



Deliverable 4.2

PILOT DESCRIPTION AND ASSESSMENT

Continental Spain (Spain)

Authors and affiliation:

David Pulido-Velazquez, Francisco Javier Alcalá; AJ. Collados-Lara, L. Baena Ruiz.

Geological Survey of Spain (IGME)



This report is part of a project that has received funding by the European Union's Horizon 2020 research and innovation programme under grant agreement number 731166.



Deliverable Data	
Deliverable number	D4.2
Dissemination level	Public
Deliverable name	Pilots description and assessment report for groundwater recharge and vulnerability
Work package	WP4
Lead WP	GEUS (WP4)
Deliverable status	
Version	Version 1
Date	14/01/2019

[This page has intentionally been left blank]

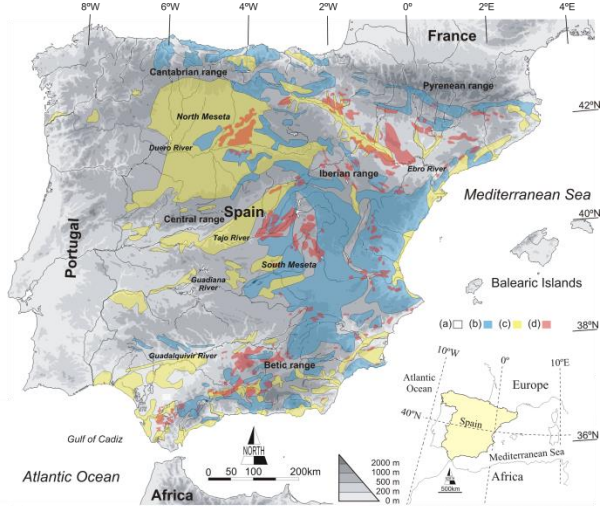
LIST OF ABBREVIATIONS & ACRONYMS

R	Net aquifer recharge
RCM	Regional climate model
GCM	General circulation model
CC	Climate change
GWB	Groundwater body
AET	Actual evapotranspiration
CMB	Chloride mass balance method

TABLE OF CONTENTS

LIST OF ABBREVIATIONS & ACRONYMS	5
1 EXECUTIVE SUMMARY	5
2 INTRODUCTION	8
3 PILOT AREA	10
3.1 Site description and data	10
3.1.1 Location and extension of the pilot area	10
3.1.2 Geology/Aquifer type	10
3.1.3 Topography and soil types	12
3.1.4 Surface water bodies	13
3.1.5 Hydraulic head evolution	13
3.1.6 Climate	14
3.1.7 Land use	16
3.1.8 Abstractions/irrigation	16
3.1.9 Flow balance components	17
3.2. Climate change challenge	19
4 METHODOLOGY	20
4.1 Methodology and future scenarios	20
4.1.3 Generation of local climate scenarios	21
4.1.4. Propagation of impacts on Net GW Recharge: Historical and Future Scenarios	21
4.1.5. Identification of Potential Strategic Groundwater Resources to Manage Droughts within Continental Spain	22
4.2 Tool(s) / Model set-up /calibration	24
4.3. Uncertainty	27
5 RESULTS AND CONCLUSIONS	28
5.1 Future local climatic scenarios	28
5.2 Impacts on Net Aquifer Recharge	29
5.3 The T Index in Continental Spain: Historical and Future Scenarios	30
6 REFERENCES	34

1 EXECUTIVE SUMMARY

Pilot name	CONTINENTAL SPAIN	 (a) Low-permeability pre-Triassic crystalline bedrock and Triassic to Miocene marly sedimentary formations; (b) moderate-to-high permeability Palaeozoic to Tertiary carbonates; (c) moderate-to-high permeability Plio-Quaternary detritic materials; and (d) Triassic to Miocene evaporitic outcrops. Modified from Alcalá and Custodio (2014)
Country	Spain	
EU-region	Mediterranean region and south-western Europe	
Area (km ²)	493519 km ²	
Aquifer geology and type classification	Varied geology, the most important aquifers being Plio-Quaternary sedimentary formations and Triassic to Tertiary carbonate massifs.	
Primary water usage	Irrigation / Drinking water / Industry	
Main climate change issues	The last climate change prediction for the mediterranean area are very significant and will increse drought and scarsity issues (Tramblay et al, 2020). Groundwater resources will play a significant role in the definition of sustainable adaptation strategies (Pulido-Velazquez et al., 2020). Therefore, an apropiate assessment of climate change impacts on grondwater recharge in continental Spain is required. We are also interested in the vulnerability to pumping in order to Identify Potential Strategic Groundwater Resources to Manage Droughts within Continental Spain.	
Models and methods used	The method for impacts of future potential CC scenarios on distributed net AR (R) from precipitation, which is proposed by Pulido-Velázquez et al. (2018) (1) generates future time series of climatic variables (precipitation, temperature) spatially distributed over Continental Spain for potential Aquifer Recharge, and (2) simulates them within previously calibrated empirocal spatial R models from the available historical information to provide distributed R time series. It employs historical climatic data comes from the Spain02 project (Herrera et al., 2016), historical spatial R from Alcalá and Custodio (2014, 2015), and Regional Climate models (RCMs) simulations for future CC scenarios from the CORDEX EU project (2013). The combination of RCMs and Circulation models (GCMs) shows a wide spentrum of variability. Assuming that the long term natural mean reserves were maintained, a preliminary assessment of GW vulnerability to pumping can be obtained by using the natural turnover time index (total storage divided by the R) as approximation of the mean groundwater residence time.	
Key stakeholders	Spanish River Basin Authorities; Spanish Groundwater Users Association; Spanish Water-Supply Companies Group.	



Contact person	F.J. Alcalá, AJ Collados-Lara, D. Pulido, L. Baena,. IGME (Spain), fj.alcala@igme.es, aj.collados@igme.es; d.pulido@igme.es, l.baena@igme.es, j.dedios@igme.es;
----------------	---

In Continental Spain we find a very varied Geology. The most important aquifers are Plio-Quaternary sedimentary formations and Triassic to Tertiary carbonate massifs. Groundwater resources play a key role in the supply of water demands within the territory. On the other hand, the latest studies on climate change (CC) expect significant decreases in water resources in Continental Spain river catchments, with significant environmental, economic and social impacts. In most of these areas, the problem will be exacerbated in the future due to CC, which is associated with an increment in the occurrence of extreme events as droughts. Desertification will also increase into the current framework of land and water degradation; nowadays 20% of the territory is degraded and an additional 1% is actively degrading (Martínez-Valderrama et al., 2016). The objective of this study is to assess and summarise impacts of potential future CC scenarios (for the horizon 2016-2045 under the most pessimistic emission scenario included in the AR5 IPCC report) on recharge in Continental Spain. We also intend to assess groundwater vulnerability to pumping, in order to Identify Potential Strategic Groundwater Resources to Manage Droughts.

The assessment of climate change impacts on the recharge in continental Spain (Pulido-Velazquez et al. 2018) has been performed following the next steps: 1) Definition of local climate scenarios by correcting the climatic model simulations in accordance with the historical data; 2) Propagation of potential climate change scenarios to assess impacts on aquifer recharge by applying a previously calibrated empirical recharge model. This model defines the relationship between the main climatic variables (precipitation and temperature) and the groundwater recharge, relationship that is assumed to be invariant also in the future to propagate the impacts. Assuming that long term natural mean reserves were maintained, a preliminary assessment of GW vulnerability can be also obtained by using the natural turnover time (T) index, defined in each GW body as the storage capacity (S) divided by the recharge (R). Aquifers where R is close to S are extremely vulnerable to exploitation.

The results show a mean lumped reduction of the rainfall recharge equal to 12%. The distribution of the impacts is quite heterogeneous. The largest reduction in mean R appears in the centre and south-east of the territory, dropping 28% in some areas. Only 6.6% of continental Spain corresponds to reductions of more than 20% in mean R. Nevertheless, 52.3% of the territory would suffer mean R reductions between 10% and 20%, while the reduction would be between 0% and 10% over 40.9% of the territory. In the case of the standard deviation on mean R, an increment of 41% on average is expected over 71.5% of the territory, being particularly marked in localized southern areas, with 36.7% of this area showing more than 50% increase. There would also be a significant reduction in the standard deviation in northern areas, with 6.9% of this area showing reductions greater than 30%.

The natural turnover time (T) analyses will be applied in the 146 Spanish GW bodies at risk of not achieving the Water Framework Directive (WFD) objectives to maintain a good



quantitative status. The analyses will be focused on the impacts of the climate drivers on the mean T value for historical and potential future scenarios, assuming that, the Land Use and Land Cover (LULC) changes, and the management strategies will allow to maintain the long term mean natural GW body reserves. Around 26.9% of those GW bodies show low vulnerability to pumping, with historical T values above 100 years, growing this percentage to 33.1% in the near future horizon values (until 2045). The results show a significant heterogeneity. The range of variability for the historical T values is around 3700 years, which is also increased in the near future to 4200 years. Those T indices will change in future horizons, and, therefore, the potential of those GW resources to define sustainable strategies to adapt to climate change will also change accordingly, making it necessary to apply adaptive management strategies.

2 INTRODUCTION

Climate change (CC) already have widespread and significant impacts on Europe's hydrological systems including groundwater bodies, which is expected to intensify in the future. Groundwater plays a vital role for the land phase of the freshwater cycle and has the capability of buffering or enhancing the impact from extreme climate events causing droughts or floods, depending on the subsurface properties and the status of the system (dry/wet) prior to the climate event. Understanding and taking the hydrogeology into account is therefore essential in the assessment of climate change impacts. Providing harmonised results and products across Europe is further vital for supporting stakeholders, decision makers and EU policies makers.

The Geological Survey Organisations (GSOs) in Europe compile the necessary data and knowledge of the groundwater systems across Europe. To enhance the utilisation of these data and knowledge of the subsurface system in CC impact assessments, the GSOs, in the framework of GeoERA, has established the project "Tools for Assessment of Climate change Impact on Groundwater and Adaptation Strategies – TACTIC". By collaboration among the involved partners, TACTIC aims to enhance and harmonise CC impact assessments and identification and analyses of potential adaptation strategies.

TACTIC is centred around 40 pilot studies covering a variety of CC challenges as well as different hydrogeological settings and different management systems found in Europe. Knowledge and experiences from the pilots will be synthesised and provide a basis for the development of an infrastructure on CC impact assessments and adaptation strategies. The final projects results will be made available through the common GeoERA Information Platform (<http://www.europe-geology.eu>).

The specific TACTIC activities focus on the following research questions:

- What are the challenges related to groundwater- surface water interaction under future climate projections (TACTIC WP3).
- Estimation of renewable resources (groundwater recharge) and the assessment of their vulnerability to future climate variations (TACTIC WP4).
- Study the impact of overexploitation of the groundwater resources and the risks of saline intrusion under current and future climates (TACTIC WP5).
- Analyse the effectiveness of selected adaptation strategies to mitigate the impacts of climate change (TACTIC WP6).

The present document reports the TACTIC activities in the pilot Continental Spain within the framework of WP4.

In Continental Spain we find a very varied Geology. The most important aquifers are Plio-Quaternary sedimentary formations and Triassic to Tertiary carbonate massifs. Groundwater resources play a key roles in the supply of water demands within the territory. On the other hand, The latest studies on climate change (CC) expect significant decreases in water resources in Continental Spain river catchments, with significant environmental, economic and social



impacts. In most of these areas, the problem will be exacerbated in the future due to CC, which is associated with an increment in the occurrence of extreme events as droughts. Desertification increases into the current framework of land and water degradation; nowadays 20% of the territory is degraded and an additional 1% is actively degrading (Martínez-Valderrama et al., 2016). New non-conventional sources of water, preferably reuse and desalinitacion for irrigation and domestic use will be needed (Sabater and Barceló, 2010). The objective of this study is to assess and summarise impacts of potential future CC on recharge in Continental Spain. We also intend to identify potential strategic Groundwater Resources to manage droughts by assessing the vulnerability of groundwater bodies to pumping.

