Establishing the European Geological Surveys Research Area to deliver a Geological Service for Europe

Deliverable 6.3

Pilot description and assessment reports work package 6

Contribution partners:

IGME, BRGM, GEUS, SGSS, HGI

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Version	Final version
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1 INTRODUCTION

The pilot description reports are compiled in this document (as a single D6.3 document) but are separate reports from the individual pilots. Reports can include more than one pilot from the same country and present work performed in other work packages (WPs) together with the work done in work package 6 in term of the analyses of adaptation strategies. Hence, there is only one pilot report for each pilot although the pilot appears in several TACTIC work packages.

The hereby presented document include all the pilot assessments reports and results performed that includes adaptation strategies analyses (WP6). It includes pilots focused on the assessments of impacts on groundwater and associated surface water conditions (WP3), including local and regional scale case studies (Avre, Storåen-Sunds, Segura, Upper Guadiana) and also coastal aquifer pilots (WP5) related with sea water intrusión (Plana de Oropesa-Torreblanca and Marecchia).

The pilot assessment reports are ordered alphabetically and organized into separate documents within D6.3 because the individual reports are used for documentation toward local stakeholders.

TACTIC GROUNDWATER

GeoERA

Establishing the European Geological Surveys Research Area to deliver a Geological Service for Europe

Deliverable 3.2 & 6.3

PILOT DESCRIPTION AND ASSESSMENT

Avre Basin (France)

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Geological Survey of France (BRGM)

Géosciences pour une Terre durable
brgm

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	D3.2 & D6.3
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Deliverable name	Pilots description and assessment report for groundwater-surface water/ Pilots description and assessment report for adaptation
Work package	WP3 & WP6
Lead WP/Deliverable beneficiary	GEUS (WP3), IGME (WP6)
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Version	Version 2
Date	23/02/2021

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LIST OF ABBREVIATIONS & ACRONYMS

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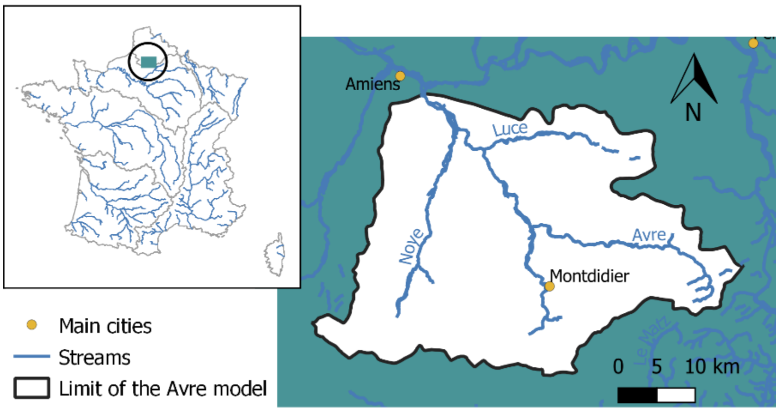
1 EXECUTIVE SUMMARY

Pilot name	Avre	
Country	France	
EU-region	North Western Europe	
Area (km^2)	1 294 km^2	
Aquifer geology and type classification	Chalk ; Porous and fissured aquifer	
Primary water usage	Irrigation and drinking Water	
Main climate change issues	The chalk aquifer is the main water resource used for drinking water supply and irrigation in the Somme river basin. Groundwater in this basin is in strong interaction with rivers, pond and Wetland, which represent outlets of the water table. Although this basin experienced historical groundwater floods in 2001, some of its sub-bassin, particularly the Avre sub-basin (located in the left bank of the Somme river) has known several drought periods in the past, which seem to be renewed with increased frequency in recent years. Extreme events (flood and drought) are predicted to increase under future climate, so it is important to assess the effects of climate change on the hydrological extreme and to design and evaluate adaptation measures in relatioship with water ressources managers and all groundwater users.	
Models and methods used	Integrated Hydrological model (Numerical model, time series analysis …)	
Key stakeholders	Water Agency; agricultural profession of Somme valley; AMEVA (territorial Public establishment), DDT 80 (water police)	
Contact person	Nadia Amraoui, BRGM French Geological survey, n.amraoui@brgm.fr	

The Avre pilot is located in the north of France in the Somme department. The Cenomanian-Turonian chalk represents the major geological structure in this basin. Chalk aquifer forms the main water resource for drinking water supply and irrigation uses. The groundwater is in strong interaction with rivers, pond and Wetland, which represent the water table outlets. In the past two decades, the Avre basin has experienced tensions over water resources due to growing water demand and a deficit in groundwater recharge due to several drought episodes. An intensification of extreme events is expected due to global warming, so it is important to assess the effects of climate change on groundwater resources under different warming scenarios, and to assess the relevance of adaptation measures to cope with the climate change effects.

As part of the TACTIC project, a study of climate change impacts on the chalk aquifer recharge, groundwater level and river discharge was performed. Moreover, two adaptation scenarios were tested and their effects on groundwater resources were assessed. The assessment of climate change impacts on water resources is carried out using four selected TACTIC standard climate change scenarios and the regional hydrological model of the Somme River basin developed with the MARTHE computer code from BRGM. MARTHE allows the simulation of flows in aquifers and in river networks, including climatic and human influences, from climatic variables taken as inputs for the model. The selected TACTIC standard climate change scenarios represent an increase of global annual mean temperature by +1 and +3 degrees compared to the reference period (1981-2010), under wet and dry precipitations conditions. The four TACTIC datasets representing the future climate conditions are generated by applying the delta change factors to current local dataset of precipitation, evapotranspiration and temperature. It supposes similar evolutions of climatic variables for the current and the future climate. Moreover, changes in groundwater abstraction in the future climate scenarios are not considered. The impact is quantified by comparing simulated results obtained with the data provided by each TACTIC standard scenario to those simulated on the reference period (1981–2010). Annual changes in mean groundwater recharge and mean groundwater levels are analysed and the seasonal responses of the system are assessed.

Two adaptation scenarios were defined based on a reduction in water demand for drinking water supply and irrigation. Their impacts on groundwater levels and river flows were assessed. The first scenario SA1 assumes a 20% reduction in withdrawals for drinking water supply, and the second scenario SA2 assumes a 30% reduction in irrigation withdrawals during irrigation period. The Somme model was used to simulate the groundwater level and river flow over the 1981-2010 period under the two adaptation scenarios. The results were compared to the reference simulation (without abstractions reduction) to assess the effects on the groundwater level and the river flow.

For the Avre basin, dry TACTIC climate change scenarios with lower precipitations show higher impacts on the groundwater conditions than wet scenarios with higher precipitations. Such results are due to a global increase of potential evaporation whatever the considered scenarios, meaning much less effective rainfall available for groundwater recharge for dry scenarios. Dry scenarios show longer drought periods with decreases of groundwater levels during all the years that can reach about -6 m (on the plateaus) in periods of lower water table (e.g. in summer) for the worst scenario (i.e. the 3°C dry scenario). River discharges decreases throughout all the year with -20 % of the river base flow expected for the 3°C dry scenario with respect to the 1981-2010 period. The wet scenarios show increases of groundwater levels (reaching +1.5 m locally) and river discharges (+ 9% maximum) during winter. Absolute changes are nevertheless lower for the wet scenarios than for the dry scenarios.

Concerning the tested adaptation scenarios, the scenario assuming a drinking water withdrawals reduction has a local impact on groundwater level, at and around wellfield. On the other side, the scenario assuming an agricultural abstractions reduction has an impact on groundwater level over a large area in Santerre plateau and Avre basin upstream where agricultural boreholes density is greater.

At the territorial level, the development of adaptation scenarios to mitigate climate change need to be done with territory actors. A participative approach involving the main actors of the territory (socio-economic actors, institutional users, etc.) and mobilizing foresight instruments should be privileged.

2 INTRODUCTION

Climate change (CC) already have widespread and significant impacts in Europe, which is expected to increase 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. In order 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 infra structure 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 present document reports the TACTIC activities in the pilot Avre River Basin located in the Northern France, in the Picardie province. Climate change effects groundwater levels, river flow is analysed, and the relevant of two adaptation scenarios is discussed.

3 PILOT AREA

The chalk aquifer forms the main water resource of the Somme administrative county located in the north of France. This unconfined aquifer is directly connected to the Somme River and its associated tributaries. The Avre River basin corresponds to the most impacted sub-basin of the Somme River basin in terms of groundwater abstractions, mainly for supplying irrigation demand and drinking water needs (Amraoui et al., 2014). Since the 90s, the overexploitation of the underlying aquifer has resulted in a decrease of the river discharges over this basin, leading to conflicts between the different usages (Arnaud, 2017). Moreover, the majority of the climate models predict an increase of the severe drought frequency over this sub-basin in the future, which could reinforce this problem. We intend in this project to evaluate the potential impact of climate change scenarios and to assess the effects of some adaptation scenarios on the water resources of this pilot area.

3.1 Site description and data

3.1.1 Location and extension of the pilot area

The case study corresponds to the Avre River basin and covers an area of about 1294 km^2 located in the north of France (cf. Figure 1). It corresponds to the main affluent of the Somme River and its sub-basin is located on the left bank. The total length of the river is 60 km. At the upstream, its path crosses tertiary terrains and then go on through the chalky plateau of the Santerre until reaching the Somme River.

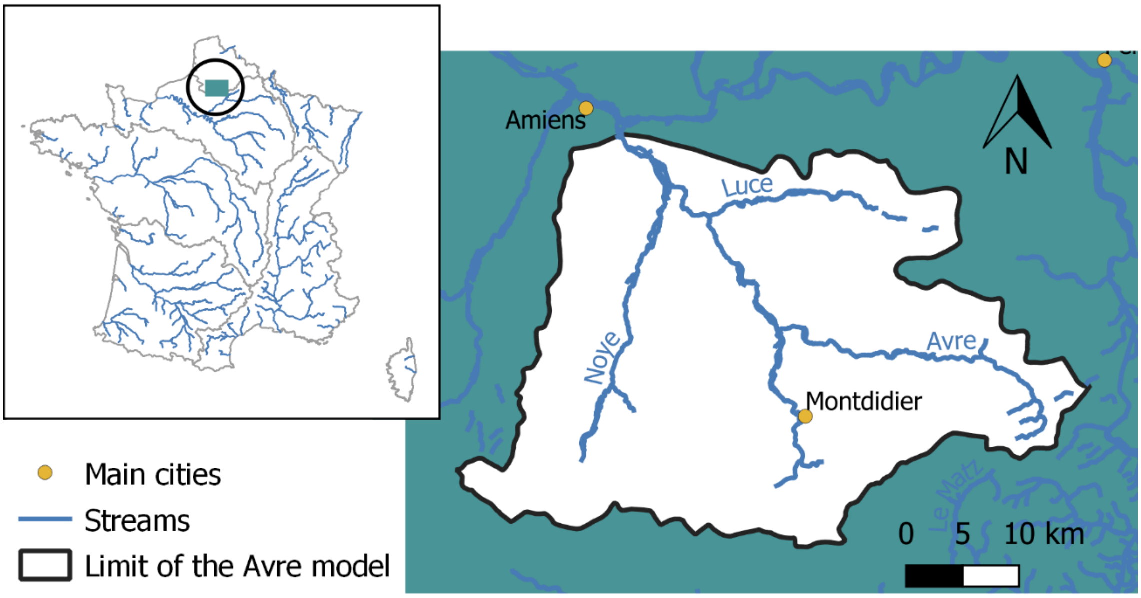


Figure 1: Location of the pilot area

3.1.2 *Geology/Aquifer type*

According to the BDLISA French hydrogeological reference system (https://bdlisa.eaufrance.fr/), the Cenomanian-Turonian chalk of the Somme River watershed represents the major geological structure of the Avre River sub-basin (green areas in Figure 2). It extends over the whole basin while some tertiary terrains covers the south and the east of the basin. A quaternary upper layer with a 1-m thickness (Ypresian period) is also present in the southeast of the basin. Ancient to recent alluviums characterized the downstream of the Avre riverbed.

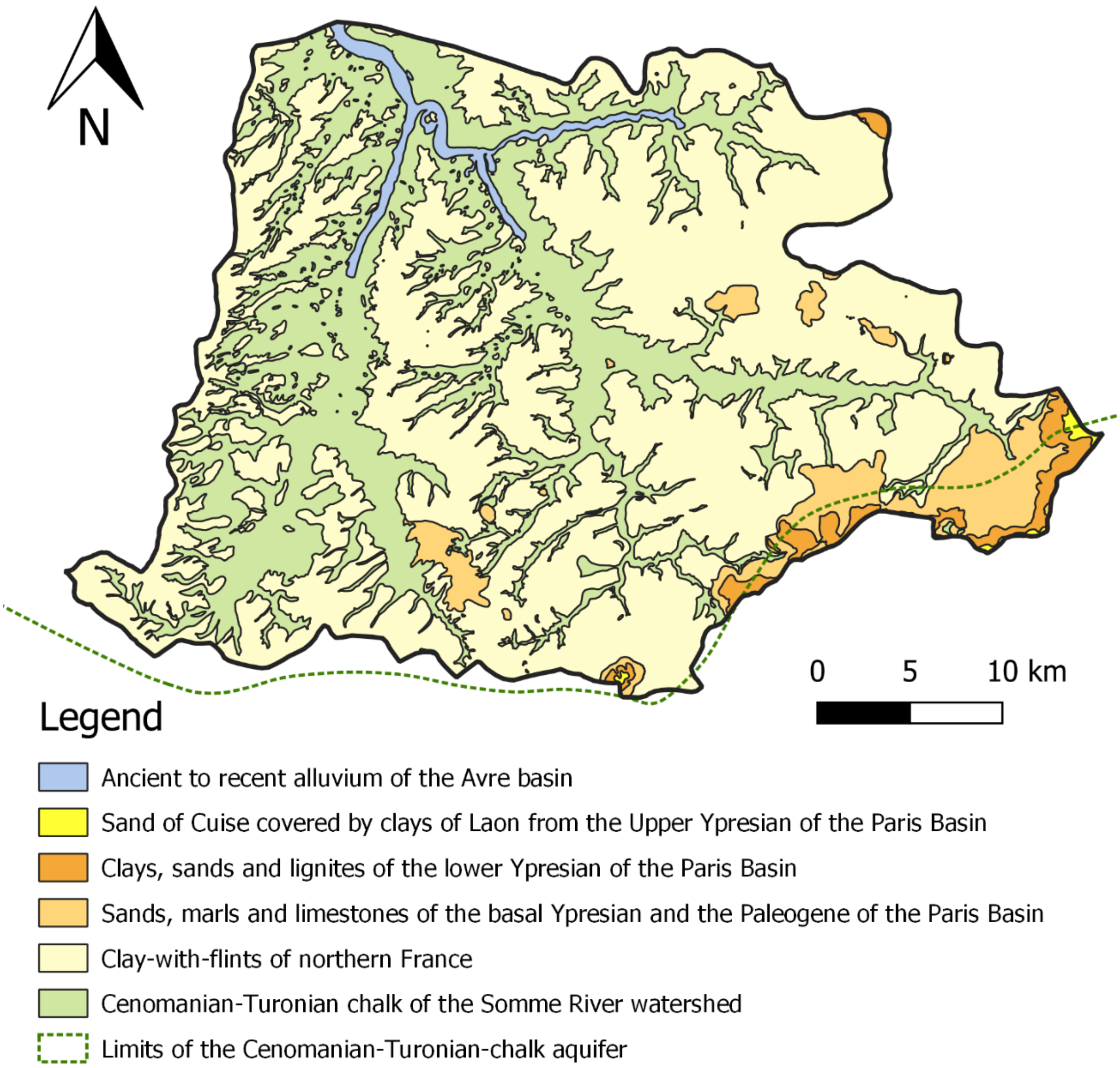


Figure 2: Groundwater bodies of the Avre River basin classified by geological type as defined in the BDLISA (database of aquifer system delineation) French hydrogeological reference system (https://bdlisa.eaufrance.fr/).

The upper chalk cretaceous formation is an extending and powerful reservoir fed by effective rainfall falling over the basin. The water table is unconfined. Groundwater flows toward the valley through fissures generally developed in the upper part of the chalk (in the tertiary terrains) and then feeds the river in the bottom of the valley. An underlying flow occurring in the coarse alluviums of the River characterized the bottom of the valley.

3.1.3 Topography and soil types

The topography varies from 23 m.a.s.L at the downstream of the Avre River to a maximum of 189 m.a.s.l. reached in the southwest of the basin (Figure 3). The area is predominantly flat with shallow valleys. The soils in the basin mainly belong to the Luvisols group according to the FAO classification (Figure 4). Alluvial plains are characterized by Regosols, Histosols and Fluvisols. Others such as Cambisols are also found in the basin.

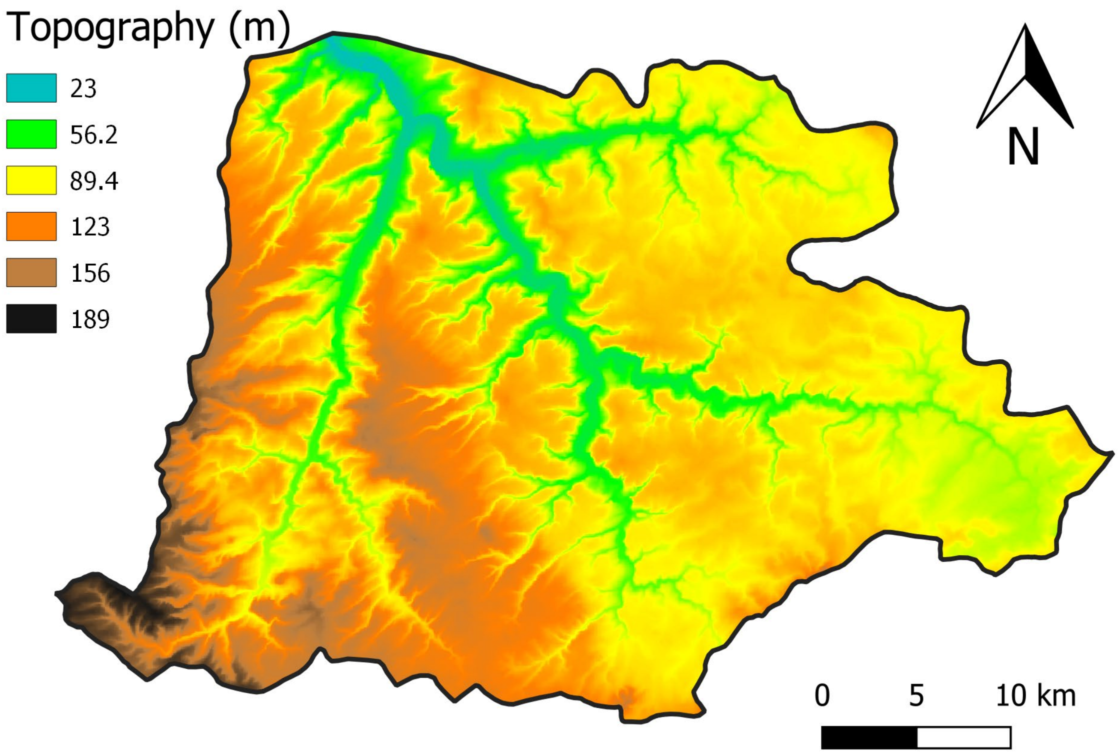


Figure 3: Topography of the Avre River basin from the BDALTI Digital Elevation Model (IGN) (25-m resolution)

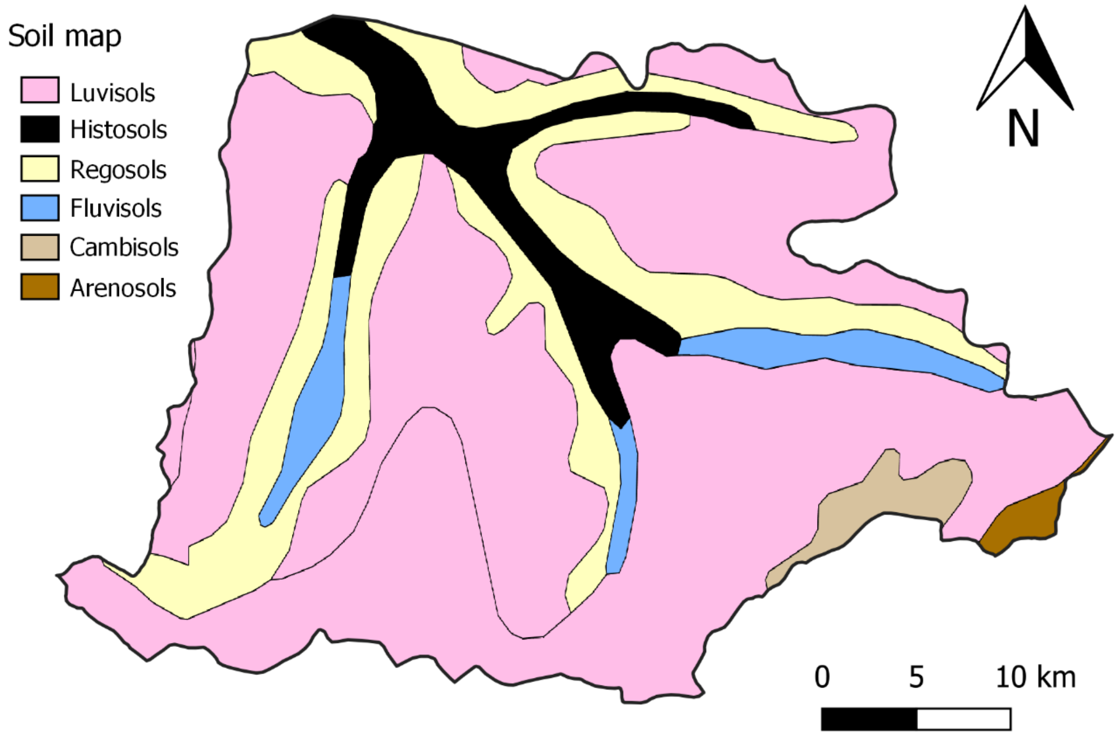


Figure 4: Soil map from BDGSF (Geographical Database of the French Soils)

3.1.4 Surface water bodies

The main affluents of the Avre River are, from upstream to downstream, the Trois-Doms River (18 km), the Noye River (26 km) and the Luce River (16 km). All these rivers drain the chalk aquifer during both dry and humid periods. Three gauging stations are available to monitor the river discharges of the Noye River and the Avre River. They are described in Table 1 and time series are shown in Figure 6.

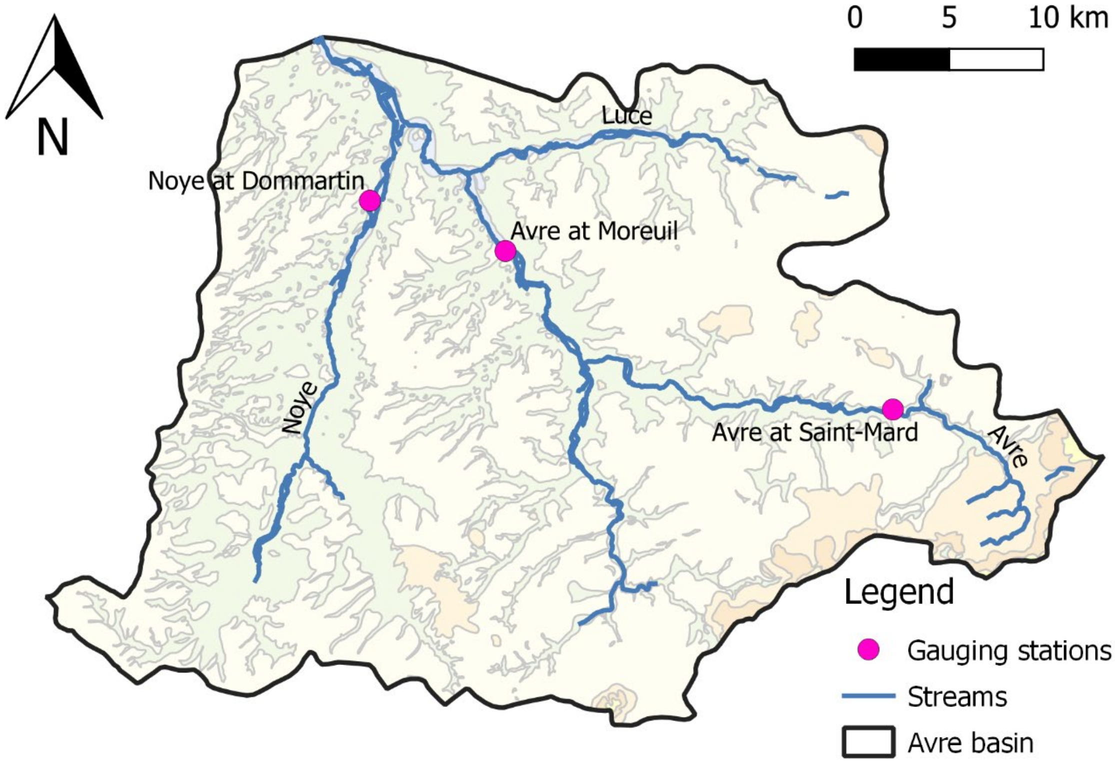


Figure 5: Main rivers and gauging stations of the Avre basin.

Table 1: Statistics of the flow gauges

Flow gauges	Average Q (m3/s)	Period	Surface (km^2)
E6406010	2.2	1968-2018	624
E6406035	0.3	2001-2018	113
E6407540	1.3	2010-2018	311

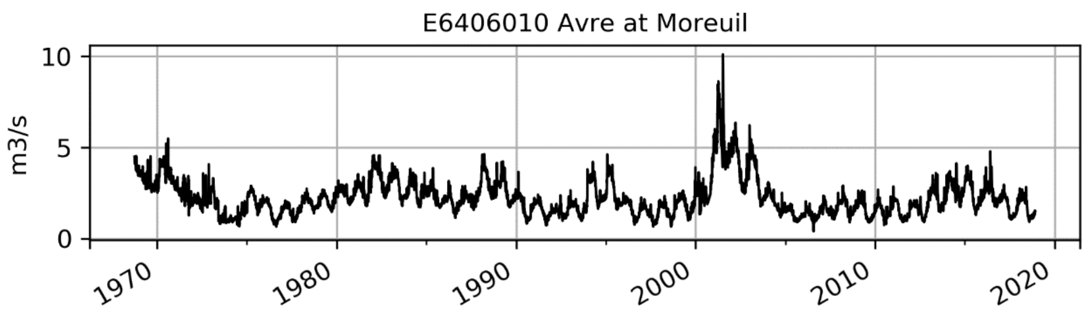


Figure 6: Time series of river discharges for the gauging station located at Moreuil.

3.1.5 Hydraulic head evolution

Figure 7 represents the spatial distribution of the hydraulic head observations and Figure 8 shows three examples of hydraulic head evolutions that are representative of the chalk aquifer behaviour. The hydraulic head evolution of the chalk aquifer is characterized by pluri-annual cycles superimposed with inter-annual cycles.

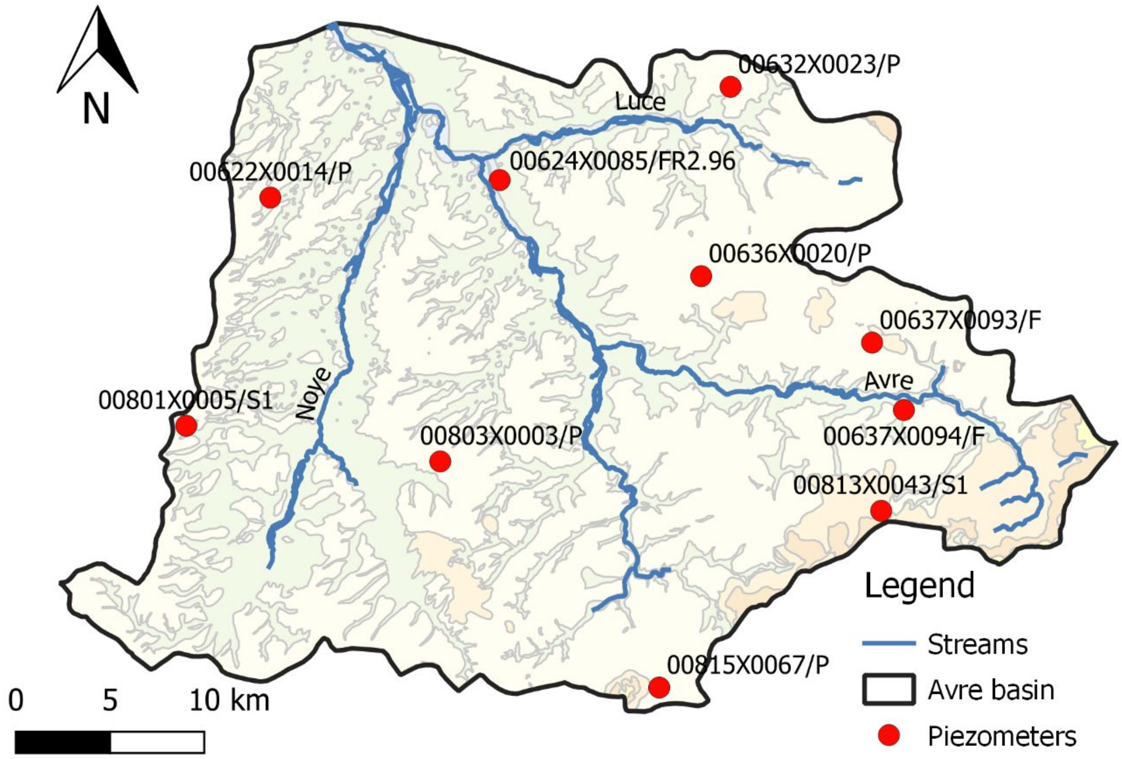


Figure 7: Spatial distribution of the available piezometers

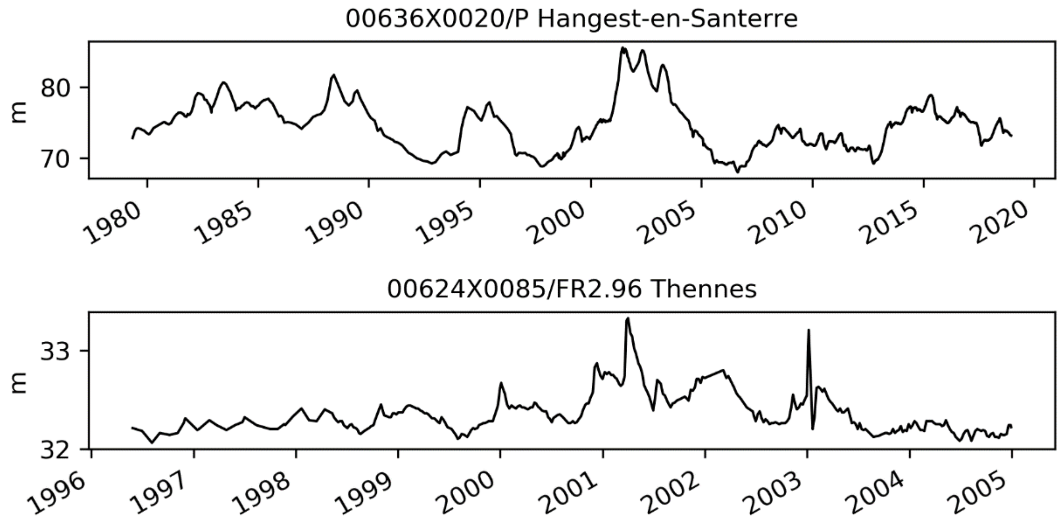


Figure 8: Time series of hydraulic head for two piezometers.

