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PILOT DESCRIPTION AND ASSESSMENT

Alto Genil Basin (Spain)

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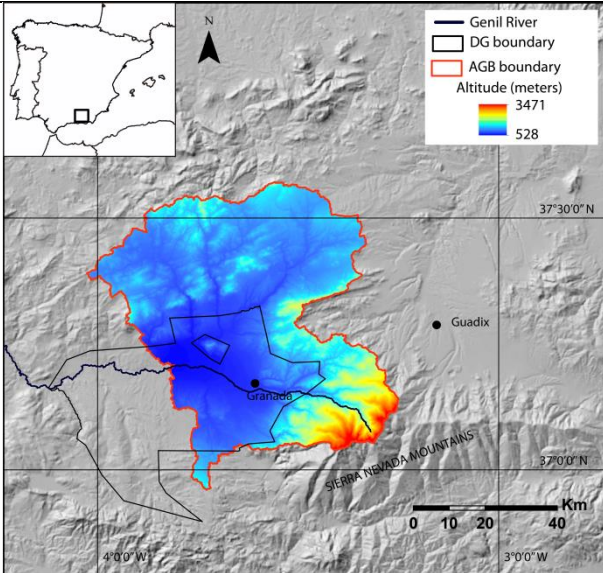
LIST OF ABBREVIATIONS & ACRONYMS

AG	Alto Genil
DG	Depression of Granada
VG	Vega de Granada

TABLE OF CONTENTS

	LIST OF ABBREVIATIONS & ACRONYMS	4
1	EXECUTIVE SUMMARY	5
2	INTRODUCTION	7
3	PILOT AREA	9
	3.1 Site description and data	9
	3.1.1 Location and extension of the pilot area	9
	3.1.2 Geology/Aquifer type	10
	3.1.3 Topography and soil types	10
	3.1.4 Surface water bodies	11
	3.1.5 Hydraulic head evolution and subsidence	12
	3.1.6 Climate	14
	3.1.7 Land use	15
	3.1.8 Abstractions/irrigation	16
	3.1.9 Flow balance components	16
	3.2 Climate change challenge	17
4	METHODOLOGY AND DATA	18
	4.1 Data	18
	4.1.1 Climate data	18
	4.1.2 Hydrological data	18
	4.1.3 Subsidence data	18
	4.1.4 Material of piezometers data	18
	4.2 Generation of Future Potential Scenarios	19
	4.2.1 Generation of Future Individual Projections	19
	4.2.2 Multi-Objective Analysis of the individual projections (Basic and Drought Statistics)	20
	4.2.3 Ensembles of Predictions to Define More Representative Future Climate Scenarios	20
	4.3 Potential Impacts of Future Climate Change Scenarios on Ground Subsidence	20
	4.3.1 Hydrological Impacts of Climate Change on Groundwater Levels	21
	4.3.2 Assessment of the subsidence from satellite data	22
	4.3.3 Propagation of Hydrological Impacts to Subsidence	23
5	RESULTS AND CONCLUSIONS	24
	5.1 Influence of the fine-grained material in the aquifer subsidence	24
	5.2 Impacts of climate change on precipitation, temperature, and droughts	25
	5.3 Impacts of climate change on hydraulic head and subsidence	26
6	REFERENCES	29

1 EXECUTIVE SUMMARY

Pilot name	ALTO GENIL BASIN	 <i>Modified from Collados-Lara et al., 2018a</i>
Country	Spain	
EU-region	Mediterranean region	
Area (km ²)	2596 km ²	
Aquifer geology and type classification	AG basin (detrital, shale, limestone and conglomerate); DG (detrital)	
Primary water usage	Irrigation / Drinking water / Industry	
Main climate change issues	The Alto Genil (AG) basin is located in a Mediterranean region where the latest studies on climate change forecast important increases in temperature and a decreases in precipitation, which will cause a decrease in water resources linked considerable increases in length, magnitude and intensity of droughts. The main contributions to the basin come from Sierra Nevada Mountains in the melt season through the Genil river. The alpine systems where the majority of precipitation is solid (snow) could be very sensitive to climate change too. On the other hand the DG (depresión de Granada) aquifer, located in the AG basin, is one of the largest groundwater bodies in Andalusia and it is considered as strategic for the economy of this semi-arid region. Decreases in water resources can provoke also important subsidence issues in this detrital aquifers.	
Models and methods used	Generation of local future climate change scenarios to analyse droughts following the method proposed in the framework of this project (Collados-Lara et al., 2018a). Analysis of the influence of the fine-grained material in the aquifer subsidence and assessment of the impact of climate change scenarios on land subsidence related to groundwater level depletion in the detrital aquifer..	
Key stakeholders	Genil River Basin Authority, water supply companies, Environmental Conservation Groups.	
Contact person	AJ Collados-Lara, D. Pulido, L. Baena, E. Pardo; JD Gómez. IGME (Spain), aj.collados@igme.es; d.pulido@igme.es; l.baena@igme.es; j.dedios@igme.es;	

The AG basin has an area of 2596 km², and it is situated in the Mediterranean region of EU (south of Spain) which is very vulnerable to climate change. The basin varies substantially in elevation,



from 528 to 3471 m.a.s.l. The main river of the basin is the Genil river, which is the most important in the province of Granada, and one of the most important in Andalusia. The main contributions to the river come from Sierra Nevada Mountains in the melt season. The main groundwater body related to the AG basin is the DG which cover an extension of around 1350 km². The aquifer is mainly detrital although there are some karstic horizons. Two subunits can be differentiated within the groundwater body, the VG aquifer and a Mioplioceno Subunit.

In the AG basin different correction approaches and climate models were used to generate local future climate change scenarios of precipitation and temperature to analyse droughts. We considered different correction techniques (first moment correction, first and second moment correction, regression and quantile mapping) under the bias correction and delta change approaches. Two ensemble scenarios were defined by combining as equiflexible members all the future projections for the two correction approaches. Two other options were defined by combining only the not eliminated projections in a multi-objective analysis that takes into account basic and droughts statistics.

The average changes predicted using the four ensembles of scenarios for the period 2071-2100 and the scenario RCP 8.5 are around -27 % in precipitation and + 32 % in temperature and all four ensembles predict considerable increases in length, magnitude and intensity of droughts. The uncertainty related to the correction approaches is lower than the related to RCMs.

In the VG aquifer we analysed the influence of the fine-grained material in the aquifer subsidence and assessed the impact of climate change scenarios on the land subsidence related to groundwater level depletion. An equiflexible ensemble of the generated projections from different climatic models is also proposed. A simple water balance approach is applied to assess climate change impacts on lumped global drawdowns. Climate change impacts are propagated to drawdowns within piezometers by applying the global delta change observed with the lumped assessment. Regression models are employed to estimate the impacts of these drawdowns in terms of land-subsidence, as well as to analyze the influence of the fine-grained material in the aquifer.

The impacts of climate change on the subsidence would be very significant for the case study. The mean increment of the maximum subsidence rates in the considered wells for the future horizon (2016-2045) and the scenario RCP 8.5 is 54%. In order to avoid undesirable consequences/risks some adaptation strategies should be applied to control and minimize land subsidence caused by groundwater withdrawals.

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).

This report describes the work undertaken by the Spanish Geological Survey (IGME) as a part of TACTIC WP4 to assess impacts of climate change on water resources at the AG basin. It also analyzes the influence of fine-grained material in the aquifer subsidence and assess impacts of climate change on subsidence in the VG detrital aquifer.

The work presented here aims to perform an analysis of several statistical approaches and RCMs, to generate future potential scenarios at a monthly scale, which is the usual timescale for the analysis of water resource management problems. We assessed different solutions, taking into account basic and drought statistics of the historical series and the climatic model simulations. A multi-objective analysis is proposed to identify the inferior approaches which



would also help to reduce the uncertainties associated. The proposed methodology is applied to the AG basin (south Spain). It also aims to perform a first assessment of potential climate change impacts on land subsidence related to groundwater-level depletion in the VG detrital aquifer and to analyse the influence of the fine-grained material in the aquifer subsidence.

3 PILOT AREA

This pilot area is very sensitive to climate change because it is located in a mediterranean alpine region where the latest studies forecast important increase in temperature and a decrease in precipitation. For the propagation of climate change impacts we will employ Hydrological lumped model approach integrating variables deduced from remote sensing earth observation (eg. Snow). Special attention will be paid to the analysis of droughts and subsidence that will be exacerbated in future due to climate change. We also intend to define methodological guidelines to assess potential future climate scenarios at river basin and aquifer scale. Different ensemble and downscaling techniques will be employed to define potential future global change scenarios for the study area based on the data coming from simulations with different Regional Circulation Models (RCMs). In this project we intent to propagate climate change scenarios considering future potential impacts of global change scenarios in droughts in the AG basin and groundwater subsidence in the DG (Depresión de Granada) groundwater body.