3 PILOT AREA

3.1 Site description and data

3.1.1 Location and extension of the pilot area

Continental Spain, between latitudes 36° and 44°N (Figure 1), occupies a large portion of the Iberian Peninsula, the rest being continental Portugal and a part of southern France. The surface area of Continental Spain is 493,519 km².

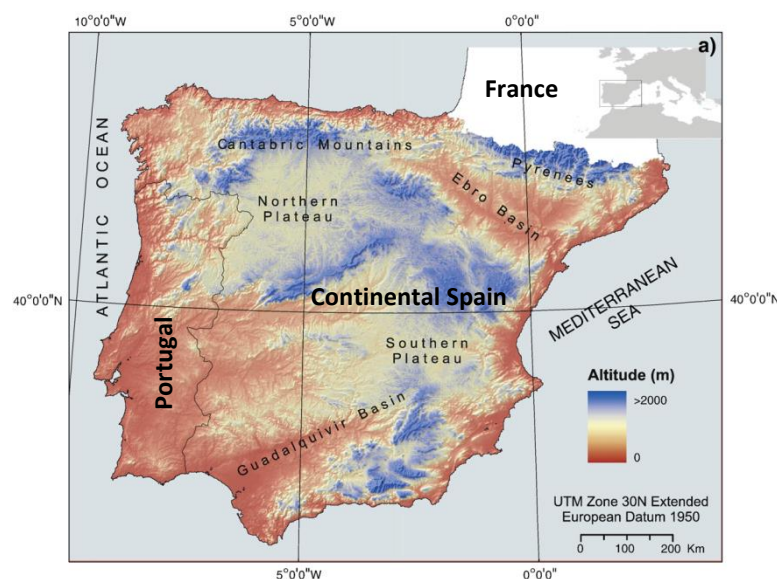


Figure 1. Location of the Iberian Peninsula, showing the elevation, and main mountain ranges and river basins; modified from Del Barrio et al. (2010).

3.1.2 Geology/Aquifer type

The varied geology of Continental Spain determines relatively small, high-yielding aquifers widely distributed throughout its area. The most important aquifers are located in Plio-Quaternary sedimentary formations and Triassic to Tertiary carbonate massifs (Figure 2). The former consist of inland groundwater bodies (GWBs) surrounded by mountain ranges, small alluvial and piedmont units, and deltaic formations on infilled estuaries in coastal areas. Carbonate massifs are common in quite extensive but compartmentalized areas along the northern, eastern, and southern ranges (IGME, 1993). To a minor extent, the weathered and fissured granite and Palaeozoic shale formations in northern, southern, and north-eastern ranges contain small aquifers of local significance.



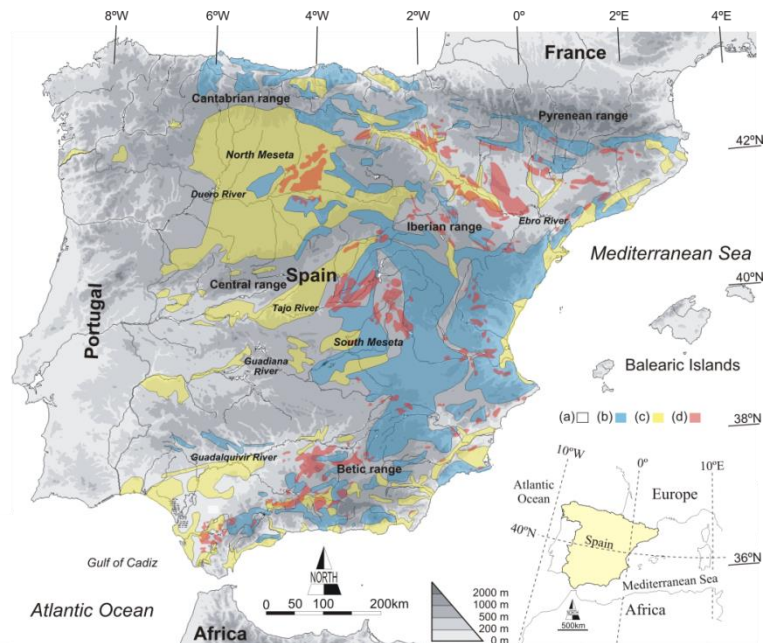


Figure 2. Lithology of continental Spain, synthesized from Alcalá and Custodio (2014), shows the hydrogeological behaviour of materials after permeability type: (a) low-permeability pre-Triassic metamorphic rocks, granitic outcrops, and Triassic to Miocene marly sedimentary formations; (b) Palaeozoic to Tertiary permeable carbonates; (c) Plio-Quaternary permeable detritic materials; and (d) Triassic to Miocene evaporitic outcrops

In Continental Spain, the number of administrative hydrogeological areas designated for groundwater management has varied over time. In the 1990s, most of the regional water formations were integrated into 370 hydrogeological units covering 252.205 km² (51% of Continental Spain), of which 165.503 km² (34% of Continental Spain) were high-permeability formations. For the implementation of the European Water Framework Directive (WFD, 2000) in Spain, 699 GWBs covering nearly 70% of the territory were defined (Figure 3). This classification included former geological formations cataloged as UH and new areas in low-permeability regions where shallow weathering and fissuration of the bedrock favours the development of shallow aquifers of local significance. The current area covered by high-permeability formations is 177.515 km² (36% of Continental Spain).

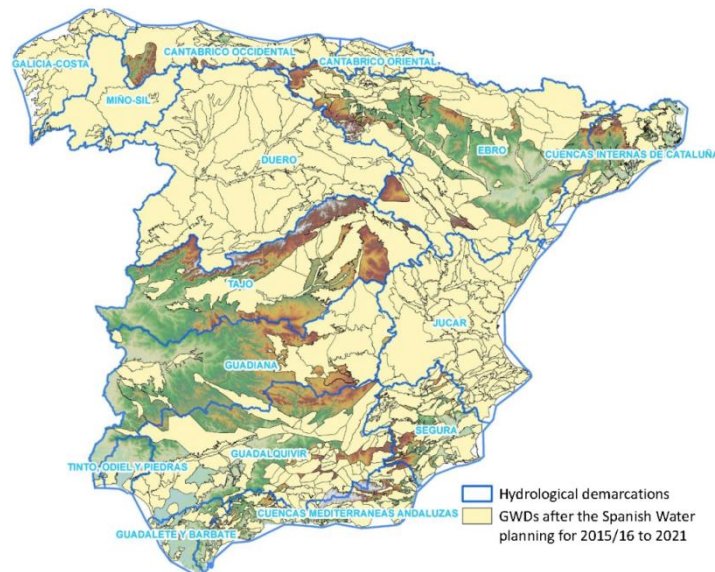


Figure 3. GWDs defined for the implementation of the European Water Framework Directive (WFD, 2000) in Spain.

3.1.3 Topography and soil types

Relatively high-altitude highlands (*mesetas*), about 900 m a.s.l. in the northern half and about 700 m a.s.l. in the southern half, constitute a large part of the country (Figure 1; Figure 2). The *meseta*, which bisected by the Central Cordillera, is surrounded by mountain ranges that may exceed 2500 m of altitude, such as the Cantabrian and Iberian ranges to the north and east and Sierra Morena to the south. This isolated configuration and elevation determines its continental climate (MIMAM, 2000). The Ebro and the Guadalquivir River basins are located outside the *meseta*. Peak elevations exceed 3000 m a.s.l. in the Pyrenean and Betic ranges. The *meseta* is sloping gently from east to west, thus determining the flow direction of the main rivers of the Iberian Peninsula to the Atlantic Ocean, except for the Ebro River (Figure 1; Figure 3).

The abrupt topography and the predominant continental-to-semiarid climatic condition induce thin soils with low organic-matter content in most of Continental Spain. Large areas are dominated by lithosols and regosols in semiarid southern regions, by poorly drained, clay-rich soils over low-permeability marly formations in the large river valleys, and by large bare areas in most carbonate landscapes (EEA, 2007). Figure 4 shows the basic soil-type distribution.



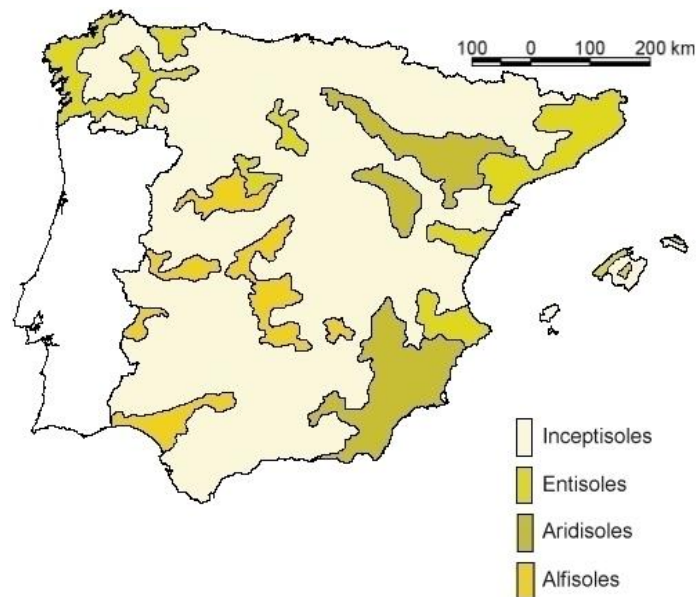


Figure 4. Basic soil-type distribution in continental Spain.

3.1.4 Surface water bodies

In countries and regions that suffer a chronic water resources shortages, as is the case of Spain, there is a necessity to adapt to the environment using a water resources system based on both, groundwater and surface water. Table 1 shows a summary of the natural surface water bodies in Spain. Rivers are the most abundant natural water bodies. Lakes and wetlands are less significant water bodies but they have a great ecological and socioeconomic importance (e.g. Daimiel and Doñana wetlands) (Willaarts et al., 2014). However, the natural surface water bodies are not enough for Spain necessities and there are many reservoirs. Spain has around 1000 large reservoirs with a surface area exceeding 8 km². In Spain there are more than 350 reservoirs with a storage capacity around 54000 cubic hectometres of water, which represents around 50% of the river's flow in the territory.

Table 1. Natural surface water bodies in Spain (information from Willaarts et al., 2014)

Surface water bodies	Total
Rivers (km)	70648
Lakes (km ²)	1010

3.1.5 Hydraulic head evolution

Because the local conditions of climate and water resources needs widely vary throughout the territory, several hydraulic head evolutions can be identified among GWBs. In northern regions, groundwater abstraction is low to moderate and the hydraulic head evolutions coarsely follows the climatic pattern. In southern, south-eastern, and eastern regions, different degrees of exploitation occur, with cases of groundwater mining in some GWBs in which groundwater reserves are being consumed (Custodio et al., 2016). In general, during the last 5



decades, piezometric levels had show a general decreasing trend in some GWBs located in the northern and southern *mesetas* and in the Mediterranean coastal fringe. Hydraulic gradient inversion between low-quality, low-exploitated shallow unconfined aquifers and heavily-exploited confined aquifers with better groundwater quality has been described in some mediterranean GWBs. The cases of overexploitation with negative consequences on groundwater quantity and quality are increasing. Figure 5 shows GWBs in quantitative risk in Continental Spain.

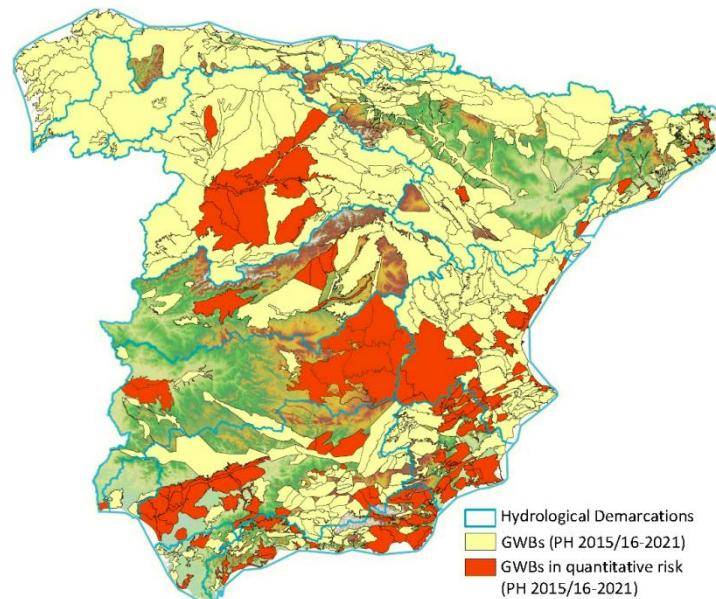


Figure 5. Groundwater bodies in quantitative risk in continental Spain.