3.1.6 Climate

The climate condition of the Avre basin is semi-oceanic and temperate. Dominant winds come from the coast. According to the SAFRAN meteorological reanalyses (Vidal et al., 2010), the annual mean rainfall is equal to 700 mm/year in the 1958-2018 period. The mean annual temperature is 9°C, oscillating between a maximum daily mean temperature of 18.5 °C in July and a minimum of 1.3 °C in January. The mean potential evapotranspiration is 665 mm/year.

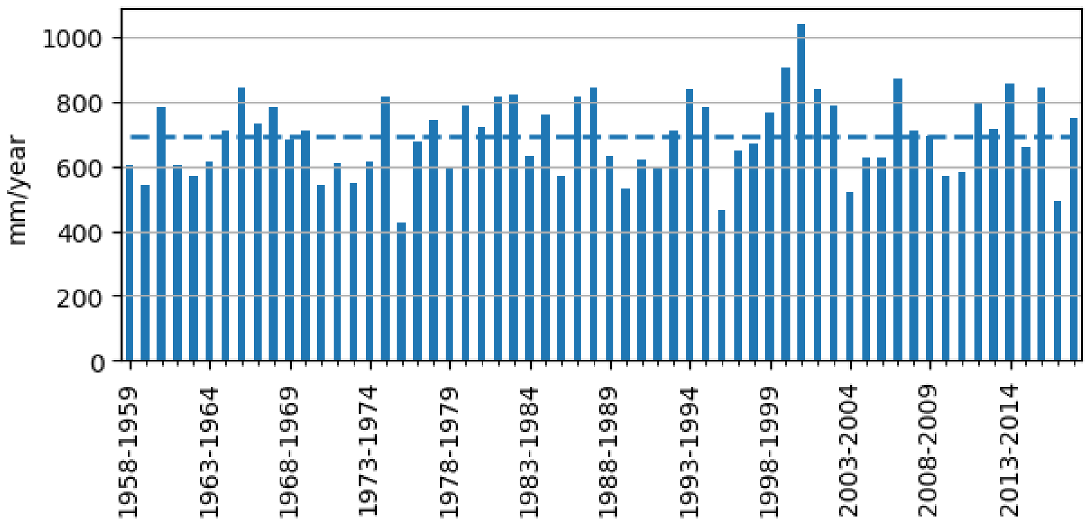


Figure 9: Time series of the precipitation (mm/year). The dashed line corresponds to the mean precipitation.

3.1.7 Land use

According to the Corinne Land Cover database (cf. Figure 10), agriculture constitutes the major part of the land use of the Avre River basin. Forests are scattered and essentially constituted of oaks, hornbeam and lime trees. Swamps are also present in some locations.
The Avre basin is classified as a wetland of international importance according to the RAMSAR convention since the beginning of 2018.

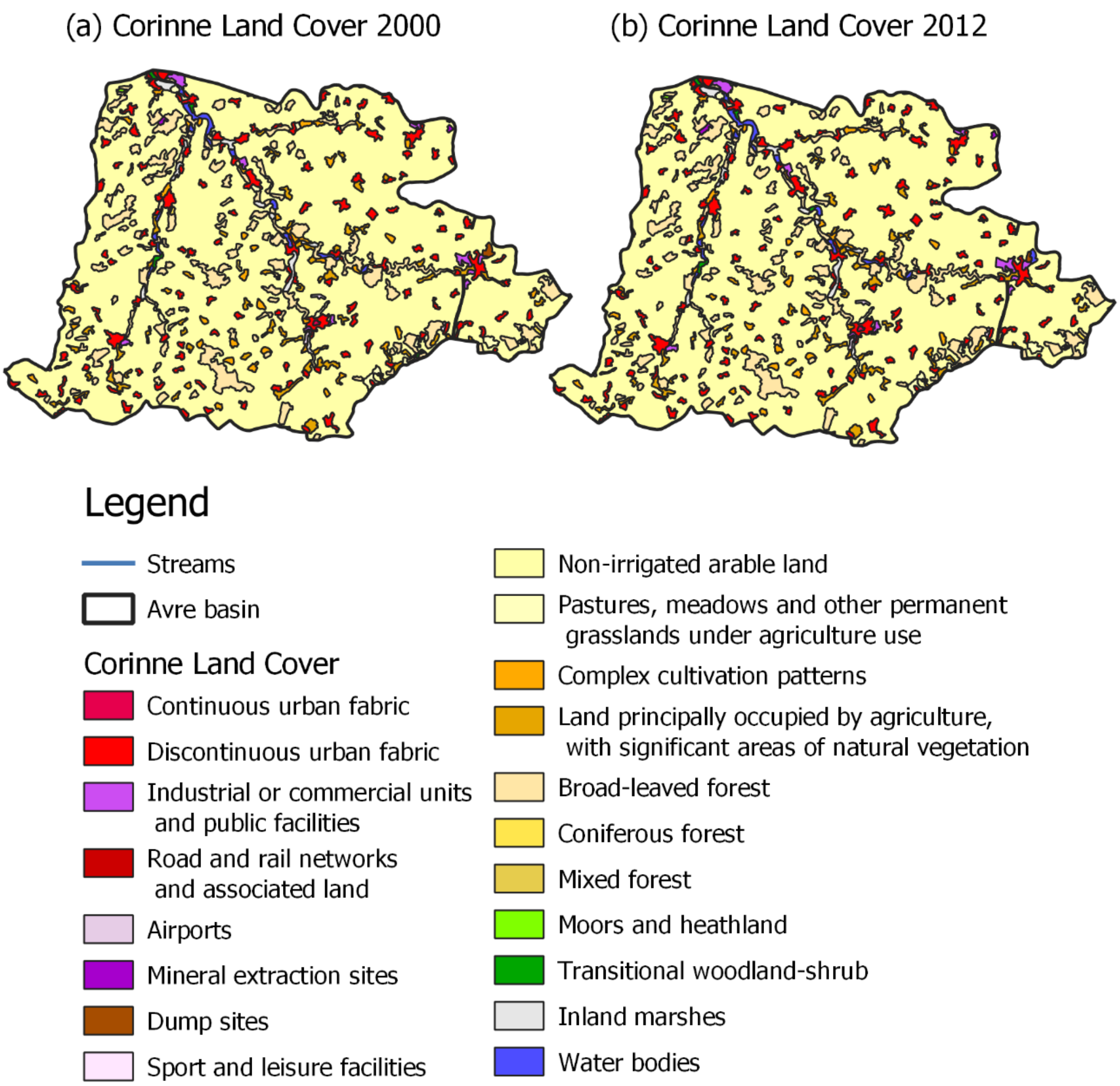


Figure 10: Land use maps from CORINE (2000 and 2012)

3.1.8 Abstraction/Irrigation

The chalk aquifer is the only groundwater resource of the Avre basin. Three usages characterize this resource: drinking water with 39 wells located for most of them in the Noye and Trois-Doms river basins, agriculture (irrigation) in 83 well, and in a lesser extent industry with four wells.

Agriculture and drinking water are the biggest water consumer. In 2003, 49% of the water use corresponds to agriculture and 43% corresponds to drinking water. During the period of irrigation, these percentages evolve to 73% and 24% respectively.

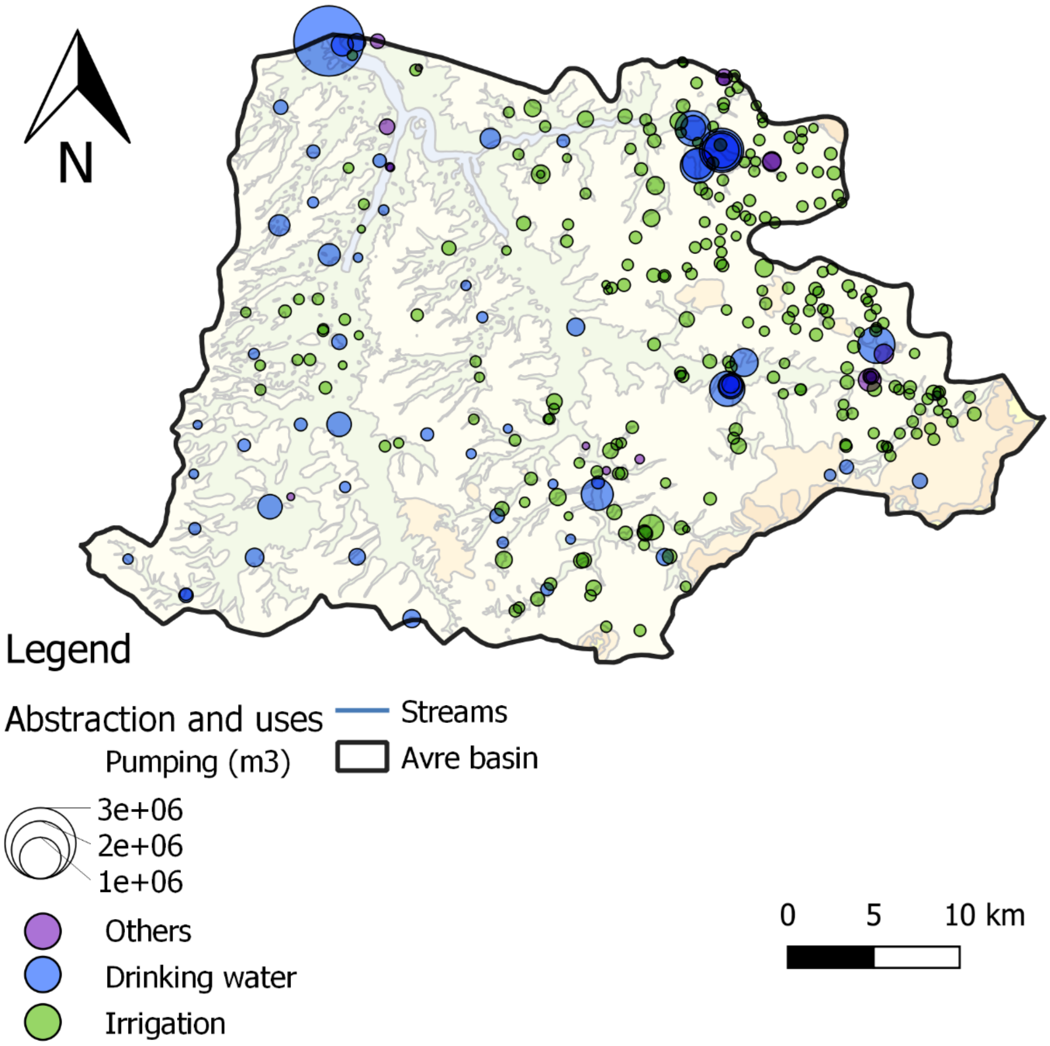


Figure 11: Spatial distribution of the pumpings classified by usages.

3.2 Climate change challenge

The Avre pilot site is located in the North-western Europe region where an increase of precipitation in winter is expected in accordance with the EEA map (Figure 12)
At France scale, recent work based on CMIP5 (Coupled Model Intercomparison Project) models simulations using several climates models, emissions scenarios and differents downscaling methods (Dayon 2015; Jouzel et al., 2014) shows an expected increase in precipitation in winter and decrease in summer. General increase in mean annual air temperature is expected that is

more pronounced in summer. Results of national Climsec project indicate a continuous increase in soil dryness over the 21-century (Soubeyroux et al. 2011)
Previous study on the hydrological climate change impact in 2 basins located in the northern France show a marked tendency towards a decrease of the water resource in the rivers and aquifers (on average in 2050 about −14 % and −2.5 m, respectively) (Habets et al. 2013). Hydrological impact study in Somme river basin using projection from 7 GCM and median emission scenario A1B, shown a decrease in groundwater recharge (around -18.7% average of 7 climate models) and decline in river flow expected by 2065 (Amraoui et al 2019) however, two climate models show that high water level are possible confirming the likelihood groundwater flooding risk.

The main challenge in this area is to find adaptation measures to anticipate the future climate conditions in order to better managed available water resources regarding to demands under drought period. In addition, as groundwater Chalk permanently support Rivers and ponds in this area, it is important to ensure a good status in these ecosystems.
In the study area, the main expected issues due to climate change are related to the groundwater droughts.

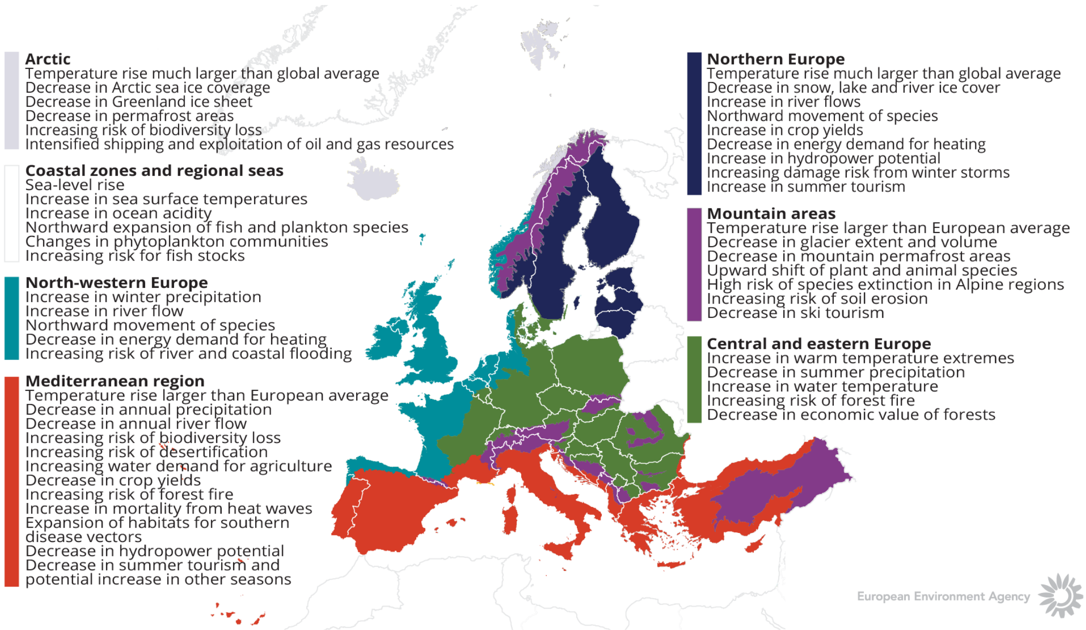


Figure 12 : Key observed and projected impacts from climate change for the main regions in Europe (European Environment Agency)

4 METHODOLOGY

The assessment of climate change effects on the groundwater resource in the Avre River basin uses the TACTIC standard climate change scenarios and the integrated hydrological model developed with the MARTHE computer code (see TACTIC toolbox reference). The ESTHER software allows to analysing droughts from output time series. Moreover, two adaptation scenarios were defined and their effects on both the groundwater levels and the river discharges were assessed by using the Somme hydrological model.

4.1 Climate data

In this study, only TACTIC standard climate change dataset are used to assess climate change impact on groundwater resources for the Avre pilot under +1 and +3 degrees global warming scenarios considering low and high precipitation conditions.

4.1.1 TACTIC Standard Climate Change Scenarios

The TACTIC standard scenarios are developed based on the ISIMIP (Inter Sectoral Impact Model Intercomparison Project, see www.isimip.org) datasets. The resolution of the data is 0.5°x0.5°C global grid and at daily time steps. As part of ISIMIP, much effort has been made to standardise the climate data (a.o. bias correction). Data selection and preparation included the following steps:

1. Fifteen combinations of RCPs and GCMs from the ISIMIP data set where selected. RCPs are the Representative Concentration Pathways determining the development in greenhouse gas concentrations, while GCMs are the Global Circulation Models used to simulate the future climate at the global scale. Three RCPs (RCP4.5, RCP6.0, RCP8.5) were combined with five GCMs (noresm1-m, miroc-esm-chem, ipsl-cm5a-lr, hadgem2-es, gfdl-esm2m).
2. A reference period was selected as 1981 – 2010 and an annual mean temperature was calculated for the reference period.
3. For each combination of RCP-GCM, 30-years moving average of the annual mean temperature where calculated and two time slices identified in which the global annual mean temperature had increased by +1 and +3 degree compared to the reference period, respectively. Hence, the selection of the future periods was made to honour a specific temperature increase instead of using a fixed time-slice. This means that the temperature changes are the same for all scenarios, while the period in which this occur varies between the scenarios.
4. To represent conditions of low/high precipitation, the RCP-GCM combinations with the second lowest and second highest precipitation were selected among the 15 combinations for the +1 and +3 degree scenario. This selection was made on a pilot-by-pilot basis to accommodate that the different scenarios have different impact in the various parts of Europe. The scenarios showing the lowest/highest precipitation were avoided, as these endmembers often reflects outliers.
5. Delta change values were calculated on a monthly basis for the four selected scenarios, based on the climate data from the reference period and the selected future period. The

delta change values express the changes between the current and future climates, either as a relative factor (precipitation and evapotranspiration) or by an additive factor (temperature).
6. Delta change factors were applied to local climate data by which the local particularities are reflected also for future conditions.

For the analysis in the present pilot the following RCP-GCM combinations were employed:

Table 4.2. Combinations of RCPs-GCMs used to assess future climate

		RCP	GCM
1-degree	"Dry"	6.0	hadgem2-es
	"Wet"	4.5	ipsl-cm5a-lr
3-degree	"Dry"	6.0	hadgem2-es
	"Wet"	8.5	miroc-esm-chem

4.2 Hydrological modelling of climate change

The regional hydrological model of the chalk aquifer of the Somme Basin (Somme model) has been developed in its first version in 2002 (Amraoui et al., 2002) and completed, updated and recalibrated since then (Amraoui, 2004; Amraoui et al., 2014; Amraoui and Seguin, 2012; Arnaud, 2017). The Somme model uses the finite difference groundwater modelling approach implemented in the MARTHE computer code to compute the groundwater evolution of the chalk aquifer (Thiéry, 2020). MARTHE allows the simulation of flows in aquifer systems and river networks, including climatic and human influences. MARTHE implements the GARDENIA lumped parameter hydrological model to compute from surface water balance from climate data (i.e. rainfall and potential evapotranspiration (PET)), which includes surface runoff and groundwater recharge. More details on MARTHE functionalities are available in the Tactic Toolbox.

The assessment of climate change effects on the groundwater resource rely on:
1) The four selected TACTIC climate change scenarios representing an increase of global annual mean temperature by +1 and +3 degrees compared to reference period (1981-2010) under wet and dry conditions
2) The Somme model simulating groundwater conditions over the current period.

The application of delta change factors to the current local dataset of precipitation, PET and temperature generated the four TACTIC climate change scenarios. This method assumes no changes in the evolution of climatic variables for the current and the future climates.

The groundwater recharge, piezometric head and river discharge evolutions were simulated over the period 1958-2018 using the historical local climate data as well as the four climate projections generated from the delta change factors provided by TACTIC. In total, five simulations are available: four Tactic future simulations corresponding to the four Tactic standard future scenarios, and one historical simulation. Future climate simulations assume no changes in groundwater abstractions. Only the results of the 1981-2010 30-years periods are used to assess climate change impacts on groundwater and surface water resources.

4.2.1 Model description

The Somme model extends over an area of 7,400 km^2 and covers the entire hydrologic catchment of the Somme basin, half of the Southwestern Authie basin in its North, and half Northwestern of the Bresle basin in its Southwest (Amraoui et al., 2019). This model integrates the data described in paragraph 3.1. The borders of the Somme River basin includes the Authie River and the Cambrésis heights to the North, the Vermandois to the East, the Noyonnais hills to the Southeast, the Bresle River to the Southwest, and the English Channel to the West (Figure 13). Figure 14 shows the location of the Avre basin in the Somme model. The Somme model includes the full extent of the Avre basin.

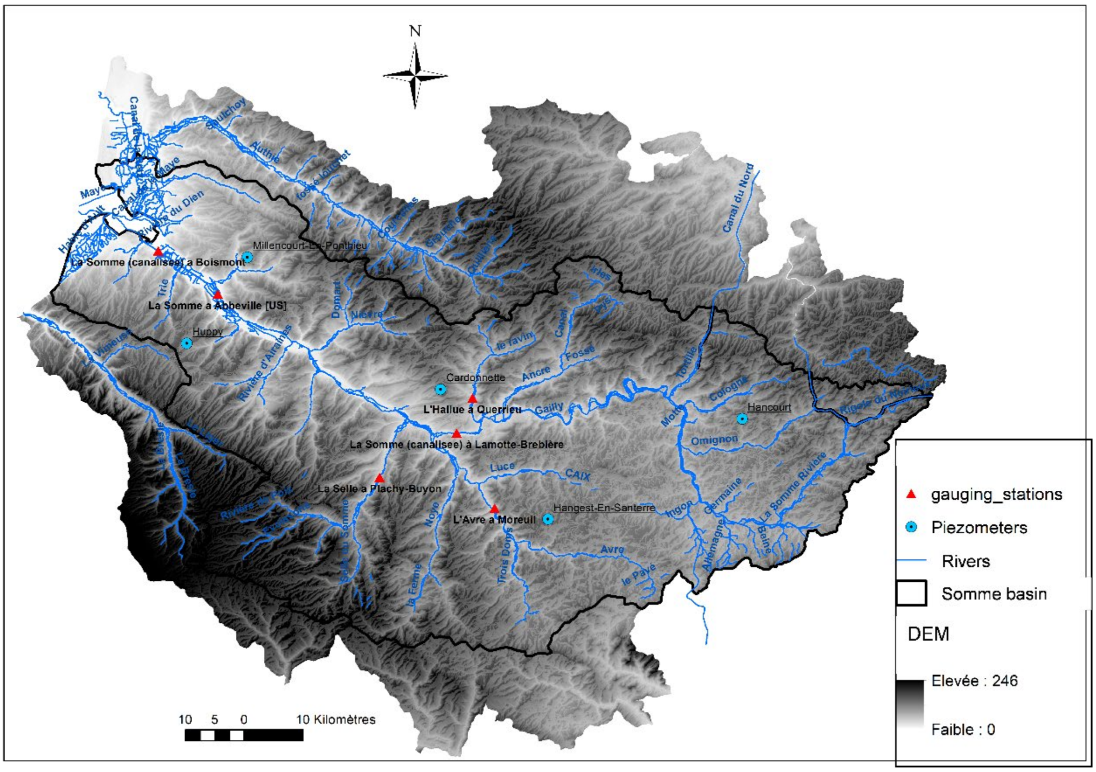


Figure 13 – Geographic map of the Somme River basin (Amraoui et al., 2019)

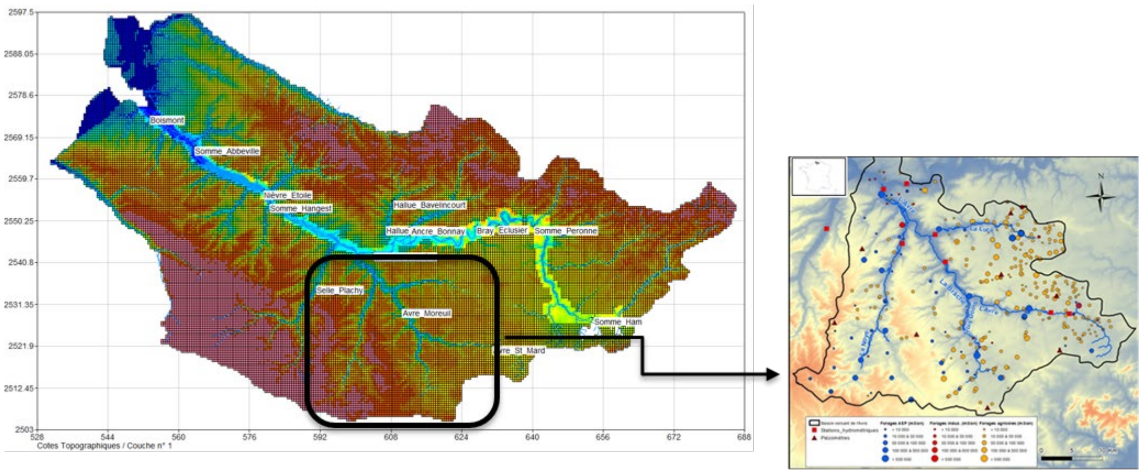


Figure 14 – Location of the Avre watershed in the Somme River basin – the black outline on the right figure represents the limits of the basin on a topographic map background

The chalky aquifer is discretized with a single layer and a computational grid of 500m x 500m resolution except in the humid valley of the Somme where the grid is locally refined down to 100m X 100m for an improved numerical discretization of the aquifer-river interactions close to the Somme river and its tributaries (Amraoui, 2004). In total, the model contains more than 66 000 computational cells. The model takes into account groundwater flow in the chalky layer, flow routing into the associated river system, and the interactions between these two sub-systems. Boundary conditions of the imposed potential type are applied to the west of the regional model and correspond to the see. Elsewhere, no flow limits are applied at the borders of the domain.

The Somme model takes into account all water withdrawals (agriculture, drinking water, industry). The model run in unsteady state conditions. It simulates the evolution of piezometric heads, stream river flows, and interactions between groundwater and surface water. The model runs with a daily time step when computing runoff and recharge and at a weekly time step when computing the groundwater flow in the aquifer system. The calibration period is 1989 - 2012 to include known observations.

The computation of the surface water balance uses spatial distributions of climate data including daily rainfall, PET, and soil parameters, using the lumped hydrological model GARDENIA. This model simulates the evolution of the piezometric heads and streamflows at each point of the river system. More details on this model are reported in Amraoui and Seguin (2012) and Arnaud (2017).

In this study, we used the 2017 version of the Somme model. In this version, the model was updated over the Avre basin with new refinement of the river grid to 100 m x 100 m, an actualisation of the withdrawal dataset over the 1989 – 2012 period, and an updated calibration of the hydrodynamic parameters (river-aquifer parameters and aquifer permeabilities).

In the frame of the TACTIC project, the model was updated over the period 1958-2018 with daily climatic data. Concerning water abstractions in aquifer and river, the acquisition of new datasets during the TACTIC project extends the withdrawal data from 1982 to 2018. Data on surface water withdrawals are available over the period 1992-2018 and over the period 1982-2018 for the groundwater withdrawals. These data, made available by the Artois Picardie Water Agency, were introduced into the Somme river model. Moreover, we assumed that the withdrawals prior to 1982 (from 1958 to 1981) are identical to those of 1982 for all types of uses (irrigation, drinking water supply, industry …). Indeed, analysis of groundwater withdrawals show that they do not vary significantly over the 1982-1992 period. The river water abstractions of the 1993 year were applied to the previous years (1958-1992).

4.2.2 Model calibration

Calibration consists in adjusting the model parameters in order to reduce the difference between the observed and simulated values at the observation points (groundwater time series and the rivers flow rates measured at the gauging stations). The calibration of the Somme model was updated in 2017 over the Avre basin by Arnaud (2017). As part of the TACTIC project, and following the update of the Somme model with recent datasets, a recalibration was undertaken. The calibration was performed over the 1989-2017 period by trial and error approach and concerns only the Avre basin. This calibration concerns the permeability values of the chalk aquifer.

The model evaluation is focused on its capacity to mimic observed groundwater dynamics and river discharges measured at different observation points. The location of the piezometers and the gauging stations used in the evaluation of model calibration is shown in Figure 7 and in Figure 5.

Examples of comparison between the simulated and observed values of groundwater levels and river discharges are shown in Figure 15 and Figure 16. In addition, statistical criteria (Root Mean Square Error: RMSE, Mean Error: ME and the Nash criteria : NSE) were calculated on the basis of monthly values of the groundwater levels and river flow over the calibration period. Chalk groundwater dynamic is well reproduced by the model for the following piezometers: Guillaucourt (ME = -0.58; RMSE = 0.97m; NSE = 0.79); Hangest-en-Santerre (ME = 0.65; RMSE = 0.6.m; NSE = 0.8); Damery (ME = 0.62 and RMSE = 1.m; NSE = 0.84). The Avre River discharge at the Moreuil gauging station is well reproduced by the model with ME = 0.1, RMSE = 0.5 m^3/s and a NSE of 0.76 (NSE criterion is considered to be very good when it is greater than 0.7).

