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Dry getting drier – The future of transnational river basins in Iberia

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ABSTRACT

Study region: Main international rivers of Iberia (SW Europe): Douro, Tagus and Guadiana.

Study focus: Iberia has long suffered from water scarcity which will worsen with projected reductions in rainfall and increases in temperature. Nonetheless, there has been almost no research concerning the future discharges of these rivers. We examine an ensemble of climate model projections from CMIP5 RCP 8.5 and use two downscaling methods to produce a range of changes in discharge using a physically-based, spatially-distributed hydrological model (SHETRAN) for historical (1961–1990) and future (2040–2070) periods.

New hydrological insights for the region: There is uncertainty in the sign of change in high (winter) discharges but most model runs show decreases in monthly, seasonal and annual discharges for all basins; especially for medium and low discharges, with all but one run showing future decreases. The magnitude of these decreases varies significantly for different CMIP5 ensemble members. However, autumn shows the biggest decreases (reaching −61% for the Douro, −71% in the Tagus, and −92% for the Guadiana) and the reductions are consistently larger for the Guadiana. This is the first study to explore a wide range of possible futures for these international basins. We show that, despite uncertainties in model projections, there is common behavior with reductions in mean and especially in low discharges which will have important implications for water resources, populations, ecology and agriculture.

1. Introduction

Portugal and Spain share five river basins which cover 40% of the Iberia peninsula. Under natural conditions around 70% of the total outlet flow of the three main international Iberian rivers, the Douro, the Tagus and the Guadiana, has its origin in Spain (INAG, 2001). The main characteristic of these rivers are shown in Table 1.

The first water treaties between Portugal and Spain date back to the 19th century and several treaties were later signed in the 1920s and 1960s. The latest, from 1998, is the Albufeira Convention. This convention seeks to balance environmental protection with sustainable use of water resources within the framework of International and EU Law (UN, 2013). In 2008 a seasonal flow regime for the Douro, Tagus and Guadiana was defined (as a revision of the convention), which includes minimum flows for different times of the year.

The seasonality of flows in these basins, with high winter discharges and low summer discharges, is typical of Iberia and is mainly a result of the seasonality of the rainfall exacerbated by the high temperatures (and therefore potential evapotranspiration − PET) of the summer months. The highest mean discharges occur in the Douro but the highest maximum discharges occur in the Tagus. Iberian rivers tend to show high coefficients of variation in flow, which increases from south to north: around 100% for the Guadiana and

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Table 1
Basin area and annual discharge of the three studied basins (INAG, 1999a; INAG, 1999b; INAG, 2001).

River	Basin area (km^2)	Annual discharge (hm^3)
Douro Spanish: Duero Portuguese: Douro	97 603 (19% in Portugal, 81% in Spain)	14 800
Tagus Spanish: Tajo Portuguese: Tejo	80 629 (30% in Portugal, 70% in Spain)	9 629
Guadiana Spanish: Guadiana Portuguese: Guadiana	66 800 (17% in Portugal, 83% in Spain)	2 680

50% for the Douro (Gámiz-Fortis et al., 2008).

Along the Douro River there are numerous hydroelectric power plants and the middle Douro is extensively used for irrigation. In Portugal, the principal crop of the Douro valley is grapes, which are used to produce Port wine (UNEP, 2003). The Tagus River acts as a natural border between “wet Iberia” in the north and “dry Iberia” in the south, with its northern tributaries having considerably higher discharges than the southern tributaries (Portela et al., 2009). It is also the source of the Tagus-Segura water transfer which was built in 1978 to transfer up to 1,100hm^3/yr from the headwaters of the Tagus to the Mediterranean basins of the Jucar and the Segura, mainly to supply water to the irrigated areas in the south-east of Spain. The transfer is controversial and in the 2005/2006 drought caused several public demonstrations in both the Tagus and the Segura basins, respectively against and in favor of this water transfer system (Beguería et al., 2009).

The headwaters of the Guadiana are one of the driest places in Europe, with mean annual rainfall of 415 mm and PET above 800 mm/yr (Kilsby et al., 2007).The upper Guadiana basin consists of streams closely connected to aquifers with both stream flows and groundwater levels in decline in line with a dramatic increase of groundwater abstraction for irrigation. Degradation of protected wetlands has occurred due to declining groundwater levels, problems with water salinity and with invasive species from the Tagus basin that have resulted from occasional water transfers between the two basins (Conan et al., 2003). The Portuguese part of the Guadiana has the largest reservoir in Europe: Alqueva. It was built with the objective of being a strategic water reserve for the south of Portugal, providing water for irrigation, urban and industrial consumption, energy production and regularization of flows (INAG, 2001). It irrigates an area of around 120,000 ha (through a complex system with 69 dams, reservoirs and weirs) and is the main source of water supply for 200,000 people (EDIA, 2016).

Despite the strategic water resources of these basins, and projections of a drier future for the region (Ekström et al., 2007; Hingray et al., 2007; Kilsby et al., 2007; Guerreiro et al., 2016, 2017), climate change studies that focus on hydrological impacts on the Douro, Tagus or Guadiana basins could not be found. Some studies can only be found for small sub-basins inside these three international river basins. The exception is Kilsby et al. (2007) who looked at the hydrological impacts of climate change on the Tagus and the Guadiana rivers for 2070–2100 under the SRES A2 scenario using one Regional Climate Model − RCM (HadRM3H driven by HadCM3), two downscaling techniques (monthly bias correction and a circulation-pattern-based stochastic rainfall model) and a conceptual rainfall-runoff routing model. Reductions in flows for both basins were projected throughout the year due to increased PET and year-round rainfall decreases. The circulation-pattern-based method produced smaller reductions in flows (21% for Guadiana and 20% for Tagus) than the bias correction method (26% and 49%). Kilsby et al. (2007) pointed towards the need for major improvements of the hydrological modelling since observed and simulated flows showed large discrepancies. This improvement is a challenge due to the effect of dams and abstractions on the observed discharges and the infeasible task of accounting for these in the absence of operational data. The only other study found was Lobanova et al. (2016) that looked at the impacts of changing climate on the hydrology and hydropower production of the Tagus river using five CMIP5 GCM runs bias corrected using the WATCH ERA40 dataset. They projected that for RCP8.5, river discharge will decrease on average by 30% for 2021–2050 and 60% for 2070–2099 with model agreement being higher for the end-of-century period. However, values for individual model projections or for intermodal spread were not provided.

European and global climate change impact studies on hydrological variables can be used to infer the general behavior expected in the area but they use simplified continental or global hydrological models that are not specifically calibrated or validated for the study area. Nevertheless, these tend to identify the Iberian Peninsula or the wider Mediterranean area as one of the most problematic regions in the world in terms of future water resources. Prudhomme et al. (2014) ran 7 global impact models with climate data from 5 Global Circulation Models (GCMs) for the period 2070–2099 and found that Iberia was one of the areas where hydrological drought (defined as daily runoff below the 10th percentile of the reference period − 1976–2005) was expected to increase, with Southern Europe being identified as a “possible hotspots for future water security issues”. Schneider et al. (2013), using a global hydrological model (WaterGAP3) for 2041–2070 and 3 bias corrected GCMs, found that the strongest impacts in terms of flow regime modification in Europe were in the Mediterranean and boreal regions (with the Mediterranean area encompassing the 3 basins of this paper). In the Mediterranean, they concluded that discharges will be lower throughout the year (in terms of the model ensemble mean) but the range of change in the winter half-year (October to March) was very high. Forzieri et al. (2014) used a 12 member ensemble of bias-corrected climate projections from the EU FP6 ENSEMBLES project (Linden and Mitchell, 2009) and one large-scale hydrological model − LISFLOOD (Burek et al., 2013) to conclude that in southern Europe strong reductions in low flows will be felt, with Iberia being one of the most affected areas. By 2020s there is around 10%-20% reduction in minimum flows, but by 2080s this reduction reaches up to 40%. Roudier et al. (2016) used 11 bias-corrected climate models (different combinations of 4 GCMs, 4 RCMs and 3 Representative Concentration Pathway − RCPs) from EURO-CORDEX (Jacob et al., 2013) to drive 2 pan-European hydrological models − LISFLOOD and E-Hype (Donnelly et al., 2016). Future changes were assessed for the 30-year period when the driving GCM reaches an increase of 2 °C in global mean temperature. Low flows (10-year return period of minimum annual flow) decreased in most of Iberia and the duration of these low flows increased. While most of Iberia showed agreement in the sign of these changes, their magnitude showed a wide spread between the different simulations. These type of studies are interesting and give a general overview of the future water resources in the area but do not provide basin specific information that is relevant for planning for climate change adaptation. Such specific information can only be provided by basin-scale hydrological models, calibrated and validated on local data.