3.1.6 Climate

Inland areas of Continental Spain constitute a large part of the country characterized by continental climate. This means hot, dry summers, and cold, relatively wet winter-spring seasons. There are recurrent dry spells lasting 2 to 5 years with variable influence of the wet and dry periods over the Atlantic and the Mediterranean areas. Other climates are semiarid in large areas of the territory, subhumid dry and wet, and humid in northern areas and high mountains (MIMAM, 2000).

The average precipitation in continental Spain ranges from 2000 mm year⁻¹ in the western and northern coastal mountain areas, to about 500-600 mm year⁻¹ over the northern *meseta*, and 380-500 mm year⁻¹ in the southern *meseta*. In the semiarid south-eastern coastal areas and north-eastern inland areas, precipitation averages around 300 mm year⁻¹ or less, reaching as low as 180 mm year⁻¹ (Figure 6a). Precipitation occurs predominantly in late autumn and winter, associated with the circulation of cold air masses from the North Atlantic Ocean and deep pressure lows, initially located over the Gulf of Cádiz, which travel eastwards and generate the inflow of air masses from the Subtropical Atlantic Ocean (Trigo *et al.*, 2004). At the same time, the eastern coast of Spain may receive precipitation from humid air masses

over the West Mediterranean Sea, which generally do not penetrate far from the coastal fringe and may be accompanied by heavy storms from convective rains, especially in late summer and autumn (Martín-Vide and López-Bustins, 2006). Although these storms may represent less than 15% of annual precipitation in these areas, they can cause flooding and are significant for aquifer recharge after the soil-water deficit is satisfied. Coefficient of variation of average yearly precipitation is irregularly distributed in the 0.2-0.5 range (MIMAM, 2000).

The annual mean temperature (T) varies from 4.6 to 21.1 °C (Figure 6b) with minimums in January and maximums in August; the daily T amplitude on a year may be as high as 50 °C in the southern meseta and river valleys. There is a pronounced gradient of T with elevation in mountain areas, thus favouring the seasonal snow-melting contribution to surface and groundwater bodies (MIMAM, 2000). The mean annual T is around 8 °C in northern areas and more than 18 °C in lowlying areas of southern and eastern regions. The average mean potential evapotranspiration is in the 600-800 mm/year range in most of the territory, with extreme values that vary from 400 mm/year in northern high mountains to 1200 mm/year in semiarid inland areas of the Ebro River (MIMAM (2000).

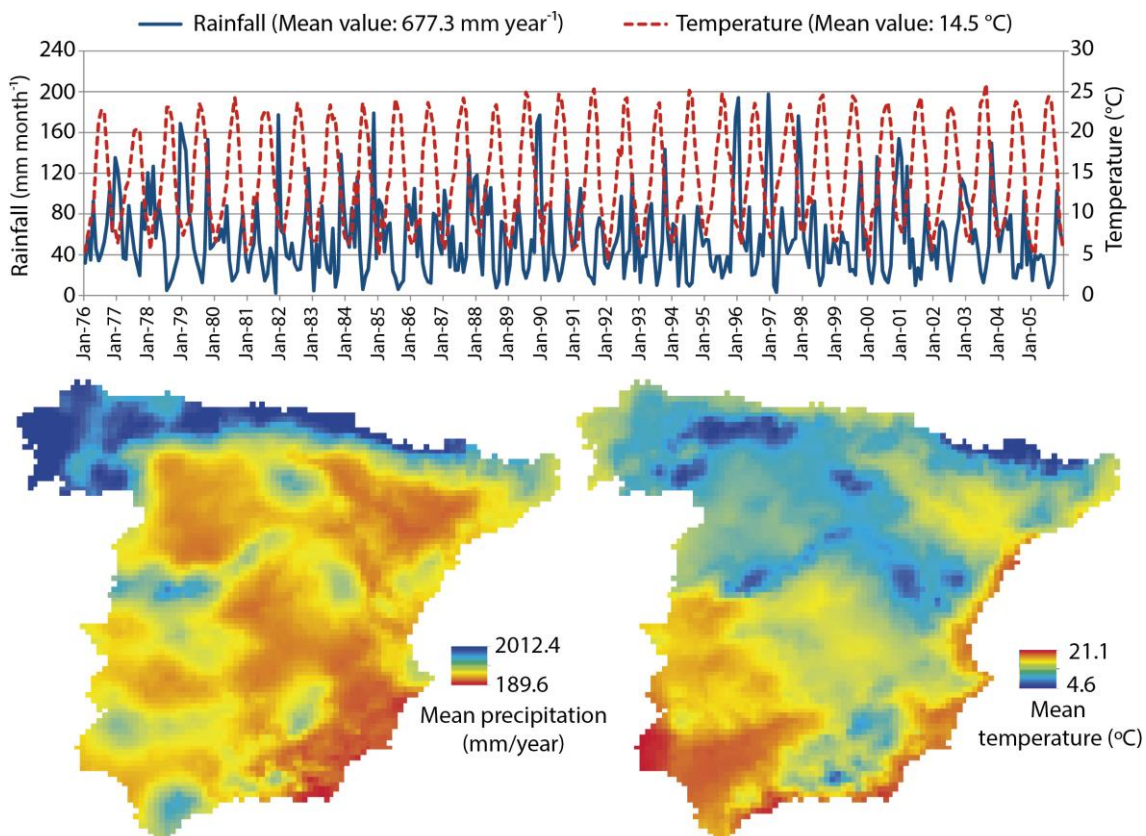


Figure 6. Spatio-temporal distribution of historical mean (a) precipitation (mm/year) and (b) temperature (°C) in continental Spain during the period 1976-2005; modified from Pulido-Velazquez et al. (2018).

3.1.7 Land use

The northern and north-western high-rainfall zones have densely vegetated areas with stable and well-drained organic-matter-rich soils (Figure 7). Natural and semi-natural vegetation cover 47% of the territory, mostly sparse scrublands. In the valleys and flat highlands, traditional rain-fed agriculture combines with newly developed irrigated agriculture to cover 49% of the territory. The rest are urbanized areas and other land uses (Del Barrio et al., 2010).

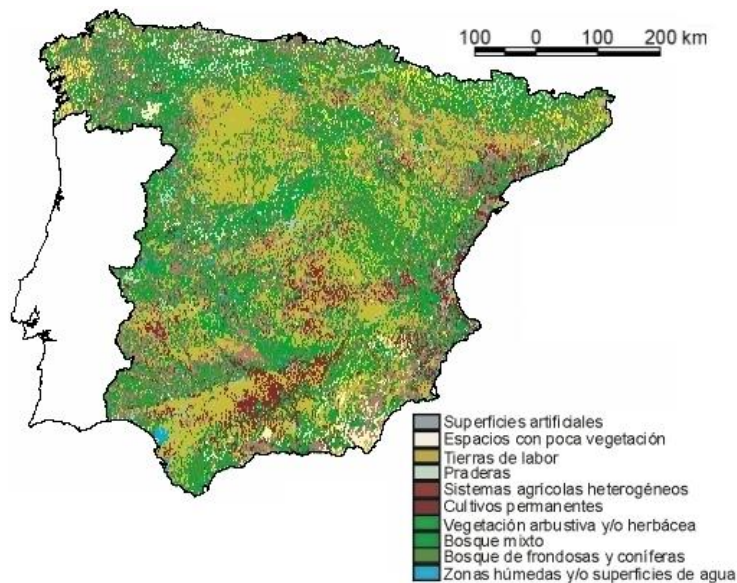


Figure 7. Land-use conditon in continental Spain from CORINE (1990 and 2012).

3.1.8 Abstractions/irrigation

Groundwater exploitation has increased more than 3-fold in the last 50 years (Garrido and Llamas, 2009). The current use of groundwater is estimated at about 6.5 km³ year⁻¹, about 75% for crop irrigation. Much of the groundwater exploitation is concentrated in the Mediterranean area for different uses. Irrigation areas are widely dispersed over the territory, surface-water developed in the main river valleys and mostly groundwater developed in the southern *meseta* and in the southern and south-eastern coastal fringes (Figure 8).

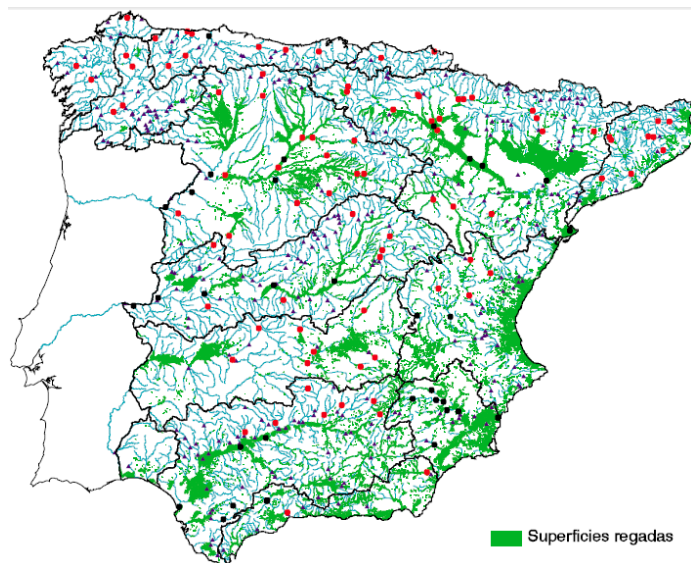


Figure 8. Irrigated areas in continental Spain, after satellite-based land-use condition in continental Spain from CORINE (1990 and 2012).

3.1.9 Flow balance components

This section refers exclusively to the component R from precipitation. In Continental Spain, the wide lithological, orographic, pedological, and climatic diversity of Continental Spain produces a large number of different conditions for R. At the Continental Spain scale, R was estimated from the second half of the 20th century through different distributed techniques (Alcalá and Custodio, 2012), but its uncertainty was not explicitly indicated. Only the permeable formations were traditionally considered in Water Planning. Recently, Alcalá and Custodio (2014, 2015) used the atmospheric chloride mass balance (CMB) method to estimate R at the same 4976 nodes of a 10 km x 10 km grid covering the whole territory. Average nodal R values vary from 17 to 715 mm/year, with 90% of results between 30 and 300 mm/year (Figure 9a). Mapped results are considered potential estimates in low permeability areas and net estimates over permeable formations. The potential estimation is around 66 km³/year over Continental Spain; the remaining 32 km³/year is for permeable outcrops. The fraction of precipitation (Figure 9b) that transforms into R vary between 0.03 and 0.65; the lower values are in low-permeability sedimentary formations in the large river valleys, crystalline outcrops, and semiarid southern regions, and the higher values in carbonate formations (Figure 9c). Two main sources of uncertainty affecting the average R estimates (given by the coefficient of variation, CV) were segregated, that induced by the inherent natural variability of the CMB variables, CV_R , and that produced when mapping the CMB variables, CV_K . The average CV_R is 0.29 (Figure 9d) and the average CV_K is 0.09 (Figure 9e). Average R varies from 23 to 41 km³/year over permeable formations when only CV_R is taken into account. Results were compared with other regional R estimates, such as provided by MIMAM (2000); the CMB estimates being 4% higher (Figure 9f). The differences were explained by the different data coverage and the different hydrological meaning of R estimates that each technique provides, as explained by Alcalá and Custodio (2014, 2015).