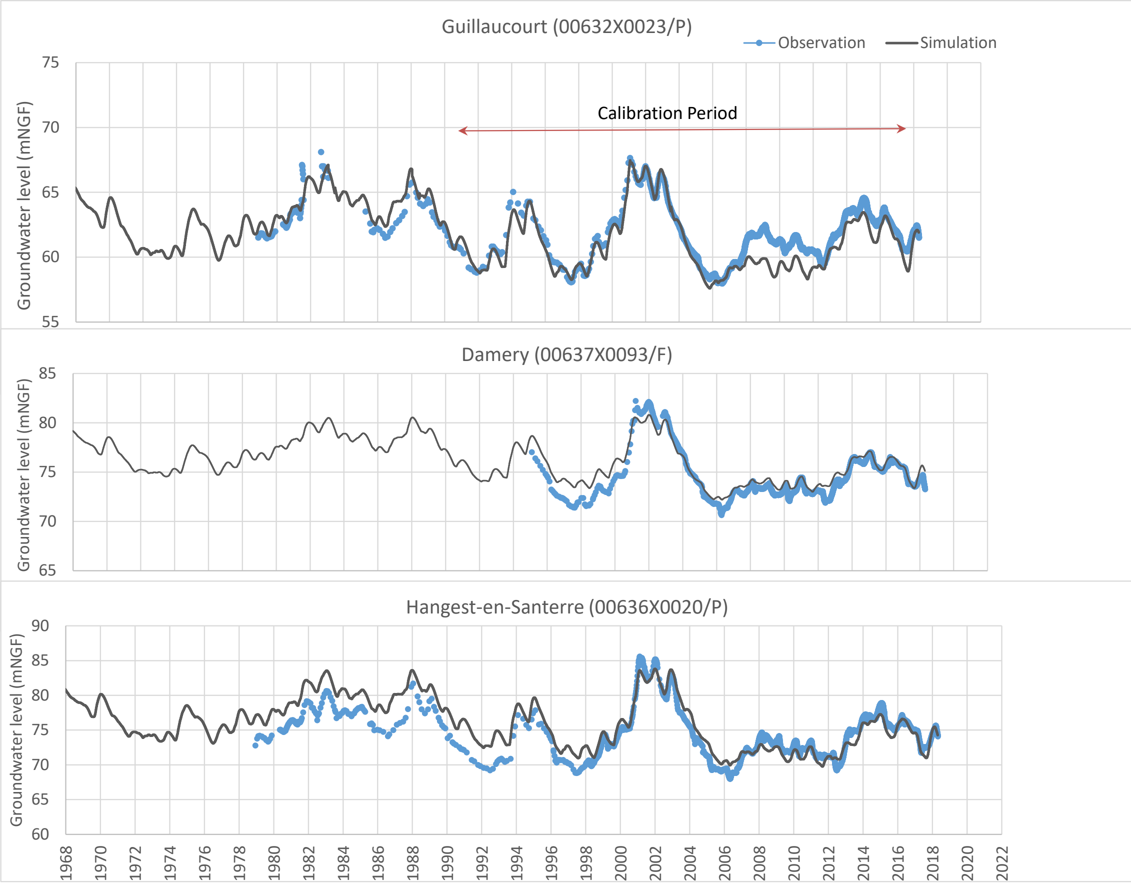


Figure 15 : Examples of observed and simulated groundwater levels in 3 piezometers located in Avre basin.

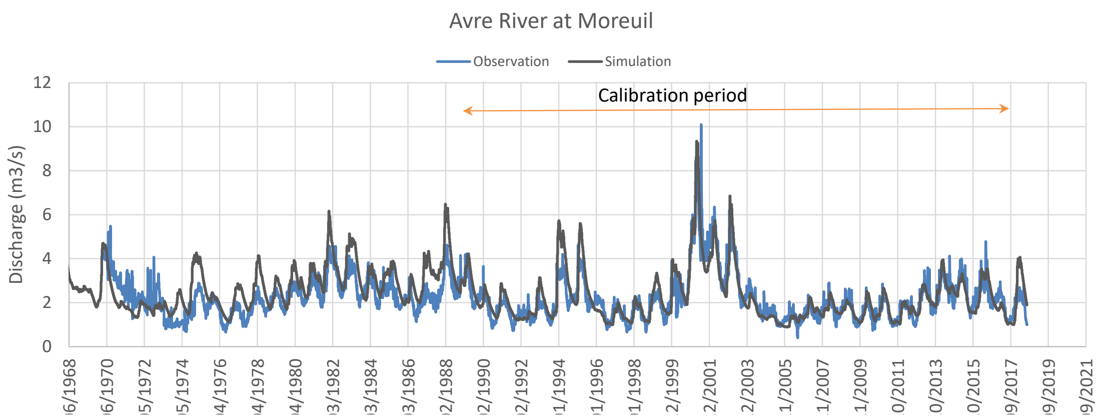


Figure 16 : Daily observed and simulated discharges in the Avre River at the Moreuil gauging station

4.3 Adaptation scenarios simulated with hydrological model

Adaptation measures to cope with the impact climate change on water resources can relate to: 1) water demand, such as land use change, adaptation of irrigation techniques and economic instruments etc. 2) water offer, which mainly lean towards complementary resources such as active management, natural water retention measures, water transfer, etc. 3) Mixed (improving resilience) such as improving planning, control and allocation of resources, technological innovation etc.Developing adaptation strategies at the territorial level is generally laborious since it involves climate, land use and socioeconomic scenarios. Two types of approaches exist: the top-down approach, which focuses on the analysis of physical vulnerability and the bottom-up approach, which attempts to assess the social vulnerability. The latter defines plausible scenarios and adaptation measures through participatory processes and workshops with the main actors. The top-down approach aims to identify the optimal measurement programs for the different climate scenarios

The implementation of a participatory approach involving the main actors of the territory (elected officials, socio-economic actors, institutional users, etc.) and mobilizing foresight tools is laborious and cannot be carried out in this study given the project budget allocated to this task. It was difficult to interact with water stakeholders because of 2020 sanitary conditions (Covid19). Therefore, the method used is to rely on some of proposed actions, in the adaptation plan to climate change of the Artois Picardie basin (developed in 2016), to define two scenarios based on orientation actions already proposed in this plan in connection with water resources, drinking water supply and agriculture.

4.3.1 Adaptation scenarios used

Two adaptation scenarios were defined based on a reduction in water demand for drinking water supply and irrigation. The location of drinking water supply wells and agricultural boreholes is reported in figure 11.

The first scenario called SA1 : this scenario assumes a **20% reduction in withdrawals for drinking water supply** that would be expected through induced by the awareness of water savings among citizens, the improvement of water leaks in the water distribution network; rainwater recovery…

The second scenario called SA3: This scenario assumes a **30% reduction in irrigation withdrawals during irrigation period** who could be reached by the optimization of irrigation (practices & innovative devices for irrigation), by using less water-consuming crop; diversification of water resources (rainwater, treated wastewater, etc.).

The Somme hydrological model is used to simulate the groundwater level and river flow over the period 1981-2010 by considering a reduction of 20% of water drinking supply withdrawals distributed in the same way over the whole year and over all the pumping wells. In the same way, a simulation was carried out taking into account a 30% reduction in irrigation withdrawals during irrigation period (May to September), this reduction is applied to all agricultural boreholes. The results were compared to the reference simulation to assess the effects of withdrawals reductions on the groundwater level and the river flows (Avre River and its main tributaries).

In addition, a third simulation was achieved without any abstraction in groundwater and rivers in order to evaluate the effect of abstractions on the river flows. Impact of tested adaptation scenarios on the groundwater level and river flow was assessed

4.4 Uncertainty

The most important sources of uncertainty concern the data on groundwater and river water withdrawals, which were not known before 1982 and 1993 respectively. Therefore, the assumption made on withdrawals before 1982 for groundwater uses and 1993 for rivers constitutes an important source of uncertainties. In addition, the withdrawal variation over time is not known, only annual volumes are known.

5 RESULTS AND CONCLUSIONS

This section assesses the impact of climate change on the evolution of groundwater recharge, groundwater levels, and river stream flows. Results show comparisons between each future periods of the four Tactic scenarios and the reference period (1981–2010) in terms of annual changes of groundwater recharge and mean, low and high groundwater level. Analyses carried out for the Tilloloy piezometer (corresponding to the 00813X0043/S1 piezometer in Figure 7) and river stream gauges propose local and seasonal responses of the system to the future climate change.

5.1 Effects of climate changes on precipitation, evaporation, and groundwater recharge

Figure 17 compares the monthly mean seasonal cycle of precipitation and PET computed for the four future Tactic simulations in relative changes with respect to the reference historical simulation. Dry scenarios corresponds to the simulations labelled with minimum changes and wet scenarios to the simulations labelled with maximum changes. Three scenarios (+1°C dry, +3°C dry and 3°C wet) present increases of precipitation during winter. Precipitation rises also occur in summer for 1°C and 3°C wet scenarios. Conversely, precipitation decreases occur in summer for both the 1°C and 3°C dry scenarios. Monthly changes in PET shows an increase for all scenarios, and it is more important in summer under +3°C global warming

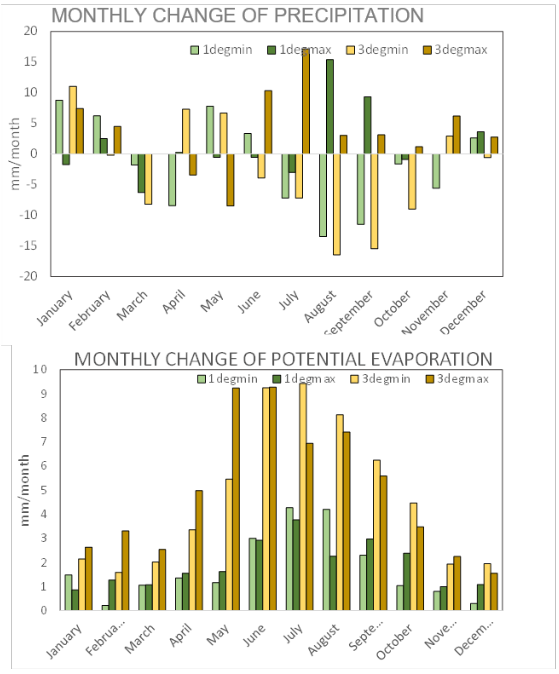


Figure 17: Monthly changes of precipitation and PET under +1° C and +3°C for the 4 Tactic standard scenarios. In the legend, the “min” suffix means dry and “max” means wet.

Regarding groundwater recharge, results shows that the 1°C and 3°C dry scenarios generate a decrease of -5.5% and -13% respectively with respect to the reference period in terms of mean annual changes in average over the Avre basin. The 1°C and 3°C wet scenarios generate an increase of +0.7 % and +3.79% respectively.

5.2 Effects on piezometric heads and river flows

5.2.1 Change in groundwater resources

Applying the Somme model with MARTHE enables simulated outputs in the format of grid/raster for pre-defined time-intervals. These gridded outputs were printed with a 30 days interval. Therefore, it was possible to analyse, not only the mean changes as the difference between the simulated future periods and the simulated reference period, but also to analyse the changes for relatively dry and wet periods throughout the years, respectively. Figure 18 shows the relative changes of simulated piezometric heads between the four future Tactic simulations and the reference period (1981-2010) computed for each grid cell of the Somme model focused on the Avre basin. Representing the time of the year with lowest groundwater levels, a change of the 5 % quantile of the simulated 30 periods is shown (Future Q5 – Past Q5). This typically occurs during the summer and fall period. In the same way, the 95 % quantile is used to illustrate the changes of the period with highest groundwater levels, typically during the winter or early spring.

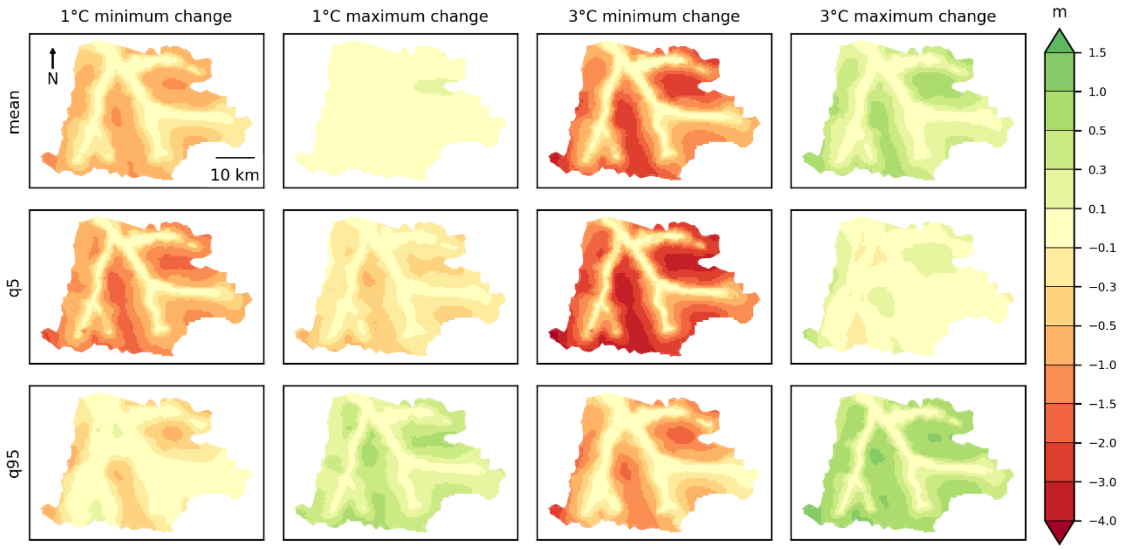


Figure 18 : Changes in mean, high and low shallow groundwater levels simulated with the four TACTIC standard scenarios

Results show an increase of mean groundwater levels for the 3°C wet scenario (maximum change scenario), while no significant changes appear for the 1°C wet scenario. The change of groundwater levels for Q95 shows increases for the two scenarios. The change for Q5 shows decreases for the 1°C wet scenario while no significant pattern appear for the 3°C wet scenario.

Both 1°C and 3°C dry scenarios show decreases of mean groundwater levels. This decrease becomes accentuated for the 3°C dry scenario and can reach locally -3 m. The changes for Q5

and Q95 are in accordance for decreases in the future, which can reach locally about -6 m locally for the 3°C dry scenario for Q5.
Changes occur mainly on plateaus than on wet valleys. Those results concord with the relative changes computed for the groundwater recharge over the Avre domain described previously.

5.2.2 Climate change impact on drought evolutions

One way to evaluate the ability of the simulation to capture extreme events is to use the Standardized Piezometric Level Index (SPLI). The SPLI is an indicator used to compare groundwater level time series and to characterize the severity of extreme events such as long dry period or groundwater overflows (Seguin, 2015). The SPLI indicator is based on the same principles as the Standardised Precipitation Index (SPI) defined by McKee et al. (1993) to characterize meteorological drought at several time scales. First, monthly mean time series are computed from time series of piezometric heads. Then, twelve monthly time series (January to December) are constituted over the N years of the time series period. For each time series of N monthly values, a non-parametric kernel density estimator allows estimating the best probability density function fitting the histogram of monthly values. At last, for each month from January to December, a projection over the standardised normal distribution using a quantile-quantile projection allows deducing the SPLI for each value of the monthly mean time series of piezometric heads. The SPLI values most often range from -3 (extremely low groundwater levels corresponding to a return period of 740 years) to +3 (extremely high groundwater levels). The SPLI allows representing wetter and drier periods in a similar way all over the simulated domain.

Figure 19 shows the SPLI evolution for the Tilloloy piezometer located over the Avre basin (corresponding to the 00813X0043/S1 piezometer in Figure 7), which presents results representative of the behavior of the other piezometers located over the Avre basin. The SPLI was computed from the 1981-2010 reference period for the four future simulation using the Tactic climate changes projections and for the historical simulation. The SPLI indicator computed for the historical simulation shows a 21-months length drought in 2005 (evolution not shown here). The SPLI evolutions of Figure 19 shows the most important increase of the severity and length of droughts for the 3°C dry scenario, especially in 1992, 1997 and 2005. In 2005, the projected length of the 3°C dry simulation drought is 41 months, i.e. twice the length of the historical drought.

The 1°C dry scenario also shows an important increase of the severity of droughts in 1997 and 2005. For this scenario, the 2005 drought lasts 26 months. At last, the 1°C and 3°C wet scenarios show an increase of the severity of droughts in 2005 less significant, with similar durations compared to the 2005 historical drought.

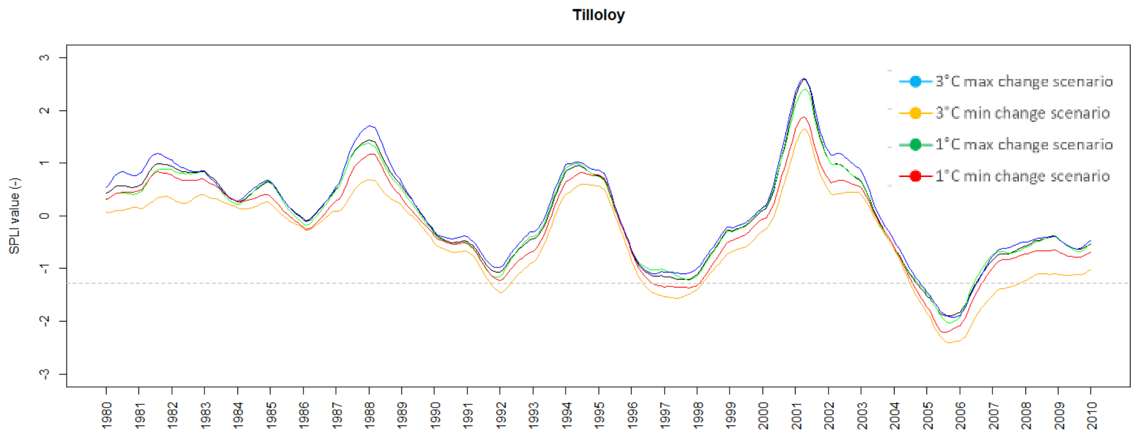


Figure 19: SPLI evolution for the reference period and the four Tactic standard scenarios for the Tilloloy piezometer.

5.2.3 Change in river flow

Figure 20 represent the monthly mean river flows of Avre river at Moreuil gauging station calculated over 30-years for the historical period and under the four Tactic climate change standard scenarios

Figure 21 shows the monthly mean seasonal cycle of the relative changes of simulated river stream flows for the Avre River at the Moreuil gauging station between the four Tactic future simulations an the historical simulation. The 1°C and 3°C dry scenarios show a decrease of the river discharges for all months. The high flow period from November to March present marked decreases with about -15% and -25% of changes in winter for the 1°C and the 3°C dry scenarios respectively. Changes for the 3°C dry scenario are more severe than for the 1°C dry scenario in all seasons.

Conversely, the 1°C and 3°C wet scenarios depict an increase of the simulated stream river flows for the high flow period, with a bigger impact of the 3°C wet scenario.

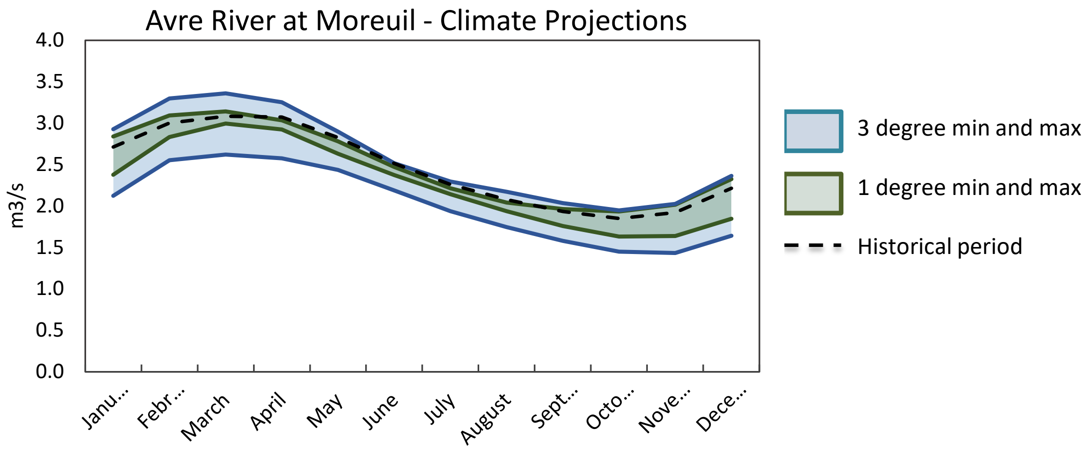


Figure 20 : Monthly mean Avre river discharge at Moreuil station calculated over 30 years for the reference period and for the Tactic standard scenarios

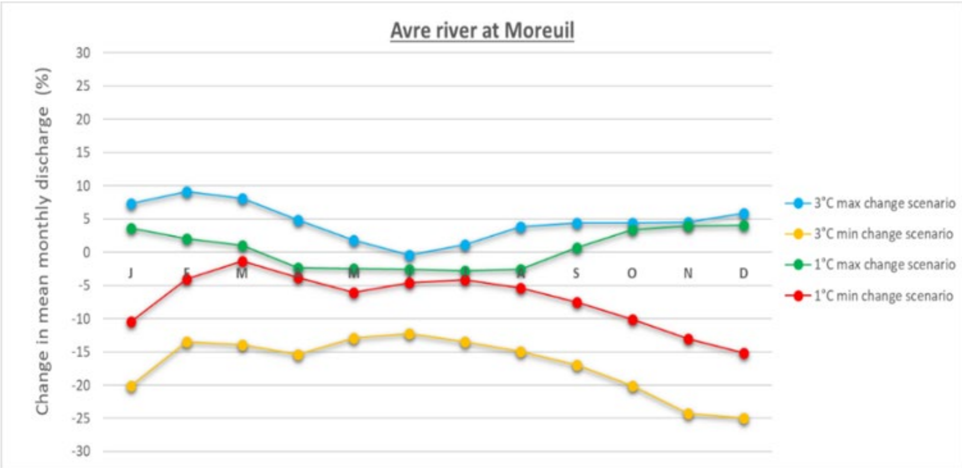


Figure 21 : Monthly mean seasonal cycles of the river discharges for the Avre River at the gauging station located at Moreuil. Results for the four Tactic future simulations are shown relative to the historical simulation.

5.3 Effects of adaptation scenarios on water resources

5.3.1 Effects on groundwater level

Figure 22 shows the change in average groundwater level over the 30-years period (1981-2010) induced by the SA1 adaptation scenario compared to the mean reference groundwater level simulated over the same period with current withdrawals. Reduction in drinking water withdrawals has a local impact at and around wellfield, in particular those located at the upstream of the Luce basin for which the rise in the water table appears significant with a maximum local groundwater level rise of +1.4 metres.

Figure 23 shows the change in mean groundwater level and average groundwater level of July, over 30 years, induced by the SA3 adaptation scenario compared to the mean reference groundwater level. Concerning the impact of SA3 scenario on the mean groundwater level, there is an increase in water table over a large area over the north of the basin. This is due to an important use of the irrigation on this part of the basin.

The impact of the SA3 adaptation scenario is much greater in July and August as shown on the right map in Figure 23. Indeed, as more than half of the annual volume used for irrigation is withdrawn between July and August, the impact on the water level is more important for these two months. The increase in the water table is greater on the plateaus (in particular the Santerre plateau) and at the head of watersheds than in the wet valley. The increase in the water table in July can reach 2.43 m locally for the AS3 scenario.

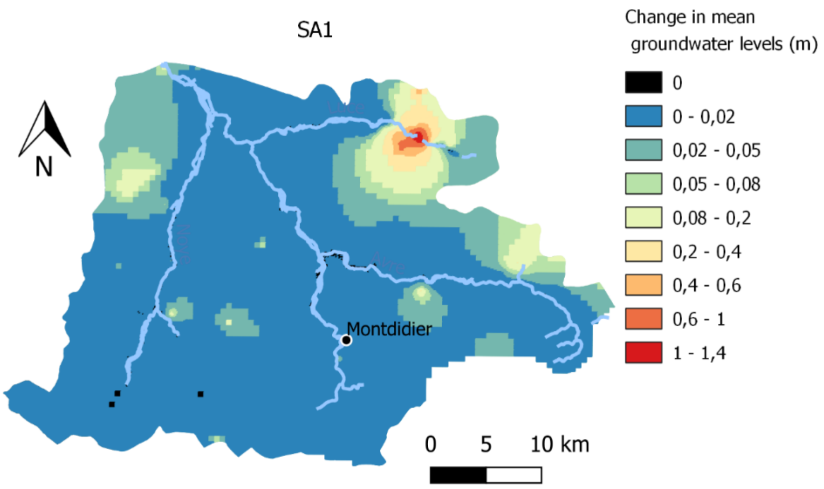


Figure 22 – Change in mean groundwater level for the SA1 adaptation scenario in relative to current situation.

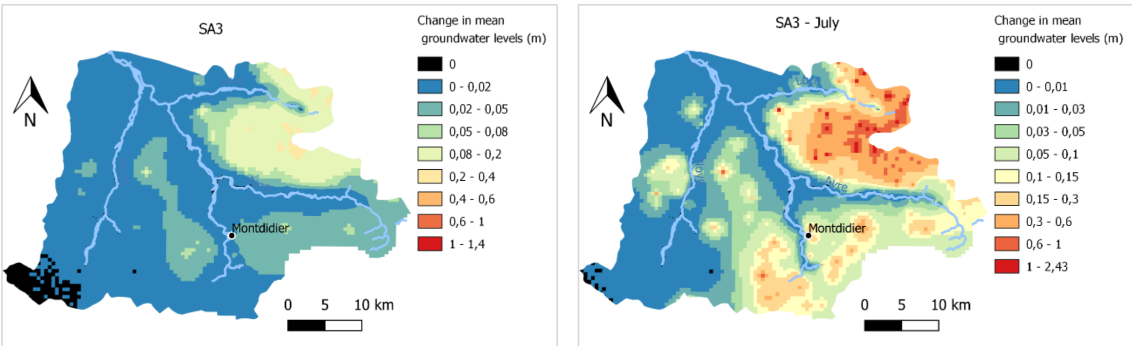


Figure 23 : Change in mean groundwater level over 30 years (map on the left) and in July mean groundwater level (map on the right) for the SA3 adaptation scenario in relative to current situation.

5.3.2 Effects on River flow

The impact of the tested adaptation scenarios on the river flow is quantified by comparing simulation results obtained for each adaptation scenarios to those obtained for the reference period (1981-2010) using current abstraction conditions. Figure 24 shows that the impact of the SA1 adaptation scenario on the mean monthly discharge of the Avre River at Moreuil is very low (less than 1%) and remains stable over the years. The impact of the SA3 adaptation scenario is significant during the irrigation period and reached 3.7% in July. The figure shows also that the impact of the current water abstraction (red curve) ranges between 4% and 10% depending on the considered month.

The impact on the Avre river flow is more visible at the upstream of the basin (i.e. the Saint-Mard gauging station in Figure 25 reaching 8.5% for the SA1 scenario and 7.5% for SA3 scenario.

Effects of current pumping(red curve) at the upstream of the Avre River and the Luce River is important, 10% to 30% and 18% à 40% respectively, as shown in Figure 25.

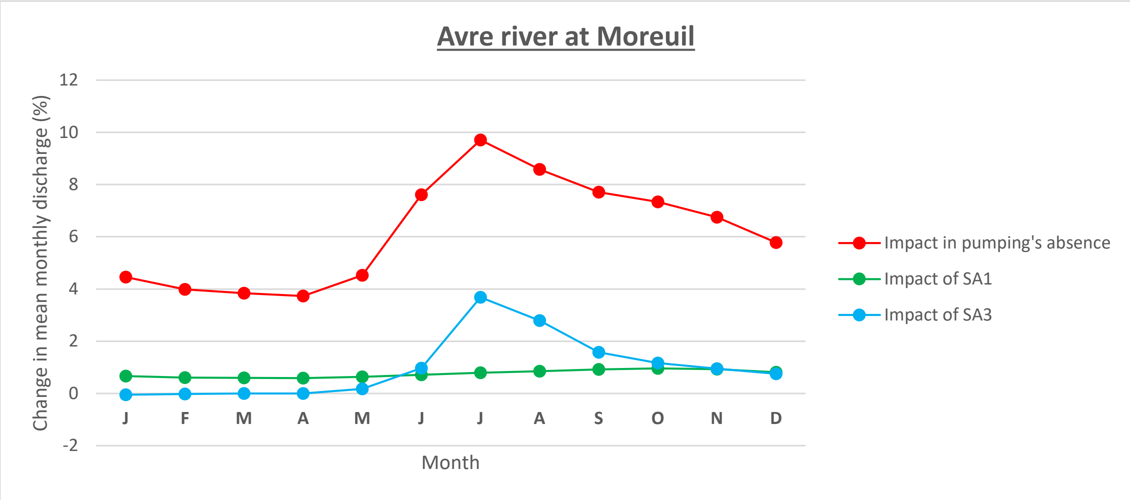


Figure 24 : Change (in %) of monthly mean discharge in Avre River at Moreuil for SA1 and SA3 adaptation scenarios compared to the reference period.