3.1 Site description and data

3.1.1 Location and extension of the pilot area

The study basin has an area of 2596 km², and it is situated in the Mediterranean region of EU (south of Spain) (see Fig. 1). The basin varies substantially in elevation, from 528 to 3471 m.a.s.l. The main river of the basin is the Genil river, which is the most important in the province of Granada, and one of the most important in Andalusia. The main contributions to the river (e.g. Dílar, Monachil or Cubillas rivers) come from Sierra Nevada Mountains in the melt season (Collados-Lara et al., 2018a). The main groundwater body related to the AG basin is the DG which cover an extension of around 1350 km² (see Fig. 1).

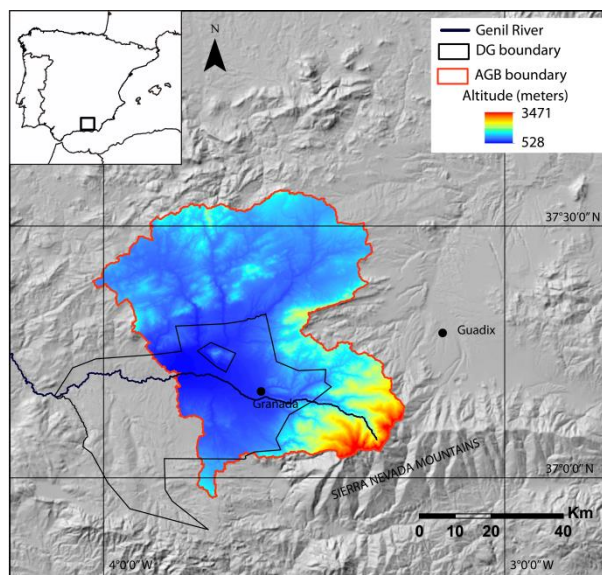


Fig. 1. Location of the pilot area (modified from Collados-Lara et al., 2018a).

3.1.2 Geology/Aquifer type

The DG groundwater body (05.32) is located in a basin between the Betics Mountains. In this basin, Neogene and Quaternary materials were deposited with high thickness and strong lateral variations (see Fig. 2). The aquifer is mainly detrital although there are some karstic horizons. Two subunits can be differentiated within the groundwater body, VG aquifer and a Mioplioceno Subunit, but we will focus on the first due to the second is not well known and its relevance is limited. The VG Subunit defines an unconfined aquifer. Its surface is around 200 Km². Recharge mainly appears in the eastern sector through rainfall and runoff infiltration. The aquifer outputs are produced in the western side by natural drainage to rivers, irrigation canals and springs. The main drainage axis is the Genil River from the Puente de los Vados and the discharge to the Cubillas River is also important. There is also pumping to supply irrigation, urban and industrial demands.

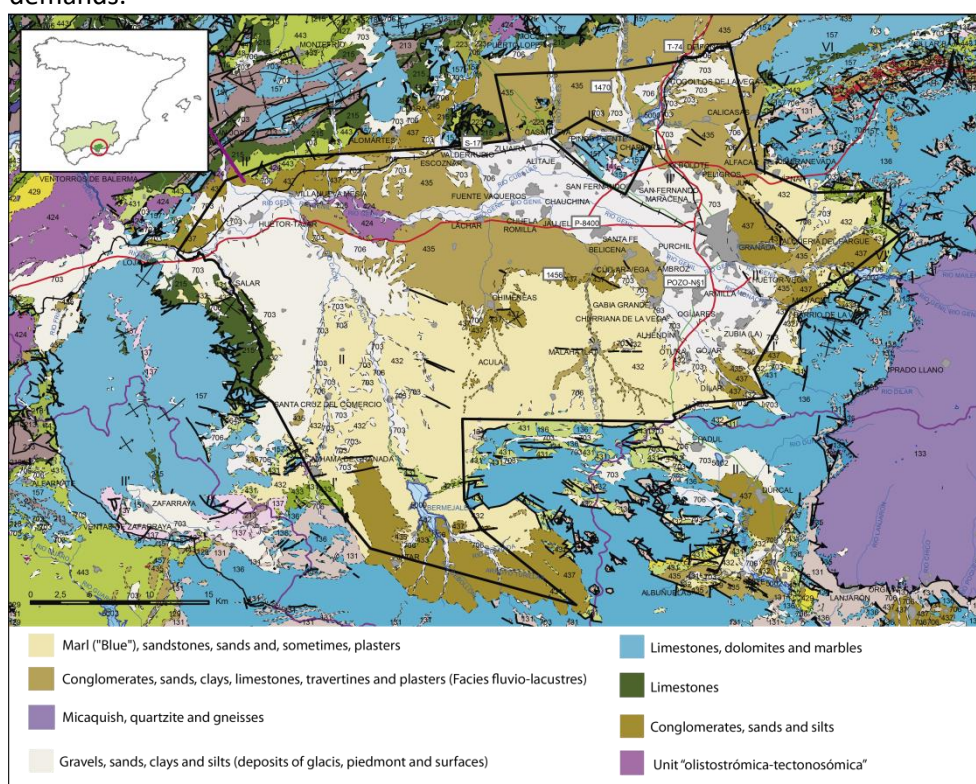


Fig. 2. Geological map of DG (modified from IGME-DGA (2009)).

3.1.3 Topography and soil types

Despite the variation in elevation in the AG basin is strong (from 528 to 3471 m.a.s.l.) (see Fig. 1), the DG groundwater body area is predominantly flat, with variation in elevation from 550 to 950 m.a.s.l. (see Fig. 3A). The soils in the groundwater body surface mainly belong to the cambisol group but it also can be found Regosol and others such as Litosol and Fluvisol in the area. Fig. 3B shows a soil map of DG groundwater body.