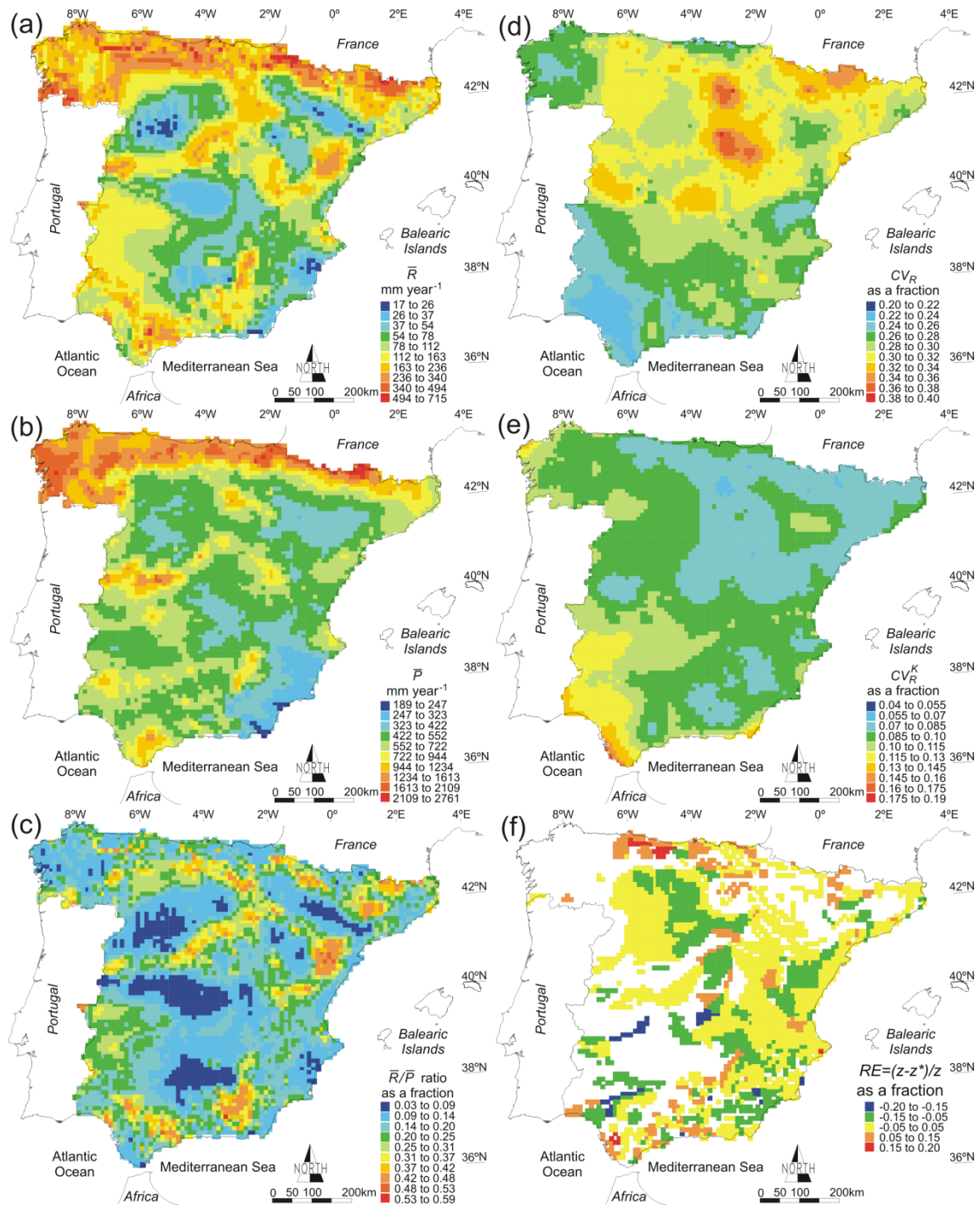


Figure 9. Mapping of R in Continental Spain: (a) average yearly R (mm/year); (b) average yearly precipitation (mm/year) from MIMAM (2000); (c) dimensionless R /precipitation ratio; (d) dimensionless natural uncertainty of R , CV_R ; (e) dimensionless mapping uncertainty of R , CV_K ; and (f) comparison of Alcalá and Custodio (2014, 2015) (z^*) and MIMAM (2000) (z) R estimates for coincident areas: the outcropping of the former Hydrological Units, where $RE=(z-z^*)/z$ is the dimensionless relative difference. Data are discretized in 10 km x 10 km cells.

3.2. Climate change challenge

In accordance with the EEA map the main expected issues due to CC in Continental Spain are those described in the Figure 10 for the Atlantic and Mediterranean regions. Existing national estimates show also a significant reduction (around a 20% for the RCP8.5 emission scenario in the horizon 2071-2100) of the R in the territory (Pulido-Velázquez et al., 2018).

The main challenge is to find adaptation measures to maintain a sustainable use of the GWBs with a positive balance between supply water demands (different uses) under future CC conditions and maintaining a good status in the related ecosystem. Additional measures for non-conventional water resources will include reuse and desalination.

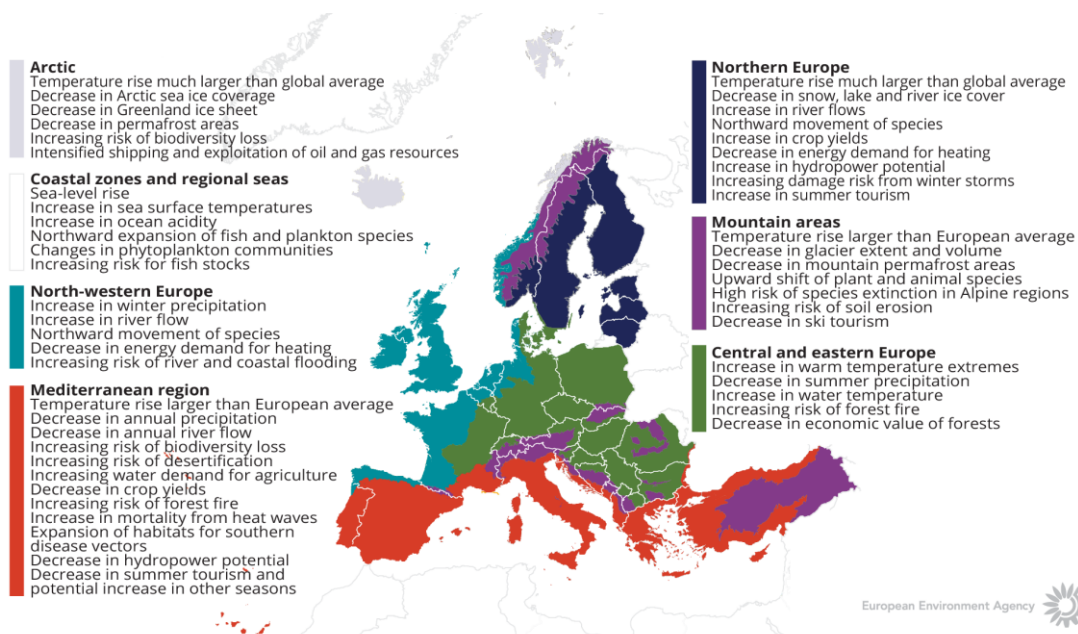


Figure 10. How is climate expected to change in Europe. The European Environment Agency map.

4 METHODOLOGY

4.1 Methodology and future scenarios

4.1.1 Tools/ model description

An impact and adaptation assessment has been performed for historical and some future potential GC scenarios. We have defined potential local climatic scenarios from RCM simulations within the horizon 2016-2045 assuming the most pessimistic emission scenarios, the Representative Concentration Pathways 8.5 (RCP8.5). The GROUNDS tool (Collados-Lara et al., 2020) was applied to generate those local future climatic series. Ensemble of all the projections derived from the RCMs simulations were defined under the hypothesis that they are equi-feasible. An empirical net aquifer recharge (R) model was calibrated from the historical climatic observations and the historical R values previously derived by chloride mass balance Alcalá and Custodio (2014). Assuming that the relationship between effective precipitation and net aquifer recharge remain invariant also in the future, the empirical model is used to propagate the generated future potential scenarios to assess climate change impacts on future net recharge in continental Spain.

4.1.2 Future scenarios. Climate data

In order to generate future local scenarios, the historical climatic data (precipitation and temperature series) in the reference period (1976-2005) were combined with the Climatic model simulations for the Control period (1976-2005) and future scenarios (2016-2045). It includes various climatic model simulations undertaken by the CORDEX EU project for the most pessimistic IPCC emission scenario, the Representative Concentration Pathways 8.5 (RCP8.5). Selected simulations consist of results from five Regional Climate Models (RCMs) (CCLM4-8-17, RCA4, HIRHAM5, RACMO22E, and WRF331F) nested within four distinctive General Circulation Models. An equi-feasible ensemble of all RCMs simulations was performed using 1976-2005 as the control/historical reference period, and fixing the future horizon scenario as 2016-2045.

The RCPs are greenhouse gas concentration trajectory adopted by the IPCC. They are named according the radiative forcing that represent. Radiative forcing is the change in the net, downward minus upward, radiative flux at the troposphere or top of atmosphere due to a change in an external driver of climate change. The RCP8.5 is the most pessimistic pathway for which radiative forcing reaches values greater than 8.5 W m^{-2} by 2100. The selected RCMs projections were performed using the simulations of the RCP8.5 trajectories to generate potential future series of precipitation and temperature. In this work, we corrected these series to generate local scenarios and to propagate their impacts on R.

The RCM climate modelling simulates climate conditions defined with some initial conditions, time-dependent lateral meteorological conditions and surface boundary conditions to drive high-resolution models. These conditions are typically wind components, temperature, water

vapor, and surface pressure. The driving data are derived from GCMs that simulates with a coarse resolution. Table 1 shows the GCMs used by the RCMs employed in this work. The World Climate Research Programme (WCRP) through the CORDEX project guarantees the quality of the RCMs collected by them. However, the uncertainties related to RCMs can be important and they must be adapted to the study area.

Table 1. Regional Climatic Models (RCMs) and General Circulation Models (GCMs) considered to define the climatic scenarios.

RCMs \ GCMs				
	CNRM-CM5	EC-EARTH	MPI-ESM-LR	IPSL-CM5A-MR
CCLM4-8-17	X	X	X	
RCA4	X	X	X	
HIRHAM5		X		
RACMO22E		X		
WRF331F				X

4.1.3 Generation of local climate scenarios

The GROUNDSD tool (Collados-Lara et al., 2020) allows us to generate local potential scenarios climatic variables. The monthly bias of the model within the reference period (1976-2005) was estimated as the mean relative differences between the control simulation and the historical precipitation and temperature time series calculated for each month of an average year. It was used to generate the future series by applying a bias correction technique (scenario E1). The monthly delta changes between control and future precipitation (2016-2045) was also estimated to generate series by applying a delta change approach (scenario E2).

4.1.4. Propagation of impacts on Net GW Recharge: Historical and Future Scenarios

An empirical precipitation-R model was employed to estimate the historical R within the reference period and the impacts of potential future climatic scenarios on R (Pulido-Velazquez et al., 2018). It is defined as follow:

$$R = C(P - E) \quad (1)$$

where R, P (precipitation), and E in mm year⁻¹, and dimensionless C. For estimating E, we used the non-global Turc formulation:

$$E = \frac{P}{\sqrt{0.9 + \frac{P^2}{L^2}}} \quad (2)$$

where $L = 300 + 25Ta + 0.05Ta^3$ is a dimensionless form parameter of annual temperature.

This model has been used to propagate the impacts of local historical and future climatic fields in continental Spain



4.1.5. Identification of Potential Strategic Groundwater Resources to Manage Droughts within Continental Spain.

This method intends to perform a preliminary analysis of GW vulnerability to intensive pumping during drought periods through the renewal time of their resources (GW age) approached by the T index as the S/R ratio. Assuming that the long term natural mean reserves is kept invariant and the actual recharge is the main inflow of groundwater resources, the GW bodies with high renewal time, will be less vulnerable to pumping than those with low values, even in periods in which pumping is smaller than mean R. It can be especially relevant in Basins or Water Resources systems with scarce reserves where long and intensive droughts appear and will be even exacerbated in the future due to climate change. The methodology is summarized in Figure 11.