Hydrological models are often classified as conceptual or physically based. Conceptual models vary in complexity but usually consider the basin as a single (or lumped) entity. Additionally, at least some of the parameters do not have a physical interpretation and therefore must be derived through calibration (Pechlivanidis et al., 2011). Physically-based models use equations based on established theory or experimental results to represent the underlying hydrological processes (e.g. evapotranspiration, infiltration and overflow). Model parameters are normally estimated using soil type and land cover spatial datasets and subsequently adjusted to improve discharge simulations. This final adjustment is necessary due to the inability of the model to account for the heterogeneity in the basin, scaling effects, and the existence of input and output errors (Reed et al., 2004). There are also issues with the extrapolation of laboratory/small scale field experiments physics to catchment scale and with the simplification of processes (Pechlivanidis et al., 2011).

The main sources of uncertainty in hydrological modelling are input uncertainty (e.g. sampling and measurement errors in rainfall data), output uncertainty (e.g. rating curve errors and extrapolations affecting discharge data), structural uncertainty (or model uncertainty) arising from lumping and/or simplifying the hydrological processes and parametric uncertainty (Renard et al., 2010). When hydrological modelling is used for assessing the impacts of climate change, the uncertainty associated with hydrological models is generally considered less important than the uncertainties resulting from selecting emission scenarios, GCMs and downscaling their output to a scale that can be used for hydrological studies (Kay et al., 2009; Prudhomme and Davies, 2009; Teng et al., 2012).

On the other hand, transferring the calibration of parameters under historical climatic conditions to futures with different climatic characteristics raises questions of validity. This is especially so when using conceptual hydrological models where the values of parameters are derived solely through calibration and there is no physical meaning and/or constraints to these values. Coron et al. (2012) applied three conceptual models to 216 water limited catchments in southeast Australia and assessed their extrapolation capacity in different climate conditions. They found a tendency in most catchments to overestimate mean runoff when the calibration period was wetter (wet to dry parameter transfer) and to underestimate mean runoff when the calibration period was drier (dry to wet parameter transfer). Despite this common tendency, the magnitude of the errors varied greatly between basins.

To minimize the problem of parameter transferability under climate change, and due to the lack of naturalized observations at the outlet of these rivers that could be used to calibrate a conceptual hydrological model, here a physically-based, spatially-distributed model with a 3D subsurface was used: SHETRAN (Ewen et al., 2000; Birkinshaw et al., 2010).

In this study SHETRAN was applied to the international basins of the Douro, the Tagus and the Guadiana for historical (1961–1990) and future (2040–2070) periods to assess changes in discharge. This paper is part of a wider study of the three basins which analyzed:

- historical rainfall records (Guerreiro et al., 2014);
- transient rainfall projections from climate models (Guerreiro et al., 2016) − used as an input to SHETRAN in this study;
- and future drought (Guerreiro et al., 2017).

The paper is organized as follows. In section 2 the datasets used for the SHETRAN calibration, validation and historical and future simulations are presented. Section 3.1 explains how the model was set up. Calibration and validation results are presented in section 3.2. While section 3.3 provides a sensitivity analysis of the model results to the calibration procedure. Section 3.4 describes the methodology of the future SHETRAN runs. The results are divided into historical discharge simulations (section 4.1) and future discharge simulations (section 4.2). The discussion and conclusions are presented in section 5.

2. Data

Running a physically based, spatially distributed hydrological model requires a considerable amount of data. Table 2 summarizes the datasets used and Table 3 provides information on the individual climate model projections.

3. Methodology

3.1. Setting up the hydrological model

SHETRAN is a physically-based distributed hydrological model that can be visualized as a set of vertical columns, with each column divided into finite-difference cells. The lower cells contain aquifer materials and groundwater, higher cells contain soil and

Table 2
Data used in the SHETRAN models for the Douro, Tagus and Guadiana basins.

Dataset	Description	Source
"Hydro1 K Europe"	30 arc-second digital elevation map (DEM) with rivers and catchment areas. The DEM of the three studied basins is shown in supplementary information (Figure S.1). The basins delimitations (shapefiles) used were also from this dataset.	U.S. Geological Survey: https://lta.cr.usgs.gov/HYDRO1K
Land use map	100 m resolution map created for project "Refuel" by merging CLC2000, GLC2000 and the Corine dataset. The 37 land use classes were aggregated (by similarity) to 9 land use classes which is a more manageable number for calibration purposes. The land use map of the three studied basins is shown in supplementary information (Figure S.2.	Provided by Dr Wiberg from IIASA
Soil map	1 km resolution raster layers of dominant topsoil texture, depth to textural change, dominant subsoil texture and depth to rock.	Joint Research Centre – European Soil Database v2.0: http://eusoils.jrc.ec.europa.eu/esdb_archive/ESDB_data_1k_raster_intro/ESDB_1k_raster_data_intro.html
Observed gridded daily rainfall dataset IB02	0.2° resolution. It is based on 2000 gauges in Spain and 400 in Portugal and is available for the period 1950–2003. It is available as two datasets: PT02 for Portugal and Spain02 v2 for Spain.	PT02 (Belo-Pereira et al., 2011): http://www.ipma.pt/pt/produtoseservicos/index.jsp?page=dataset.pt02.xml Spain02 v2 (Herrera et al., 2012): http://www.meteo.unican.es/en/datasets/spain02
Climate model outputs of daily gridded rainfall and temperature	General Circulation climate Model (GCM) runs for RCP8.5. See Table 3 for information on individual models.	Coupled Model Intercomparison Project Phase 5 (CMIP5): http://cmip-pcmdi.llnl.gov/cmip5/, downloaded from http://climexp.knmi.nl
Potential evapotranspiration (PET) data: cru_ts_3.10	Monthly time-series spanning 1901–2009 with a resolution of 0.5° x 0.5° calculated using more than 4000 weather stations distributed around the world.	Climatic Research Unit (Jones and Harris, 2008): https://crudata.uea.ac.uk/cru/data/hrg/
Observed discharge gauge data	Observed time-series used for SHETRAN's calibration and validation	Compiled from various sources. For Portugal, daily data from the water institute (INAG – Instituto da Água) were retrieved from http://snirh.pt/during 2012. For Spain, daily data were provided by "Sistema integrado de información del Agua" which is an integrated information system from the Spanish government. However, these data finished in 2006. Complementary daily data was retrieved from the Spanish Ministry of development website: http://hercules.cedex.es/general/default.htm during 2012. This website has data until September 2009. Also, for the Douro basin, annual discharge books until the hydrological year 2009–2010 were retrieved from the following website: http://www.chduero.es/Inicio/ElaguaenlacuencaCantidad/Datosdecaudales/Anuariosdedatosforon%C3%B3micosydeembalses/tabid/486/Default.aspx The location of the gauges used in this study is discussed in the methodology section.

soil water and the uppermost cells contain surface waters and the vegetation canopy. River channels are specified around the edge of the finite-difference columns and the location and elevations of these channels are calculated automatically using the method demonstrated in Birkinshaw et al. (2010). Subsurface flow is modelled using the variably saturated flow equation (3D). The channel and overland flow is modelled using the Saint-Venant equations with a diffusion approximation (1D and 2D respectively). The model uses an hourly time step (with the time-step automatically reduced during rainfall events) although in this work daily precipitation and potential evapotranspiration data were used. The model is free to use and can be downloaded at http://research.ncl.ac.uk/shetran/

All simulations were performed at a 5 km spatial resolution. So for example, for the Douro there are 3810 vertical columns, with each column divided into up to 40 finite-difference cells (giving a total of around 150,000 finite difference cells). Overall, 970 river channel sections were specified (see Figure S.3 in supplementary information). The spatial resolution was a compromise between the resolution of the available data and the processing time of model runs needed to explore the future climate change impacts.