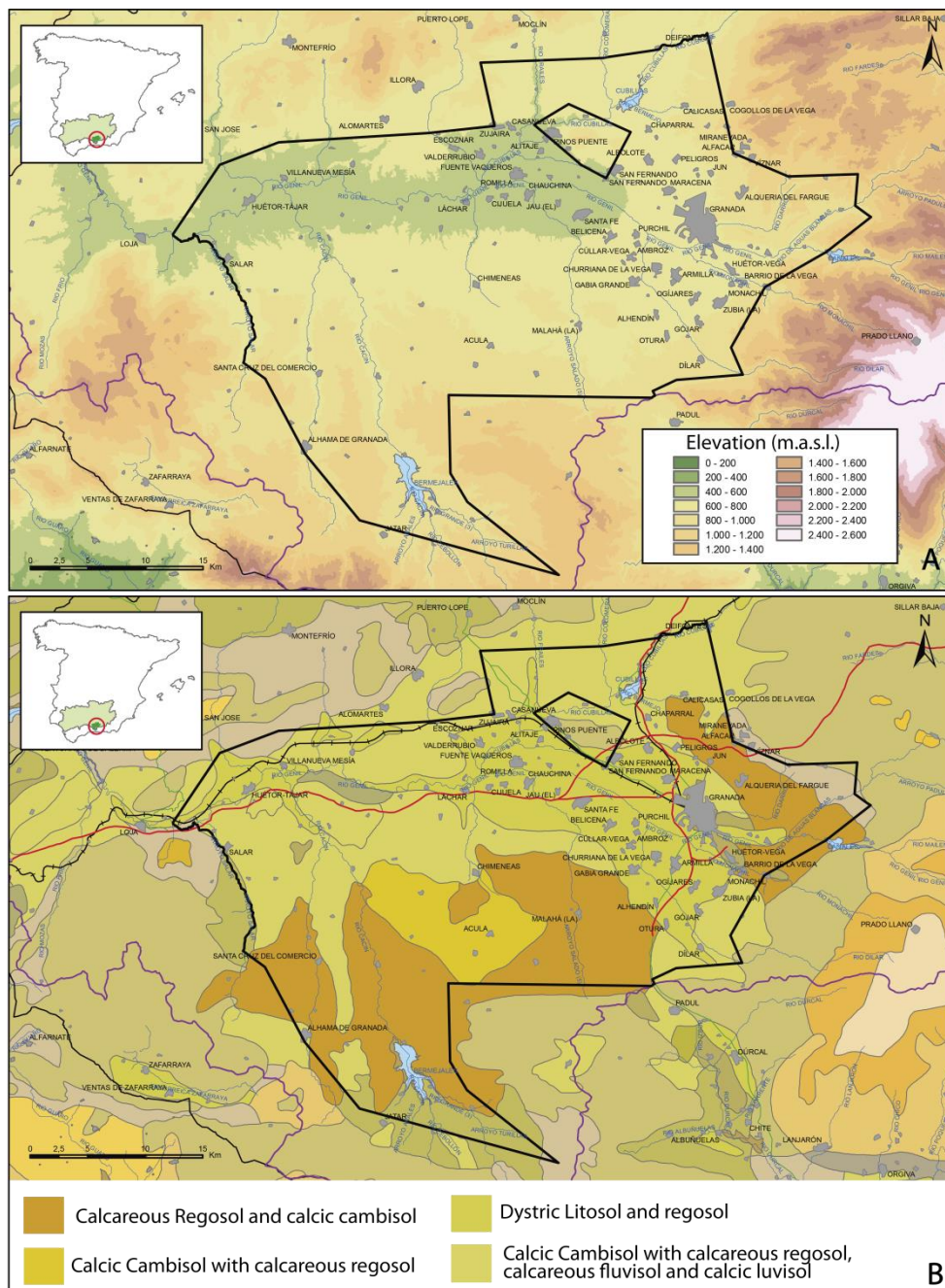


Fig. 3. A) Digital elevation map and B) soil map of DP ground water body (modified from IGME-DGA (2009)).

1.1.4 Surface water bodies

At the headwaters of the AG basin, streamflows are regulated by the reservoirs of Colomera, Cubillas, Bermejales, Quéntar and Canales. Fig. 4 shows the surface water system (rivers and reservoirs) of the AG basin. The quality of the surface water resources is higher in the high mountain reservoirs (Canales and Quéntar). Most of the surface resources comes from the Sierra



[illegible]

Table 1: Maximum and minimum volumes in the reservoirs (hm³) from 1970 to 2002 (modified from UPV (2004)).

		Maximum											
Reservoir	Minimum	October	November	December	January	February	March	April	May	June	July	August	September
Cubillas	5	19	19	15	15	15	19	19	19	19	19	19	19
Colomera	5	42	42	34	34	34	42	42	42	42	42	42	42
Quentar	1	14	14	11	10	10	10	14	14	14	14	14	14
Canales	1	71	71	58	58	58	58	71	71	71	71	71	71

As we have already pointed the main aquifer of the DG groundwater body is the VG detrital aquifer, which is one of the largest groundwater reservoirs in Andalusia and considered as strategic for the economy of this semi-arid region. Fig. 5 shows the historical evolution of the hydraulic head in three representative piezometers of the aquifer. A significant reduction trend in the piezometric levels is observed. These drawdowns are more important in the area of preferential recharge (piezometers A and B) (Castillo et al., 2010). On the other hand, in this aquifer, subsidence processes have been detected and related to groundwater level depletion (Mateos et al., 2017). Fig. 6 shows the evolution of hydraulic head and land displacements observed in six boreholes located in the Vega the Granada aquifer. All the subsiding areas detected by Mateos et al. (2017) are located in areas with higher clay composition.

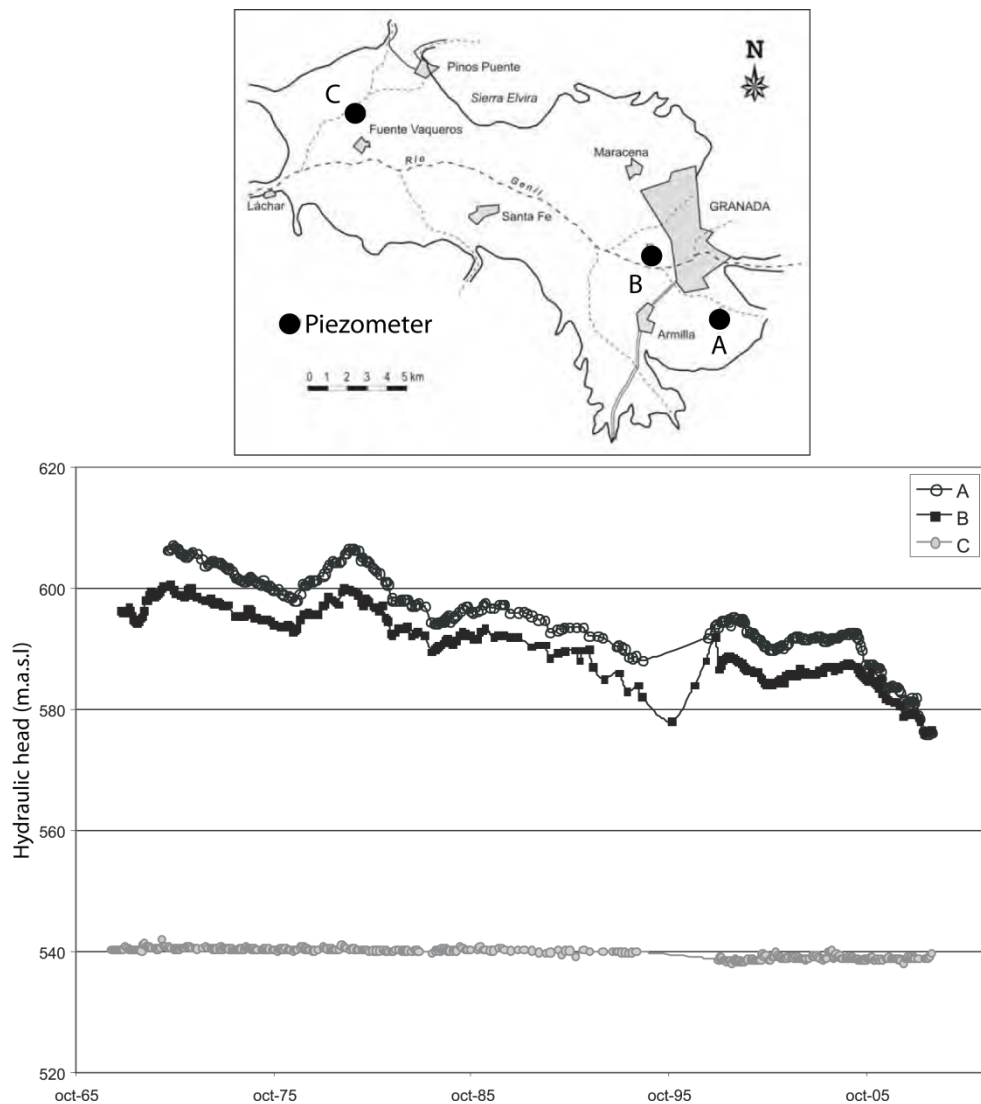


Fig. 5. Historical evolution of hydraulic head in three representative piezometers of the VG Aquifer (modified from Castillo et al., 2010).

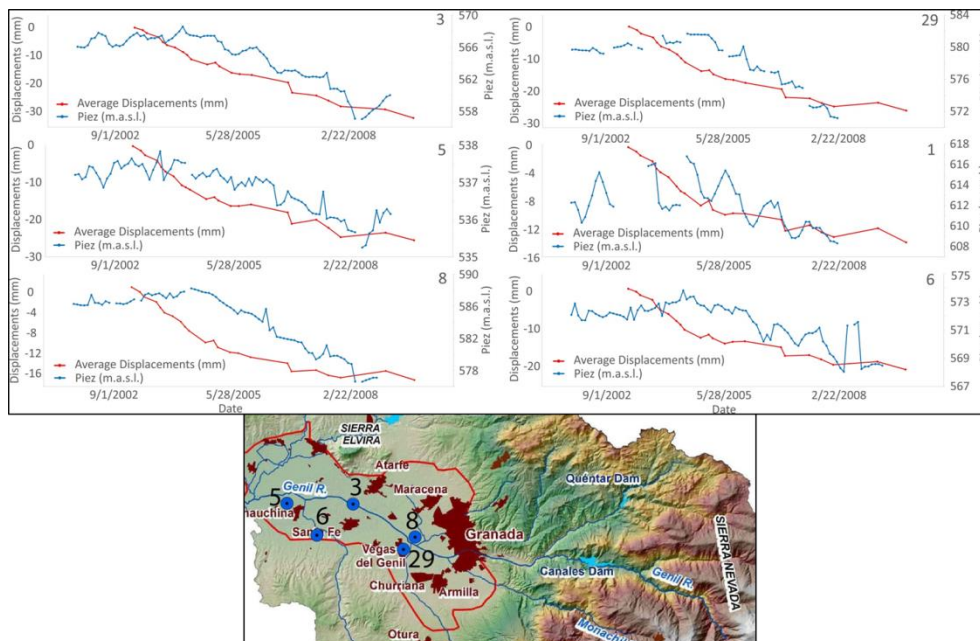


Fig. 6. Hydraulic head and displacements in the DG groundwater body from 2002 to 2008 (modified from Mateos et al., 2017).