VULNERABILITY TO PUMPING ► MEAN GROUNDWATER TURNOVER TIME (T) INDEX

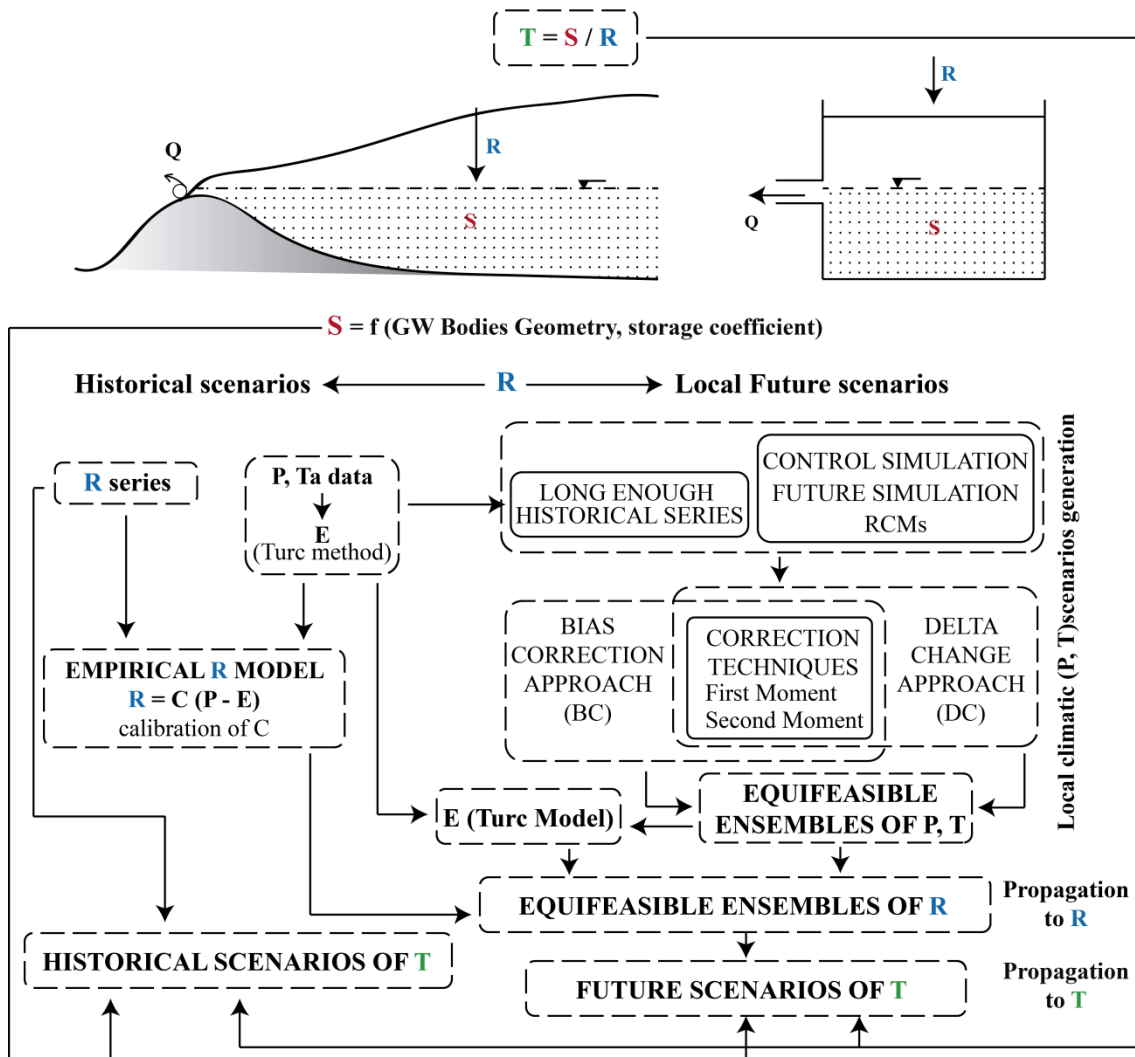


Figure 11. Flowchart of the methodology developed to assess GW Bodies vulnerability to pumping. Notation and units for variables used: P, E, R, and Q are respectively precipitation, actual evapotranspiration, net GW recharge from P, and net GW discharge in mm year⁻¹; Ta is temperature in °C; C and S are respectively a dimensionless effective recharge coefficient (-) and a GW storage (Mm³); and T is the natural turnover time index in years. (Pulido-Velazquez et al., 2020)

Making a parallelism between unconfined aquifers and reservoirs, the GW discharge (Q) will start when the potential aquifer storage reaches the threshold level of the surface connection (See Figure 11). Assuming that there is not any pumping, a preliminary assessment of the natural mean age of the groundwater leaving the GB body through the connection with the surface system (springs and or stream-aquifer interaction boundary conditions), can be obtained through the natural mean T index, defined as:

$$T = S/R \quad (3)$$

where T, S, and R are defined in Figure 11 caption.

In each GW body, S can be obtained by combining information about the geometry and the storage coefficients, which can be derived from different sources of information (eg. field works, models and/or research papers and official reports, as well as the River Basin Plans published by the different River Basin authorities). The historical R can be estimated through field work or previously calibrated models. The historical mean T value can be estimated by combining the mean historical R values with S in accordance with Equation 3.

The impacts of future potential climatic scenarios on GW bodies R, and, therefore, on their T index, requires climatic scenarios to be downscaled and propagated with the previous calibrated recharge model. The impacts of the generated potential local scenarios on the mean T will require future mean R to be estimated, which will be assessed by propagating/simulating the generated climatic scenarios with previously calibrated recharge models.

For each of the selected GW bodies, we have taken the available information about the potential GW storage under the surface connection. They were collected from the last River Basin Plans (2015-2021) published by the different River Basin authorities. It summarizes geological and topographical information to define the GW body geometry, that combined with the storage coefficients provide the S (Mm³) value for these GW bodies.

This preliminary method has been applied only in the 146 Spanish GW bodies at risk of not fulfilling the WFD (2000) quantitative objectives (see Figure 12). After the WFD went into effect, the European Environment Agency established the guidelines for declaring those GW bodies at risk of not fulfil a good quantitative and qualitative level in the 2020 horizon, as well as some general measures to mitigate negative impacts.



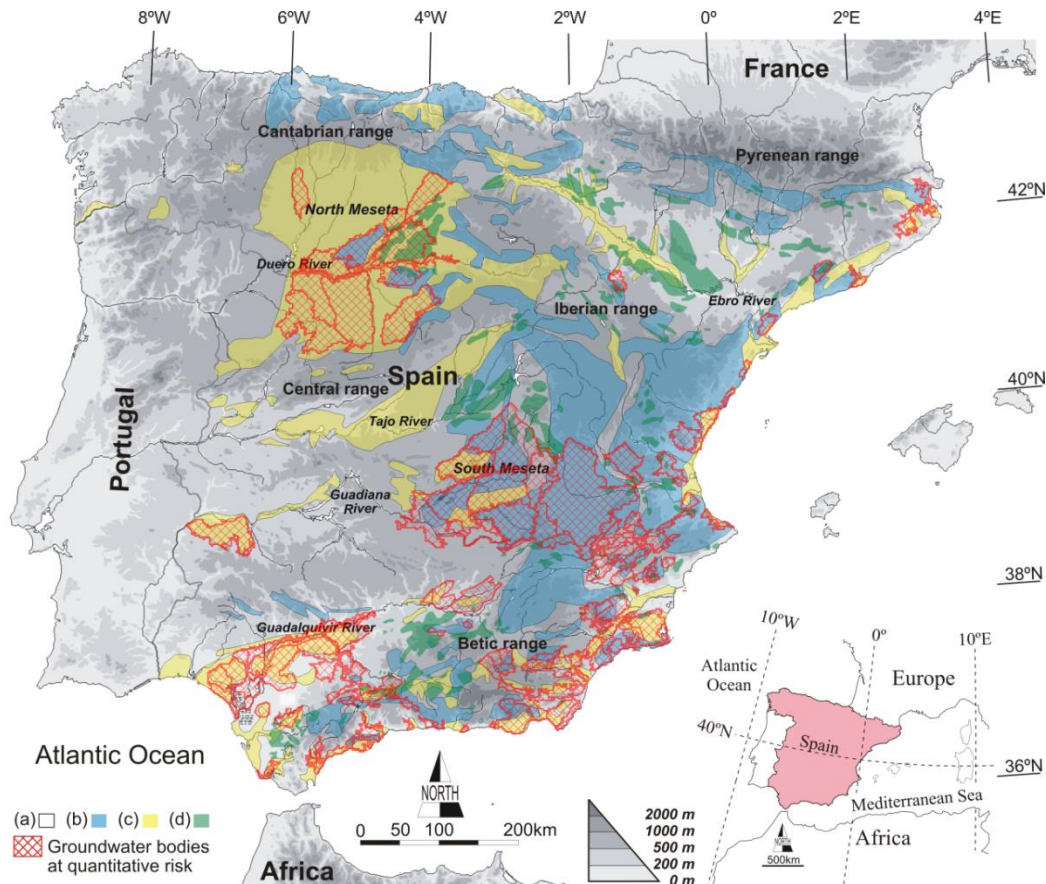


Figure 12. Map of continental Spain, showing the 146 Spanish GW bodies at quantitative risk of not fulfilling the WFD (2000) objectives (red shadowed areas), the main mountain ranges and hydrographic basins, and the hydrogeological behavior of geological materials forming the GW bodies according to permeability type as: (a) low to moderate permeability pre-Triassic metamorphic rocks, granitic outcrops, and Triassic to Miocene marly sedimentary formations; (b) moderate to high permeability Palaeozoic to Tertiary; (c) moderate to high permeability Plio-Quaternary detritic; and (d) Triassic to Miocene evaporitic outcrops.

4.2 Tool(s) / Model set-up /calibration

4.2.1. Generation of local climate change scenarios. GROUNDSD tool (Collados-Lara et al., 2020)

The differences between the control simulations and the historical data are employed to calibrate the downscaling approach to be applied. Figure 13 summarize these differences in mean monthly precipitation.