SHETRAN was set up with freely available standard elevation, soil and land-use datasets (see section 2) from which most of the required parameters could be obtained. For soil data, the appropriate raster layers from the JRC dataset (dominant topsoil texture, depth to textural change, dominant subsoil texture and depth to rock) were selected and combined using a python script. These describe the soil and Van Genuchten parameters (θs, θr, Ks, α, n) and the depth of each soil/rock layer that SHETRAN requires for each grid square. 73 classes of soil types were used, consisting of different combinations of different soil types in layers at different depths. The soil parameters used in SHETRAN were derived from the original (JRC) dataset and only the aquifer layers were subject to calibration.

We used simplified descriptions of the aquifers within the model due to the complex aquifer systems within the basins and the

Table 3
List of GCMs runs selected for analysis and general characteristics of each model).

Model run number (used in this study)	Model name	Modelling center	Horizontal resolution on the x axis	Horizontal resolution on the y axis	Calendar
1 and 2	CanESM2	Canadian Centre for Climate Modelling and Analysis	2.8125	2.8125	365
3	IPSL-CM5A-LR	Institut Pierre-Simon Laplace	3.75	1.875	365
4 and 5	CNRM-CM5	Centre National de Recherches Météorologiques/ Centre Européen de Recherche et Formation Avancée en Calcul Scientifique	1.4063	1.4063	366
6	CSIRO-Mk3-6-0	Commonwealth Scientific and Industrial Research Organization (CSIRO) and Bureau of Meteorology (BOM), Australia	1.875	1.875	365
7	EC-EARTH	EC-EARTH consortium	1.125	1.125	366
8	GFDL-CM3	NOAA Geophysical Fluid Dynamics Laboratory	2.5	2	365
9	GFDL-ESM2M	NOAA Geophysical Fluid Dynamics Laboratory	2.5	2.5	365
10	GISS-E2-R	NASA Goddard Institute for Space Studies	2	2.5	365
11 and 12	HadGEM2-ES	Met Office Hadley Centre (additional HadGEM2-ES realizations contributed by Instituto Nacional de Pesquisas Espaciais)	1.875	1.25	360
13	INM-CM4	Institute for Numerical Mathematics	2	1.5	365
14	MPI-ESM-LR	Max-Planck-Institut für Meteorologie (Max Planck Institute for Meteorology)	1.875	1.875	365
15	MRI-CGCM3	Meteorological Research Institute	1.125	1.125	366

difficulty of assessing all the necessary data. We feel this is justified by the size of the study area and the type of outputs of interest: long-term changes of the monthly discharges of the three main rivers. To identify areas with aquifers, maps from the Spanish Mineral and Geological Institute (IGME, 2012) and from the Portuguese Water Institute (INAG, 2012) were consulted and visually matched with different soil types present in the three basins (see section 2.1 and figures S.4 and S.5 in the supplementary information). Aquifer layers (detrital or karstic) were then added to the soil types identified.

We analyzed discharge at locations used in the Albufeira convention, which is the international agreement between Portugal and Spain that regulates discharges in these rivers. However, some gauges had to be substituted since they had no available data online (or had only a few years). Fig. 1 shows the location of the gauges used in this study compared to those in the convention.

3.2. Calibrating and validating the hydrological model

Ideally the calibration and validation of a hydrological model would be performed using measured outputs of the simulated rivers. However, measured discharges from the Douro, Tagus and Guadiana basins are highly impacted by human activities, with thousands of dams (Spanish Government, 2017). For example, abstractions in the Spanish Douro, Tagus and Guadiana were estimated at 3860 hm^3/yr, 4041 hm^3/yr and 2331hm^3/yr (or roughly 26%, 42% and 87% of annual discharge) respectively (CHD, 1999; CHG, 1999; CHT, 1999) (see Table 4). Calibration and validation therefore had to be performed in sub-basins with "natural discharges". An assumption was made that for sub-basins without the presence of a dam the discharges could be considered "natural", although we cannot exclude the existence of water abstractions or other human activities in these locations. Four suitable sub-basins were identified and these were used for model calibration and validation (Fig. 2); these represent different climatic zones, different soil types (some with and some without aquifers) and different land-uses classes.

Calibration was done using different aquifer saturated hydraulic conductivities (in the x, y and z direction) and parameters associated with each vegetation/land use class. A split-sample calibration-validation strategy was used, although restricted by the period of available measured discharge for each sub-basin. Since the main objective is to simulate monthly discharges, the widely used Nash–Sutcliffe Efficiency (NSE) was not used for calibration assessment, because in basins with high discharge variability the NSE is not very susceptible to volume errors and favors simulations that underestimate variability (Gupta et al., 2009). Instead the following monthly measures of goodness of fit were used in combination with daily and monthly discharge plots and annual water-balance plots:

- bias.total = sum of simulated discharge/sum of observed discharge
- bias.var = variance of simulated discharge/variance of observed discharge
- cor = Spearman's rank correlation coefficient (Spearman's rho)

The calibration of these sub-basins consisted of the adjustment of the following parameters:

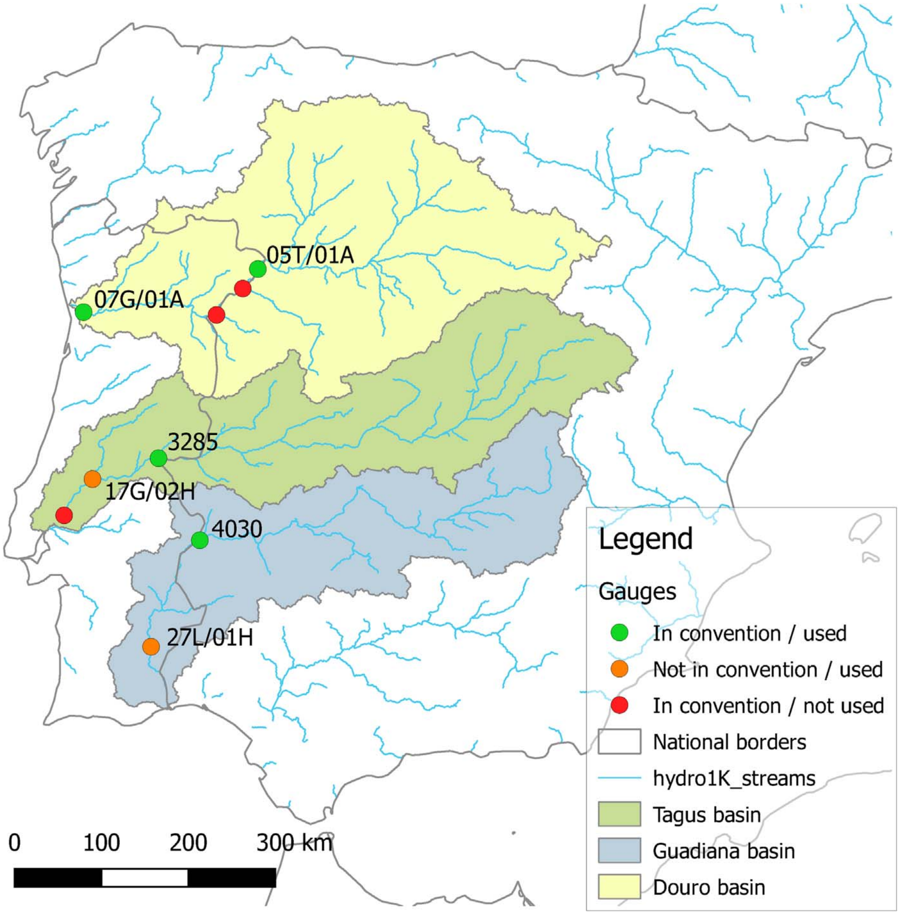

Fig. 1. Map of Iberia with the three studied basins, the locations where discharge was analyzed and the locations of the Albufeira convention discharge points.