3.1.6 Climate

The region has a Mediterranean climate very influenced by the proximity of Sierra Nevada Mountain. Summers are hot and dry and winters are cool and relatively damp, with most of the rainfall concentrated between November to January. The coldest months are December, January and February while the hottest months are July and August. The annual mean temperature and precipitation for the period 1971-2000 in the AG basin are respectively 14 °C and 525 mm/year. The mean values of temperature and precipitation for the different months are showed in Fig. 7. For the AG basin, Collados-Lara et al. (2018b) observed an inversion of the precipitation gradient (it become negative above a certain elevation) and a linear variation of temperature (see Fig. 8).

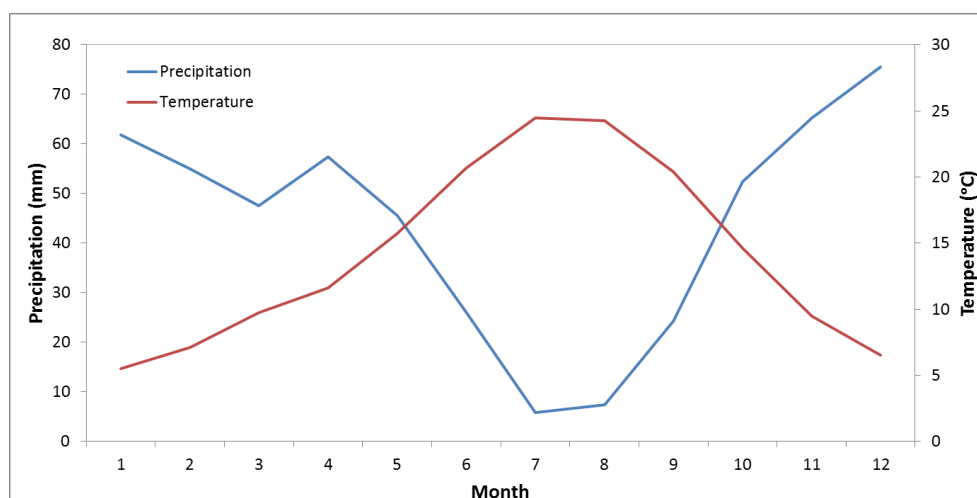


Fig. 7. Mean temperature and precipitation for the AG basin in the period 1971-2000 (Data from Spain02 v4 project (Herrera et al., 2016)).

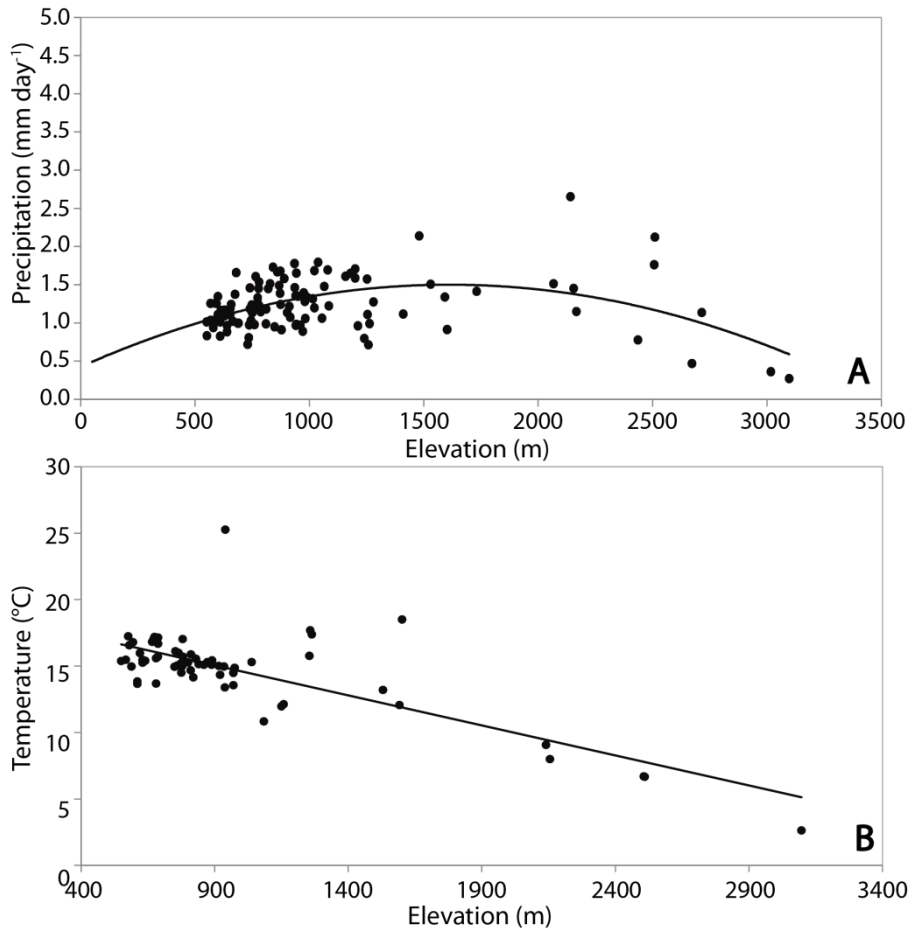
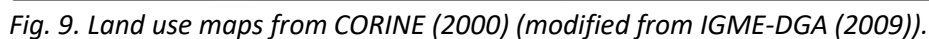


Fig. 8. (A) Mean daily precipitation data for different elevations. (B) Mean daily temperature data for different elevations. (modified from Collados-Lara et al., 2018b)).

3.1.7 Land use

The AG basin and especially the VG aquifer have suffered in the last decades significant territorial transformations (physical, demographic, socio-economic). Thus, a mainly agriculture sphere has become a complex and interrelated urban agglomeration (Fernández, 2010). The main land use in the Vega the Granada aquifer is irrigated agriculture and urban use while the non-irrigated agriculture is located in the Mioplioceno Subunit (see Fig. 9). In the DG groundwater body surface the preferential irrigated agriculture are herbaceous crops and the predominant non-irrigated agriculture are olive trees.



The irrigated agriculture has been the economic engine of the region before 1960s. From the 1960s a transformation process began in favor of other economic activities. The crisis of the agriculture sector is understood as a change in the economic model. The causes of the crisis of the agriculture sector in the VG are the fragility of the agriculture structures and the pressure provoked by the urban-industrial growth (Fernández, 2010). As we pointed previously, nowadays the main water uses in the AG basin are due to irrigation, drinking water, and industry demands. For the DG groundwater body these activities represent 48, 46, and 6 % of water use respectively. Table 2 shows the groundwater amounts destined for the different activities in the year 2007.

Year	Water supply population	Agriculture and Livestock	Industry	Total
2007	24.34	25.14	3.31	52.8

The flow balance proposed by different authors in the Vega the Granada aquifer is summarized in Table 3. The main inputs to the aquifer are recharge from precipitation and irrigation and the main outputs are abstractions and gaining rivers.



Water budget (hm ³ /year)	FAO (1972)	Castillo (1986-2005)	AAA (2008)	Calvache et al. (2013)
Surface Recharge (Precipitation)	6	24	30	66
Surface Recharge (Irrigation)	62	141	155	
Rivers infiltrations	6	19	25	50
Lateral Transference	-	-	-	17
TOTAL INFLOWS	74	184	210	133
Pumping	10-60	32-50	40	43
Gaining in Rivers	40-60	100-110	160	54
West Border	—	—	4	40
Evapotranspiration	9-14	7	6	-
TOTAL OUTFLOWS	59-134	139-167	210	137

3.2 Climate change challenge

In accordance with the EEA map the main expected issues due to climate change in this case study are those described in the Figure 10 for the Mediterranean regions. Existing national estimates in Spain showing also a significant reduction (around a 19% for the RCP8.5 emission scenario in the horizon 2071-2100) of the aquifer recharge in the area (see Pulido-Velazquez et al., 2017). The main challenge is to assess potential impacts of future climate change scenarios on the resources of the basin and the subsidence in the VG aquifer.