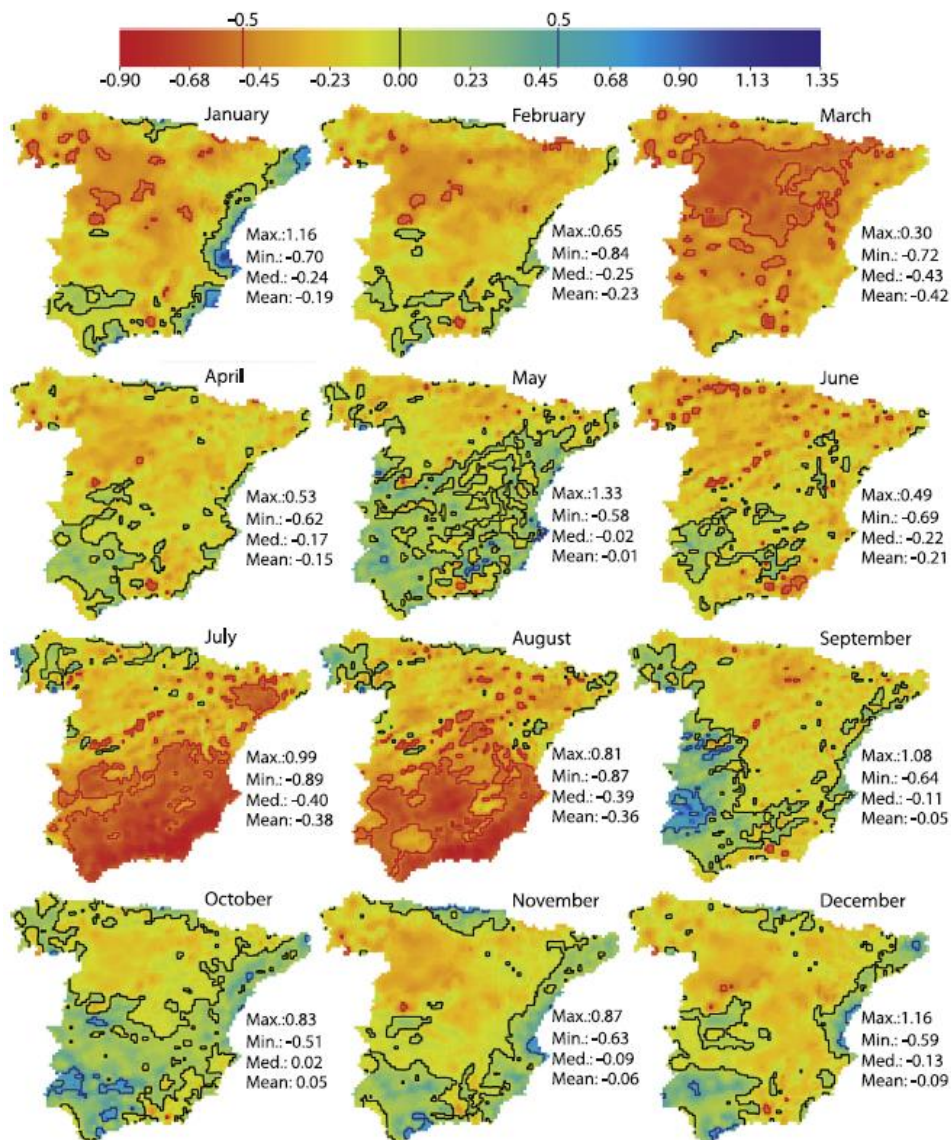


Figure 13. Dimensionless spatial monthly mean relative differences between the control simulation and the historical precipitation time series for an average year in the reference period (1976–2005). The ± 0.5 range is indicated.

The transformation functions to correct the historical series also need information about the differences between future and control simulations (showed in Figure 14).

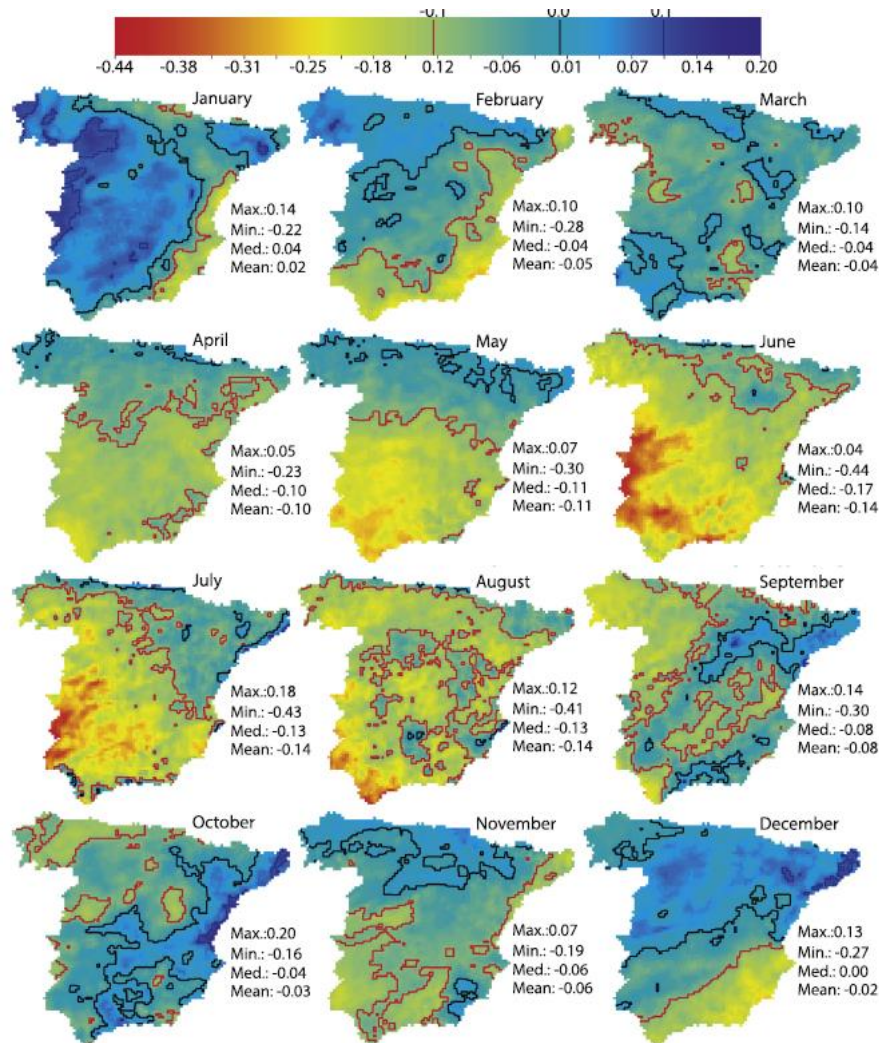


Figure 14. Dimensionless spatial monthly mean relative differences between future (2016–2045) and control (1976–2005) precipitation time series. The ± 0.1 range is indicated.

4.2.2. Definition of a R model

The R model was calibrated using precipitation recharge time series from historical climatic data and historical R data from the CMB method for the period 1996–2005. We assume that the statistics (mean and standard deviation) of R time series from the CMB method for the period 1996–2005 and R time series generated from a longer historical period 1976–2005 do not differ substantially, and can be considered identical. This assumption is supported by assuming steady-state conditions of the mean and standard deviation of the balance variables determining the historical recharge when simulating the period 1976–2005. The distributed mean annual recharge was 139 mm and 144.4 mm, respectively, thus the relative difference was less than 4% on average. The mean estimated recharge in the period 1976–2005 is represented in Figure 15.



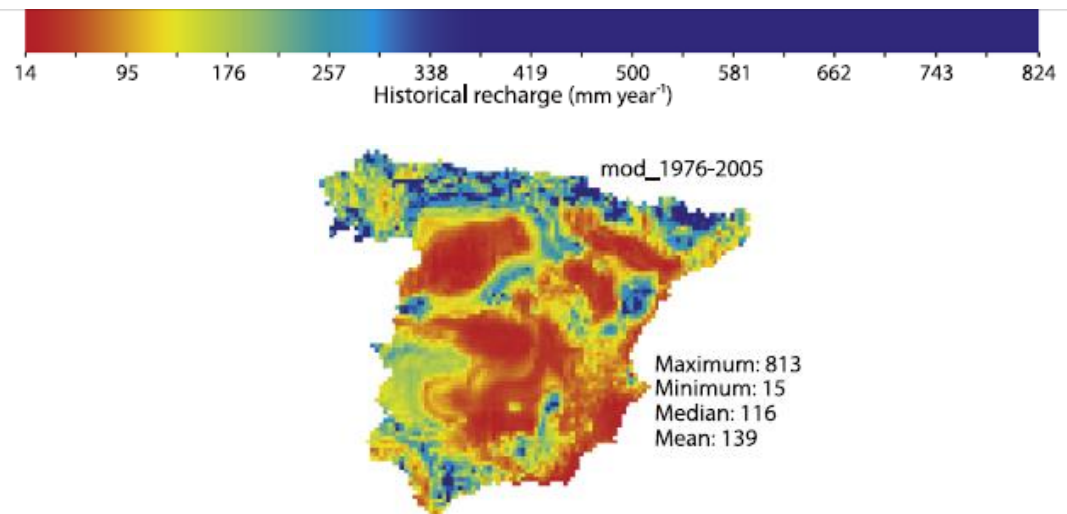


Figure 15. Mean net aquifer recharge (mm year₋₁) for the period 1976–2005

4.3. Uncertainty

In this study the dominating source of uncertainty is related to RCMs future simulation. In general, there is a large degree of uncertainty in climate change impacts assessments. There are different climate models (both RCMs and GCMs) that can be used to make future climate projections. Every climate model includes its own model for the atmosphere, the ocean, the Earth's surface, and ice sheets as well, as different parameterizations of the physical processes that must be considered within each of these models. The correction approaches are another source of uncertainty but its importance in climate change impacts assessments is lower (Collados-Lara et al., 2018).

In this study we considered different combinations of RCMs nested to GCM (nine) and two correction approaches to take into account uncertainty. Note that the impacts on recharge was assessed by considering 18 future projections. It allows us to calculate mean changes and the ranges of variability of these changes. Nevertheless, this study is focused on the mean assessment, and for this reason two equi-feasible ensembles of projections (one for the bias (E1) approach and another for delta (E2) approach) have been employed to define the scenarios to be propagated within the recharge model to assess future impacts.

5 RESULTS AND CONCLUSIONS

5.1 Future local climatic scenarios

Despite the temporal series being different, the two equifeasible ensembles E1 (applying bias correction techniques) and E2 (applying delta change techniques) produced identical future mean temperature maps (Figure 16).

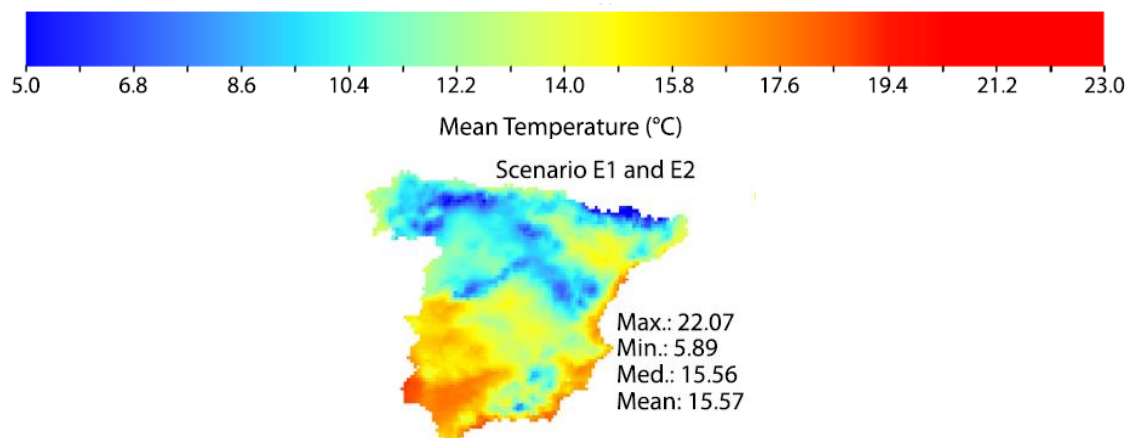


Figure 16. Potential future mean temperature (°C) scenarios obtained with the two ensemble options (E1, E2)

In terms of precipitation, there are very small differences between the two equi-feasible ensembles E1 and E2 due to a reduced number of negative values appearing in some cells when correcting using the second moment approach (Figure 17).