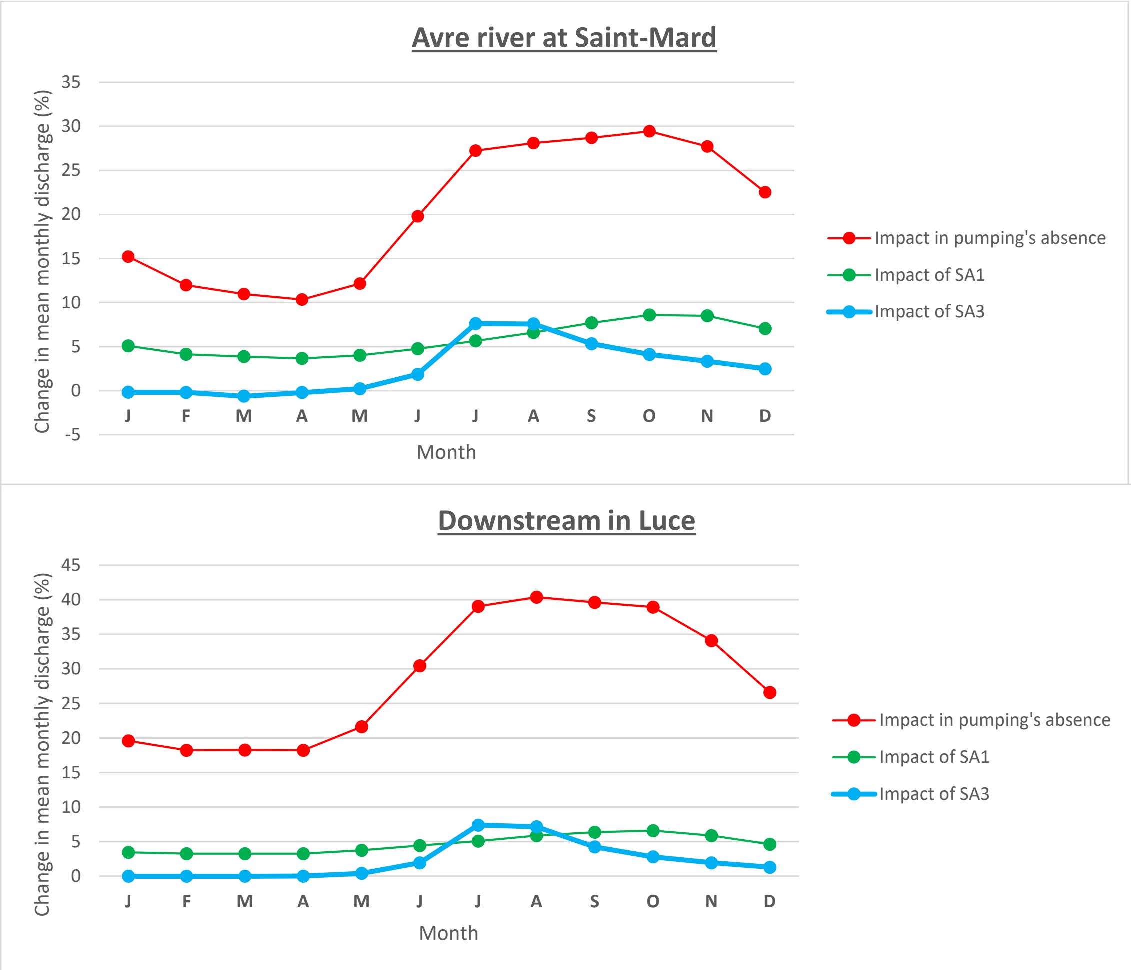


Figure 25 : Change (in %) in monthly mean discharge in Avre River at Saint-Mard and at the outlet of the Luce River for SA1 and SA3 adaptation scenarios compared to the reference period

5.4 Conclusion

For the Avre basin, dry scenarios with lower precipitations show higher impacts on the groundwater conditions than wet scenarios with higher precipitations. Such results is due to a global increase of PET whatever the considered scenarios, meaning much less effective rainfall available for groundwater recharge for dry scenarios. Dry scenarios shows longer drought periods with decreases of groundwater levels during all the years that can reach about -6 m (on the plateaus) in periods of lower water table (e.g. in summer) in the worst scenario (i.e. the 3°C dry scenario). River discharges diminishes throughout all the year with -20 % of the river base flow expected for the 3°C dry scenario with respect to the 1981-2010 period. The wet scenarios shows increases of groundwater levels (reaching +1.5 m locally) and river discharges (+ 9% maximum) during winter. Absolute changes are nevertheless lower for the wet scenarios than for the dry scenarios.

Concerning the tested adaptation scenarios, the scenario assuming a drinking water withdrawals reduction has a local impact on groundwater level, at and around wellfield. On the other side, the scenario assuming an agricultural abstractions reduction has an impact on groundwater over a large area in Santerre plateau and Avre basin upstream where agricultural boreholes density is greater.

At the territorial level, the development of adaptation scenarios to mitigate climate change need to be done with territory actors. A participative approach involving the main actors of the territory (socio-economic actors, institutional users, etc.) and mobilizing foresight instruments should be privileged.

Finally, raising public awareness of the climate change effects on water resources and the implementation of several actions and adaptation measures will reduce the climate change effects on groundwater resources.

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TACTIC GROUNDWATER

GeoERA

Establishing the European Geological Surveys Research Area to deliver a Geological Service for Europe

Deliverable 6.3

PILOT DESCRIPTION AND ASSESSMENT

Marecchia river alluvial fan

Authors and affiliation:

Paolo Severi, Luciana Bonzi, Lorenzo Calabrese

[Geological, Seismical and Soli Survey of Emilia – Romagna Region - Italy]

RegioneEmiliaRomagna
servizio geologico sismico e dei suoli

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	
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Deliverable name	Pilot description and assessment
Work package	WP6
Lead WP/Deliverable beneficiary	IGME
Deliverable status	
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LIST OF ABBREVIATIONS & ACRONYMS

CC	Climate Change
GC	Global Change
LULC	Land Use and Land Cover
SWI	Sea Water Intrusion
GSO	Geological Survey Organisations
MAR	Managed groundwater recharge

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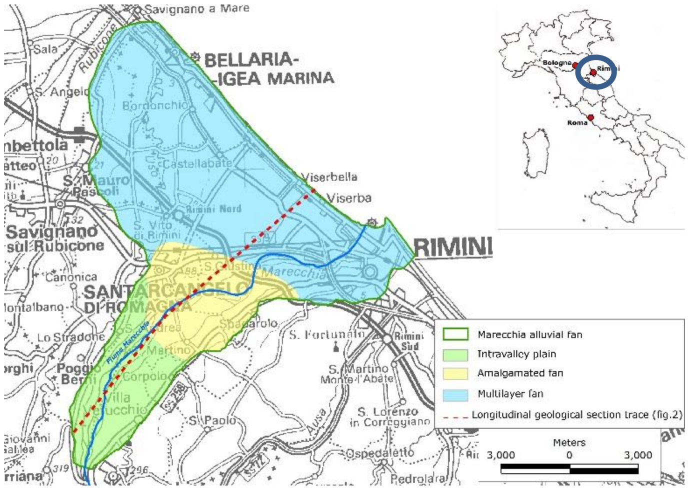
1 EXECUTIVE SUMMARY

Pilot name	Marecchia river alluvial fan	
Country	Italy	
EU-region	Mediterranean Region	
Area (km²)	About 125	
Aquifer geology and type classification	Alluvial fan gravels, sands and silts; complex of porous phreatic to confined aquifers.	
Primary water usage	Drinking water and irrigation	
Main climate change issues	Higher temperature, drought	
Models and methods used	3d geological and geotechnical modelling of aquifers (Leapfrog) integrated with piezometric and salinity monitoring data; Managed aquifer recharge	
Key stakeholders	Local municipality, tourism operators, enviromental heritage authorities	
Contact person	SGSS . Paolo Severi (paolo.severi@regione.emilia-romagna.it)	

The study area of this pilot is located in northern Italy, in the Emilia-Romagna Region in the province of Rimini and it is about 125 km^2 large. From a geological point of view, it is an alluvial fan consisting of alternations of coarse and fine deposits that form complex of porous from phreatic to confined aquifers, well described in the chapter 3.
The study concerns the water resources of the Marecchia River alluvial fan which have a strategic importance for the drinking water supply and irrigation of the entire Rimini area, which is an important truistic location. In fact, about 28 million cubic meters of water a year are taken from aquifers of this alluvial fan, 19 of which are used for drinking water. A series of some very hot and dry summers since 2007 has led the Emilia-Romagna Region to establish a technical committee for the management of recurrent water crises. One of the practicable actions to prevent and mitigate future water crises is managed groundwater recharge (MAR), which would increase the availability of groundwater and also contrast land subsidence and salt-water intrusion, due to exciding in groundwater withdrawal. The MAR project is a specific measure to contrast drought due to climate changes, included the Management Plan done by Emilia-Romagna Region and the Po River Authority in compliance with the 2000/60 EU Directive; it

consists of putting water from the Marecchia River into an infiltration basin (site of a former quarry) in the maximum recharge area of the alluvial fan. To dimension the project and evaluate its functioning, we assess the structure of the subsoil with a series of cross-sections and with a 3d geological modelling of aquifers, integrated with piezometric and salinity monitoring data. A first trial period produced the expected effects: an increase in the volume of water in the lake induced a rise in the water table and a groundwater quality improvement. So the MAR projec is going on. The great attention paid during these years to this natural area has also helped the development of an important green ecosystem and a large wetland area which is already subject to observation and protection for biodiversity and for the particular ornithological species that have found here the suitable environment for nesting. At the present time this area has therefore become a natural area that can also be available for the local population.
This project has therefore proved to be a valid measure to contrast the drought due to climate change and also as a valid recovery and return to the population of and old quarry area.

2 INTRODUCTION

Climate change (CC) already have widespread and significant impacts in Europe, which is expected to increase 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. In order 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 infra structure 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 present document reports the TACTIC activities in the pilot Marecchia River alluvial fan, located in the Adriatic coast of Emilia-Romagna Region, Italy.
It is a detrital alluvial fan aquifer, which extends for about 125 km^2. The shape and the dimension are indicated in figure 1; along the Adriatic coast the length is about of 20 km and the alluvial fan starts out of the catchment basin almost 15 km far from the coast. Rimini is the main town present in the area. This Pleistocene – Holocene aquifer is unconfined in the upper part (see green and yellow portions in figure 1) and consists of amalgamated gravel with a silty sandy matrix. In these portions the thickness goes from 10 to 80 metres, from the SW toward the Adriatic Sea. In the blue portion (figure 1) the aquifer is composed by a multilayer fan, formed by alternating gravelly levels and mainly fine levels, for the maximum thicknesses along the Adriatic coast (up to 250 m and more). All this geological information has been taken first of all from a National Geological Mapping Project (Progetto CARG, Foglio Geologico n. 256 "Rimini"), and they were used to implement a 3D geological model (software Leapfrog) in the surrounding area where a MAR project was realised. Hydrogeological information results from a local monitoring network composed by almost 35 wells, with four time per years level measure since 2001.
In the last decades during many hot and dry summer, the availability of drinking water decreased because of the poor presence of water inside the local dam located in the mountain areas. At the same time the demand for drinking water increases, because of the tourist presence. For these reasons the abstraction of groundwater in the alluvial fan aquifer of the Marecchia strongly increased, with potential problems for subsidence and saltwater intrusion.

The overall objective of this study is to use all the geological available information to implement and keep active over time a MAR project, in order to contrast the impact of climate change in water availability, and the reduction of natural groundwater recharge in the Marecchia river alluvial aquifer.

3 PILOT AREA

Overall introduction to the site and its challenges

The Marecchia River is 70 km long and has a catchment basin of about 600 km^2; its average annual flow at the entrance of the alluvial fan is estimated at about 6 m^3 per second (Basin Authority of Marecchia - Conca, 2004). The Marecchia alluvial fan (Figure 1) develops at the end of a mountain basin and it is divided, from a geological point of view, into three different areas: an intramountain plain, formed by a thickness of not more than 10 m of mostly gravel deposits directly flat on the marine substrate; an amalgamated fan, also comprised of prevailing gravels, for a maximum thickness of up to 80 m above the sea clays; and a multilayer fan, formed by alternating gravelly levels and mainly fine levels, for thicknesses up to 250 m and more, above the coastal marine deposits of the Imola Sands (Severi et Al., 2014, Geological Survey of Italy - Emilia-Romagna Region, 2005; Emilia-Romagna & ENI-AGIP, 1998;). From the hydrogeological point of view, the intramountain plain corresponds to a phreatic aquifer, as well as the amalgamated fan, although there can be local confinement conditions inside it. The amalgamated portion corresponds to the area of maximum recharge of the entire fan, which is mainly due to effective infiltration of rainwater and dispersion from the Marecchia River. The multilayer fan is formed by a system of superimposed confined and semi-confined aquifers. Above them, in direct contact with the surface, there is a phreatic aquifer about 10 meters thick, mainly made of sandy silt deposits.
These geological knowledges permitted to find the recharge areas of the overall Marecchia river alluvial fan, which area indicated in yellow in figure 1 (amalgamated fan). Thanks to this information it has been possible to locate the best place to implement a MAR project, in order to fight the natural groundwater recharge reduction due to climate change.

3.1 Site description and data

- *Location of pilot area (Figure 1):* Pilot area is located in the south portion of Emilia-Romagna Region coastal area, in the Rimini Province. Colours in figure 1 are descripted in paragraph “*Geology/Aquifer type*”.

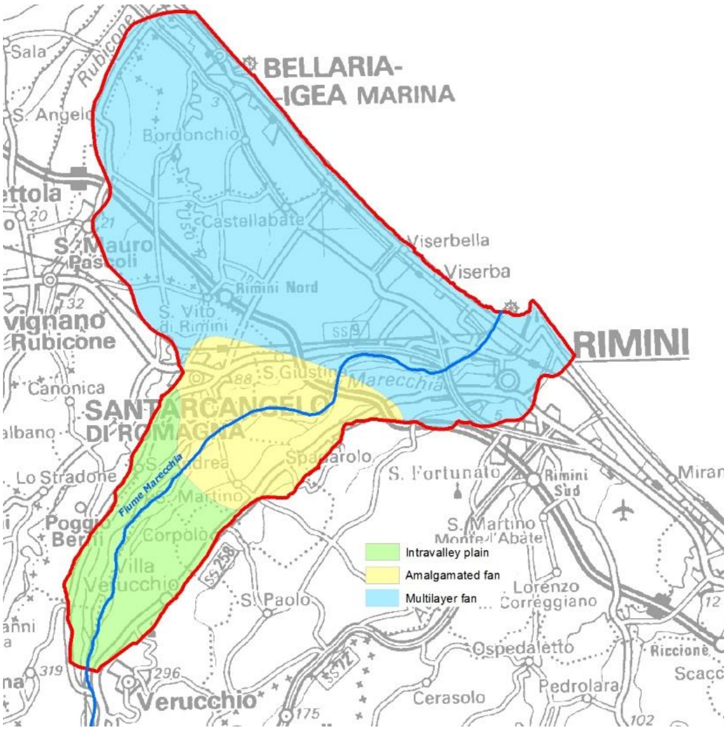


Figure 1 – Location of pilot area

- *Climate*
  - *climate type* is sub-continental/temperate type, with moderately cold winters (the average seasonal temperatures are about 5° C) and hot summers, with temperatures that stand at average values around 23° C. The average temperature in Rimini is about 13.6 °
  - *precipitation and evapotranspiration:* The average annual rainfall is about 750 mm. Rain falls throughout the year in Rimini. Most of the rain falls around October, with an average total accumulation of 75 millimeters. The least amount of rain falls around January and July, with an average total accumulation of about 42 millimeters.
  -
- *Topography (Figure 2):* the territory is quite flat and low, with altitude between 0.5 m along the coastal strip and 100 m towards the hinterland, where the hills begin (Villa Verucchio area in the southern portion of Figure 2). There aren't areas below sea level.

Figure 2 – Topography of the pilot area

- *Land use (Figure 3):* most of the territory consists of areas for agricultural use and/or green areas and parks; the urban areas include the city of Rimini with its large tourist reception area and all the smaller touristic towns that develop along the whole coastline. Shrubby areas, wooded areas and orchards are shown in green. Along the course of the Marecchia River there are some active and inactive quarries, one of whicth is used as an infiltration pond in this MAR experience.

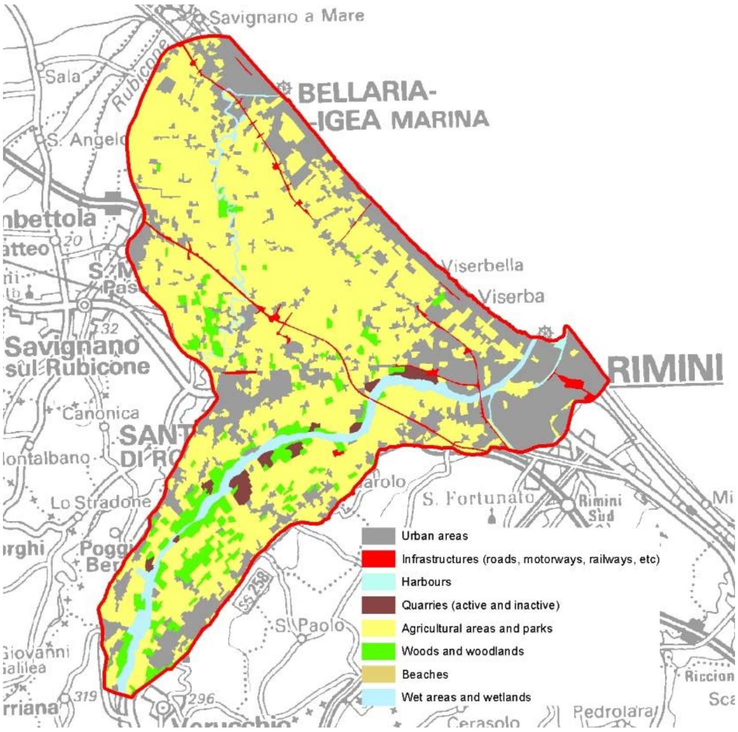


Figure 3 – Land use

- *Soil types (Figure 4):* Soils in this area are mainly calcaric-moderately alkaline except the 3Cb type, which are not calcareous but neutral-moderately alkaline, the 4Ba type, not calcareous - from neutral to high alkaline, and the 5Bb type, moderately alkaline. 1D type are soils of the coastal plain and they have a coarse texture; 2C are soils in morphologically depressed areas of the alluvial plain and they have a fine texture; 3A and 3B type are soils in morphologically higher areas of the alluvial plain and they have a medium texture; also 3C are soils in morphologically higher areas of the alluvial plain and they have a medium texture, but they are not calcareous; 4B are soils of Appennine edge with a fine texture; 5B and 5C are both soils of the lower Appennine but very different from each other: 5Bb soils are rocky, with an average texture and locally they are saline in the deepest part; 5Cc are soils with a fine texture. The AVL polygon represents the ordinary flood plain.

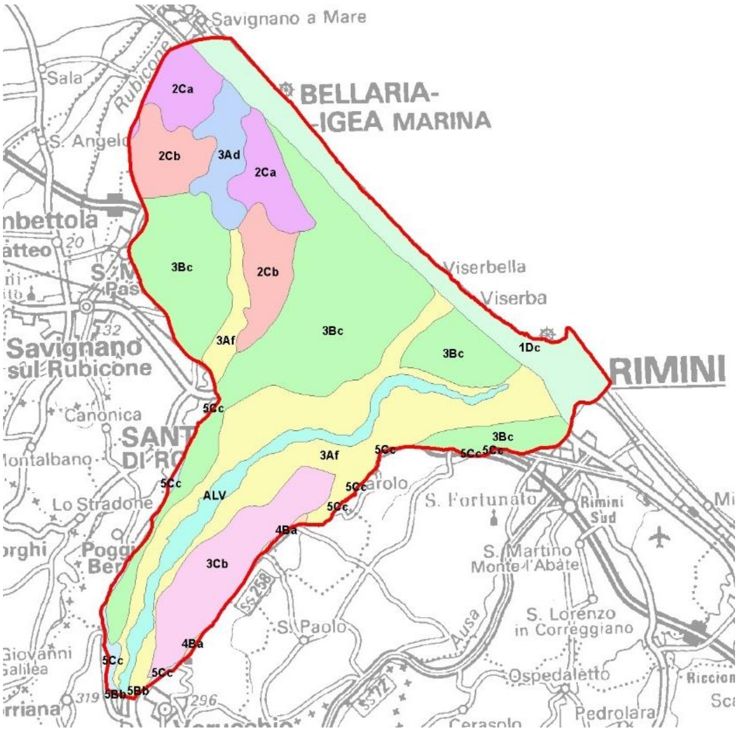


Figure 4 – Soil Types

- *Geology/Aquifer type (Figure 5a, 5b and 5c)*: alluvial deposits characterize all of this pilot area, except the coastal area where geology consists of coastal cord and wind dunes deposits (Figure 5a). In the subsoil, the Marecchia alluvial fan develops at the end of a mountain basin and it is divided, from a geo-hydrogeological point of view, into three different areas (Figure 5b): an intramountain plain, formed by a thickness of not more than 10 m of mostly gravel deposits directly flat on the marine substrate (green area in figure 5b) ; an amalgamated fan, also comprised of prevailing gravels, for a maximum thickness of up to 80 m above the sea clays (yellow area in figure 5b) ; and a multilayer fan, formed by alternating gravelly levels and mainly fine levels, for thicknesses up to 250 m and more (blue area in figure 5b) , above the coastal marine deposits of the Imola Sands (Severi et Al., 2014, Geological Survey of Italy - Emilia-Romagna Region, 2005; Emilia-Romagna & ENI-AGIP, 1998;). The intramountain plain corresponds to a phreatic aquifer, as well as the amalgamated fan, although there can be local confinement conditions inside it. The amalgamated portion corresponds to the area of maximum recharge of the entire fan, which is mainly due to effective infiltration of rainwater and dispersion from the Marecchia River. The multilayer fan is formed by a system of superimposed confined and semi-confined aquifers. Above them, in direct contact with the surface, there is a phreatic aquifer about 10 meters thick, mainly made of sandy silt deposits. A geological cross-section shows in a more detailed way the subsoil distributions of coarse and fine alluvial deposits, and different type of aquifers in the Marecchia river alluvial fan (figure 5c).

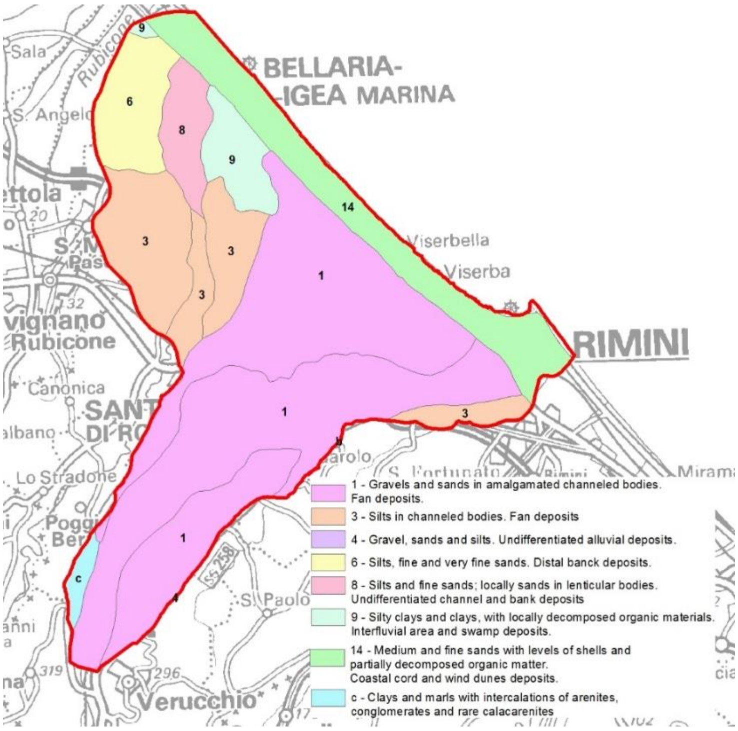


Figure 5a – Surface geology at 1:250.000 scale

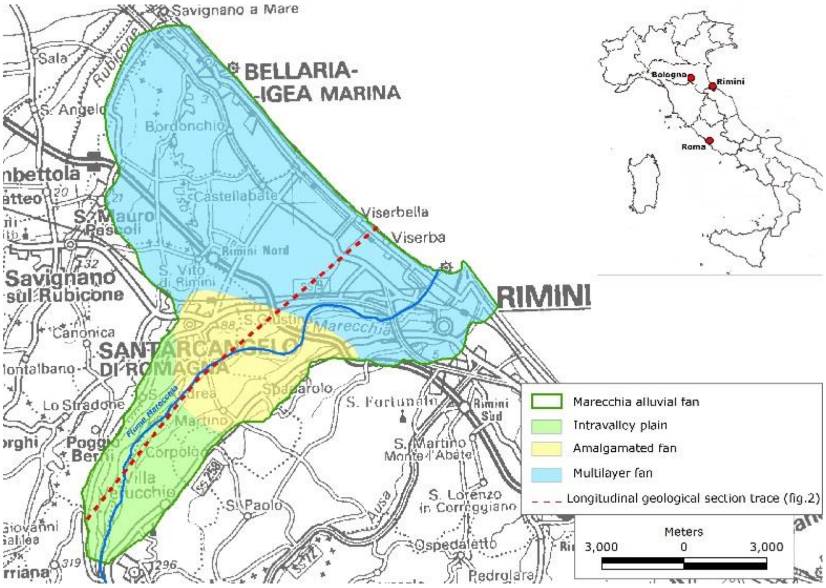


Figure 5b – subsoil geo-hydrogeology

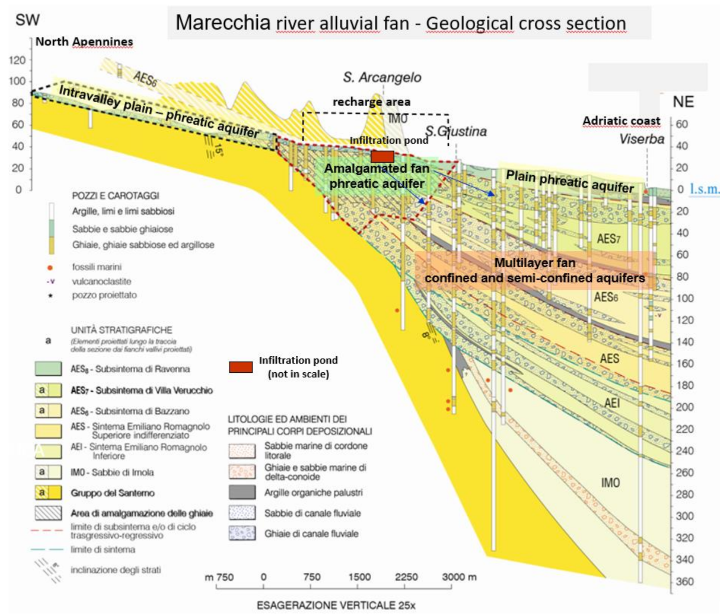


Figure 5c – Geological cross-section, with indication of the infiltration pond used for MAR project.

- *Surface water bodies (Figure 6)*: besides the Marecchia river, the main surface water bodies of the area are the Torrente Uso which flows in the northern part and the Marecchia River which crosses the entire pilot area. The rest of the surface waters bodies are artificial channels and minor watercourses.

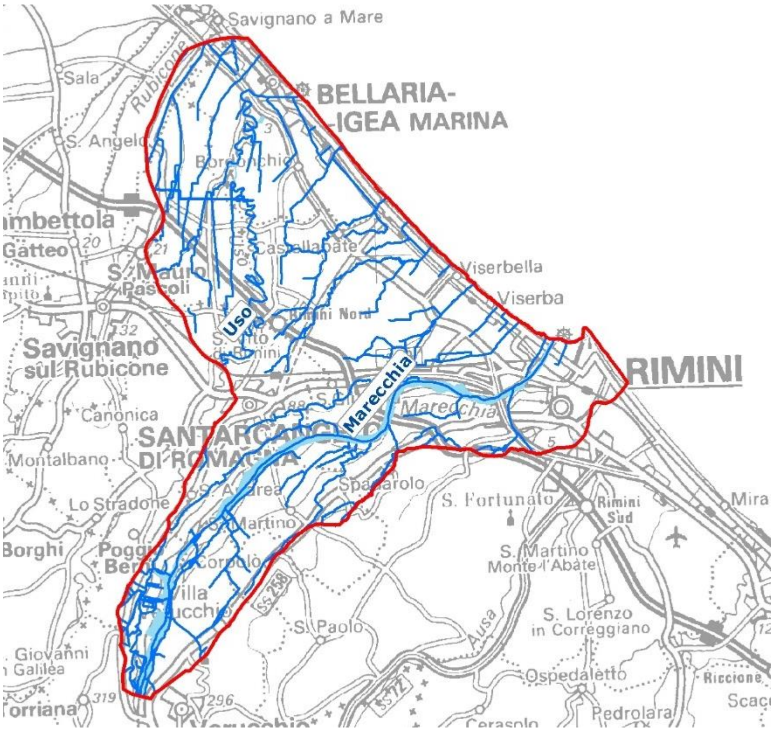


Figure 6 – Surface water bodies

- *Abstractions/irrigation:* Water resources of the alluvial fan of the Marecchia River have strategic importance for the drinking water supply of the entire Rimini area. In fact, about 28 million cubic meters of water a year are taken from aquifers of this alluvial fan, 19 of which are used for drinking water (Emilia-Romagna Region, 2005). Water for irrigation comes from some well and from the channel network, but it’s not so considerable so the drinking water use of groundwater. Abstraction for domestic use and for industrial use are quite low.

3.2 Climate change challenge

In accordance with the EEA map the main expeted issues due to climate change in this case study are those described in the Figure 7 for the Mediterranean regions, with strong rising in summer temperatures, rainfall reduction with a result of drought increasing and salinization of solis and groundwaters, and strong reduction of natural groundwater recharge and water availability.
The main challenge is to find adaptation measures to obtain water availability for all uses, and to maintain a good status in the related water ecosystem or to promote their controlled and sustainable tranformation; it’s important to support a dynamic management of groundwater bodies through a in-depth knowledge of balance between subtraction of fresh water and recharge of the aquifer troughtout the future climate change conditions.