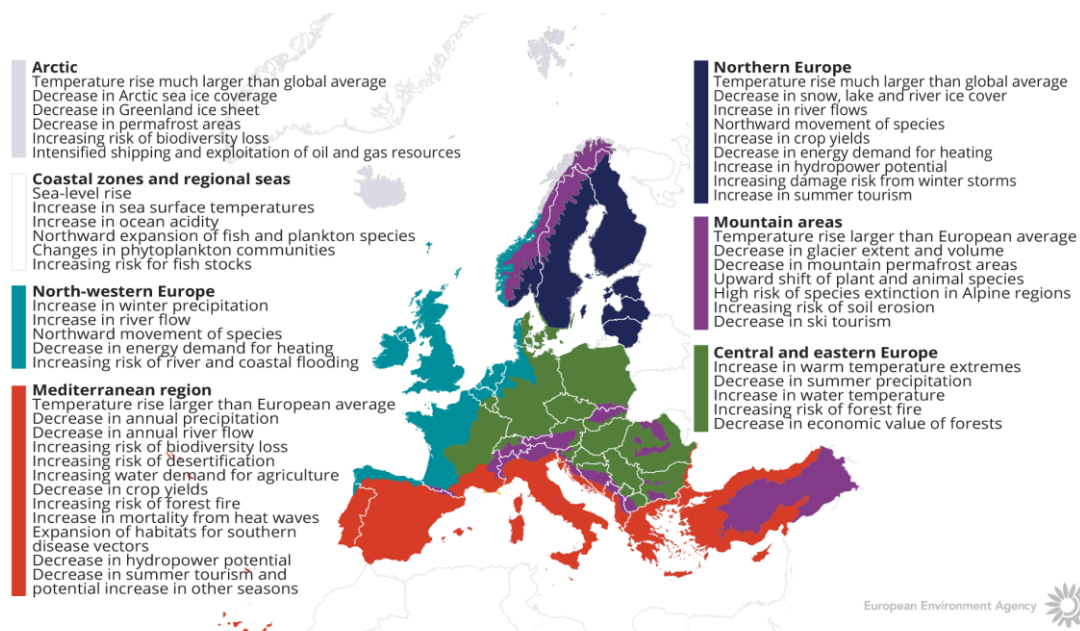


Fig. 10. How is climate expected to change in Europe. The European Environment Agency map.

4 METHODOLOGY AND DATA

4.1 Data

4.1.1 Climate data

The historical precipitation and temperature data have been taken from the project Spain02 v4 (Herrera et al. 2016) for the period 1971–2000 in the case of AG basin and 1986–2015 in the case of VG aquifer. Periods of 30 years are frequently employed in climate change impact studies. The Spain02 project provides an estimation of precipitation and temperature obtained using the original data from the Agencia Estatal de Meteorología (State Meteorological Agency—AEMET). The spatial resolution of the data is around 12.5 km and the spatial support is the same than the Euro-CORDEX project, from which the different RCMs were obtained. We used nine RCMs (see Table 4) nested to different GCMs under the most pessimistic scenario of the AR5 of the IPCC, the RCP 8.5, for the period 2071–2100 in the case of AG basin and 2016–2045 in the case of VG aquifer.

Table 4. RCMs and GCMs considered.

RCM \ GCM				
	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

4.1.2 Hydrological data

We also employed some hydrological information. It includes hydraulic head evolution in different piezometers obtained from the Spanish official network for monitoring the quantitative state of groundwater (see their location in Figure 6) and the historical recharge and pumping rates within the aquifer, which were taken from the information included in the Guadalquivir River Basin Plan (2015–2021).

4.1.3 Subsidence data

For those wells we also have information about the land subsidence rates obtained by applying PInSAR techniques (Mateos et al., 2017). The average vertical displacement based on the time series was estimated by using buffer areas with a radius of 1000 m for each piezometer and considering all PSI (Persistent Scatterer Interferometry) data included in the area.

4.1.4 Material of piezometers data

The percentage of fine-grained material (clay and silt) for each piezometer was obtained by exploiting geological data recorded in 38 boreholes drilled in the area. They were interpreted (Mateos et al., 2017) providing isolines of fine-grained sediment percentage taking into account the clay and silt content in the first 50 m of the borehole, as the borehole depths are quite

variable (from 50 m to 122 m). Results showed higher clay content in the piezometers located in the northern and southern extremes of the aquifer as well as in its central part (see Table 5).

Table 5. Content of clay and silt in the considered piezometers (see Fig. 6).

Piezometer	Clay and silt content (%)
5	40
3	5
6	70
8	20
29	20

4.2 Generation of Future Potential Scenarios

The steps of the proposed methodology to generate potential monthly future climate scenarios (precipitation and temperature) are represented in Figure 11. It includes the analysis of data and generation of future individual projections, a multi-objective analysis to identify inferior models, and different ensembles of predictions.

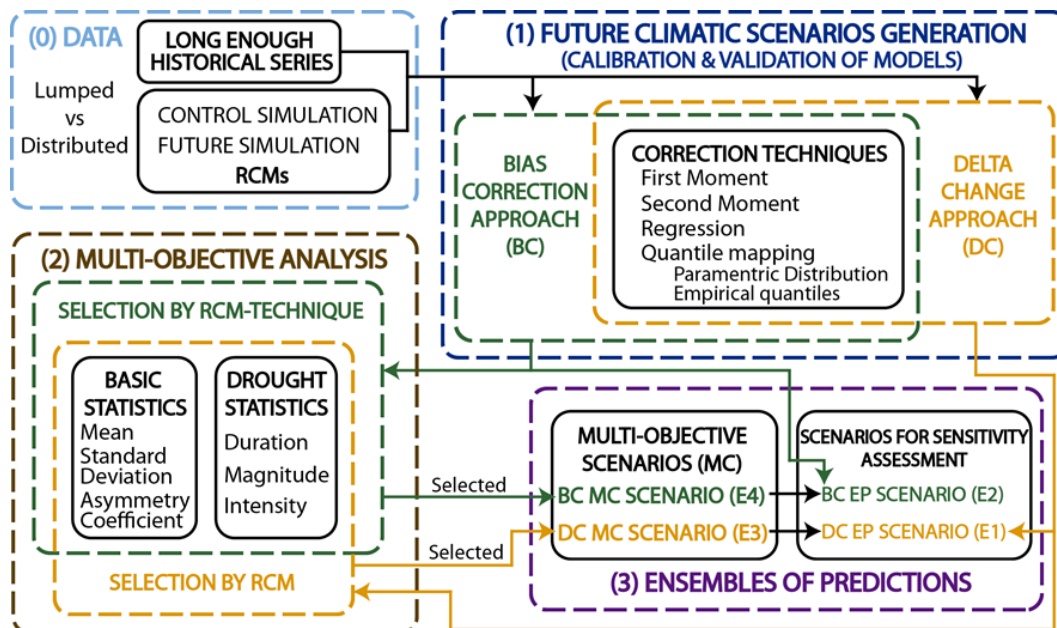


Fig. 11. Flow chart of the methodology to generate future potential scenarios (from Collados-Lara et al., 2018a)

4.2.1 Generation of Future Individual Projections

An analysis of historical data and RCMs simulations allows to identifying the necessity of applying statistical correction techniques to generate future scenarios. These techniques can be employed under two different approaches, bias correction and delta change. The first applies a transformation function to the control simulation series to force some of its statistics or quantile distribution to get closer to the historical ones. This transformation function is also applied to



the future simulation series to obtain the corrected future scenarios. It assumes that the bias between the statistics of historical data and the control simulation will remain invariant in the future. On the other hand, the delta change approach assumes that the relative changes between future simulation and control simulation from RCMs are accurate and applies these changes to the historical series to obtain the corrected future series.

For both conceptual approaches, we tested several statistical techniques with various degrees of complexity and accuracy that intend to preserve different statistics: correction of first- and second- order moments, regression approach (we used the GROUNDST tool developed by Collados-Lara et al. 2020) and quantile mapping (we used qmap package developed by Gudmundsson et al. 2002), which are described below.

- a) Correction of first moment: In the first-moment correction techniques the transformation function only intends to provide a good approximation to the mean values.
- b) Correction of first and second moment: It is focused on the approximation of the mean and standard deviation to define the transformation function.
- c) Regression: It defines the transformation function by adjusting a regression function. Usually, a linear function can provide reliable results in the adjustment.
- d) Quantile mapping: The transformation function is elaborated using the cumulative distribution function of the series.