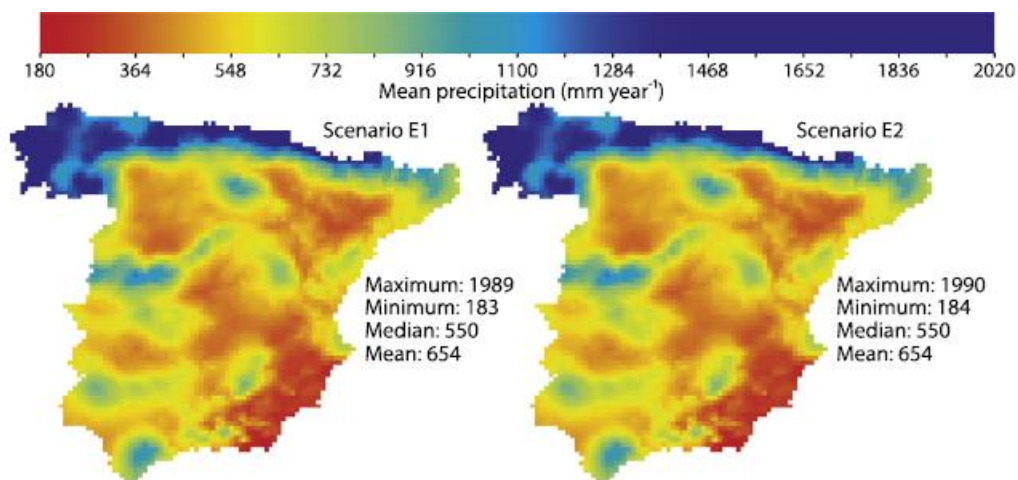


Figure 17. Potential future mean precipitation (mm.year⁻¹) scenarios obtained with the two ensemble options (E1, E2)

5.2 Impacts on Net Aquifer Recharge

Figure 18 shows that, although a small reduction in mean R is expected over 99.8% of continental Spain, there are two small north-eastern (600 km²) and eastern (100 km²) areas of the territory where a small increase is expected. A largest reduction in mean R in the centre and south-east of the territory is expected, dropping 28% in some areas. Only 6.6% of continental Spain corresponds to reductions of more than 20% in mean R. Nevertheless, 52.3% of the territory would suffer mean R reductions between 10% and 20%, while the reduction would be between 0% and 10% over 40.9% of the territory. In the case of the standard deviation on mean R, an increment of 41% on average is expected over 71.5% of the territory, being particularly marked in localized southern areas, with 36.7% of this area showing more than 50% increase. There would also be a significant reduction in the standard deviation in northern areas, with 6.9% of this area showing reductions greater than 30%.

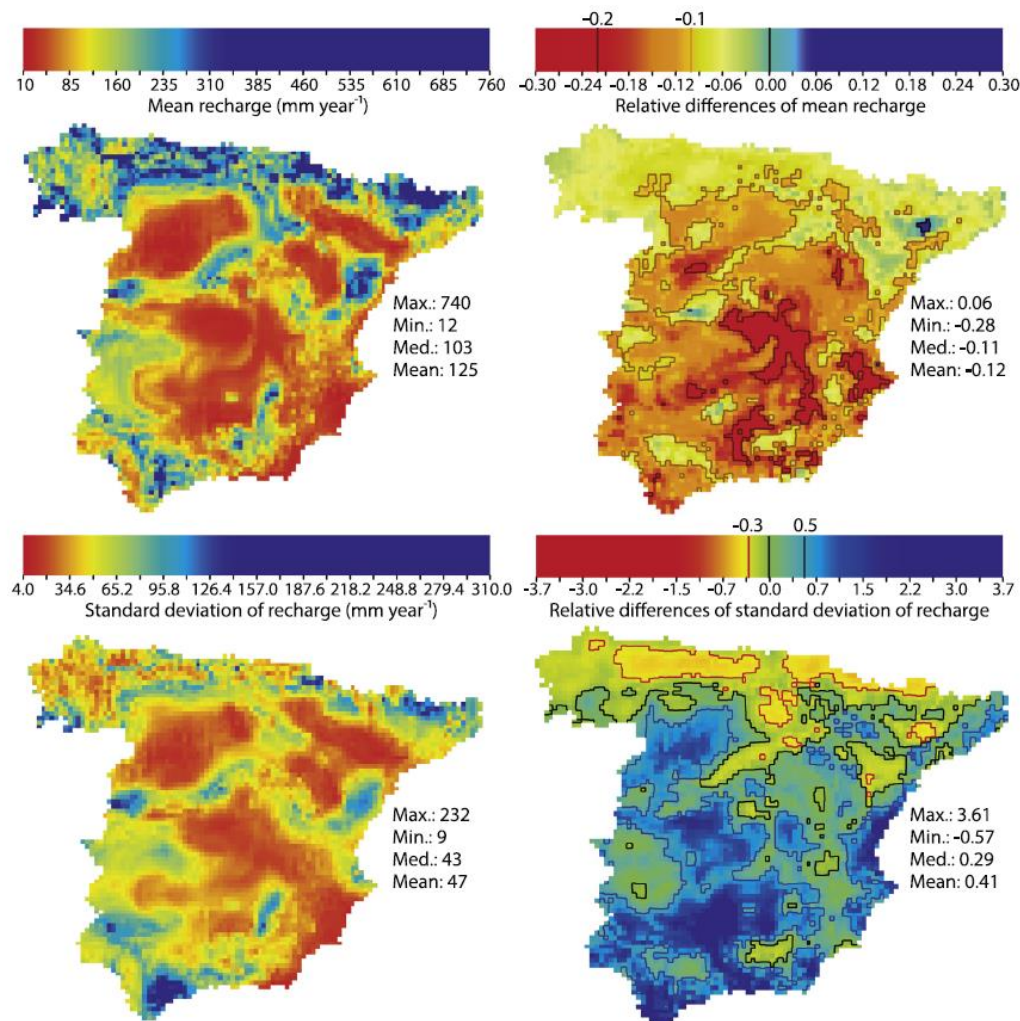


Figure 18. Potential future mean net aquifer recharge (R) (mm year⁻¹), standard deviation of future mean R (mm year⁻¹), and dimensionless relative differences between historical and future scenarios (equi-feasible ensemble of all the scenarios).

5.3 The T Index in Continental Spain: Historical and Future Scenarios

The information previously summarized was used to assess the natural T for the historical period (reference period 1976-2005) and future potential scenarios in the horizon 2016-2045 that correspond to the RCP 8.5 emission scenario. Two different local climatic scenarios have been considered to assess the potential impacts on T values, one generated by an ensemble of bias correction approaches (E1=EB) and another by an ensemble of delta change approaches (E2=ED). The methodology and the series generated for those scenarios were described in section 4.1.3. Figure 19 shows a heterogeneous distribution of T values within the 146 selected GW bodies as case studies. The box whiskers plot also reflects this wide range of T values moving from a minimum of 0.25 to a maximum of 3693 years in the historical period. The minimum and maximum values in the future scenarios are 0.32 and 4176 years for EB, and



0.28 and 3953 years for ED. In order to understand the variability of this value, we should take into account the formulation applied to estimate T (Equation 3) in each GW body, defined as S divided by R, where S depends on the geometry ("the size" of the GW body) and the storage coefficients (hydrodynamic parameter depending on the geology and hydraulic behavior of the aquifer). Therefore, this variability in T values is logical taking into account the varied geology, size and hydraulic behavior of the considered GW bodies.

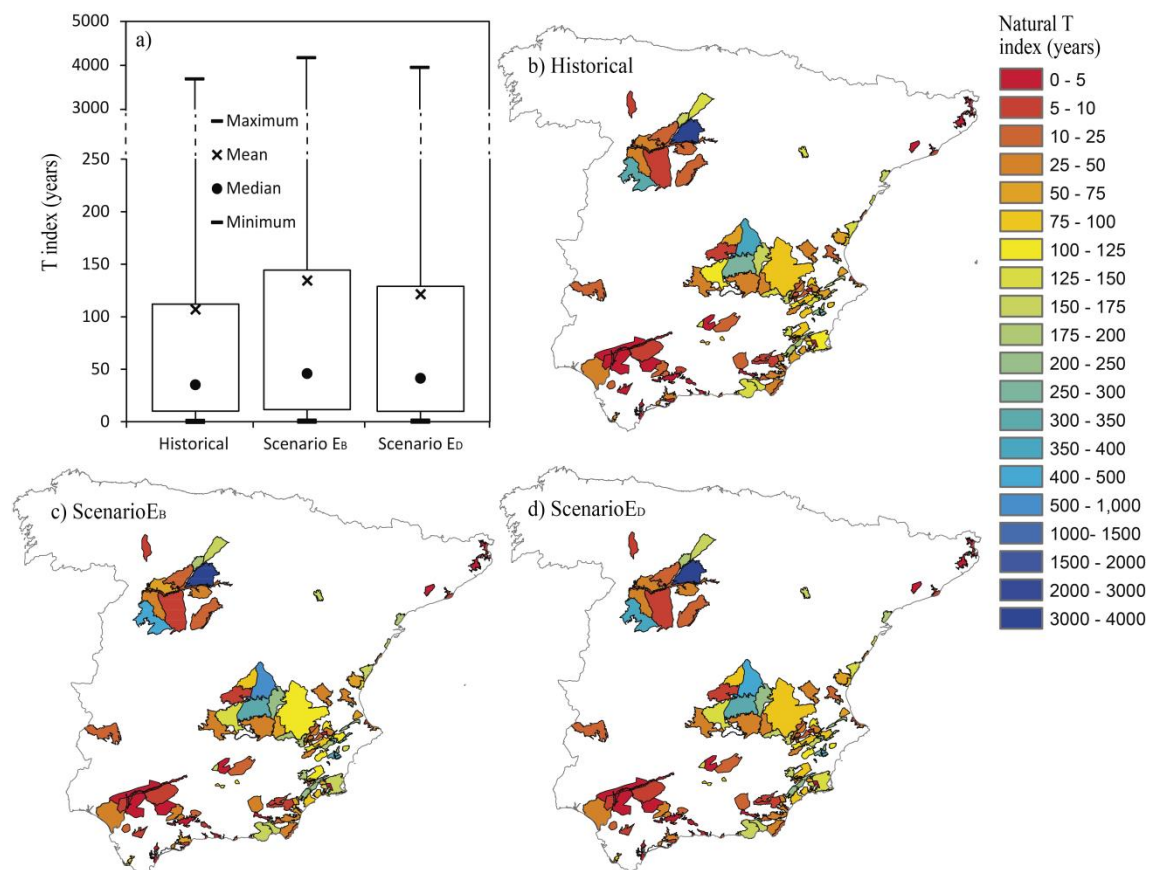


Figure 19. Box-whiskers (a) and maps of the T index in the 146 Spanish GW bodies at risk. Historical (b) values and future potential scenarios (EB (c) and ED (d)) in the horizon 2011-2045. The differences between the future scenarios (EB and ED) in terms of impacts on the T index are small, due to the differences between the impacts on mean R are also small (see maps of Figure 6). The mean values of R for both scenarios are very similar, although the monthly series are different.

Low T values means that R is close to S, and therefore, they are extremely vulnerable to exploitation, even in periods when pumping is smaller than the average R. It can be especially relevant in areas with scarce resources where long and intensive drought appear and will be even exacerbated in the future due to climate change. If we assume that the long term management of the Water Resources Systems allows to maintain the natural mean reserves (the mean S) of the GW bodies, the highest values of T correspond to GW bodies that can be very useful due to their buffer values role to manage drought periods. Around 26.9% of the



studied GW bodies show low pumping vulnerability with historical T values above 100 years, with this percentage increasing to 33.1% in the near future horizon values (until 2045).

Taking into account the formulation employed to assess T as S divided by R (see Equation 1), the impacts of the future scenarios on T are explained by the change in R, which is the only variable that depends on the climatic conditions. The T values will increase in the future in most of the GW bodies (Figure 20) due to the recharge (R) being reduced, meanwhile the total potential storage under the surface connection (S) will stay invariant. The impacts of potential future scenarios on T values will be heterogeneous (see maps of Figure 20). The box whiskers plot also reflects a wide range of T value changes with respect to the historical values moving from a reduction of 2.8 years to an increment of 483 years, which is due to the variability observed also for the recharge, where we estimate changes with respect to the historical between a reduction $47.0 \text{ mm} \cdot \text{year}^{-1}$ to an increment of $2.7 \text{ mm} \cdot \text{year}^{-1}$.

The increments in T values will force to apply more restrictive long-term management strategies within the systems to maintain the natural mean reserves, but if this long term constraint is fulfilled, the potentiality of those GW bodies to be used playing a buffer role to manage drought periods, will be even in many cases higher than in the historical period (Figure 19a).

