing almost 50% of the indicators value (Haro-Monteagudo et al., 2017). So that the proposed indicator can serve as an approximation of the current drought indicator and complement it.

Although the results are not conclusive, we think that the methodology applied is feasible when integrating future projections in the decision-making processes, but for this area the skill of climate projections need to be improved, since the uncertainty makes decision making more complex (Lemos and Rood, 2010). According to Lemos and Rood (2010), this uncertainty and the absence of a clear and real danger leads the decision makers to justify inaction, but the decreasing tendencies of future flows and the indicator for the near future are signals to be considered, since taking preventive measures may be the key to avoid severe impacts on the environment, the society and the economy.

It should also be noted that decisions made on the basis of knowledge of the basin may not be correct and the models may have some parameterization flaws that increase the initial uncertainty, although every effort made to adapt them to the conditions of the basin. In addition, all simulations were made considering the current conditions of demands and other limitations for water allocation (as the ecological flows regulation), which may change in the future and affect the water availability at the expense or benefit of certain uses.

6. Conclusion

In this paper was presented a complete and adaptable methodology for the integration of climate projections in the decision-making. The aim of this specific case was the drought risk assessment in a highly regulated basing from the Mediterranean area. This method is completely applicable to other basins without forgetting that an intimate knowledge of their features is necessary.

After the characterization of river flows applying both types of bias correction (to meteorological and hydrological variables) it was concluded that the tendency of future flows in the JRB is decreasing and very similar in both approaches. However, the average change rates are not as drastic as other reference studies, due to the decisions made during the process of adaptation to the basin, as the reduction of the reference period to avoid the "80s effect", which was more scarce in water resources, as the current state of this basin.

These decreasing tendencies were not reflected in the drought risk indicators and the future water storage due to the high dispersion of the EMs, indicating that anything could happened from the middle century onwards. Thus, the uncertainty in this basin was considerable since the beginning of the process and it also seems to grow during the model chain procedure, despite the attempts of diminish it by taking decisions to adapt it to the basin.

All this leads to the conclusion that more research is needed, and the climate projections need to be improved for the Mediterranean area. Hence, when that occurs this methodology will be ready to be implemented with some improvements for the future decision-making. Meanwhile, the decreasing tendency of future river flows is concerning, as is confirmed in many other studies of this area, so this paper may help to be aware of what will happen if no measures are taken from now on, it is time for action.

7. Data availability

The full Spain02 v4 dataset is freely distributed (in NetCDF format) for research purposes (http://www.meteo.unican.es/files/images/copyright_en.pdf) from the Escenarios-PNACC dataset from the UC climate data service. It is available at http://www.meteo.unican.es/datasets/spain02.

The climate projection from SWICCA portal can be freely downloaded at http://swicca.climate.copernicus.eu/indicator-interface/graphs-and-download/ under Creative Commons Attribution-ShareAlike 4.0 International (CC BY-SA 4.0) license conditions.

The natural flows from the Júcar River Basin were provided by the CHJ for research purposes.

8. Author contribution

SSA, AS and JM collected the data. SSA and AS designed the methodology. SSA performed the calculations and analysed the results with AS and JA. SSA prepared the manuscript with contributions from all co-authors.

9. Competing interests

The authors declare that they have no conflict of interest.

10. Acknowledgments

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