Table 4
Water uses (in hm^3/yr) in the Spanish Douro, Tagus and Guadiana (CHD, 1999; CHG, 19999). Followed by differences between simulated and measured discharge (hm^3/yr) at the outlet gauges calculated in this study and reservoir storage capacity in Portugal and Spain from Almeida et al. (2009).

Water uses in Spain	Douro		Tagus		Guadiana	
	urban	214	urban + industrial (includes	2643	urban	119
	irrigation	3603	irrigation)		irrigation	2157
					livestock	18
	industrial	43			industrial	36
			power stations cooling	1397	others	2
	environment	1658	environment	765	environment	79
Total consumptive use in Spain	3 860		4 041		2 331	
Difference between simulated and measured annual Q at the outlet gauges (hm^3/yr)	3 407		4 410		1 516	
Storage capacity in Spain (hm^3)	1 670		11 140		9 222	
Storage capacity in Portugal (hm^3)	1 080		2 750		3 610	

- Ratio of actual/potential evapotranspiration for each vegetation/land use class;
- Storage capacity of canopy for each vegetation/land use class;
- Permeability and depth of aquifers associated with each soil type;
- Overland flow roughness parameter for the different land cover classes.

The initial values for these parameters were based on expert knowledge. The manual calibration was performed using the same values for these parameters in all the sub-basins so they could be extrapolated for the three main basins. This means the value for the parameters are not optimal for any sub-basin but the best values for all the sub-basins. It is important to note that the spatial resolution used in the simulation (5 km) and the rainfall dataset used are appropriate for the simulation of the three big basins but not for the simulation of the small sub-basins. Unfortunately, in order to extrapolate the results of the calibration of the sub-basins to the

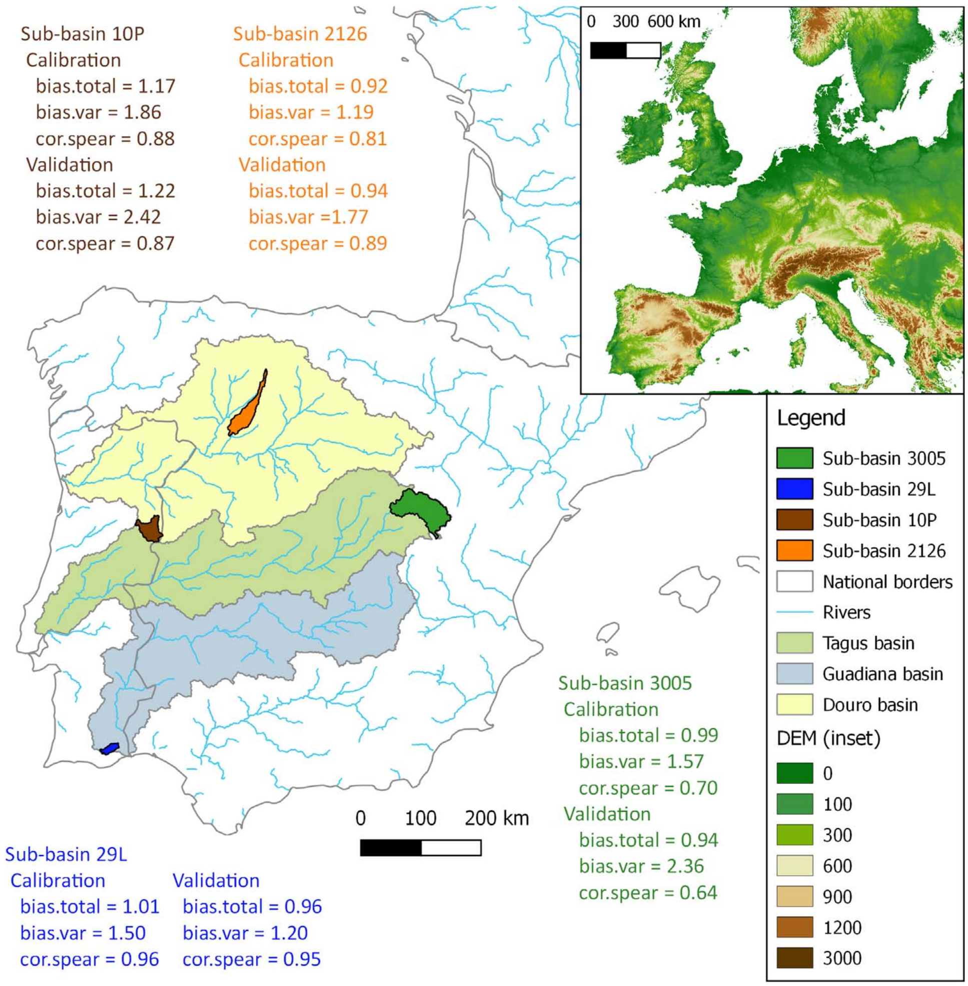

Fig. 2. Map of Iberia with the Douro, Tagus and Guadiana basins and the four sub-basins used for calibration and validation. The calibration and validation goodness of fit results are also presented for each sub-basin where bias.total is the sum of simulated monthly discharge divided by the sum of observed monthly discharge, bias.var is the variance of simulated monthly discharge divided by the variance of observed monthly discharge and cor.spear is the Spearman's rank correlation coefficient.

bigger basins, the same datasets and the same spatial resolution must be used.

Fig. 2 shows the location of the sub-basins and a summary of the results of the calibration and validation (more information is provided in supplementary information section 3). Despite potential issues with scale and simulated variance being too high (discharge peaks are slightly too high causing bias.var values between 1.19 and 2.42), the calibration results were considered good for the sub-basins (with biases in simulated discharge between 8% underestimation and 22% overestimation and Spearman's rank correlation coefficients between 0.64 and 0.95). Therefore, the same parameter values were used for the whole basin model simulations.

3.3. Sensitivity to calibration

To assess the sensitivity of the SHETRAN model calibration on the simulated monthly discharge of the rivers Douro, Tagus and Guadiana (at their border gauges and outlets), SHETRAN simulations were performed for the 1961–1990 period using uniform parameters for all land use/vegetation classes. We also produced simulations with different aquifer parameters to assess the sensitivity of these for simulated discharges for the Tagus.

The effects of parameter sensitivity on the monthly discharges at the border and outlet gauges of the three rivers are small, possibly due to the large size of the basins (see Fig. 3 for the outlet of the Tagus as an example). Bias in the total discharge between calibrated and non-calibrated runs varies from 0.83 (Guadiana-outlet) to 0.94 (Douro-outlet). Bias in the discharge variance between calibrated and non-calibrated runs ranges between 0.87 (Tagus and Guadiana border) to 0.97 (Douro-border). The Spearman correlation between calibrated and non-calibrated results is always very high (from 0.98 to 1) and the NSEs are also always very high (0.96–0.99).