4.2.2 Multi-Objective Analysis of the individual projections (Basic and Drought Statistics)

A multi-objective analysis based on the goodness-of-fit to some statistics is proposed to identify the approaches (RCMs in the case of delta change and combination of RCM – technique in the case of bias correction) that provide more reliable approximations to historical basic (mean, standard deviation and asymmetry coefficient) and drought statistics (duration, magnitude and intensity). An approach is inferior if any other approach provides approximations significantly better for all the cited statistics (basic and drought statistics).

4.2.3 Ensembles of Predictions to Define More Representative Future Climate Scenarios

Two ensemble scenarios were defined by combining as equifeasible members all the future series (that correspond to different RCMs simulations) generated by applying delta change (scenario E1) or bias correction (scenario E2) approaches. Note that, in the equifeasible ensembles, the number of members employed to define the future scenarios can be obtained by multiplying the number of RCMs and the number of techniques. Two other options were defined by combining only the not eliminated models (E3) (in delta change approach) or the not eliminated combinations of models and correction techniques (E4) (bias correction techniques), assuming that we do not trust the eliminated ones. Note that eliminate models are the identified as inferior in the multi-objective analysis.

4.3 Potential Impacts of Future Climate Change Scenarios on Ground Subsidence

A flowchart of the proposed method used to assess potential impacts of climate change on subsidence has been represented in Fig. 12.

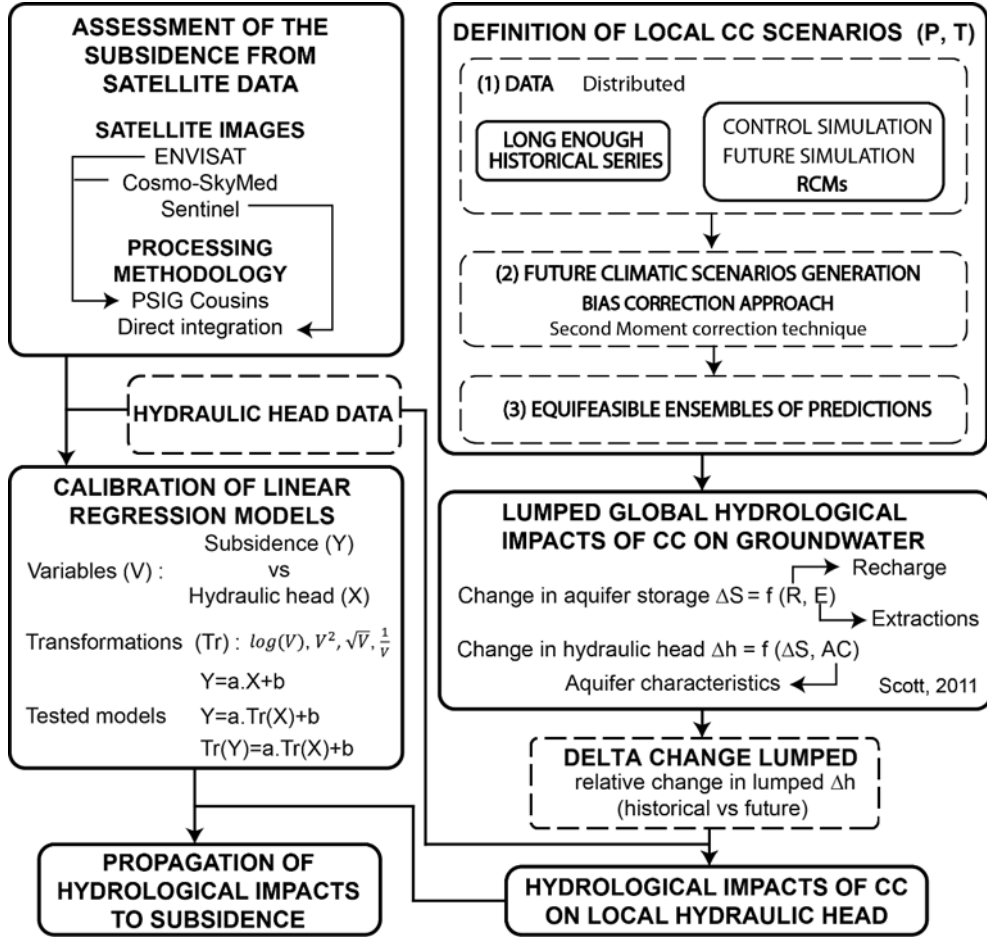


Fig. 12. Flow chart of the methodology to assess impacts of climate change on subsidence (from Collados-Lara et al., 2020)

4.3.1 Hydrological Impacts of Climate Change on Groundwater Levels

A simple approach proposed by Scott (2011) is applied to assess future CC impacts on global lumped drawdowns due to the future potential rainfall recharge and pumping. Following this approach, simple balance equations are applied in order to assess the global lumped change in hydraulic head (Δh_t) from aquifer storage (ΔS_t), which is calculated as follow:

$$\Delta S_t = R_t - E_t \quad (1)$$

where R_t is the aquifer rainfall recharge and E_t are the aquifer extractions which can be obtained from Eq. 2.

$$E_t = Eag_t - Enonag_t \quad (2)$$

where Eag_t represents the agricultural extractions and $Enonag_t$ the non-agricultural extractions. They have been calculated using Eq. 3 and 4 respectively.

$$Eag_t = Eag_{t-1} \left[1 + \frac{ET_t - ET_{t-1}}{ET_{t-1}} \right] \quad (3)$$



$$Enonag_t = Enonag_{t-1} \left[1 + \frac{Pop_t - Pop_{t-1}}{Pop_{t-1}} \right] \quad (4)$$

where ET is the evapotranspiration calculated using the Blaney-Criddle method ($ET = p(0.46T_{mean} + 8)$) on the basis of monthly temperature in °C (T_{mean}) and latitude-derived sunshine-hour fraction (p) and Pop is the population of the area.

Finally, the hydraulic head (Δh_t) is obtained using Eq. 5:

$$\Delta h_t = \frac{\Delta S_t}{A \cdot S_y} \quad (5)$$

where A is the aquifer area S_y the specific yield.

The initial conditions to simulate the recharge (R_{t-1}) and pumpings (agricultural or non-agricultural, Eag_{t-1} and $Enonag_{t-1}$) evolutions were taken from the information included in the Guadalquivir River Basin Plan (2015-2021).

The lumped approach proposed by Scott (2011) has been also applied to estimate the lumped hydraulic head drawdowns in the reference historical period (1986-2015). It allows to estimate the delta change (percentage of increment) in the lumped aquifer drawdowns, taking into account the relative difference between the maximum lumped drawdowns in the historical and the future period (2016-2045). These results are obtained assuming that a business as usual management scenario will be maintained in the future. The future potential hydraulic head in each piezometer will be obtained by applying a delta change correction, using the lumped change to modify the historical evolution (for the reference period) of this variable within the piezometer.

4.3.2 Assessment of the subsidence from satellite data

In the present study, spatial and temporal ground surface deformation assessment was obtained by exploiting 70 SAR images from 3 different satellites: ENVISAT (2003-2009, C band), Cosmo-SkyMed (2011-2014, X band) and Sentinel 1A (2015-2016, C band). The processing methodologies applied for each dataset were: (1) PSIG Cousins for ENVISAT and COSMO-Sky-Med datasets, and (2) Direct integration approach for Sentinel 1A dataset. More detailed specifications can be found in Mateos et al. (2017). This combination allows a thorough assessment of the ground deformation pattern in the aquifer and both temporal and spatial dimensions of the subsidence.

PSInSAR measurements were obtained in the VG aquifer, covering a large temporal span of 13 years (from 2003 to 2016). Along this time, a severe drought affected the area during the ENVISAT period (2003-2006), when greater groundwater withdrawals took place.

PSInSAR data were correlated (temporally and spatially) with hydraulic head changes in the aquifer along the monitoring period and with geological data (from boreholes) regarding the clay and silt content in the aquifer. Based on the borehole information, isolines of fine sediments percentage were obtained by Mateos et al. (2017). Clay and silt content is a key information which can explain spatial response of the aquifer-system to hydraulic head changes and the subsequent vertical land movements.



4.3.3 Propagation of Hydrological Impacts to Subsidence

Simple linear regression models have been defined in order to approximate subsidence as a function of hydraulic head drawdowns in the selected head observation wells. We have tested different transformation ($Tr(X)$) of the explanatory and target variables (logarithm, inverse, square, and square root mathematical transformations) in order to identify the one that provides better approximation to the empirical data for this problem (see Table 6).