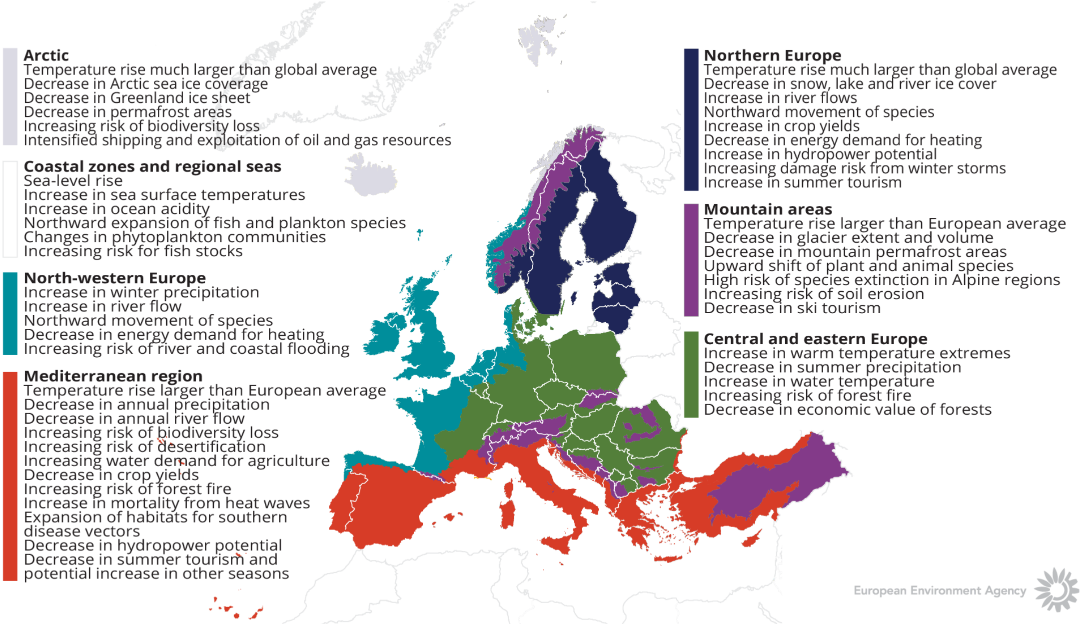


Figure 7 - Climate expected change in Europe. The European Environment Agency map

4 METHODOLOGY

4.1 Methodology and climate data

4.1.1 Tools/ model description

Due to the succession of particularly hot and dry summers, in relation to the climate changes in the Rimini area, a MAR project has been active since 2014. The MAR project consists of putting surface water from the Marecchia River into an infiltration basin in the recharge area of the alluvial fan (Figure 8, and 5c). This MAR project is a specific measure of the Management Plan done by Emilia-Romagna Region and the Po River Authority in compliance with the 2000/60 EU Directive.

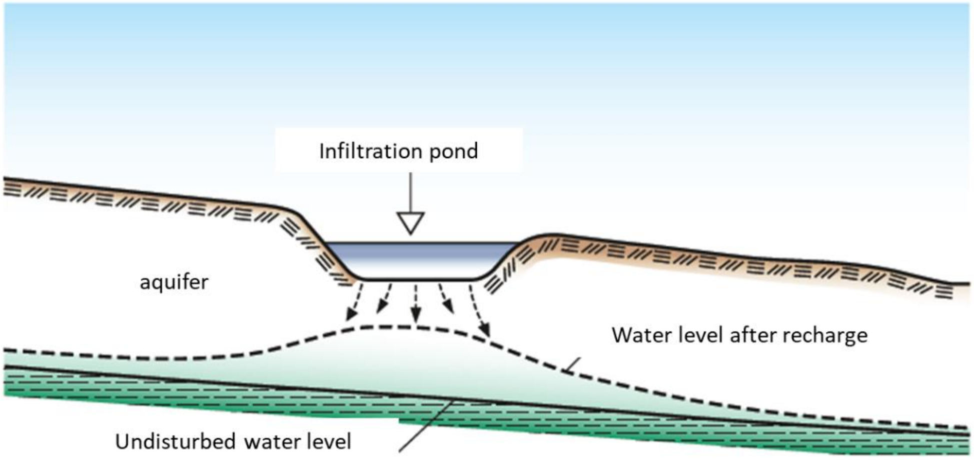


Figure 8 – MAR scheme applied on Marecchia alluvial fan

Within this pilot, we kept on with the piezometric level measures campaigns (four per year), with the groundwater quality monitoring (two per year) and with the quality monitoring (two per year) of the lake used as a pond for our MAR project.
A numerical groundwater model is not available. Nevertheless since 2014, in five years of MAR, 5.8 million cubic meters of water were introduced into the infiltration basin. It is in medium 1.15 million cubic meters per year, which represent the 4% of the overall groundwater abstraction in the Marecchia aquifer.
During the last year, the recharge had been stopped because of the damage of the weir used for the water transfer, caused by an extreme river overflow in the last winter season, but we know that during the last recharge period (October 2018 - April 2019), 2.3 million cubic meters of water were introduced into the recharging lake, which represent the maximum value respect all the precedent years.
At the end of 2020, a new weir has been built and now we are going to install a multiparametrical datalogger, useful for improve monitoring and for the early warning in case of the passing of alert levels of some parameters.

The great attention paid during these years to this natural area has helped the development of an important green ecosystem and a large wetland area which is already subject to observation and protection for biodiversity and for the particular ornithological species that have found here the suitable environment for nesting.
At the present time this area has therefore become a natural area that can also be available for the local population.

4.1.2 Future scenarios. Climate and land use data

In this case study no modeling was developed for a quantitative assessment of the changes in groundwater due to climate change. However, it is possible to already have an idea of how the climate will vary in the future in Emilia-Romagna and foresee a clear deterioration of the water resources in question.
Arpae-Emilia-Romagna Region has conducted several studies on the impact of the climate on the environment at a regional and local scale; in particular, the effects of rising temperatures on the water resource have been investigated (EU Interreg IVC Water CoRe Project). The results show that in the climatic projections predict an increase in the average annual temperature for the Italian peninsula, between 1.5 and 2 ° C, in the period 2021-2050. In the same period, for the Emilia-Romagna region there is a signal of 2 ° C increase for both the minimum and maximum temperatures. The change in the last part of the century, 2071-2100, will be much more marked, in which an even more marked increase in the average annual temperature will occur, around 3.5-4 ° C and for the summer season an increase in the maximum number of consecutive days without precipitation is expected. There will therefore be an increase in both mean and extreme values. This means that very hot (with positive anomalies of 3-4 degrees) and relatively prolonged periods, which today are extreme events, will be more frequent in the 2021-2050 period and will be the norm at the end of the century.
In the Emilia-Romagna Region in recent years there is evidence of the impacts of climate change on natural areas and cities, but ecosystems, such as forests and wetlands, biodiversity, the availability of drinking water resources and the agriculture are also affected by climate change.
In this scenario, the MAR project implemented could be a reasonable methodology to contrast the loss of natural groundwater recharge due to climate change.

5 RESULTS AND CONCLUSIONS

Thanks to the availability of geological and hydrogeological data, it has been possible to reconstruct the subsurface geology of the Marecchia river alluvial aquifer and to recognize the recharge area of this aquifer. The presence of an old quarry located in the recharge area, and the presence of an artificial canal that brings superficial water from the Marecchia river to the quarry, permitted since 2014 to implement a MAR project. In five years of project activity 5.8 million cubic meters of water were introduced into the infiltration pond, distributed in time as in table 1. No MAR activities were realised in 2016-2017 (because of realization of the Environmental Impact Assessment) and in 2019-2020 (because of the damage of the weir used for the water transfer). The MAR project is active only during fall – spring seasons (October – April), because during the other seasons the water from the canal is used only for irrigation. The medium amount of water introduced in the infiltration pond is 1.15 million cubic meters, which represent the 4% of the overall groundwater abstraction in the Marecchia aquifer.

2014:	**1.283.000 m^3**
2014 - 2015:	**677.000 m^3**
2015 - 2016:	**488.000 m^3**
2016 – 2017:	//
2017 - 2018:	**1.105.000 m^3**
2018 - 2019:	**2.250.000 m^3**
2019 – 2020:	//
	Total 5.803.000 m^3

Table 1: water amount introduced into infiltration pond with MAR project.

In order to evaluate the MAR efficiency, a specific groundwater monitoring network has been realised, that permitted to measure the rising of piezometric level after a period of recharge, (Figure 9).

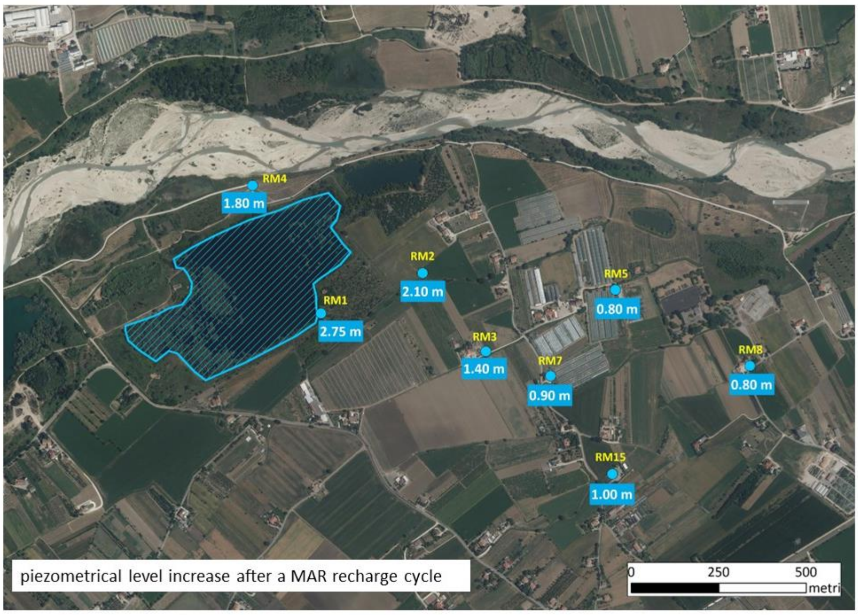


Figure 9 - Piezometrical level increase after a MAR recharge cycle (m)

At the same time it was noted that in the area surrounding the infiltration pond the water quality is better in terms of nitrate quantity than in more distant areas (Figure 10).

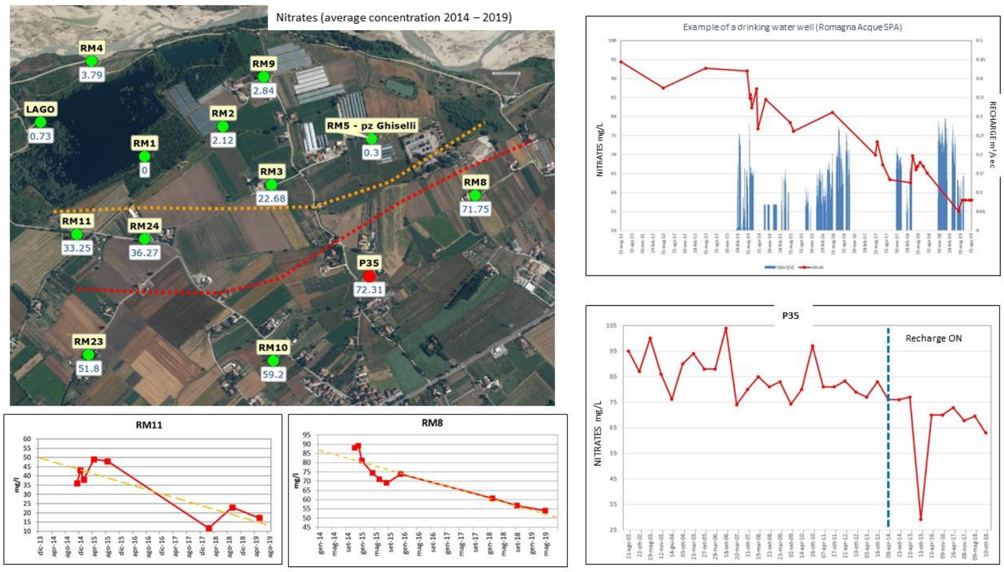


Figure 10 – Nitrates trend after a MAR recharge cycle: groundwater quality gets better.

Arpae-Emilia-Romagna Region has conducted several studies on the impact of the climate on the environment at a regional and local scale (EU Interreg IVC Water CoRe Project). The results show that in the climatic projections predict an increase in the average annual temperature for

the Italian peninsula, between 1.5 and 2 ° C, in the period 2021-2050. In the same period, for the Emilia-Romagna region there is a signal of 2 ° C increase for both the minimum and maximum temperatures. This temperature increase, associated with a different way of precipitations, will induce a reduction in natural groundwater recharge.
In this scenario, the MAR project implemented could be a reasonable methodology to contrast the loss of natural groundwater recharge due to climate change.

5.1 Performance to historical data

The lack until today of a numerical groundwater model does not allow to evaluate the quantitative and qualitative efficiency of the MAR project respect the precedent natural hydrogeological situation. However, the piezometric data indicate that with the MAR project the local recharge of the aquifer has certainly increased compared to the period prior to the start of this project (Figure 8). This means that this project could be an interesting way to contrast the water scarcity during the future predicted climate change in the Mediterranean region.
The actuation of our MAR project has been facilitated by the geological and hydrogeological previous knowledge, by the presence of a topographic depression due to an old quarry activity located exactly in the recharge area of the aquifer, and the presence of an artificial canal that can bring directly water from the Marecchia River to the topographic depression. So it was quite simple and inexpensive to implement the infiltration pond.
A MAR project like this descript here (infiltration pond), is surely quite easily applicable in other places in Emilia-Romagna Region. Many other technical possibilities are proposed for MAR projects (Dillon, et al. 2018), and surely it could be possible to use those to contrast the reduction of water availability due to the climate change in Mediterranean Region.

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Establishing the European Geological Surveys Research Area to deliver a Geological Service for Europe

Deliverable 5.3 and 6.3

PILOT DESCRIPTION AND ASSESSMENT

Plana de Oropesa-Torreblanca

Authors and affiliation:

David Pulido-Velazquez, Leticia Baena-Ruiz, AJ. Collados-Lara, Juan de Dios Goméz-Gómez.

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	D5.3 & D6.3
Dissemination level	Public
Deliverable name	Pilot description and assessment
Work package	WP5: **ASSESSMENT OF SALT-/SEA WATER INTRUSION STATUS AND VULNERABILITY;** WP6: **GROUNDWATER ADAPTATION STRATEGIES**
Lead WP/Deliverable beneficiary	IGME
Deliverable status	

Version Date	Final version 05/11/2020

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LIST OF ABBREVIATIONS & ACRONYMS

CC	Climate Change
GC	Global Change
LULC	Land Use and Land Cover
SWI	Sea Water Intrusion
GSO	Geological Survey Organisations

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1 EXECUTIVE SUMMARY

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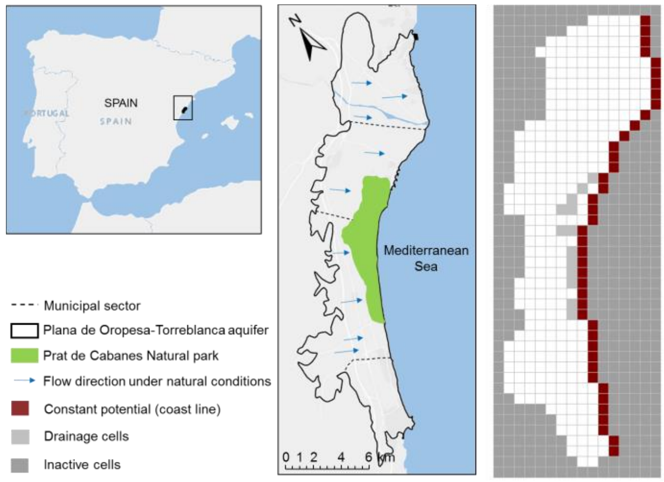
<tr><td>Pilot name</td><td>Plana de Oropesa-Torreblanca</td><td rowspan="6">
</td></tr>
<tr><td>Country</td><td>Spain</td></tr>
<tr><td>EU-region</td><td>Mediterranean region</td></tr>
<tr><td>Area (km^2)</td><td>89 km^2</td></tr>
<tr><td>Aquifer geology and type classification</td><td>Coastal sedimentary plain (gravel and sand levels in a silty clay matrix). Porous aquifer.</td></tr>
<tr><td>Primary water usage</td><td>Irrigation / Drinking water</td></tr>
<tr><td>Main climate change issues</td><td colspan="2">The increasing population since 1970, especially in summer, and the transformation from dry to irrigated croplands led to an increase in pumping volume that extended over two decades (1975-1995, especially in the period 1985-1995), provoking a drop in groundwater level and seawater intrusion (SWI) problems. From 1995 to 2010 there was a progressive reduction in pumping due to the abandonment of certain crops and irrigated areas. Impact studies are proposed to assess status and vulnerability taking into account future climatic and global change (GC) scenarios. In general, in the Mediterranean area an increase in temperature and a decrease in precipitation are expected. The available potential future scenarios show higher evapotranspiration, a lower groundwater recharge and an increase of the sea level. In coastal areas the problem is exacerbated due to overexploitation, intensifying SWI. In order to reduce the impacts of climate change (CC) on SWI, different adaptation strategies could be applied. Measures to reduce aquifer demands (Adaptation strategies are mainly focused on changes Land Use and Land Cover in the area) and measures on the offer (eg. Water reuse) could be applied to obtain complementary resources to supply demands.</td></tr>
<tr><td>Models and methods used</td><td colspan="2">Generation of potential future climate change scenarios and definition of adaptation scenarios (Land Use and Land Change scenrios and complementary resources to supply demands). Propagation with a chain of auxiliary models (recharge, agricultural) to generate inputs for a density dependent flow model (The finite-difference numerical code SEAWAT). An index method to summarize results using different spatial resolution (maps, cross sections and lumped indices). Distributed model (3D finite-difference numerical code SEAWAT); index method.</td></tr>
</table>

Key stakeholders	Jucar River Basin Authority, agricultural associations, water supply companies.
Contact person	L. Baena and D. Pulido, IGME (Spain), l.baena@igme.es; d.pulido@igme.es

The Plana de Oropesa-Torreblanca aquifer is a detrital Mediterranean aquifer, which extends over 75 km^2. This Plio-Quaternary aquifer is unconfined and heterogeneous and consists of a silty clay matrix with gravel and sand levels. The aquifer is wedge shaped and it can reach 90 m thickness near the coast. The transmissivity varies between 300 and 1000 m^2/day and the storage coefficient ranges from 2 to 12%. In the study area, there have been important land use changes from the 1970s. Before 1995 there was a significant transformation in the crop water demand due to new irrigated lands appeared. From this date to 2010, the main change was an increase of artificial surfaces (mainly residential Lan Use and Land Cover [LULC] along the coast) and an improvement in the efficiency of irrigation techniques. Pumping was deduced from historical data. The mean annual pumping in the historical period is 22 Mm^3/year approximately. The land use changes are reflected in the evolution of total pumping in the Plana de Oropesa-Torreblanca aquifer. First, the transformation into irrigated croplands from 1975 to 1995 produced an increase in pumping from 15 Mm^3/year to a maximum of 35 Mm^3/year. It produced a drop in Groundwater level and higher SWI problems. Later on, the transformation of irrigation techniques and land uses led to a reduction in pumping to a minimum rate around 13 Mm^3/year. Nevertheless, SWI has been a significant issue in this aquifer during the historical period that might be exacerbated in the future. Therefore, the main challenge of this work is to assess and summarise impacts of potential future CC and GC scenarios on SWI in the aquifer, and to identify and study potential adaptation strategies.

An impact and adaptation assessment has been performed for future potential scenarios. Representative future CC scenarios are generated and a future LULC scenario was defined in accordance with the plan approved by the local government (PGOU Torreblanca, 2009). Four GC scenarios were defined by combining the LULC scenario and the CC scenarios. These GC scenarios and a LULC scenario without CC have been propagated to assess hydrological impact by simulating them within a coupled modelling framework based on a density-dependent model whose inputs are defined by a sequential coupling of different models (rainfall-recharge models, crop irrigation requirements and irrigation return models). Finally, based on the outputs of this chain of models, a method is applied to summarise the impacts of GC scenarios in the global status and vulnerability to SWI at the aquifer scale including some management strategies. It allows to compare the significance of the SWI problems in different historical and future periods for an aquifer and between different aquifers. The effect of CC in the GC scenarios is also analyzed.

Results show that GC scenarios would imply a greater deterioration in the aquifer than LULC scenario. The adaptation strategies will produce a reduction of pumping in some areas of the aquifer, which would reduce the impacts of the potential future LULC and GC scenarios. The lumped indices reveal that GC would involve more variability in SWI problems (global status and vulnerability) and CC would increase the degradation of the aquifer. On average, it is expected that a greater area affected by intrusion and extreme climatic conditions might produce an increase in the vulnerability of the aquifer. GC would produce a greater impact on SWI global status than in the aquifer’s vulnerability. Nevertheless, the resilience capacity of the aquifer would allow recovering from the impacts of the extreme climatic conditions.

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2 INTRODUCTION

It is a detrital Mediterranean aquifer, which extends over 75 km^2. It has a length of 21 km and a width of between 2.5 and 6 km. This Plio-Quaternary aquifer is unconfined and heterogeneous and consists of a silty clay matrix with gravel and sand levels. The aquifer is wedge shaped and it can reach 90 m thickness near the coast. The transmissivity varies between 300 and 1000 m^2/day (Renau-Pruñonosa et al. 2016) and the storage coefficient ranges from 2 to 12%. Different Researchers and technicians from the Spanish Geological Survey (IGME) have participated in the assessment summarised in this report.

The overall objective of this study is to assess and summarise impacts of potential future CC and GC scenarios on SWI in the aquifer, and to identify and study potential adaptation strategies. SWI has been a significant issue in this aquifer during the historical period. In general, the available potential future scenarios show higher evapotranspiration, a lower groundwater recharge and an increase of the sea level. In coastal areas the problem is exacerbated due to overexploitation, intensifying SWI. In order to reduce the impacts of CC on SWI, different adaptation strategies could be applied. Measures to reduce aquifer demands (adaptation strategies are mainly focused on LULC changes in the area) and measures on the offer (eg. Water reuse) could be applied to obtain complementary resources to supply demands. In this report we analyse some potential adaptation strategies and their influence on future SWI. Therefore, the information generated could be usefull to identify and assess potential future sustainable management strategies to reduce SWI problems.

3 PILOT AREA

The Plana de Oropesa-Torreblanca is not a large coastal groundwater body (75 km^2), but it is very relevant for the local water supply and to maintain the optimal environmental conditions in a RAMSAR wetland area, "the Prat de Cabanes", which is located just above the aquifer and is hydraulically connected to it (Sanz-Garrido and Capilla 2015). There is no permanent rivers on this area and some of them only show runoff immediately after a long rainfall period. The increasing population since 1970 and the continuing agricultural exploitation have produced SWI problems of different entity in this aquifer (Baena-Ruiz et al. 2018).
This problem might be exacerbated in the future due to CC impacts. In this project we intend to assess and analyse impacts of future potential CC and GC scenarios on SWI and evaluate some adaptation strategies. We will consider measures to reduce groundwater demand (LULC changes) and measures based on the offer to obtain complementary resources to supply demands (water reuse and desalination).

3.1 Site description and data

- Location and extension of the pilot area (figure)
The Plana de Oropesa-Torreblanca aquifer is located in the Mediterranean region of EU, in the province of Castellón in Spain (See Fig. 1). It is a coastal aquifer that extends for 21 km parallel to the coast in a NE-SW direction, with a width of between 2.5 and 6 km, covering approximately 75 km^2 (Renau-Pruñonosa et al. 2016).

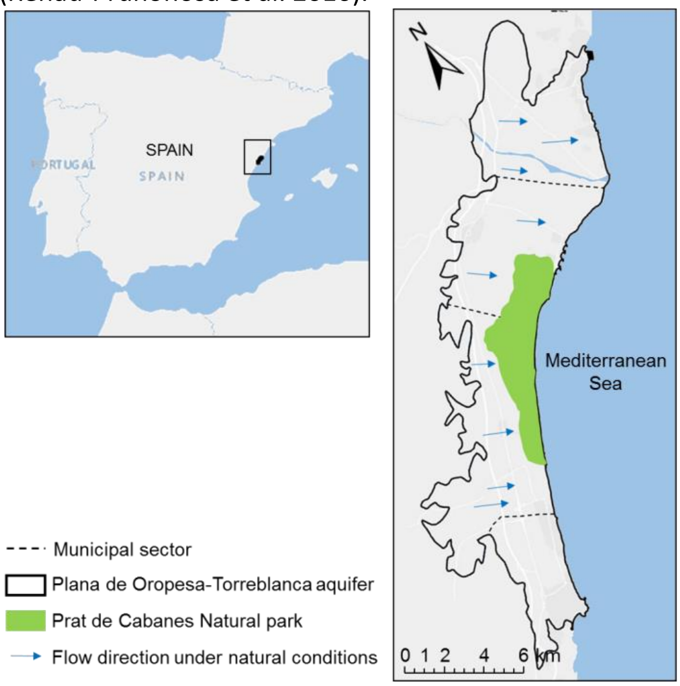


Fig. 1. Location of the pilot area

- Geology/Aquifer type

The Plana Oropesa-Torreblanca is an unconfined, heterogeneous, detrital and multilayer aquifer composed of gravel and sand levels in a silty clay matrix (Ballesteros et al. 2016). The Plioquaternary detrital materials comprising limestone pebbles, gravel and conglomerates derived from the adjacent mountain ranges, with abundant lenses of coarse sand, silt and clays. There are frequent lateral and vertical changes in facies and the overall distribution is irregular. The aquifer is overlain by more recent alluvial fans, colluviums, dunes and peatlands. The transmissivity ranges from 300 to 1000 m²/day (García-Menéndez et al. 2016) and the storage coefficient varies between 2 and 12%. Fig. 2 shows the geological map and two representative cross sections.