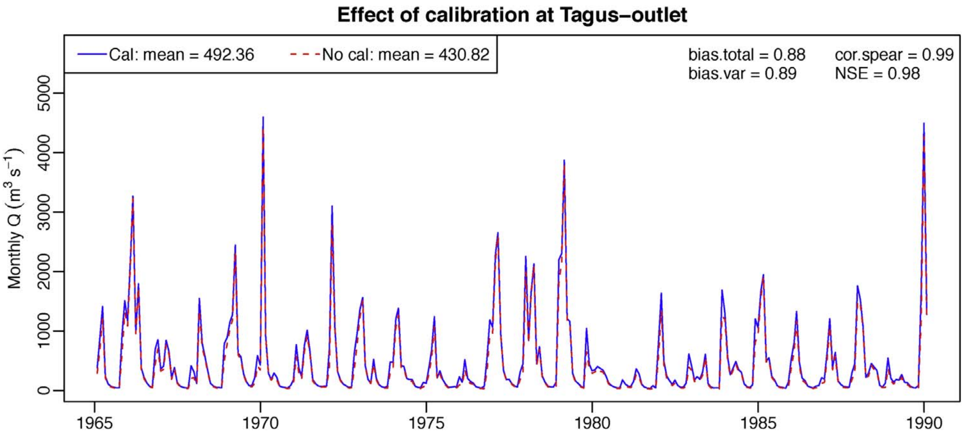

Fig. 3. Time-series of simulated monthly discharge with (blue) and without (red) calibration for Tagus-outlet. The no-calibration run was done using the same parameters for all land use/vegetation classes (i.e. assuming the entire study area had a uniform land use/vegetation class).

The effect of aquifer parameterization (varying saturated hydraulic conductivities) was also very small and restricted to the low discharges (see Fig. 4). The simulations are virtually indistinguishable in the time-series plot and differences are only noticeable for the low flows in the logarithmic scale of the flow duration plot.

These results suggest that the parameter sensitivity of the SHETRAN model calibration on historic monthly river discharges of the Douro, Tagus and Guadiana is relatively small and, as a result, the influence of calibration to future discharge should also be small.

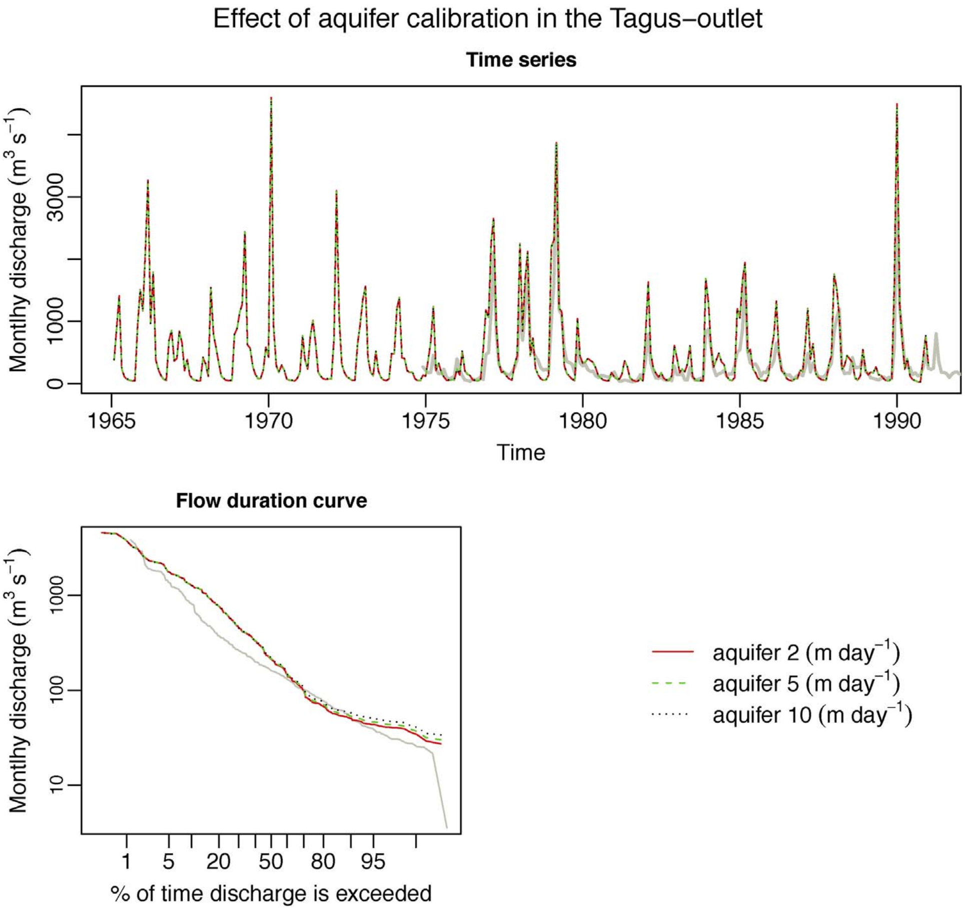

Fig. 4. Time-series (top) and flow duration curves (bottom-left) of monthly mean discharges for Tagus-border. Observations (available from 1975 onwards) are plotted in grey and SHETRAN simulations with different aquifer saturated hydraulic conductivities (in meters per day) are plotted according to the legend. Please note that the simulated discharges are naturalized flows and the observed flows are not (therefore a match would not be expected).

3.4. Future simulations

We obtained rainfall projections over the international basins of the Douro, Tagus and Guadiana for 1961–2100 for 64 Global Climate Model (GCM) runs from CMIP5 for Representative Concentration Pathway (RCP) 8.5. This RCP was chosen since Sanderson et al. (2011) showed that despite being the highest emission scenario considered in CMIP5, RCP8.5 assumes emissions below what the current energy mix would produce in the future. From this set, we chose a sub-set of scenarios representative of the range of regional seasonal changes in mean temperature and precipitation projected by the whole ensemble (see Figures S.25 and S.26 in Supplementary information), as running the hydrological model for these big basins for all 64 GCM runs was not feasible. We selected the 15 GCM runs detailed in Table 3; since the selection of projections to use was done with the aim of including the whole range of possible futures and did not consider the source of the projection, some GCMs have two runs selected − same GCM but different initial conditions. Guerreiro et al. (2016) give more detail on the process of climate model selection.

For each GCM run, rainfall output fields were downscaled for the region, for the periods 1961–1990 and 2041–2070 (thereafter called the 2050s), using two different methods: modified empirical quantile mapping (MEQM) and monthly change factor (CF). It would have been ideal to also use results from dynamical downscaling; however, at the time of the data download no projections from regional climate models downscaling CMIP5 model runs were available. At the time of this paper submission only 5 GCMs had been downscaled to 0.11 ° (through the project "EURO-cordex") which is not enough to capture the whole range of CMIP5 projections, which is our goal. Therefore, only statistical methods were used to downscale/bias correct the GCM projections. However, two methods were used to provide an understanding of the uncertainty associated with the choice of statistical downscaling method.

For the MEQM method, empirical cumulative distribution functions were calculated for historical rainfall from each GCM run and for the observed rainfall dataset IB02 (spatially aggregated to the GCM grid cell scale). Simulated monthly rainfall output for each GCM was matched (using quantiles) to the corresponding observed value for corresponding months. The final dataset has the temporal and spatial resolution of IB02 while keeping the inter-annual variability of each model run. Nevertheless, the whole distribution of rainfall is corrected by the quantile mapping technique. For the CF method, a future series was produced for the 2050s by calculating a CF for each month and GCM grid by dividing future modelled rainfall by historical modelled rainfall. The observed gridded rainfall (IB02) was then multiplied by this monthly change factor and the above process repeated.