*Table 6. Regression models and transformation of variables applied. The symbol * represents the tested combinations of model and transformation of variables.*

Model	$Tr(X)$				
	X^2	$\sqrt{X}$	$\log(X)$	$1/X$	
$Y=a.X+b$	*	-	-	-	-
$Y=a.Tr(X)+b$	-	*	*	*	*
$Tr(Y)=a.Tr(X)+b$	-	*	*	*	*

The models assume that there is a linear relation between both variables, the depending variable and the explanatory variable and its transformations, which is reasonable if the deformation is elastic. An analysis of the linear correlation depending on the percentage of clay and silt content in the ground is also proposed in order to identify and discuss when the linear regression provides better approaches.

5 RESULTS AND CONCLUSIONS

5.1 Influence of the fine-grained material in the aquifer subsidence

In the VG aquifer, we have analyzed the influence of the percentage of clay and silt (in the surrounding area of the piezometer) on the historical subsidence rate and the linear behaviour of the subsidence, assessed in term of the R^2 of the regression models.

Fig. 13a shows the relationship between the percentage of fine-grained material and the historical subsidence rate and Fig. 13b the coefficient of determination obtained for the best approach in each piezometer vs the percentage of clay and silt. In general, a higher percentage of fine-grained material is related to a lower subsidence rate but the correlation of this relationship is poor ($R^2=0.24$). On the other hand, higher coefficients of determination are related with a more linear behaviour between hydraulic heads and subsidence, which is observed for the cases with lower percentage of clay and silt. Note that, in general, the relationship between the percentage of fine-grained material and the coefficients of determination of the linear models has a good correlation (R^2 higher than 0.8).

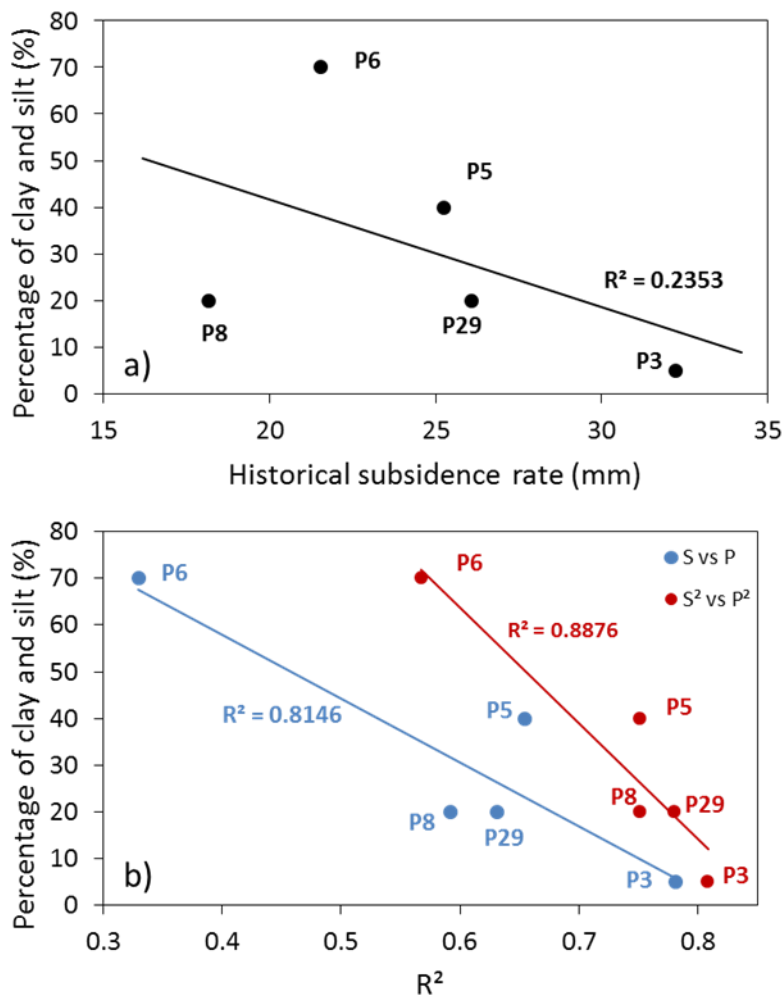


Fig. 13. Relationship between the percentage of clay and silt and the historical subsidence rate (a) and between the correlation coefficient obtained for the two best linear regression model [$S=a.P+b$; $S^2=a.P^2+b$] (b) (from Collados-Lara et al., 2020)

5.2 Impacts of climate change on precipitation, temperature, and droughts

We considered four options to define the most representative future scenarios by applying different ensembles of potential scenarios deduced from the available climate models in the AG basin (see section 4.2.3). In terms of future temperature statistics, the ensemble scenarios defined with the lumped approach (Fig. 14) show practically the same increment in monthly means. The standard deviation estimated using delta change approaches are quite similar to the historical, but both ensembles defined by applying bias correction show significantly lower values.

In terms of future precipitation statistics, almost the same reduction in future mean values are predicted by all the ensembles for every month (Fig. 14). The standard deviation of the future precipitation predicted using the delta change approaches are more similar to the historical (as for temperature variable) than those defined by applying bias correction, whose values are significantly lower. The scenarios under the same approach provide very similar statistics. The average changes predicted using the four ensembles of scenarios are around -27 % in precipitation and + 32 % in temperature.

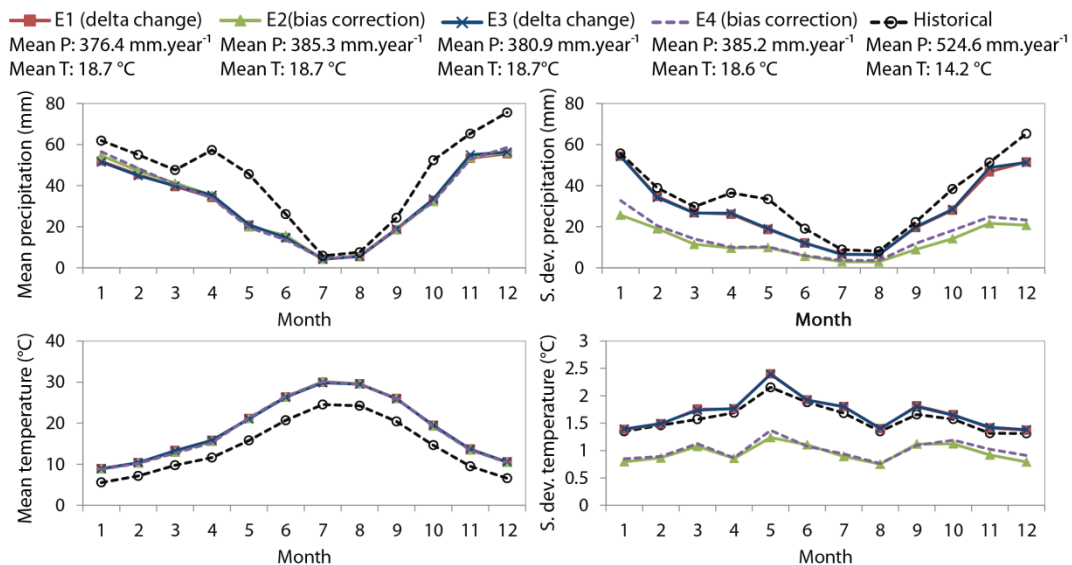


Fig. 14. Mean and standard deviation of future precipitation and temperature series obtained by the four ensemble options (E1, E2, E3, and E4) (from Collados-Lara et al., 2018a).

The future ensemble precipitation scenarios were also analysed in terms of drought statistics (Fig. 15). All four ensembles predict considerable increases in length, magnitude and intensity of droughts. The hypothesis assumed to define the ensembles (equifeasible or non-equifeasible) is higher in the bias correction approach.