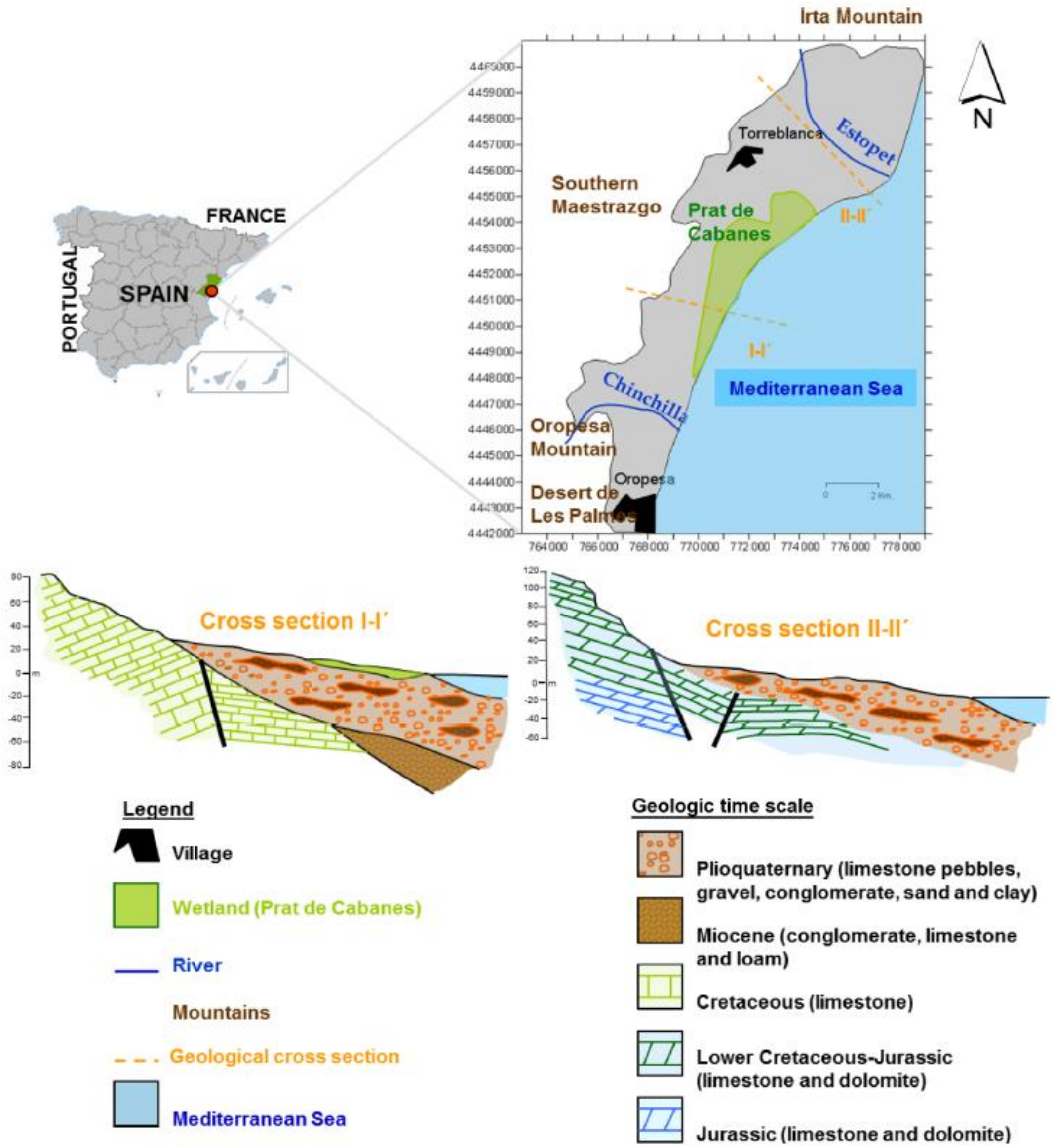


Fig. 2 Geological map and cross sections (Pulido-Velazquez et al. 2018)

- Geometry, Topography and soil types

The Plana de Oropesa Torreblanca is located in the eastern coast of Spain, in the Mediterranean Sea (Fig. 1). It is formed by an underlying aquifer which has the same name. Fig. 3 shows a representation of topography and bottom surface of the Plana de Oropesa-Torreblanca aquifer. This aquifer is wedge-shaped being the maximum thickest located near to the coastline, where it can reach 90 m thick. The area is predominantly flat and it is surrounded inland by mountain ranges. The soils in the Plana de Oropesa-Torreblanca mainly belong to the Entisol group (71.6%) and the Inceptisol group (28.4%) (IGME-DGA 2015)

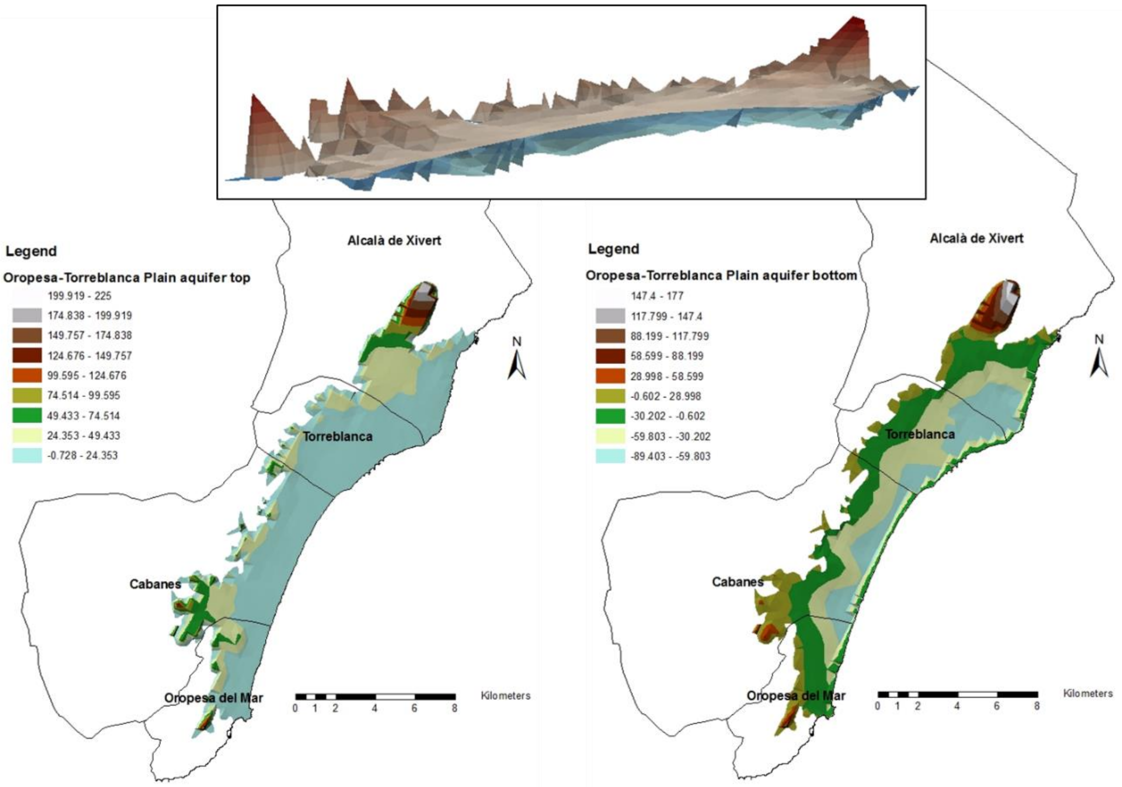


Fig. 3 Aquifer Geometry (top and bottom of the aquifer)

- ***Surface water bodies***

There is a wetland area of high environmental value known as “Prat de Cabanes”. It is one of the largest in the Region of Valencia (812 ha), and is listed under the RAMSAR convention (Convention on Wetlands of International Importance)—site No. 458 (RAMSAR Convention Bureau 1990). There is a well-developed typical wetland vegetation with submerged and emergent plants, halophytic and dune communities. There are also a number of endemic plants, fish, and invertebrates, and the area supports several species of nesting birds. Thus, it is also a Special Protection Area (SPA), as recognized under the European Union Directive on the Conservation of Wild Birds (Directive 2009/147/EC). The area extends from Torrenostra to Torre la Sal, with a transversal dimension of 1.5 km. It is permanently flooded, with a relatively slow process of siltation. It was developed through the long-term sedimentation of a coastal lagoon, underlain by extensive areas of peat, and is separated from the sea by a dune complex (Sanz-Garrido and Capilla 2015).

The seasonal variation of the rainfall and the groundwater table usually results in a very important reduction of the surface water in the wetland during late spring and early summer. In fact, according to the conclusions from different studies developed for the Spanish National Hydrologic Plan (Alfonso 2002), the hydrologic equilibrium of the area is seriously threatened and it is posing a severe risk for the wetland in terms of water balance and water quality (Sanz-Garrido and Capilla 2015).

- ***Hydraulic head evolution***

In the Plana de Oropesa-Torreblanca the hydraulic head usually varies between 0.25 and 0.5 m near the coast and it is depressed at certain times in zones close to the coast. At points furthest from the coast the hydraulic head is about 1.5-2.5 m a.s.l. Hydraulic head decreases from June to October and increase from Novemeber to May.
The increasing population since 1970 and the continuing agricultural exploitation have produced SWI problems of different entity in these aquifers. A continuous decreasing trend is observed from 1974 in a yearly scale.
Fig. 4 shows the hydraulic head in dry, medium and wet years. The main differences are the variation in the hydraulic gradient and the appearance of inverted flow in the south and east areas. In the southern sector, there are permanent SWI problems. To the east of Torreblanca there are also situations of piezometric depression in the dry years, although they seem to be restored in the middle and wet years.

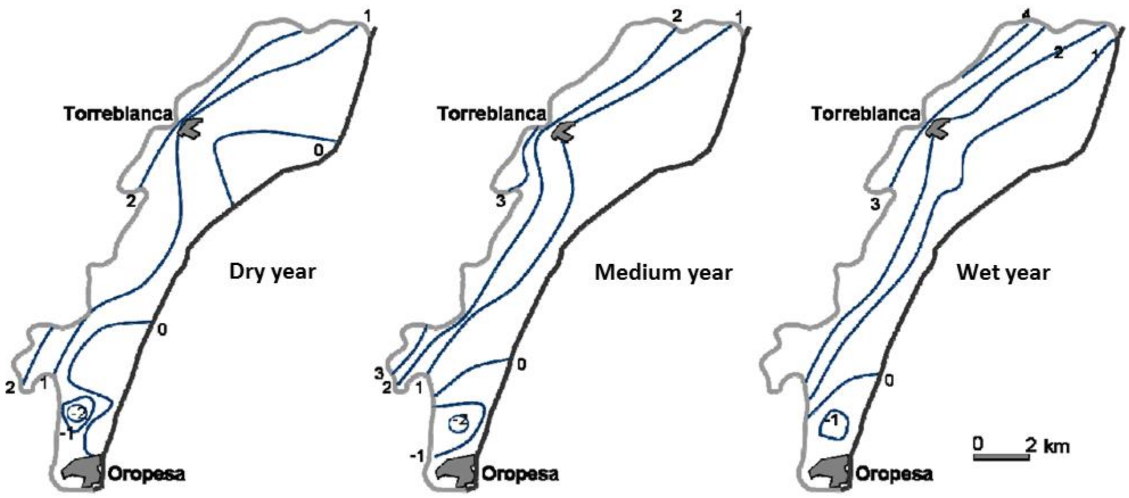


Fig. 4. Hydraulic head in dry, medium and wet years (modified from Renau-Pruñonosa 2013)

The hydraulic head tamporal evolution for some representative observation wells has been also represented in Fig. 5.

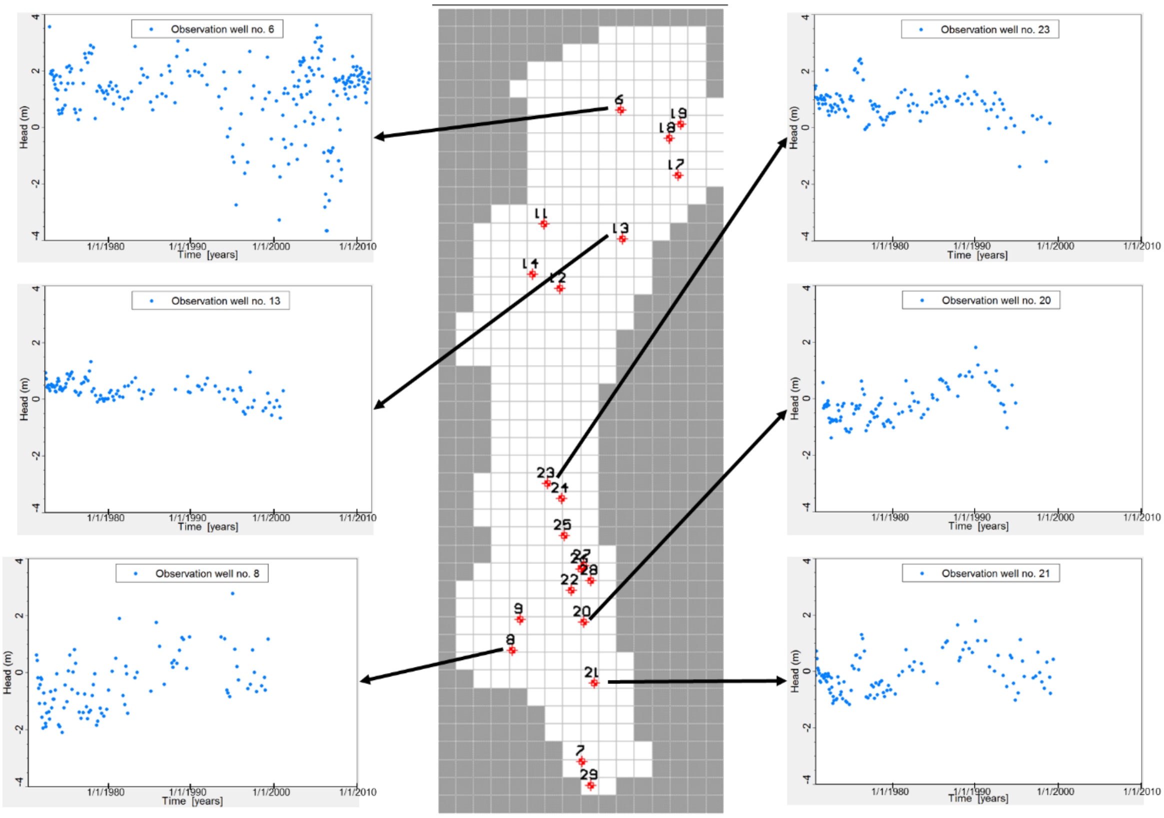


Fig. 5. Historical evolution of hydraulic head at some observation points

- ***Climate***

The Plana de Oropesa Torreblanca has a Mediterranean climate with hot, dry summers and wet winters. Historical monthly average precipitation (1973-2010) varied between 20-30 mm in summer and it reached almost 80 mm in the rainiest month. The monthly average Temperature changes from 12ºC to 28ºC throughout the year. Yearly scale does not show a clear trend in precipitation and temperature. Fig. 6 shows rainfall and temperature for the period from 1973 to 2009. Evapotranspiration in the wetland is estimated to be around 10.80 Mm^3/year.

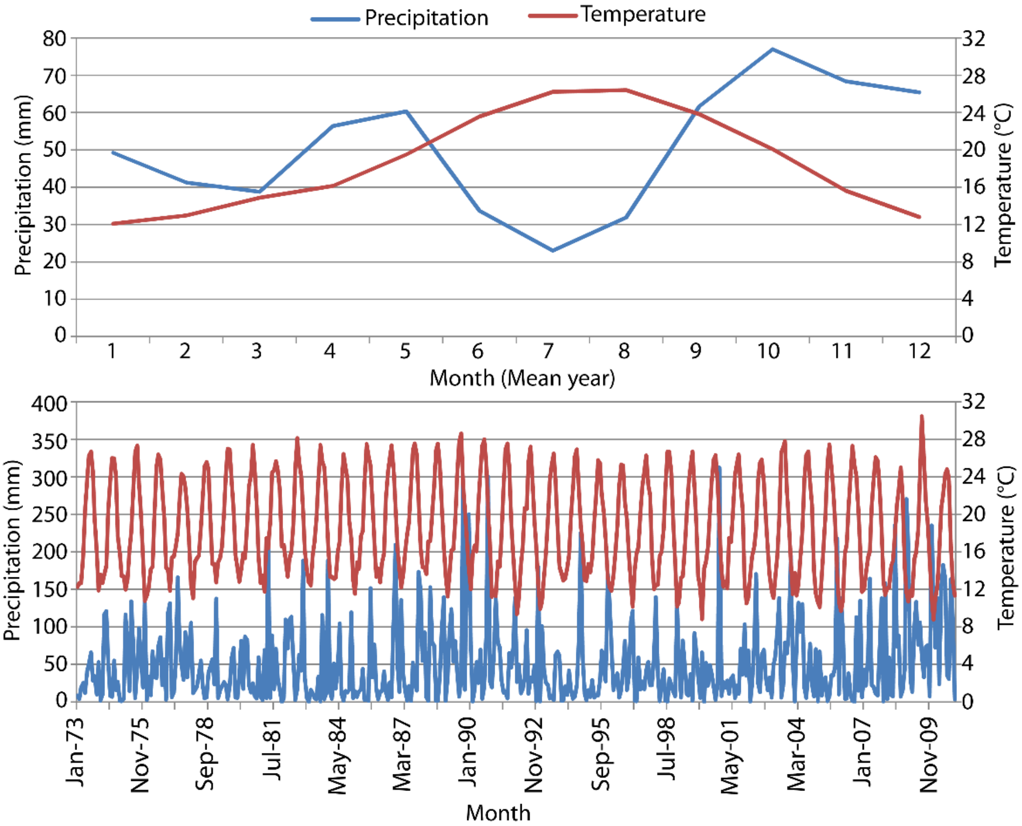


Fig. 6. Historical rainfall and temperature in Plana de Oropesa-Torreblanca aquifer (modified from Pulido-Velazquez et al. 2018)

- Land use

In the 1960s and early 1970s the Oropesa-Torreblanca Plain was sparsely populated and land was dedicated mostly to non-irrigated cropping. From 1975 to 1995 there was a significant transformation from dry to irrigated lands, especially in the period 1985–1995 (Pulido-Velazquez et al. 2018). From 1995 to 2010 the main change was an increase of artificial surfaces (mainly residential LULC along the coast) (Feranec et al. 2010) and an improvement in the efficiency of irrigation techniques (CHJ 2015). Fig. 7 shows the CORINE land use map in 2006 (Feranec et al. 2010).

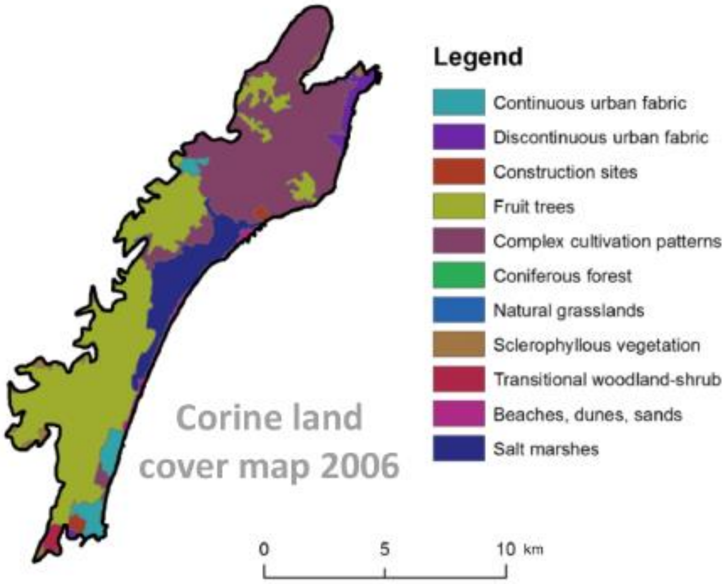


Fig. 7 CORINE Land use maps in 2006 (modified from Pulido-Velazquez et al. 2018)

- ***Abstractions/irrigation***

The land use changes are reflected in the evolution of total pumping in the Plana de Oropesa-Torreblanca aquifer. The transformation into irrigated croplands from 1975 to 1995 produce an increase in pumping and drawdowns of groundwater levels. In this period the SWI problem has grown. Later on, the transformation of irrigation techniques and land uses led to a reduction in pumping (Pulido-Velazquez et al. 2018).
Agriculture is the main economic pillar, with a greater water demand than other activities such as tourism or industry. The pumping for agricultural use is 32.5 Mm^3/year and for human consumption are 3.35 Mm^3/year making a total of 35.85 Mm^3/year (IGME-UJI 2009).
Fig. 8 shows the annual historical temporal evolution of the pumping.

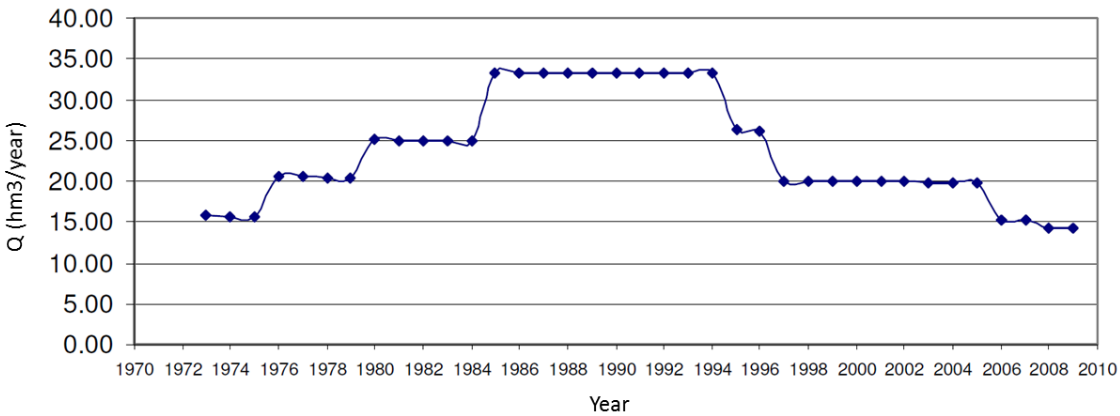


Fig. 8 Historical temporal evolution of pumping (Mm^3/y). (modified from Renau-Pruñonosa 2013)

- ***Flow balance components***

The main Groundwater flow direction is NW-SE under natural conditions (Morell and Giménez 1997; Renau-Pruñonosa et al. 2016). The aquifer is laterally connected with adjacent aquifers that produce inflows to the system. There is recharge that comes from infiltration of precipitation and irrigation returns. The groundwater outflows are produced by Pumping, discharge to the Prat de Cabanes wetland, and groundwater discharges to sea (Pulido-Velazquez et al. 2018). The mean flow balance in the period 1948-1983 is sumarized in Table 1.

Inflow/outflow	Flow balance
Inflows (Mm^3/yr)	
Rainfall recharge	7
Lateral transfer	4.3
Seepage from irrigation	12.7
Total inflows	**24**
Outflows (Mm^3/yr)	
Outflows to the sea	3.9
Drains	1.5
Groundwater pumping	18.6
Total outflows	**24**

Table 1. Approximate water balance in the Plana de Oropesa-Torreblanca aquifer in the period 1948-1983 (IGME 1989).

3.2 Climate change challenge

In accordance with the EEA map the main expeted issues due to CC in this case study are those described in Fig. 9 for the Mediterranean regions. Existing national assessments show significant potential reductions (around a 18% for the RCP8.5 emission scenario in the horizon 2071-2100) of the future aquifer recharge in the area (see Pulido-Velazquez et al., 2018)

The main challenge is to find adaptation measures to maintain a sustainable use of the groundwater body with a balance between supply water demands (different uses) under future climate change conditions and maintaining a good status in the aquifer (constraining SWI problems) and the related ecosystem.

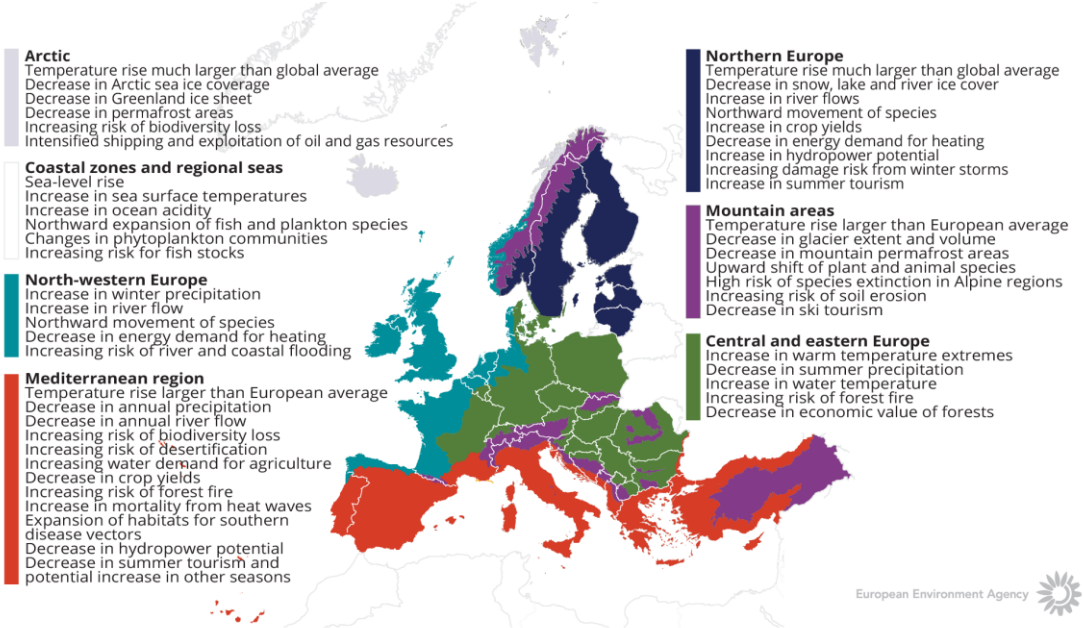


Figure 9. How is climate expected to change in Europe. The European Environment Agency map

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. In order to assess the hydrological impacts of those climatic and management scenarios we simulate them within a modelling framework based on a density-dependent SEAWAT model whose inputs are defined by a sequential coupling of different models (rainfall-recharge models, crop irrigation requirements and irrigation return models). It allows to estimate hydraulic head and chloride concentration fields within the aquifer from the historical period and other potential scenarios.

Representative future CC scenarios were generated by ensembles of different local projections and a future LULC scenario was defined in accordance with the plan approved by the local government (PGOU Torreblance, 2009). Four GC scenarios were defined by combining the LULC scenario and the CC scenarios. These GC scenarios have been propagated by simulating with the cited calibrated chain of models.

Finally, based on the outputs provided by this chain of models in the historical and future potential scenarios assessment, we will apply a method based on indices and variables to summarise SWI status and vulnerability at aquifer scale. It is described in detail in the Deliverable 5.2. The **inputs** required **and the steps to be followed** to apply the method are compiled in that cited report. Information on the aquifer volume affected by SWI at different spatial scales will be generated, moving from areal maps to representative conceptual cross section and lumped indices. The sensitivity of the affected volumes to the threshold employed to define them should be also tested. This threshold is defined from the natural background level in the aquifer. The proposed indices-based method has been implemented in a general GIS tool (Baena-Ruiz and Pulido-Velazquez., ur) to facilitate its application and comparison between SWI problems in different groundwater bodies and temporal periods. The resilience and trend of the system to SWI can be deduced from the time series of the proposed indices. Impacts of potential GC scenarios (CC and LULC change scenarios) can be also analysed. A published paper in Environmental Earth Science journal (Baena-Ruiz et al., 2020) shows an application of this method to analyse potential climatic scenarios. The method has been also applied to perform historical assessment (Baena-Ruiz et al., 2018). The deliverable 5.2 was made by compiling the methodological descriptions included in the cited papers. The partner will test the applicability of the method to different typologies of aquifers depending on the available information and previous modeling activities.

4.1.2 Future scenarios. Climate and land use data

Several future local CC scenarios have been generated for a short term horizon (2011-2035) under the most pessimistic emission scenario RCP8.5 included in the IPCC Fifth assessment report (AR5). Their impacts on SWI will be estimated by propagating them within the cited modelling framework. The outputs generated will be employed as inputs of the proposed method to analyze and summarize SWI at aquifer scale.

4.1.2.1 TACTIC standard Climate Change scenarios

The TACTIC standard scenarios are developed based on the ISIMIP (Inter Sectoral Impact Model Intercomparison Project, see www.isimip.org) datasets. The resolution of the data is 0.5°x0.5°C global grid and at daily time steps. As part of ISIMIP, much effort has been made to standardise the climate data (a.o. bias correction). Data selection and preparation included the following steps:

1. Fifteen combinations of RCPs and GCMs from the ISIMIP data set where selected. RCPs are the Representative Concentration Pathways determining the development in greenhouse gas concentrations, while GCMs are the Global Circulation Models used to simulate the future climate at the global scale. Three RCPs (RCP4.5, RCP6.0, RCP8.5) were combined with five GCMs (noresm1-m, miroc-esm-chem, ipsl-cm5a-lr, hadgem2-es, gfdl-esm2m).
2. A reference period was selected as 1981 – 2010 and an annual mean temperature was calculated for the reference period.
3. For each combination of RCP-GCM, 30-years moving average of the annual mean temperature where calculated and two time slices identified in which the global annual mean temperature had increased by +1 and +3 degree compared to the reference period, respectively. Hence, the selection of the future periods was made to honour a specific temperature increase instead of using a fixed time-slice. This means that the temperature changes are the same for all scenarios, while the period in which this occur varies between the scenarios.
4. To represent conditions of low/high precipitation, the RCP-GCM combinations with the second lowest and second highest precipitation were selected among the 15 combinations for the +1 and +3 degree scenario. This selection was made on a pilot-by-pilot basis to accommodate that the different scenarios have different impact in the various parts of Europe. The scenarios showing the lowest/highest precipitation were avoided, as these end members often reflects outliers.
5. Delta change values were calculated on a monthly basis for the four selected scenarios, based on the climate data from the reference period and the selected future period. The delta change values express the changes between the current and future climates, either as a relative factor (precipitation and evapotranspiration) or by an additive factor (temperature).
6. Delta change factors were applied to local climate data by which the local particularities are reflected also for future conditions.

For the analysis in the present pilot the following RCP-GCm combinations were employed:

Table 2. Combinations of RCPs-GCMs used to assess future climate

		RCP	GCM
1-degree	"Dry"	rcp4p5	hadgem2-es

	“Wet”	rcp6p0	noresm1-m
3-degree	“Dry”	rcp4p5	hadgem2-es
	“Wet”	rcp6p0	hadgem2-es

4.1.2.2 Local climate change scenarios generated in addition to the TACTIC standard

In Plana de Oropesa-Torreblanca, the generation of future local GC scenarios (including CC and LULC scenarios), and the description of the modeling framework employed to propagate their impacts is presented in detail in the paper Baena-Ruiz et al., (2020). Four potential future climate scenarios (CC scenarios) were generated for a short term horizon (2011-2035) under the most pessimistic emission scenario RCP8.5. They were defined by ensembles of 36 different local climatic projections generated by applying different statistical corrections (correction of first and second order moments) taking into account historical data and climatic projections simulated with 9 different climatic models, obtained by combining results from 4 RCMs nested to some GCMs (results from 5 GCM were employed, but the RCMs simulations were only available for some of those GCMs) generated in the framework of the CORDEX Project (2013). They have been generated under two conceptual approaches or downscaling techniques: bias correction techniques and delta change techniques (Räisänen and Räty, 2012).

We considered four options to define representative future scenarios by applying different ensembles of corrected projections. All of them will produce practically the same monthly changes in temperature and precipitation (Figure 12), but differences in other monthly statistic of the series as the standard deviation or the variability of the series. They are described in detail in Baena-Ruiz et al., (2020). Two ensemble scenarios were generated by an equi-feasible linear combination of all the future series generated by delta change (E1) or bias correction (E2). The bias correction techniques are based on the analysis of the statistical difference between the climatic variables in the historical data and the control simulations produced by the climate models for the same period. They aim to define a transformation function to correct the control series to obtain a better approximation of the historical statistic. They assume that in the future the bias between model and data will be the same as observed in the historical period (e.g. Watanabe et al., 2012; Haerter et al., 2011). The delta change approaches assume that the model can obtain a good approximation of the relative changes in climate variables’ statistics, but do not provide a good prediction of the absolute values. Accordingly, they try to characterize the “delta change” produced in the main statistics of the climatic variables by analysing the relative difference between the future and control scenario
simulations. The future series will be obtained by perturbation of the historical series in accordance with the estimated “delta change” (e.g. Pulido-Velazquez et al., 2011a, 2014; Räisänen and Räty, 2012). Two other options were defined by non-equifeasible ensembles defined by combining only the models (E3, for the delta change approach) or combinations of models and correction techniques (E4, for the bias correction techniques) that were “not inferior” (better calibrated) in terms of approaching the historical statistics (mean, standard deviation and asymmetry coefficients). These non-equifeasible ensembles we do not consider the inferior models because they provide worst approximations to the historical series that make us mistrust their predictions.

All these ensemble climate scenarios showed (Figure 10) an increase in mean temperature (≈ 1 °C on average) with respect to the historical period (1973–2010). The future mean rainfall showed a decrease (up to 24% monthly) for every month except September and October, in which a relative increase was predicted (up to 30%). These months are the rainiest in the study area and frequent storms occur. The local future scenarios show an increment in these extreme rainfall events (Pulido-Velazquez et al. 2018).