Historical and future GCM based PET was calculated using the Thornthwaite equation (Thornthwaite, 1948) using the SPEI package for R (Vicente-Serrano et al., 2010). This simple empirical method correlates mean monthly air temperature and PET for any determined latitude. We did not use the Penman-Monteith formula (Penman, 1948) as it requires time-series for several variables that are not well simulated by GCMs and can give physically unrealistic results (Weiland et al., 2012). PET calculated from GCM output varied considerably between different GCMs, but all were consistently below PET estimates from the CRU dataset (Jones and Harris, 2008) which uses Penman-Monteith. These estimates were then used to provide a CF for each month and GCM grid by dividing future modelled PET by historical modelled PET. For the calculation of future PET under the MEQM method, the same year that was selected for the rainfall during the quantile matching was also selected for PET (in order to keep the physical relationships between the two variables). However, the differences in PET between 1961 and 90 and the 2050s were negligible, therefore a monthly change factor approach was also applied (following the procedure described above). More information on the selection, downscaling and bias-correction of these projections can be found in Guerreiro et al. (2016).

After the calibration and validation was performed in the sub-basins, the chosen parameters were used to run historical (1961–1990) and future (2041–2070 referred to as the 2050s) SHETRAN runs for the Douro, the Tagus and the Guadiana. The following simulations were performed:

- observed rainfall and PET − control run
- downscaled rainfall and PET using the change factor method − change factor runs
- downscaled rainfall and PET using the modified empirical quantile mapping method − MEQM runs.

The first four years of each simulation were discarded to allow model stabilization and results will be presented for the periods 1965–1990 and 2045–2070. The Kolmogorov-Smirnov test (at 0.05 significance) was used to assess the statistical significance of seasonal and annual changes in discharge for the outlet of the three rivers (between 1965 and 1990 and 2045–2070).

4. Results

4.1. Historical discharge simulations

As explained previously, simulated discharges are natural discharges and will be significantly different to the observed discharges due to the high degree of management in the Douro, Tagus and Guadiana. This management consists of major surface and groundwater abstractions as well as regulation by hundreds of storage reservoirs dams that exist in these basins. Nevertheless, annual observed and simulated discharge time-series (for the available periods) for outlet gauges of the three rivers and are shown in Fig. 5.

The mean annual differences between simulated and observed discharges (for the period when both are available) for the Douro-outlet gauge is 3407 hm^3/yr, for the Tagus-outlet gauge is 4410 hm^3/yr and for the Guadiana-outlet gauge is 1516 hm^3/yr. These are the same order of magnitude as the water uses in the Spanish section of the three basins shown in Table 3 and suggest that the model is adequately simulating the water balance in the three catchments.

In this simple comparison, we do not consider inter-basin water transfers which have long existed in Spain, with examples dating

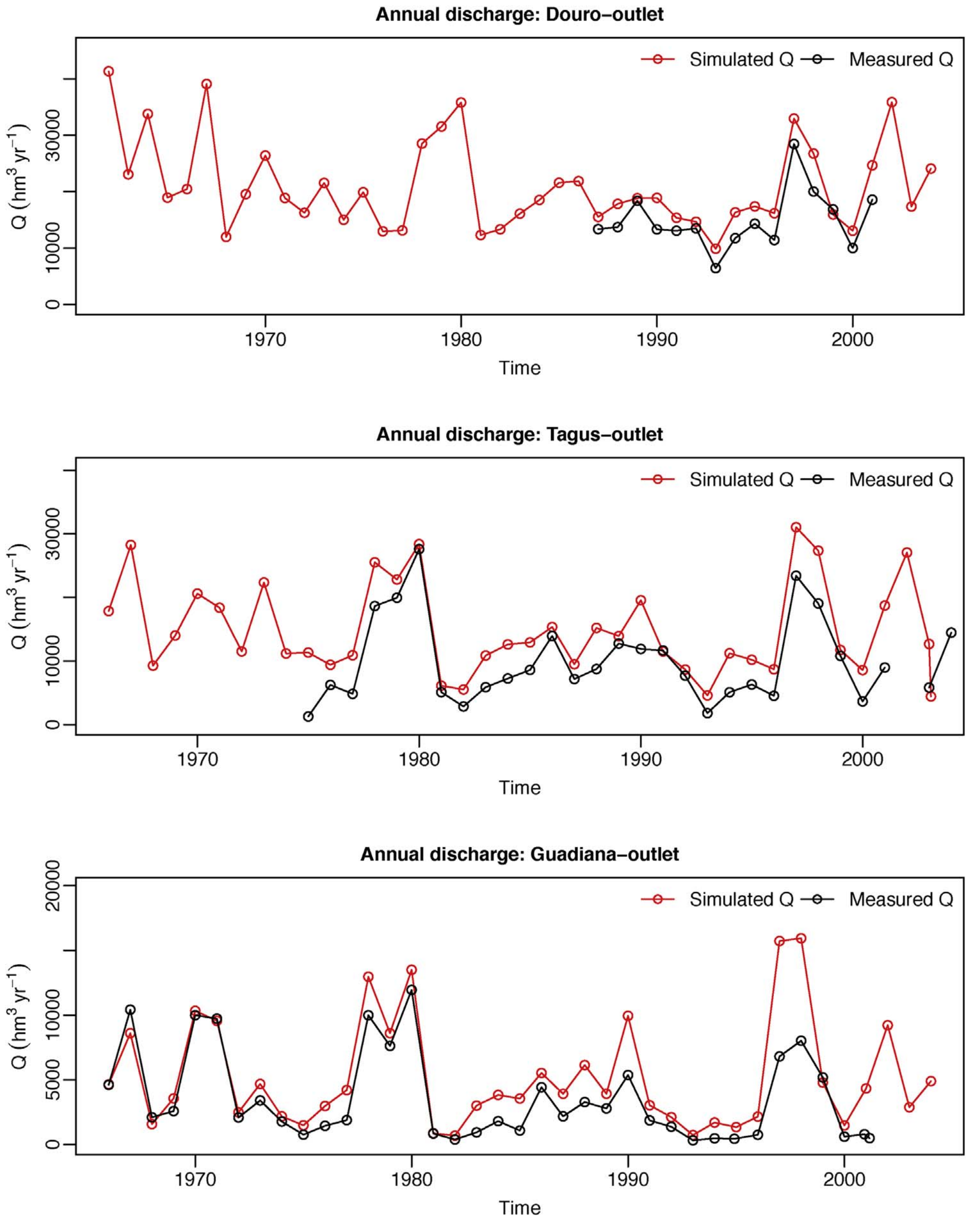

Fig. 5. Simulated (in red) and measured (in black) annual discharge for the Douro- outlet (top), Tagus-outlet (center) and Guadiana-outlet (bottom) for the period 1965–2003.

from the sixteenth century (MIMAN, 1998). The most important current water-transfer in Spain is the “Tajo-Segura” aqueduct which brings water from the high Tagus to the Guadiana, Sur, Segura and Júcar basins (MIMAN, 1998). The volume of water transferred annually from the Tagus varies significantly, at a maximum of $650hm^3/yr$, which can only be transferred when a number of conditions are met (CHT, 1999). We also do not consider the evaporative losses from the hundreds of dams in the area. For example, for the Spanish area of the Tagus, the *Confederación Hidrográfica del Tajo* (C.H.TAJO, 2014) lists 83 dams with a combined storage area of 47,564 hm^2.

Despite these caveats, the temporal evolution of simulated and observed annual discharges for the three basins are as expected and the differences between the two are of the same order as the Spanish water abstractions. Furthermore, the biggest simulated differences are in the Tagus and the smallest in the Guadiana, as would be expected considering the water uses and the Tagus-Segura transfer. Although these results cannot be used to definitively validate the SHETRAN simulations, they do increase confidence in them.

A comparison of monthly simulated and measured discharges is harder to make since monthly measured discharges are strongly affected by dam operations. Therefore, these results are shown only in the supplementary material (section 4). The performance of the simulations was considered good but some low flows appear too low in the simulations, especially in the Tagus.