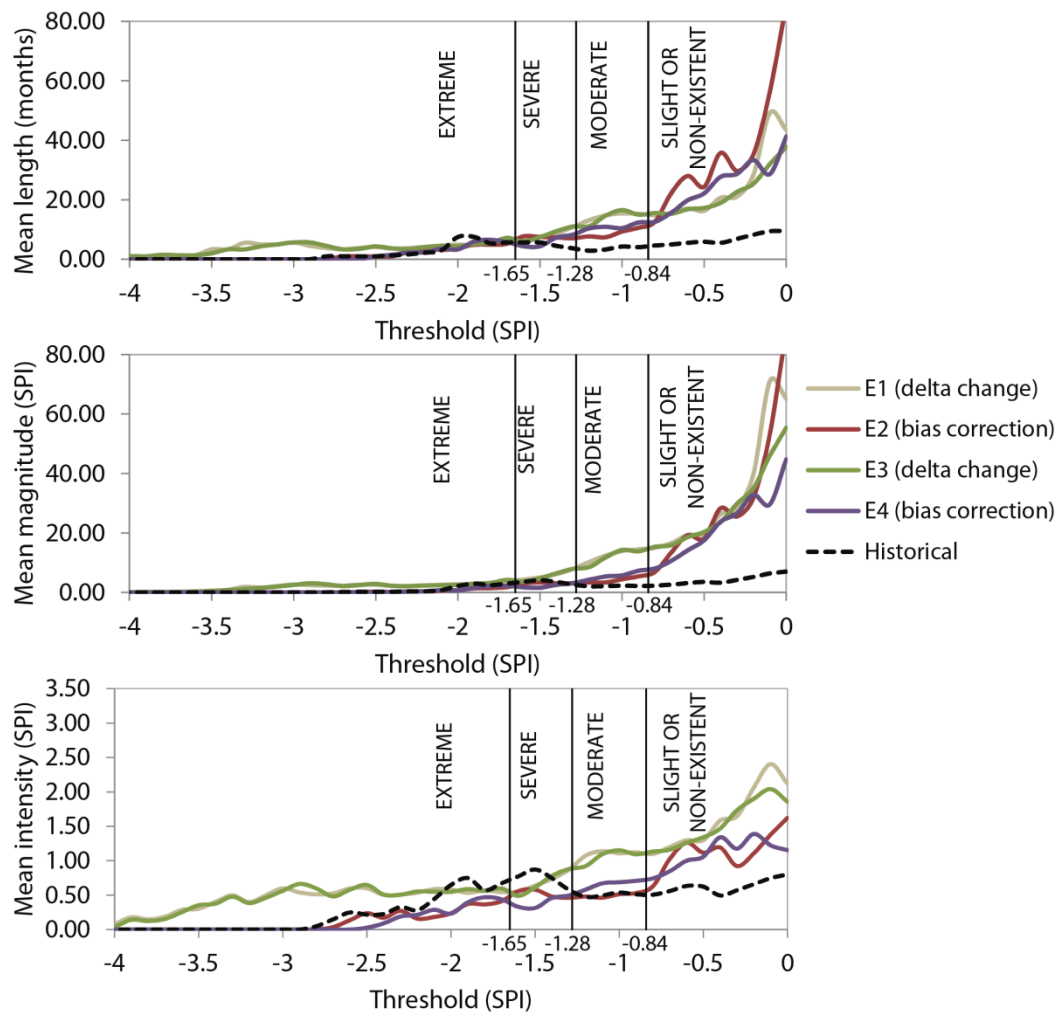


Fig. 15. Drought statistics of future precipitation series obtained by the four ensemble options (E1, E2, E3 and E4) (from Collados-Lara et al., 2018a).

5.3 Impacts of climate change on hydraulic head and subsidence

In the case of the VG aquifer we used an ensemble of different projections generated by using the bias correction approach, the first and second moment correction and the nine considered RCMs. Note that uncertainty related to correction approaches is low compared to the uncertainty related to RCMs. The global lumped hydraulic head drawdowns in the VG aquifer are obtained by applying the Scott approach (Scott, 2011). The maximum lumped drawdown obtained in the future is 3.3% greater than the one obtained in the historical period. This relative change is employed to apply a delta change to correct the historical drawdowns in the selected head observation wells (See Fig. 12) obtaining for the future period the values represented in Fig. 16.

The propagation of the impacts of the potential future CC scenario on subsidence (Fig. 16) shows important increment of the maximum subsidence (55,3 and 52,7% for the models $[S=a.P+b]$ and



$[S^2=a.P^2+b]$ respectively) with respect to the historical maximum observed values. The higher increment of the maximum subsidence (68,3 and 65,7% for the models $[S=a.P+b]$ and $[S^2=a.P^2+b]$ respectively) with respect to the historical maximum observed values occurs in the piezometer 5, which is located in the western area where the percentage of clay is 40%.

In terms of mean subsidence (see Fig. 17) the mean increment of subsidence is 4,1 and 4,5 mm for the models $[S=a.P+b]$ and $[S^2=a.P^2+b]$ respectively. The piezometer with the higher increment of mean subsidence is the number 3 with 5,4 and 5,9 mm for the models $[S=a.P+b]$ and $[S^2=a.P^2+b]$ respectively. This piezometer shows the higher variability of subsidence in the historical and future period and has the lower content of clay and silt.

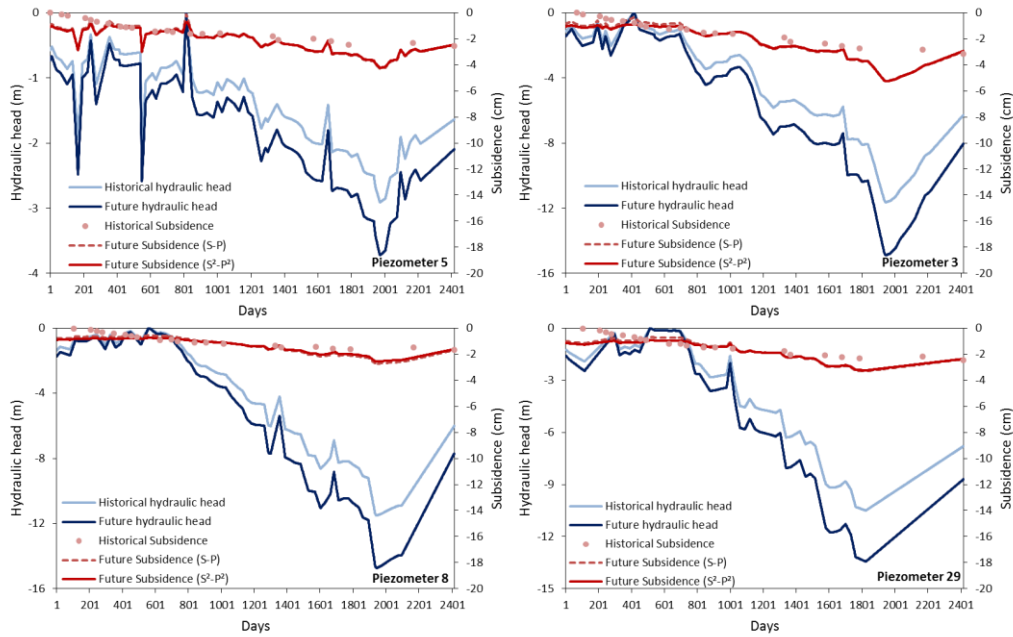


Fig. 16. Historical and future subsidence and hydraulic head for the two best linear regression model $[S=a.P+b; S^2=a.P^2+b]$ (from Collados-Lara et al., 2020).

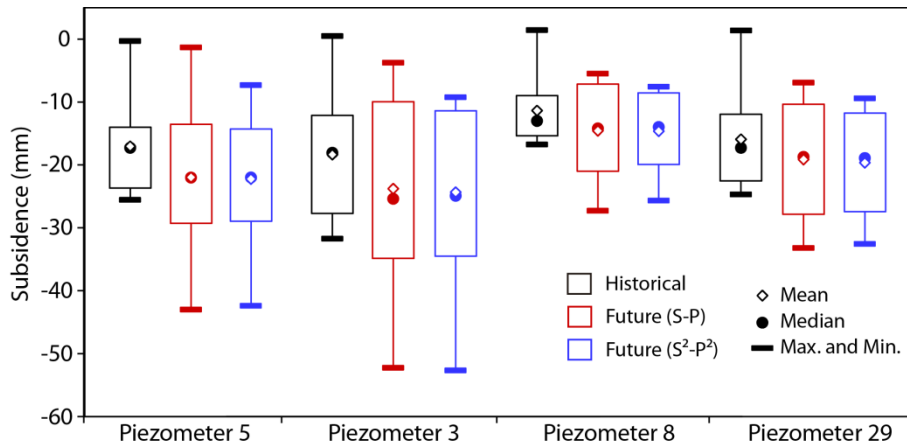


Fig. 17. Historical and future subsidence for the two best linear regression model $[S=a.P+b; S^2=a.P^2+b]$ (from Collados-Lara et al., 2020).



The analyses of results show that, assuming a business as usual management scenario, the impacts of CC on the subsidence would be very significant for the case study. The mean increment of the maximum subsidence rates in the considered wells for the future horizon (2016-2045) and the scenario RCP 8.5 is 54%. In order to avoid undesirable consequences/risks some adaptation strategies should be applied to control and minimize land subsidence caused by groundwater withdrawals.

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