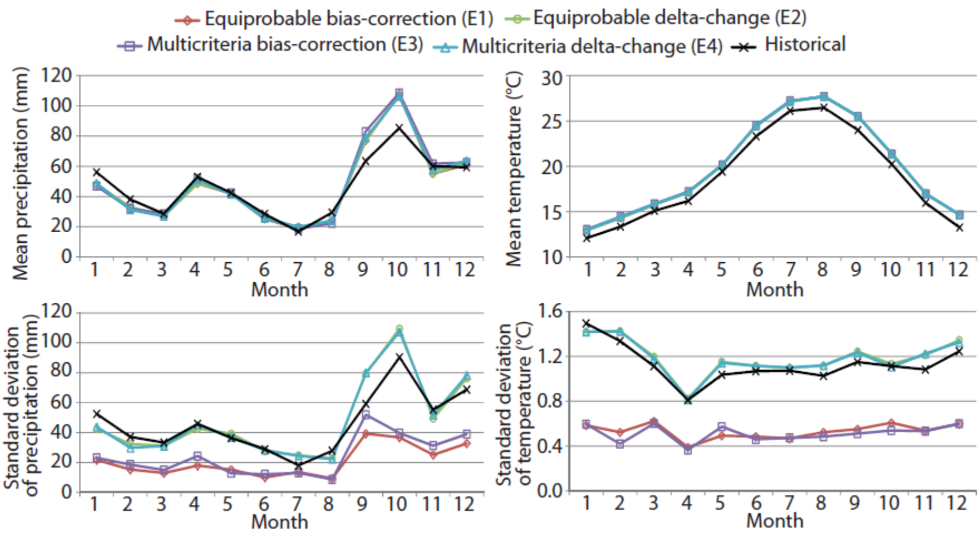


*Figure 10. Monthly mean and standard deviation of future temperature and precipitation for the f*our ensemble scenarios (taken from Pulido-Velazquez et al., 2018)

The changes in LULC were obtained from both fieldwork undertaken in the area and from the European CORINE Land Cover database (Feranec et al., 2010). These data were used to estimate the pumping and the irrigation returns.

The transformation from dry to irrigated croplands led to an increase in pumped abstractions that extended over 2 decades (1975–1995, especially in the period 1985–1995), provoking a drop in groundwater level and seawater intrusion problems. From 1995 to 2010 there was a progressive reduction in pumping due to the abandonment of certain crops and irrigated areas. The LULC information was used to estimate agricultural water requirements following a procedure to compute crop water requirements based on the FAO Irrigation and Drainage Paper (Allen et al., 1998). The estimated irrigation demands have also been employed to assess pumping taking into account information about the origin of the water that supplies each demand. The irrigation demands are multiplied by the irrigation return coefficients obtained for the crops in this area in previous studies (Tuñon, 2000) to assess recharge from irrigation.

The predicted future changes in LULC over the Plana Oropesa-Torreblanca are of greater magnitude than the historical ones and could drastically modify the rural and urban landscape (See Figure 11). The already-approved tourist developments (the public urbanization work – PAI – for the Marina d'Or Golf in Oropesa and Cabanes, and the General Town Plan – PGOU – for Torreblanca) anticipate an increase in population of more than 130 000 inhabitants, as well as the disappearance of most of the agricultural activity in the area. These significant changes in LULC will produce significant impacts on water demands, and, therefore in pumping and recharge and so to the hydrodynamics of the aquifer. In contrast, there are no significant changes to LULC anticipated in the area belonging to the municipality of Alcalà de Xivert, also situated on the Plana. These changes are described with more detail in Pulido-Velazquez et al., (2018).

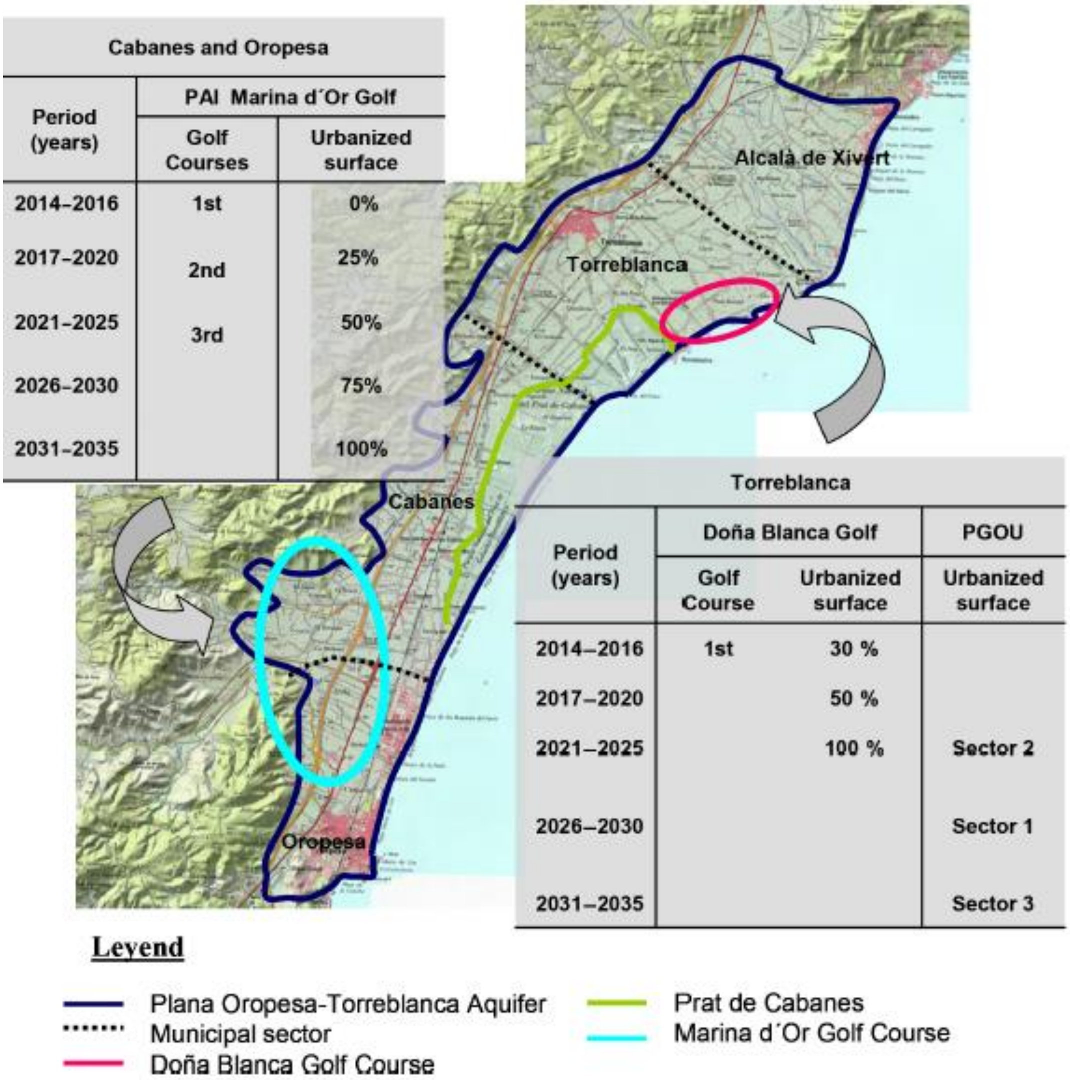


Figure 11. Future land use scenarios in 2035. (taken from Pulido-Velazquez et al., 2018)

Finally we considered 4 potential future scenarios:
- Baseline (BL) scenario: no LULC change and no CC
- LULC scenario: it considers the described future LULC scenario and assumes that there is not CC.
- GC scenarios (GC1, GC2, GC3, GC4) assuming constant sea level: we consider four GC scenarios that simultaneously consider the potential impacts of the described future LULC

scenario under the four generated CC scenarios (E1, E2, E3 y E4). The comparison of these scenarios with the BL provides information about the GC impacts.

4.2 Tool(s) / Model(s) set-up: chain of models (SEAWAT simulations) and proposed SWI assessment method (status and vulnerability)

A chain of models was defined to assess the impacts of the future scenarios on the hydraulic head and the chloride concentration within the aquifer. It is described in detail in Pulido-Velazquez et al., 2018. It includes a sequential coupling of three “auxiliary models” (rainfall-recharge models, crop irrigation requirements and irrigation return models) with this density dependent model SEAWAT model, in which the outputs of the auxiliary models are used as inputs of the groundwater model. The density dependent SEAWAT flow model was defined in accordance with the conceptual approach deduced from the available information in our case study. The aquifer is unconfined, heterogeneous, detrital and multilayer composed of gravel and sand levels in a silty clay matrix (Ballesteros et al., 2016). The transmissivity in the Plio-Quaternary Plana de Oropesa-Torreblanca aquifer ranges from 300 to 1000 m^2/day (García-Menéndez et al., 2016) and the storage coefficient varies between 2 and 12%. Groundwater flow approximately follows a NW-SE direction before discharging to the sea. The range of piezometric levels varies in the Plana de Oropesa-Torreblanca reaching maximum about 3 m a.s.l. at points furthest from the coast. The piezometric level is depressed in zones close to the coast. Aquifer geometry is derived from previous 3D models (Renau Pruñonosa 2013). The Plana de Oropesa-Torreblanca aquifer is wedge-shaped being the maximum thickest located near to the coastline, where it can reach 90 m thick.

The SEAWAT model was calibrated in accordance with the available historical information about hydraulic head (described in Section 3.1. See Figure 5) and chloride concentration within the aquifer. There are no chloride concentration data for this study area from 1988 to 1989 neither from 2001 to 2005. The number of monitoring points of chloride concentration varies over time between 12 and 34, while the monitoring points of hydraulic head ranges between 9 and 1.

The chloride concentration exceeds 1000 mg/l in zones close to the coast. Points inland exhibit lower concentrations that are more stable through time. Concentrations increased over the 1980s as a consequence of the expansion in irrigated croplands, associated with a period of scarce rainfall. Subsequently, there was a drop in mean chloride concentrations due to the reduction in pumping, together with improved hydrological planning (Figure 12).

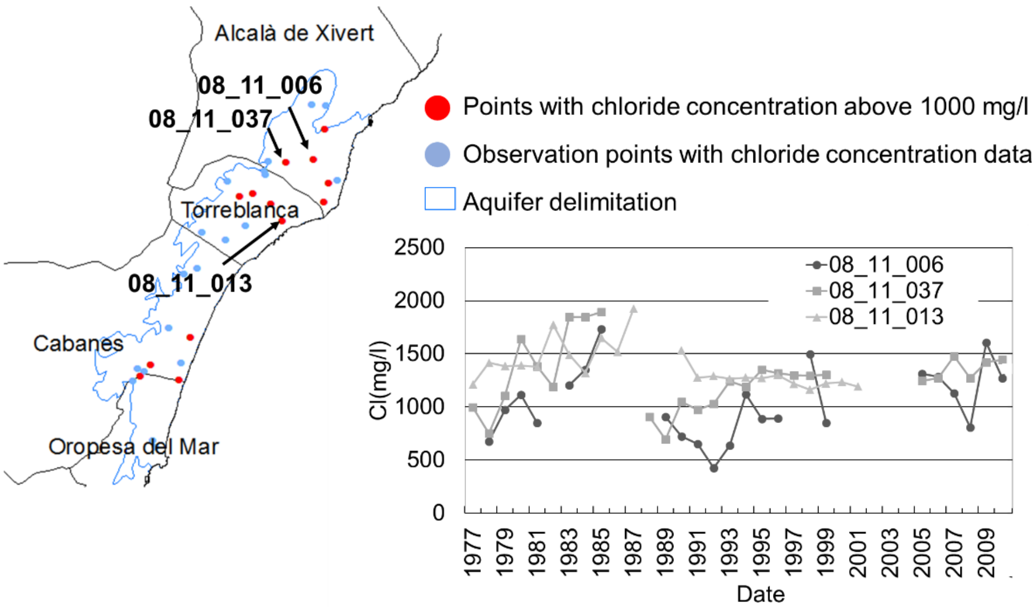


Figure 12 Location of the observation points in Plana de Oropesa-Torreblanca and evolution of the chloride concentrations in monitoring points (modified from Baena-Ruiz et al., 2018)

Groundwater flow approximately follows a NW-SE direction before discharging to the sea. The range of piezometric levels varies in the Plana de Oropesa-Torreblanca reaching maximum about 3 m a.s.l. at points furthest from the coast. The piezometric level is depressed in zones close to the coast. Aquifer geometry is derived from previous 3D models (Renau Pruñonosa 2013).

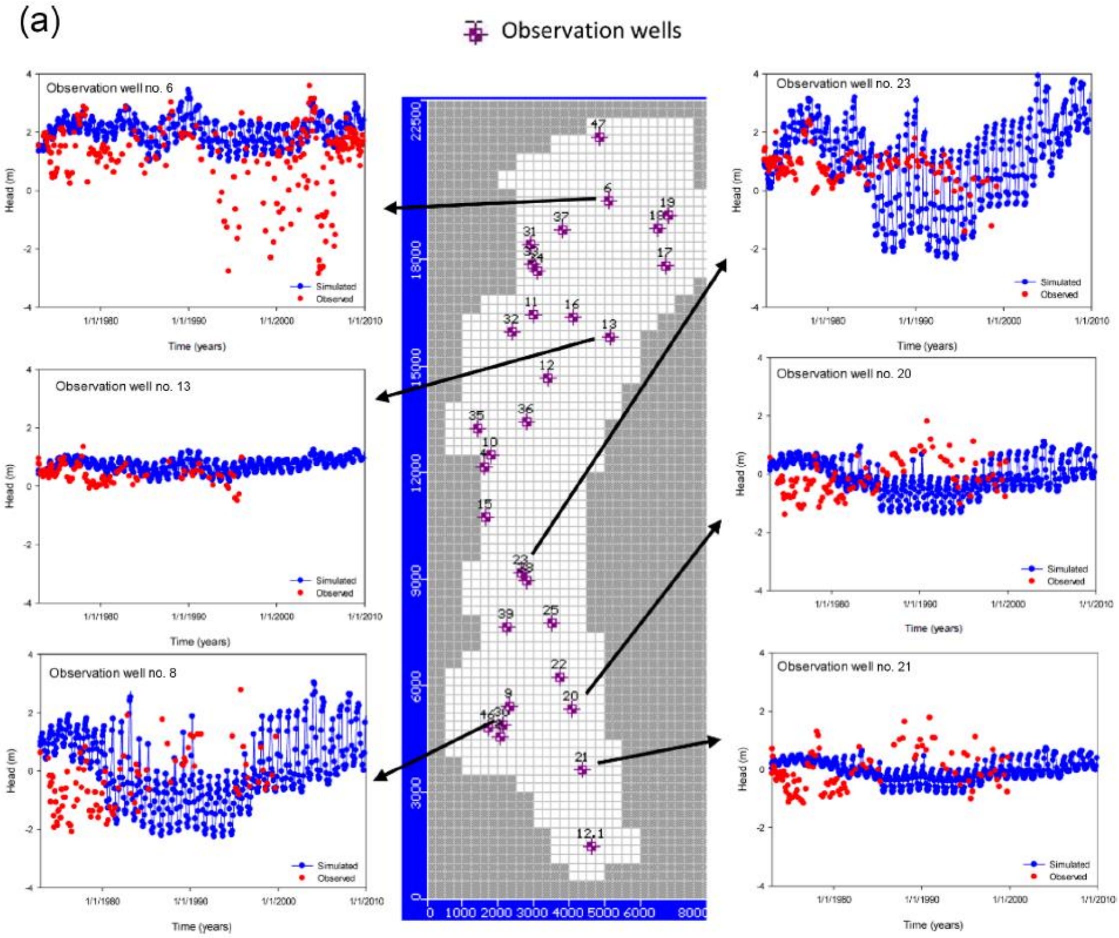
The chain of models were employed to assess the information required by the proposed **method/tool (Deliverable 5.2) in order to assess and summarize the status and vulnerability** to SWI through visual pictures and time series. The **inputs** of this method have been taken from the outputs and data integrated within the chain of models. They include variables (to characterize the historical evolution of hydraulic head and chloride concentration) and parameters (to define aquifer geometry and hydrodynamic behavior) to determine the overall status of the aquifer. For the vulnerability assessment and analyses, other intrinsic information (aquifer type, conductivity, distance from the shoreline, bicarbonate concentration) is also needed as inputs to apply the proposed method. It is based on the SWI vulnerability maps generated by applying the GALDIT method (Chachadi and Lobo-Ferreira 2005), which is described in detail in Deliverable 5.2. A chloride concentration threshold is used to determine the volume of aquifer affected by SWI. Different method can be applied to define this threshold value (see deliverable 5.2). In this application we have performed a sensitivity analysis of the proposed method results to the adopted threshold values, by assuming two different potential values. The **final results** SWI status and vulnerability results will be summarized by using: 1. Maps of SWI affected aquifer volumes; 2. 2D conceptual cross-sections (with mean penetration and thickness in specific dates or mean values in periods); 3. Lumped Index (Mass of affected area and lumped vulnerability index) to summarise the global dynamic of SWI within the aquifer.

4.3 SEAWAT Model calibration / test

The SEAWAT model was calibrated by a trial and error procedure to minimize the differences between the model results and the observations. It is described in detail in Pulido-Velazquez et al., 2018.

4.3.1 Observation data

The model reproduce with a reasonable accuracy the trends and dynamic of the historical hydraulic head and chloride concentration (see Figure 13a and 13b respectively) for the period 1973–2010.



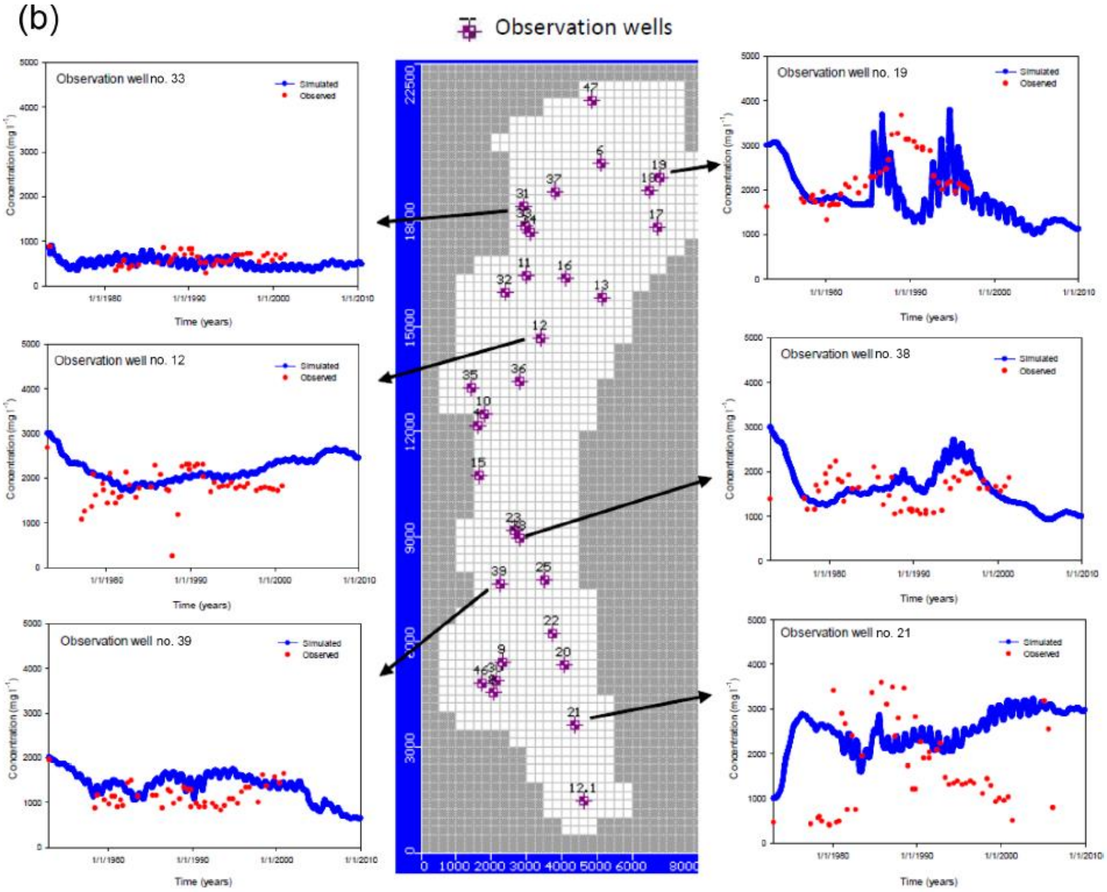


Figure 13. (a) Hydraulic head obtained with the models vs. data at some observation points. (b) Salinity obtained with the models vs. Data at some observation points. (Figure taken from Pulido-Velazquez et al., 2018)

The chain of cited models were employed to estimate the information required by the proposed method/tool (Deliverable 5.2)

5 RESULTS AND CONCLUSIONS

In this section we show the results for the historical and future potential scenarios assessment. We have split them in: results from the chain of models that integrates SEAWAT simulations (described in subsections 5.1, 5.2 and 5.3), which were employed to generate the inputs of the proposed method to assess SWI status and vulnerability; and results obtained when applying the proposed index method to assess and summarise SWI status and vulnerability (subsections 5.4, 5.5 and 5.6).

5.1 SEAWAT simulation of historical conditions. Inputs required to apply the proposed method to assess historical SWI.

We include an example of the historical maps of chloride concentration and groundwater volumes/resources (Figure 14) generated to apply the method to assess and summarize SWI status. They were generated from the described chain of models that includes SEAWAT simulations. In the presented maps for October 1985, we have represented the mean chloride concentration in the aquifer depth. The historical status shows that the majority of the aquifer is affected by high chloride concentration. In most of the aquifer area (more than 80 %), the salinity is above 1100 mg/l, and, therefore, it is in general affected by intrusion.

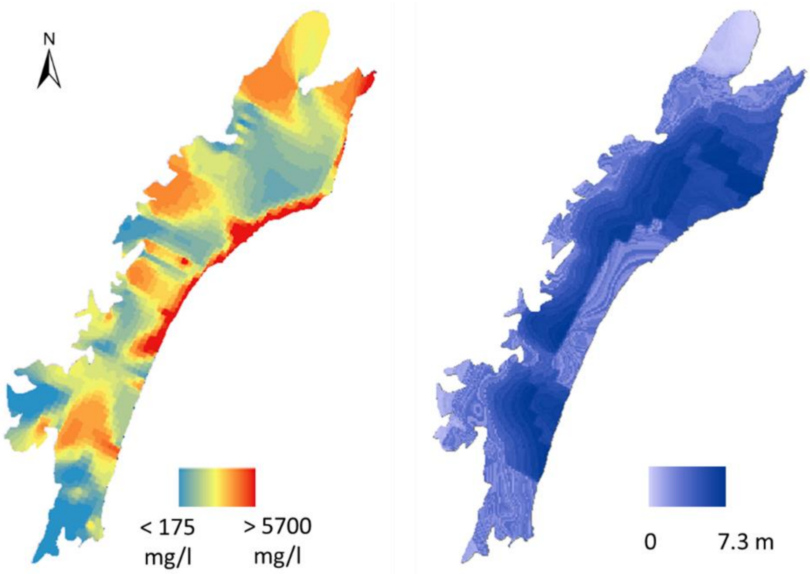


Figure 14. Historical maps of chloride concentration (left) and groundwater resources (right) (October 1985)

We also show an example of the historical vulnerability maps required to assess SWI vulnerability (Figure 15). In general, the Plana de Oropesa-Torreblanca aquifer is highly vulnerable due to the characteristics of its formation (it is an aquifer lying parallel to the coast with a wedge shaped geometry, very shallow inland, thicker close to the coastline, and with high conductivity) and to the elevated chloride concentration along the coastline.

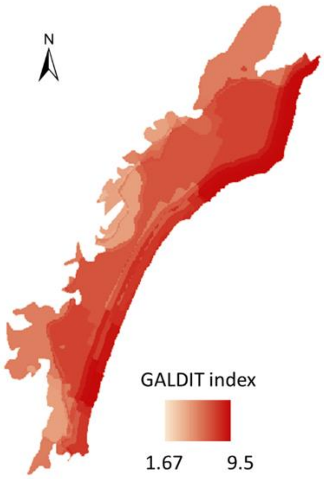


Figure 15 Historical maps of vulnerability (October 1985)

5.2 SEAWAT simulations of future scenarios. Inputs required to apply the proposed method to assess future SWI.

This section shows an example of the future maps of chloride concentration and groundwater resources (Figure 16) required to apply the method to assess and summarize impacts on SWI status. They were generated by propagating the described GC scenarios. The expected future climatic conditions would have a negative impact on the salinization of the aquifer resources, and also on the aquifer vulnerability to SWI.

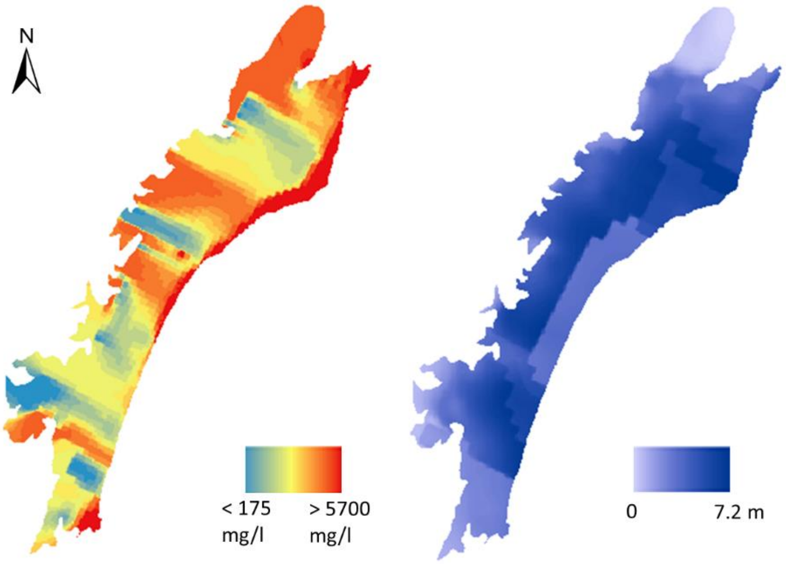


Figure 16. Maps of potential future chloride concentration and groundwater resources for the simulated scenario GC4 (September 2027)

We have also included an example of the future vulnerability maps for the simulated scenario GC4 (Figure 17). It shows that the vulnerability is less sensitive to CC due to other factors that are used in the index (conductivity and distance from the coast), which have greater weight and are invariant in time.

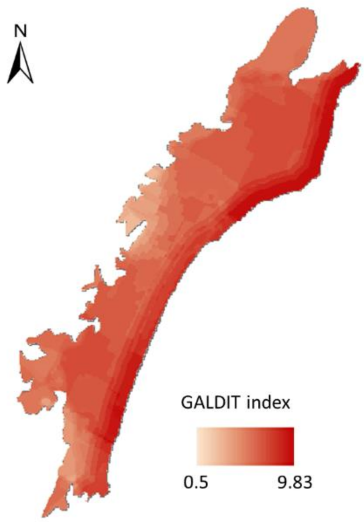


Figure 17 Maps of potential future vulnerability for the simulated scenario GC4 (September 2027)

5.3 Uncertainty on future impacts simulated with SEAWAT

There are significant uncertainties in future GC conditions and their impacts. In this report we do not intend to perform a detailed analysis of hydrological uncertainty. For an appropriate uncertainty analyses of hydrological impacts it would be more appropriate to obtain results from each individual climate model projections instead to the ensemble scenarios employed in this study. Note that it would require us to deal with different sources of uncertainty (Matott et al., 2009). The complexity is even greater for the presented methodology, since it entails the coupling of several numerical codes and a large amount of data and a long simulation time period.

5.4 SWI Method results: Maps of SWI status and vulnerability

Following the steps described in section 2.1.1 and 2.2.1 of Deliverable 5.2 we obtain the maps of affected volumes in terms of SWI status and vulnerability respectively. We assumed two different chloride concentration threshold values to identify groundwater volumes affected by SWI. The adopted thresholds are 250 mg/l, which is the consumption limit and the default value adopted in other previous studies (Ballesteros et al. 2016); and 1100 mg/l. It allows us to show the sensitivity of the results to this parameter.

The affected volume using a threshold of 250 mg/l is much greater than when using a 1100 mg/l threshold (Figure 18). This phenomenon highlights the need to determine properly this threshold in each aquifer, since the assessment of whether there are SWI problems is quite sensitive to this value. Nevertheless, in both cases the majority of the aquifer volume is affected by SWI.