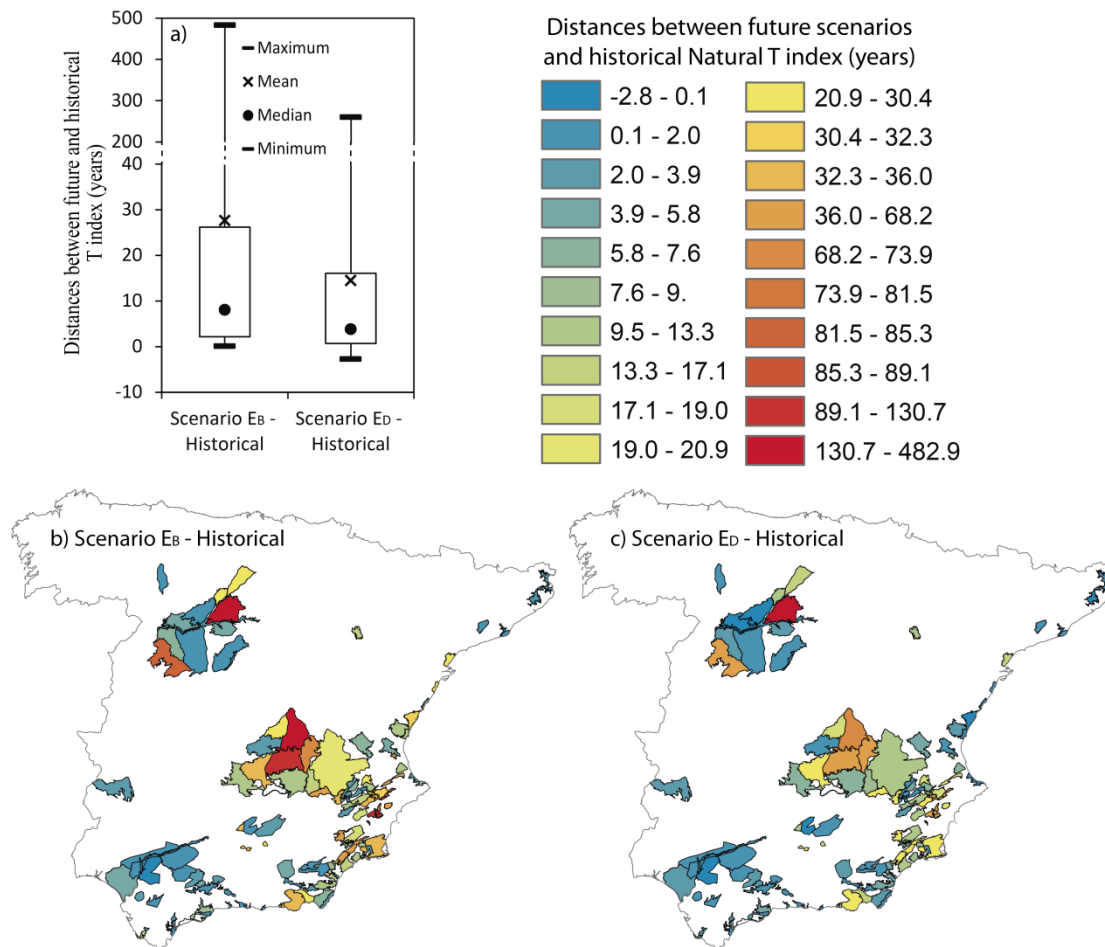


Figure 20. Box-Whiskers (a) and maps (b and c) of the distances between historical Natural T and future potential values in horizon 2011-2045.

6 REFERENCES

AEMET (2009). Generación de escenarios regionalizados de cambio climático para España, Agencia Estatal de Meteorología, Mto, Medio Ambiente, Medio Rural y Marino.

Alcalá, F.J., Custodio, E. (2012). Evaluación de la recarga a los acuíferos mediante balance de masa de cloruro atmosférico y su incertidumbre en el territorio continental español. J. Zurutuza (Ed.) In VII Asamblea Hispano Portuguesa de Geodesia y Geofísica, 1, 549-554. San Sebastián, Spain.

Alcalá, F.J., Custodio, E. (2014). Spatial average aquifer recharge through atmospheric chloride mass balance and its uncertainty in continental Spain. *Hydrological Processes*. 28, 218-236.

Alcalá, F.J., Custodio, E. (2015). Natural uncertainty of spatial average aquifer recharge through atmospheric chloride mass balance in continental Spain. *Journal of Hydrology*. 524, 642-661.

Christensen, N.S., Lettenmaier, D. precipitation. (2007). A multimodel ensemble approach to assessment of climate change impacts on the hydrology and water resources of the Colorado River Basin. *Hydrol. Earth Sys. Sci.*, 11, 1417-1434.

Collados-Lara, A.J., Pulido-Velazquez, D., Pardo-Igúzquiza, E. (2018). An Integrated Statistical Method to Generate Potential Future Climate Scenarios to Analyse Droughts. *Water*, 10, 1224. doi:10.3390/w10091224.

CORDEX EU Project (2013). The Coordinated Regional Climate Downscaling Experiment CORDEX. Program sponsored by World Climate Research Program (WCRP). Available at: <http://wcrp-cordex.ipsl.jussieu.fr/>.

Custodio, E., Andreu-Rodes, J., Aragón, R., Estrela, T., Ferrer, J., García-Aróstegui, J.L., Manzano, M., Rodríguez-Hernández, L., Sahuquillo, A., del Villar, A. (2016). Groundwater intensive use and mining in south-eastern peninsular Spain: Hydrogeological, economic and social aspects. *Science of the Total Environment*, 559, 302-316.

Del Barrio, G., Puigdefabregas, J., Sanjuan, M.E., Stellmes, M., Ruiz, A. (2010). Assessment and monitoring of land condition in the Iberian Peninsula, 1989-2000. *Remote Sensing of Environment*, 114, 1817-1832.

Earman, S., Campbell, A.R., Newman, B.D., Phillips, F.M. (2006). Isotopic exchange between snow and atmospheric water vapor: Estimation of the snowmelt component of groundwater recharge in the southwestern United States. *J. Geophys. Res.*, 111, D09302.

EEA. 2007. Corine land cover 2000 (CLC2000) seamless vector database. European Environment Agency: Copenhagen. (<http://www.eea.europa.eu/data-and-maps/data/corine-land-cover-2000-clc2000-seamless-vectordatabase>).

Escriva-Bou, A., Pulido-Velazquez, M., Pulido-Velazquez, D. (2017). The economic value of adaptive strategies to global change for water management in Spain's Jucar basin. *J. Water Resour. Plann. Manage.* [https://doi.org/10.1061/\(ASCE\)WR.1943-5452.0000735](https://doi.org/10.1061/(ASCE)WR.1943-5452.0000735).

España, S., Alcalá, F.J., Vallejos, A., Pulido-Bosch, A. (2013). A GIS tool for modelling annual diffuse infiltration on a plot scale. *Comput. Geosci.*, 54, 318-325.

Garrido, A., Llamas, M.R. (2009). *Water policy in Spain*. John Wiley & Sons, Boca Raton, FL; 254 pp.

Herrera, S., Fernández, J., Gutiérrez, J.M. (2016). Update of the Spain02 gridded observational dataset for Euro-CORDEX evaluation: assessing the effect of the interpolation methodology. *Int. J. Climatol.*, 36, 900-908.

Hurrell, J.W. (1995). Decadal trends in the North Atlantic Oscillation, regional temperatures and precipitation. *Nature*, 269, 676-679.

IGME (1993). *Groundwater in Spain: synthetic study*, Technical Report. Ministry of Industry and Energy of Spain: Madrid; 591 pp. [in Spanish]. (<http://aguas.igme.es/igme/publica/libro20/lib20.htm>).

Martínez-Valderrama, J., Ibáñez, J., Del Barrio, G., Sanjuán, M.E., Alcalá, F.J., Martínez-Vicente, S., Ruiz, A., Puigdefábregas, J. (2016). Present and future of desertification in Spain: implementation of a surveillance system to prevent land degradation. *Science of the Total Environment*. 563-564, 169-178.

Martín-Vide, J., López-Bustins, J.A. (2006). The Western Mediterranean Oscillation and Rainfall in the Iberian Peninsula. *International Journal of Climatology*, 26, 1455-1475.

MIMAM (2000). *White book of water in Spain*. Ministry of the Environment, State Secretary of Waters and Coast, General Directorate of Hydraulic Works and Water Quality: Madrid; 637 pp. [in Spanish]. (http://hercules.cedex.es/Informes/Planificacion/2000-Libro_Blanco_del_Agua_en_Espana/).

Pardo-Iguzquiza, E., Collados-Lara, A.J., Pulido-Velazquez, D. (2017). Estimation of the spatiotemporal dynamics of snow covered area by using cellular automata models. *J. Hydrol.*, 550, 230.238.

Pulido-Velazquez, D., Romero, J., Collados-Lara, AJ, Alcalá, Francisco FJ, Fernández-Chacón, F. and L. Baena-Ruiz, (2020). Using the Turnover Time Index to Identify Potential Strategic Groundwater Resources to Manage Droughts within Continental Spain. *Water* 2020, 12(11), 3281; <https://doi.org/10.3390/w12113281> (registering DOI)

Pulido-Velazquez, D., Garrote, L., Andreu, J., Martín-Carrasco, F.J., Iglesias, A. (2011). A methodology to diagnose the effect of climate change and to identify adaptive strategies to



reduce its impacts in conjunctive-use systems at basin scale. *Journal of Hydrology*, 405, 110-122.

Pulido-Velazquez, D., García-Aróstegui, J.L., Molina, J.L., Pulido-Velazquez, M. (2015). Assessment of future groundwater recharge in semi-arid regions under climate change scenarios (Serral-Salinas aquifer, SE Spain). Could increased rainfall variability increase the recharge rate? *Hydrological Processes*, 29, 828-844.

Pulido-Velázquez, D., Collados-Lara, A.J., Baena-Ruiz, L., Fernández-Chacón, F., Alcalá, F.J. (2017). Assessment of present and future vulnerability to pumping in Spanish GW bodies using a natural turnover time index. In 44th Annual Congress of the International Association of Hydrogeologists: Groundwater Heritage and Sustainability (IAH, Ed.). e-Poster. Session T2.5. Abstract T2.5.24. Dubrovnik. ISBN: 978-953-6907-61-8.

Pulido-Velázquez, D., Collados-Lara, A.J., Alcalá, F.J. (2018). Assessing impacts of future potential climate change scenarios on aquifer recharge in continental Spain. *Journal of Hydrology*. 567, 803-819.

Quintana-Seguí, precipitation., Turco, M., Herrera, S., Miguez-Macho, G. (2017). Validation of a new SAFRAN-based gridded precipitation product for Spain and comparisons to Spain02 and ERA-Interim. *Hydrol. Earth Syst. Sci.*, 21, 2187-2201.

Räisänen, J., Räty, O. (2012). Projections of daily mean temperature variability in the future: cross-validation tests with ENSEMBLES regional climate simulations. *Clim. Dyn.*, 41, 1553-1568.

Sabater, S., Barceló, D. (2010). *Water Scarcity in the Mediterranean. Perspectives Under Global Change*. Springer-Verlag Berlin Heidelberg. 234 pp. doi:10.1007/978-3-642-03971-3.

Trigo, R.M., Pozo-Vazquez, D., Osborn, T.J., Castro-Diez, Y., Gamiz-Fortis, S., Esteban-Parra, M.J. (2004). North Atlantic Oscillation influence on precipitation, river flow and water resources in the Iberian Peninsula. *International Journal of Climatology*. 24, 925-944.

WFD (2000). Water Framework Directive Directive 2000/60/EC of the European Parliament and of the Council, of 23 October 2000, establishing a framework for Community action in the field of water policy, *Official Journal of the European Union* L 327/1, 22.12.2000 (http://europa.eu.int/comm/environment/water/water-framework/index_en.html).

Willaarts, B.A., Ballesteros, M., Hernández-Mora, N. (2014) Ten years of the Water Framework Directive in Spain: An overview of the ecological and chemical status of surface water bodies. *Integrated Water Resources Management in the 21st Century: Revisiting the Paradigm*, 99.

Winograd, I.J., Riggs, A.C., Coplen, T.B. (1998). The relative contributions of summer and cool-season precipitation to groundwater recharge, Spring Mountains, Nevada, USA. *Hydrogeol. J.*, 6, 7793.