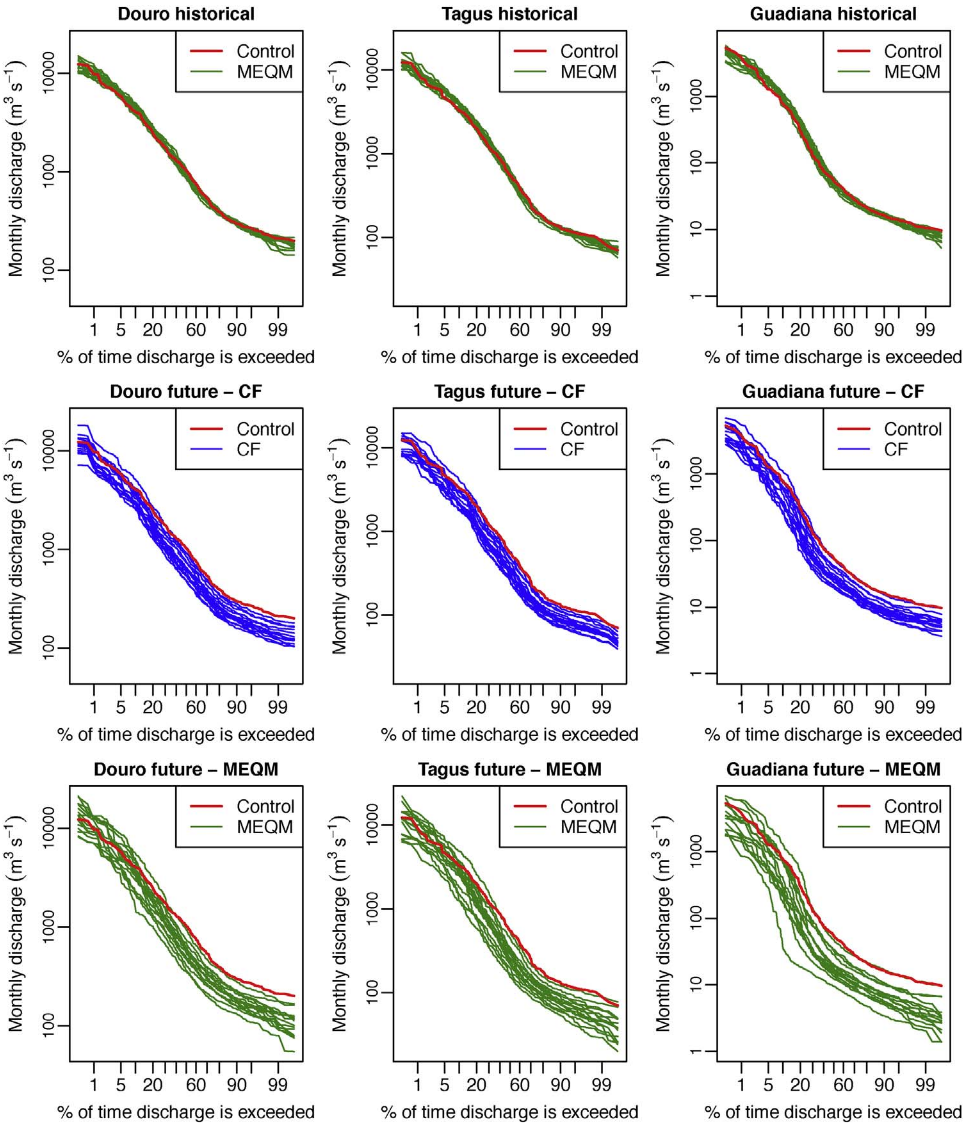

Fig. 6. Flow duration curves for Douro-outlet (left) Tagus-outlet (center) and Guadiana-outlet (right) for historical (1965–1990) monthly discharge (top), future (2045–2070) monthly discharge obtained using the change factor method (middle) and future (2045–2070) monthly discharge obtained using the Modified Empirical Quantile Mapping (MEQM) method (bottom). The flow duration curve of monthly discharge for the control run (SHETRAN simulation using observed meteorology) was added to all plots (red line).

4.2. Future discharge simulations

Despite a wide range of results, the only positive significant changes in future discharge are in winter (two runs in the Douro and one in the Tagus). All other seasons, and annual discharge, show reductions or no significant change in discharge (see Table 4). The MEQM downscaling method projects more significant change to discharge than using the simple change factor approach and the seasons showing more significant changes are spring and summer. The Guadiana River shows the largest number of simulations with significant changes, and in spring and summer almost all simulations showed significant reductions in discharge in this basin.

Results for the three basins, including those that are not statistically significant using the Kolmogorov-Smirnov test (at 0.05 significance) will be shown here for the outlet of the basins. The non-statistically significant results are also shown because in noisy series, like the discharges of these three basins, it is hard to assess significance using just 25 years of data.

Fig. 6 shows the flow duration curve (FDC) of monthly discharge for the outlets of the Douro, Tagus and Guadiana. The simulations for the control runs (SHETRAN runs using observed rainfall and PET) are encompassed by the historical MEQM runs, which increases the confidence in the SHETRAN MEQM runs. All models (except one run for the Tagus and one for the Guadiana) show a decrease in medium and low monthly future discharges, which is more accentuated in the MEQM runs. The behavior of high flow is strongly model dependent (Table 5).

Table 5
Number of models showing positive (pos) and negative (neg) significant changes in discharge between 1965–1990 and 2045–2070 using the Kolmogorov-Smirnov test at 0.05 significance level for each basins' outlet and for each season (annual values also included). Results are shown for the change factor runs (CF) and the modified empirical quantile mapping runs (MEQM).

Season	Douro − outlet				Tagus − outlet				Guadiana − outlet			
	CF		MEQM		CF		MEQM		CF		MEQM	
	pos	neg	pos	neg	pos	neg	pos	neg	pos	neg	pos	neg
OND	0	9	0	8	0	6	0	7	0	9	0	9
JFM	0	0	2	4	0	1	1	6	0	1	0	8
AMJ	0	6	0	11	0	11	0	10	0	14	0	14
JAS	0	12	0	14	0	12	0	13	0	13	0	14
Annual	0	8	0	8	0	5	0	7	0	3	0	10

All basins display a wide spread of results for change to future discharge, with most GCMs projecting a decrease in mean discharge for all seasons. However, the climate model MRI-CGCM3 has a different behavior from the rest of the ensemble. Despite not projecting significant long term trends (1961–2100) for annual rainfall in any of the basins (Guerreiro et al., 2016), in this study we found that it is projecting substantial increases in mean annual discharge in all basins for both downscaling methods. It is also the model projecting the highest discharges for winter, spring and summer in all basins. This happens because, for this area, the 2050s just happen to coincide with a period of high winter (and consequently annual) rainfall. The impact of which is felt in winter, spring and summer discharges but not in autumn where MRI-CGCM3 does not have a distinct behavior. Therefore, the discharge results obtained with MRI-CGCM3 are not due to a trend associated with climate change but with the impact of (simulated) natural variability and the choice of a particular time-slice of analysis.

Fig. 7 show results for the whole GCM ensemble. There is a wide range of results for mean change in seasonal and annual discharge but most GCM runs project a decrease in discharge for all seasons in all basins. Most GCMs also projected decreases in the mean annual discharge, ranging between −52% to +25% (or +2% excluding MRI-CGCM3) for Douro-outlet, −60% to +32% (or +2% excluding MRI-CGCM3) for Tagus-outlet and −82% to +68% for Guadiana-outlet (-3% excluding MRI-CGCM3).

The most pronounced decreases in discharge are projected for autumn (Oct-Dec) when almost all GCMs project decreases for all basins. These can reach −61% for the Douro, −71% in the Tagus, and −92% for the Guadiana.

In contrast, in winter some GCM runs project an increase in discharge and MRI-CGCM3 projects particularly high increases in discharge when using the MEQM method: 51% in the Douro, 65% in the Tagus and 91% in the Guadiana. Nonetheless, most GCMs still project mean winter discharge decreases, which can reach −50% in the Douro, −56% in the Tagus and −78% in the Guadiana.

In spring, all runs except MRI-CGCM3 show decreases in mean seasonal discharge that can reach −59% in the Douro, −65% in the Tagus and −86% in the Guadiana. In summer all runs show decreases in discharge (except MRI-CGCM3 for the Guadiana) reaching −51% in the Douro, −49% in the Tagus and −71% in the Guadiana.

5. Discussion and conclusions

A spatially distributed, physically-based, hydrological modelling system (SHETRAN) was used to simulate historical (1965–1990) and future (2045–2070) discharges for the international basins of the Douro, Tagus and Guadiana. Calibration and validation of historical discharges were performed using sub-basins deemed to have 'natural' flows due to the very high level of abstractions in these basins. These calibrated parameter sets were then transferred to model the larger basins. Despite this, the temporal evolution of the simulated and observed/measured annual discharges for the three basins was as expected (similar behavior despite the differences in magnitude), as were the order of magnitude of the differences between observed and simulated discharges, when considering the water consumption in the region. The performance of the simulations in terms of monthly flows was also good; however, some simulated low flows appear rather low, especially in the Tagus. This may be due to the very simplified aquifer system used in the hydrological model.

For an ensemble of 15 GCM runs from CMIP5 which span the range of projected changes in temperature and precipitation for the whole CMIP5 ensemble, future decreases in monthly, seasonal and annual discharges were projected for all basins, especially for medium and low discharges. Some GCMs also project increases in high/winter discharges. This is in agreement with Roudier et al. (2016) who projected low flows to decrease in Iberia but with a wide spread in the magnitude of this decrease and Schneider et al. (2013) who found that discharges decreased but with high uncertainty during the winter half-year. However, in depth analysis of the model MRI-CGCM3, which projects the highest increase in winter discharge, has shown that this is due to the effects of (simulated) natural variability and the choice of a particular time-slice of analysis, not a significant increasing rainfall trend.

The magnitude of the projected decreases in discharge varies significantly throughout seasons and basins, partly due to the high natural inter-annual variability of precipitation in the region and partly due to the wide spread in future projections of change to precipitation and temperature for the CMIP5 ensemble.

The annual changes in discharge found by Kilsby et al. (2007); −21% to −26% for the Guadiana and −49% to −20% for the Tagus for 2070–2100 are within the range of the changes found in this study (−60% to +32% for the Tagus and −82% to +68% for the Guadiana). Lobanova et al. (2016) projected average changes in the Tagus to be −30% for 2021–2050 and −60% for 2070–2099.

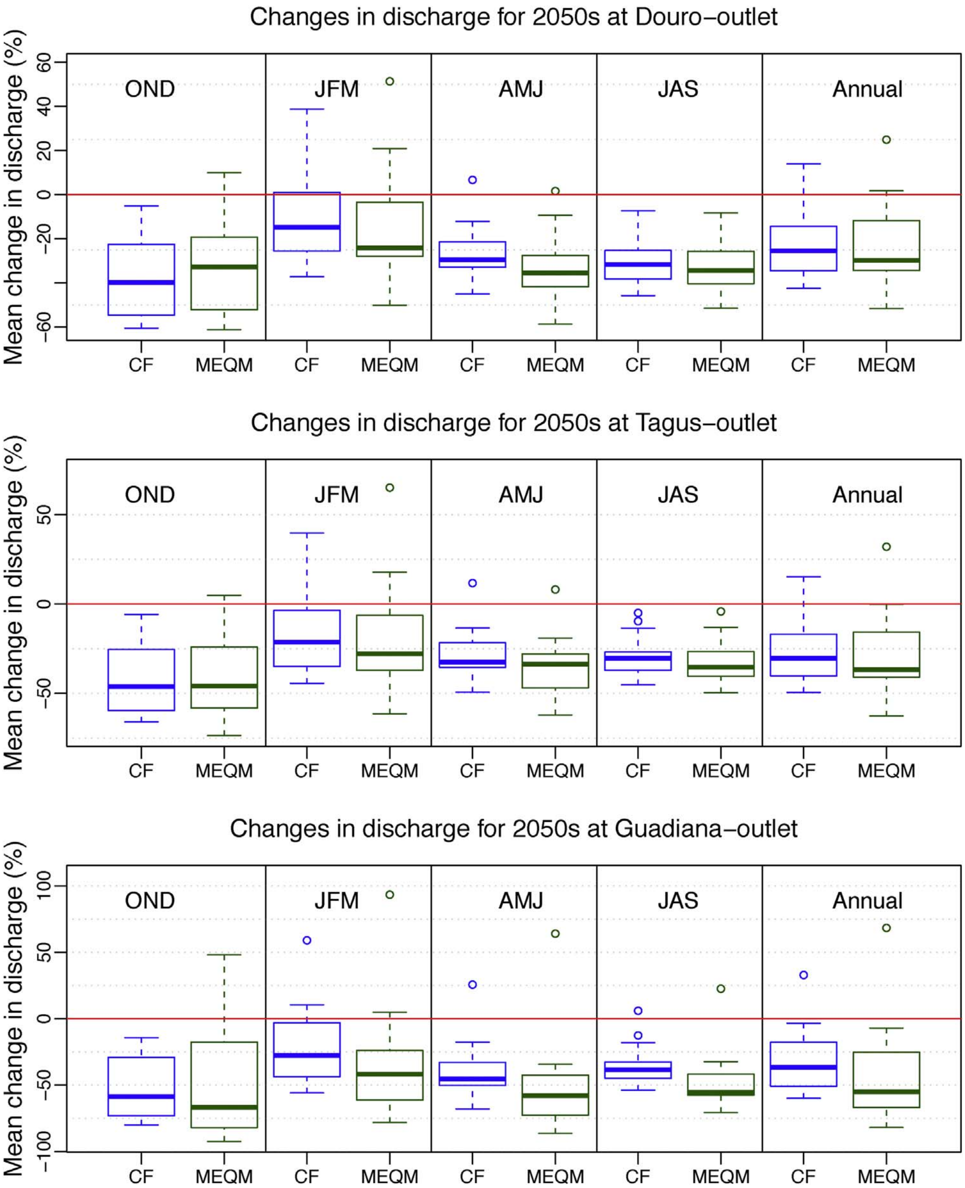

Fig. 7. Boxplots of mean change (2045–2070 in relation to 1965–1990) for seasonal and annual discharges for Douro-outlet (top), Tagus-outlet (center) and Guadiana-outlet (bottom). Results using the change factor method are shown in blue, while MEQM results are shown in green. Please note the different scales on the y-axis.

The changes for the earlier period are within the ranges found in this study, although the end-of-century projections are higher, which is not surprising since our period of analysis was 2045–2070. Nevertheless, the present study showed the substantial increase in the range of mid-century discharge projections that arises from using several climate models and downscaling techniques.

The MEQM runs show a wider range of projected changes to discharge than the CF runs, with the bigger decreases in discharge always being from the MEQM runs (all seasons and all basins). This is explained by the extra information in the quantile mapping method where the changes in inter-annual variability projected by the climate models are retained.

Most projections showed decreases in annual future discharges which are more pronounced for low discharges and for the MEQM runs in all basins. Autumn is the season showing the biggest decreases in discharge throughout the models and the Guadiana is the basin consistently presenting the biggest discharge reductions throughout the year.

In this study we explored a wide range of possible futures, based on the emission scenario RCP8.5, for the entirety of the main international basins in Iberia and showed that despite uncertainties in model projections, there is a common behavior of reductions in mean and especially in low discharges in these rivers. This study can therefore be used to assess adaptation measures that need to be considered in order to make regional agriculture and water resources resilient to future climates. Also, in light of these estimates of future discharges we argue that there is the need to reassess the Albufeira Convention – the international water treaty between Portugal and Spain. Future work will assess the changes in rainfall from Guerreiro et al. (2016) and the changes in discharge projected in this study in light of the Albufeira Convention regulations.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ejrh.2017.05.009.

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