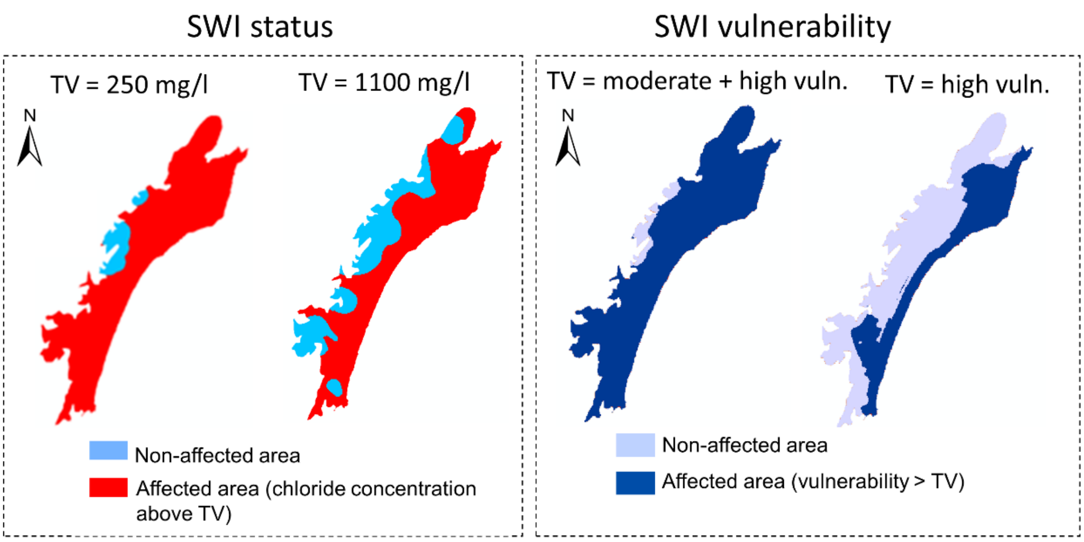


Figure 18. Maps of historical SWI status and vulnerability "affected volumes" (October 1985)

In the future assessment, we have considered only one threshold value (1100 mg/l for SWI status and the high vulnerability values of the GALDIT index to assess vulnerability to SWI). In terms of SWI status, the worst hypothetical scenario is the GC4, in which practically the whole aquifer would have a chloride concentration above 1100 mg/l (Figure 19). In GC4 scenario the aquifer would suffer an increment of 10% in the affected volume compared to the baseline scenario in 2010 (the starting point of the future period in this study). Nevertheless, the aquifer already had a large affected volume in 2010 (more than 80%) (Pulido-Velazquez et al. 2018). The affected areas in terms of high vulnerability is significantly smaller (less than 40%). The GC4 scenario shows a zone of high vulnerability at the north of the aquifer that corresponds with an area with high conductivity.

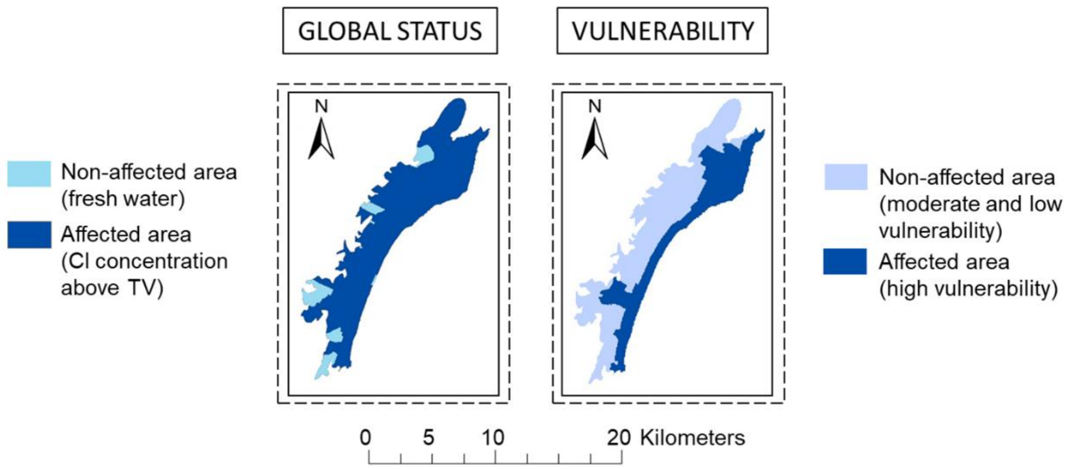


Figure 19. Maps of potential future SWI status and vulnerability "affected volumes" for the GC4 simulated scenario (September 2027)

5.5 SWI Method results: 2D conceptual cross-sections (mean penetration and thickness)

Following the steps described in section 2.1.2 and 2.2.2 of Deliverable 5.2 we obtain the conceptual cross section to summarise results in terms of SWI status and vulnerability respectively. They are also obtained for two different values of the thresholds values in the historical period to SWI status (250 mg/l and 1100 mg/l) and vulnerability (moderate + high vulnerability and high vulnerability) to show the sensitivity of the results to this parameter (Figure 20). Again, this conceptual-visual approach show the high volume of groundwater affected by seawater intrusion within the aquifer, and the sensitivity of the results to the adopted threshold.

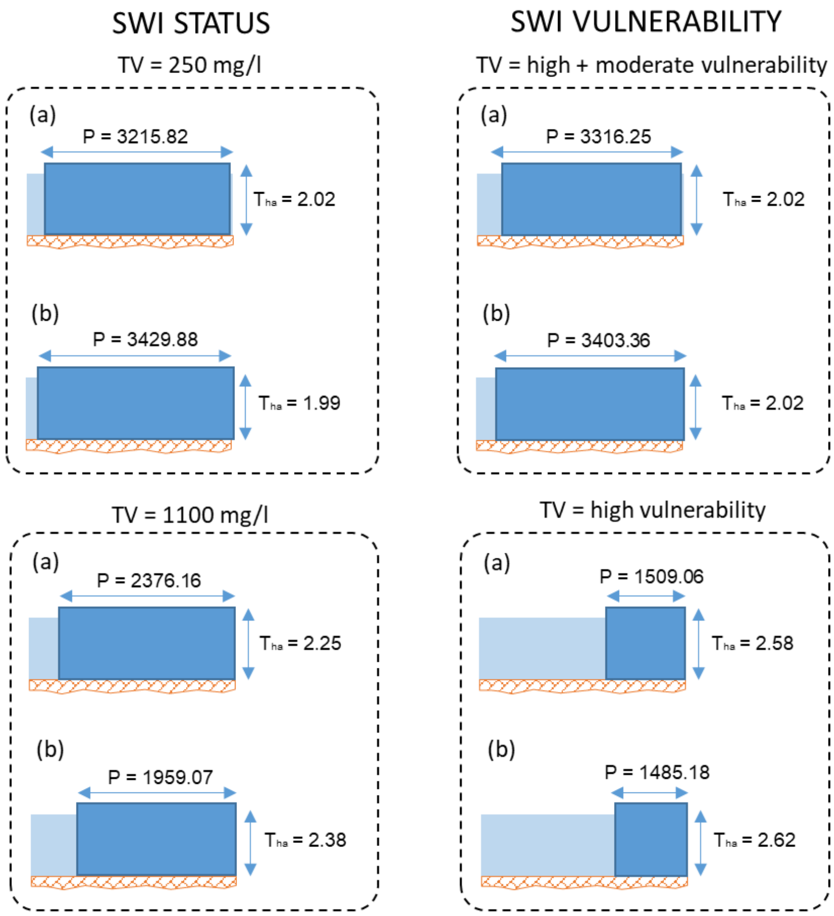


Figure 20. 2D conceptual cross-sections. Historical results in October 1985 (a) and mean values for the period 1973-2010 (b) (units in m)

In the future assessment we considered only one threshold value (1100 mg/l for SWI status and the high vulnerability values of the GALDIT index to assess vulnerability to SWI) (Figure 21).

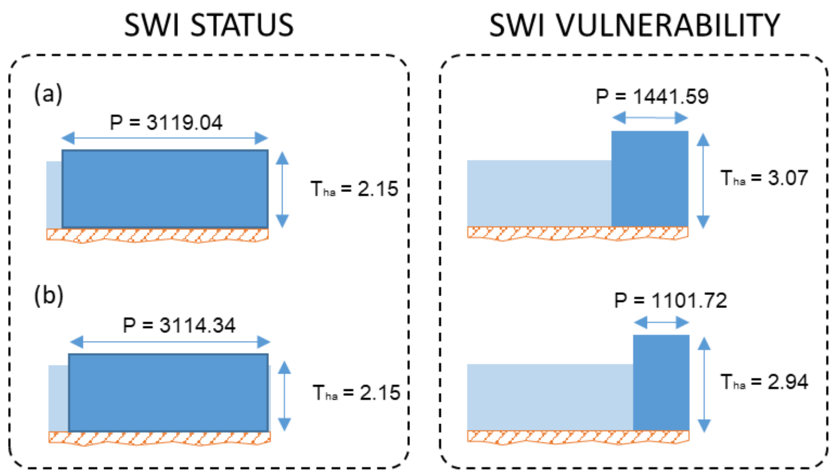


Figure 21. 2D conceptual cross-sections. Potential Future Results for the simulated scenario GC4 in September 2027 (a) and mean values for the period 2011-2035 (b) (units in m)

All potential future GC scenarios would undergo an increase in the average affected volume in accordance with the conceptual cross section, although the aquifer was largely affected in the historical period (Pulido-Velazquez et al. 2018).

5.6 SWI Method results: Lumped indices Ma and L-GALDIT.

Following the steps described in section 2.1.3 and 2.2.3 of Deliverable 5.2 we obtain the lumped indices Ma and L-GALDIT, to summarise the global dynamic of affected volumes in terms of SWI status and vulnerability respectively (Figure 22).

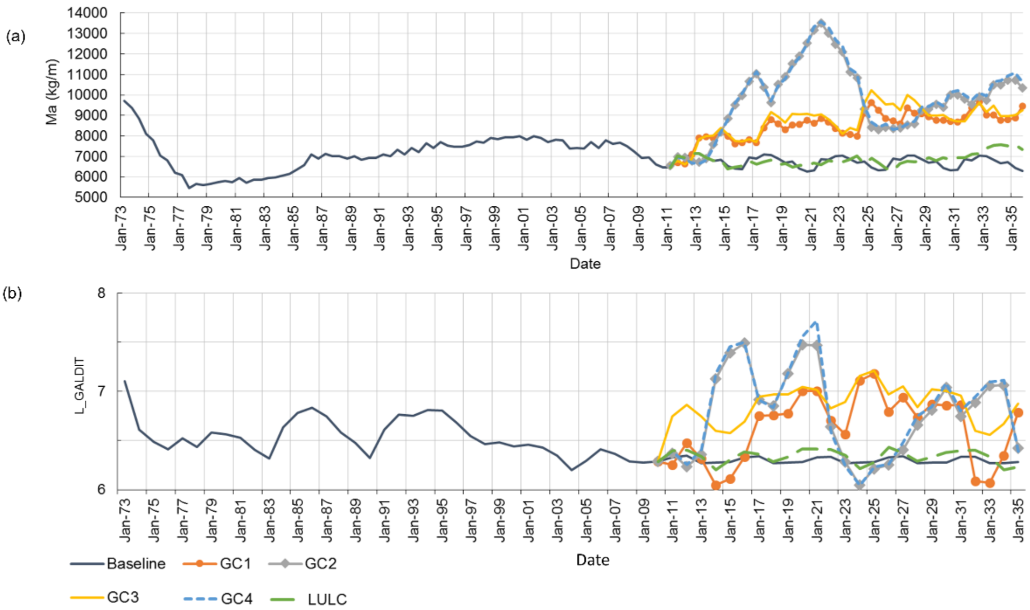


Figure 22. Time series of the indices Ma and L-GALDIT in the historical (1973-2010) and potential future results for the simulated scenarios in the horizon 2011-2035 (modified from Baena-Ruiz et al., 2020).

The result show that the future LULC changes scenario would not produce a clear deterioration of the global status and vulnerability of the aquifer. The continuous growing trend (in the LULC and GC scenarios) in the Ma index observed from 2025 is related to the impacts of the planned urbanization of a large area in Torreblanca, which produces an increase of chloride concentrations. GC scenarios forecast a large affected mass in the future, which is mainly due to the potential climatic conditions. The maximum values of the lumped indices (Ma and L_GALDIT) during the GC scenarios are induced by periods with high temperature and low precipitation.
The LULC scenario does not produce significant changes in the vulnerability. The vulnerability is more sensitive to the GC scenarios. All of them show a significant increase in its variability and

a mean increase in the vulnerability, but there are some periods in which the vulnerability even decreases.

From this future series we can assess the recovery/degradation rate (see Deliverable 5.2) of the lumped index Ma (Figure 23).

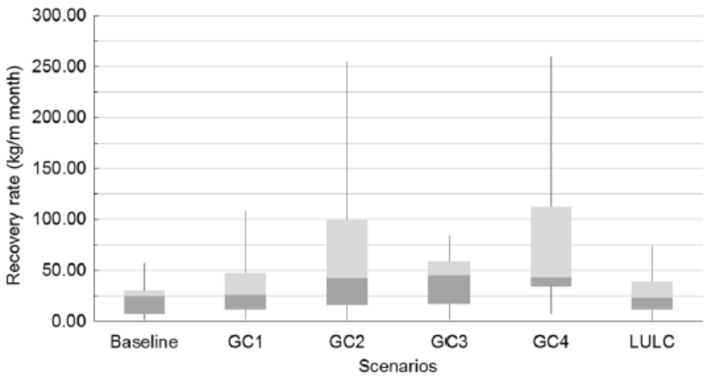


Figure 23. Statistics of recovery rate for all scenarios analyzed in the simulated scenarios in the horizon 2011-2035.

It shows that the aquifer is able to respond to the severe climatic conditions estimated in GC scenarios. Based on the calibrated model, GC2 and GC4 scenarios present more extreme values, but also show higher recovery rates.

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Establishing the European Geological Surveys Research Area to deliver a Geological Service for Europe

Deliverable 3.2 and 6.3

PILOT DESCRIPTION AND ASSESSMENT

Segura Basin

Authors and affiliation:

Juan de Dios Goméz-Gómez, AJ. Collados-Lara, David Pulido-Velazquez, Leticia 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	D3.2 & D6.3
Dissemination level	Public
Deliverable name	Pilot description and assessment
Work package	**WP3:** INTEGRATED GROUNDWATER - SURFACE WATER ASSESSMENT OF CLIMATE CHANGE **and WP6:** GROUNDWATER ADAPTATION STRATEGIES

Lead WP/Deliverable beneficiary	WP3 (GEUS); WP6 (IGME)
Deliverable status	
Version Date	Final version 09/03/2021

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LIST OF ABBREVIATIONS & ACRONYMS

SB: Segura Basin
CU: Conjunctive Use

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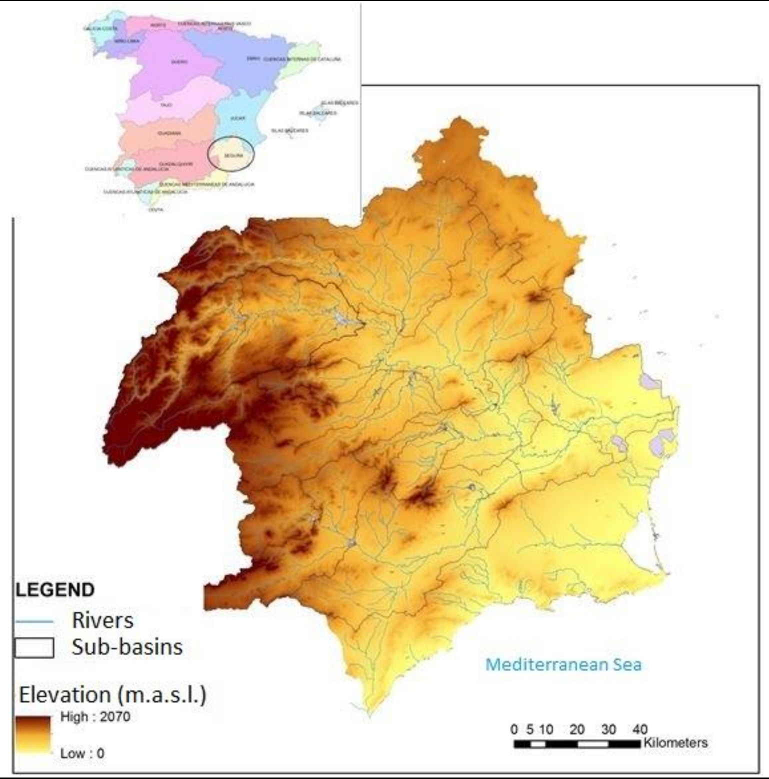
1 EXECUTIVE SUMMARY

Pilot name	SEGURA BASIN	
Country	Spain	
EU-region	Mediterranean region	
Area (km^2)	14778 km^2	
Aquifer geology and type classification	Detrital and carbonated. Sedimentary & karstic.	
Primary water usage	Irrigation / Drinking water / Industry	
Main climate change issues	This coastal basin is an example of a Mediterranean area with a significant water demand, mainly for irrigation but also for urban supply (with an important seasonal component for the touristic sector), and low availability of resources. The supply reliability in this case depends on an appropriate conjunctive use (CU) operation of resources taking into account the interaction between surface and groundwater resources. In fact, it is a deficitary system that needs water transfers from Tagus Basin and addicional supply from desalination plants. Global change will exacerbate these problems by reducing the availability of resources and increasing irrigation requirements (higher temperatures and lower precipitations). It will also cause an incraese in the magnitude and frequency of extreme phenomena such as floods and droughts. An integrated analysis of future climate change impacts and adaptation strategies based on some indexes obtained from the results of a system management model is proposed to help in the decision making process.	
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., 2018) and definition of adaptation scenarios. Propagation with a chain of auxiliary models (recharge, agricultural) to generate inputs for a CU management model at basin scale, defined with the AQUATOOL code; Assessment of different types of drought and its propagation.	

Key stakeholders	Segura River Basin Authority, farmers associations, Canal del Taibilla (public water supply company), Regional Authorities, Environmental Conservation Groups.
Contact person	J.D. Gómez, D. Pulido, L. Baena, A.J. Collados. IGME (Spain): j.dedios@igme.es; d.pulido@igme.es; l.baena@igme.es; aj.collados@igme.es

This pilot is an example of a Mediterranean coastal basin with a significant water demand, mainly for irrigation but also for urban supply (with an important seasonal component for the touristic sector), and low availability of resources. The supply reliability in this case depends on an appropriate conjunctive use (CU) operation of resources taking into account the interaction between surface and groundwater resources. In fact, it is a deficitary system that needs water transfers from Tagus Basin and addicional supply from desalination plants. Global change will exacerbate these problems by reducing the availability of resources and increasing irrigation requirements (higher temperatures and lower precipitations). It will also cause an incraese in the magnitude and frequency of extreme events such as floods and droughts. An integrated analysis of future climate change impacts and adaptation strategies based on some indexes obtained from the results of a system management model is proposed to help in the decision making process.

Local future climate change and adaptation scenarios has been developed to analyse droughts following the method proposed in the framework of this project (Collados-Lara et al., 2018). They have been propagated with a chain of auxiliary models (recharge, agricultural) to generate inputs for a CU management model at basin scale, defined with the AQUATOOL code. Finally different types of drought and its propagation have been assesed.

Results observed for the whole Segura Basin system for the period 2071-2100 show lower resources available to meet the different demand elements, which means higher deficits for that demands. Higher pumping rates in aquifers are estimated for future scenarios and the impacts would also be reflected on lower guarantees to meet demands. The four studied scenarios show important reduction of precipitation and increase of temperature and large increments of the number, duration, intensity and magnitude of droughts. The study of the correlation of hydrological and meteorological droughts shows significant correlations for a gap from 0 to 6 months depending of the scenario considered. However the correlation of meteorological and operational droughts shows a maximum of correlation for a gap around 4 months for all cases.

2 INTRODUCTION

Climate change (CC) already have widespread and significant impacts in Europe, which is expected to increase in the future. Groundwater plays a vital role for the land phase of the freshwater cycle and have 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. In order 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 infra structure 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 Segura basin pilot is one of the basin scale pilots that have been analysed in Tactic, focusing on climate change impacts and adaptation strategies with special attention to the propagation of drought events. So the main challenge of the pilot is to perform an integrated analysis of future climate change impacts and adaptation strategies based on some indexes obtained from the results of a system management model.

3 PILOT AREA

The Segura basin is a representative case of a Mediterranean basin with semi-arid climate. It is located in one of the driest regions of Spain, with low availability of resources but significant water demand. Agriculture is the main socioeconomic activity in the middle and lower basin together with the touristic activity in the coast. The supply reliability in this case depends on an appropriate conjunctive use (CU) operation of surface and groundwater resources. In fact, it is a deficitary system that needs water transfers from Tagus Basin (in Central Spain), causing social conflicts between regions, and addicional supply from desalination plants. This problem might be exacerbated in the future due to climate change impacts (higher temperatures, lower precipitations and more extreme phenomena). So the aim of this case study is to perform an integrated analysis of future climate change impacts and adaptation strategies based on some indexes obtained from the results of a system management model.

3.1 Site description and data

- Location, extension and topography of the pilot area

The case study cover and area of 14778 km^2 located in Southeastern Spain, in the Mediterranean region of the EU (See Fig. 3.1). The River Segura is the main stream of the basin together with its tributaries Mundo, Argos, Quípar, Mula and Guadalentín. The main city of the system is Murcia with a population of 440,000 inhabitants, and also Alicante (330,000) is partially supplied by the system.

The altitude ranges from 2070 m.a.s.l. at the Sierra de Segura mountains (Northwest) to 0 m.a.s.l. at the seashore.

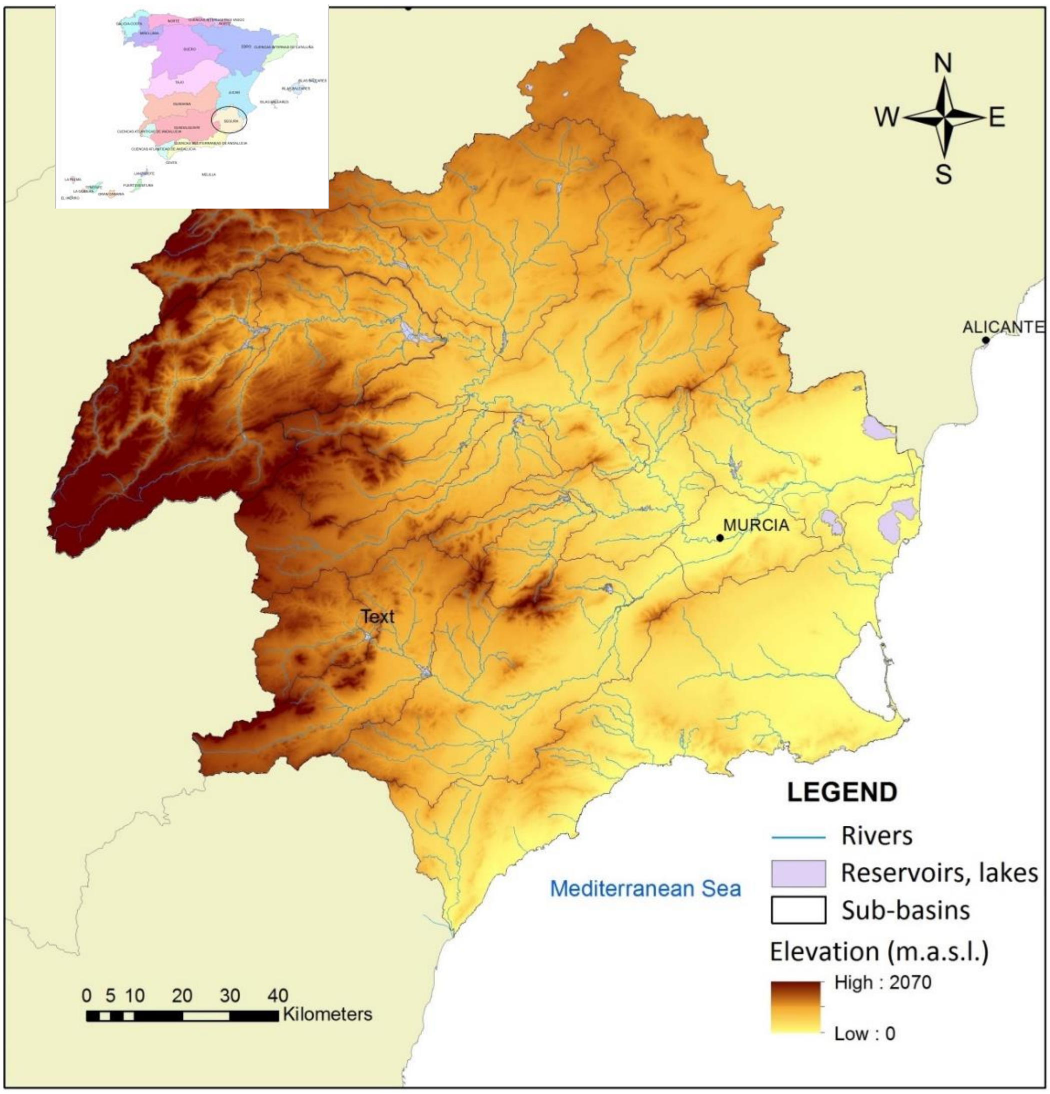


Fig. 3.1. Location of the pilot area

- Geology/Groundwater bodies type

The Segura Basin is almost totally included in the geological domain of the Bética Mountain Range. Only in its northern part, materials from the tabular cover overlying the Hercynian basement can be found. The Bética Mountain Range is the group of mountain chains generated by the Alpine folding that extends across Andalusia, Murcia and south of Valencia.

A total of 60 GW bodies are included in the Segura Basin, with a complex geology and different lithologies such detrital as carbonate and mixed (see Fig. 3.2).

One of the main groundwater bodies in the system is the Middle-Lower Segura Plain, a Plioquaternary aquifer located in the lower part of the basin, partially connected to the sea, wich concentrates most of the urban and agricultural water demands of the system. It has been thoroughly studied and described, and several models have been developed.

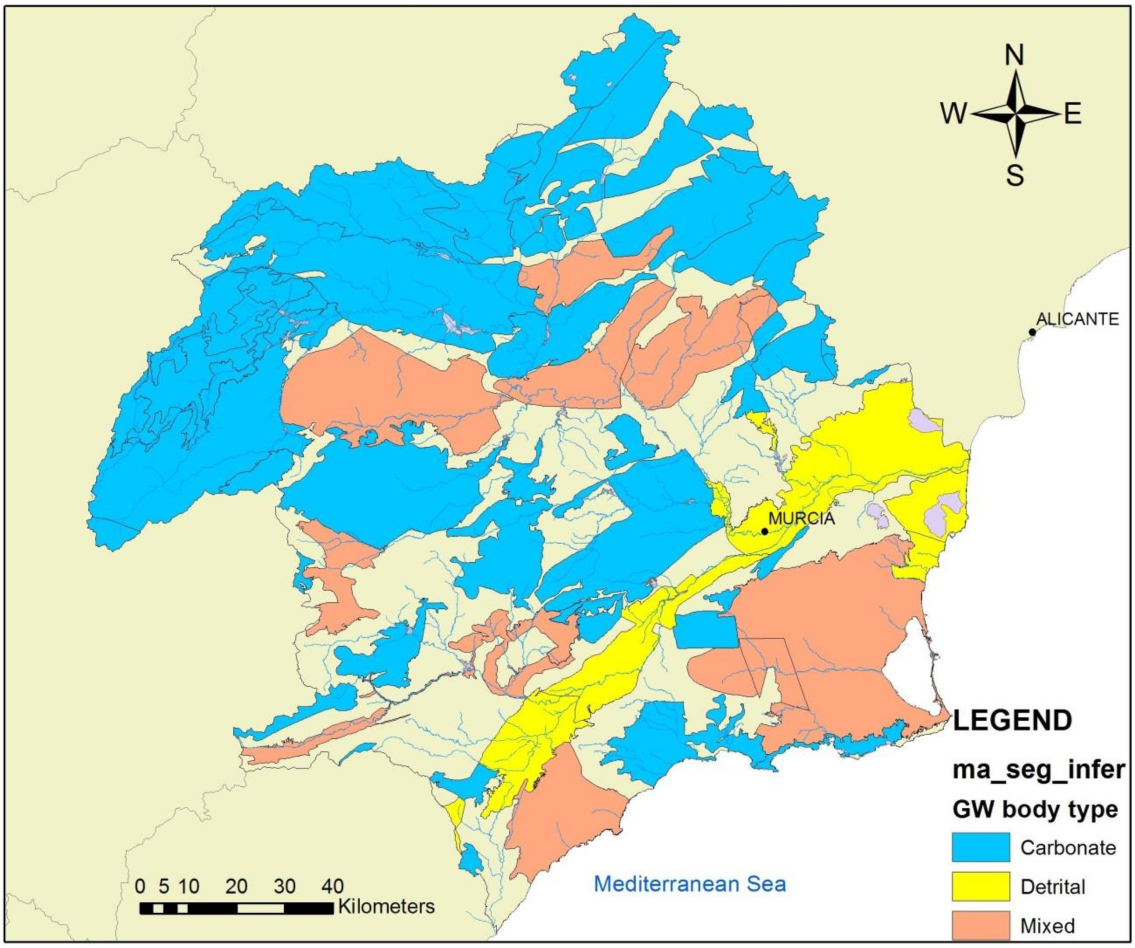


Fig. 3.2 Groundwater bodies type

CODE	NAME	EXTENSION (KM2)	GROUP	TIPOLOGY
070.001	CORRAL RUBIO	170	CARBONATE	Folded sedimentary (Mesozoic and Cenozoic)
070.002	SINCLINAL DE LA HIGUERA	210	CARBONATE	Folded sedimentary (Mesozoic and Cenozoic)
070.009	SIERRA DE LA OLIVA	73	CARBONATE	Folded sedimentary (Mesozoic and Cenozoic)
070.005	TOBARRA-TEDERA-PINILLA	151	CARBONATE	Folded sedimentary (Mesozoic and Cenozoic)
070.008	ONTUR	155	CARBONATE	Folded sedimentary (Mesozoic and Cenozoic)
070.004	BOQUERÓN	283	CARBONATE	Folded sedimentary (Mesozoic and Cenozoic)
070.007	CONEJEROS-ALBATANA	159	CARBONATE	Folded sedimentary (Mesozoic and

				Cenozoic)
070.013	MORATILLA	29	CARBONATE	Folded sedimentary (Mesozoic and Cenozoic)
070.012	CINGLA	379	CARBONATE	Folded sedimentary (Mesozoic and Cenozoic)
070.003	ALCADOZO	505	CARBONATE	Folded sedimentary (Mesozoic and Cenozoic)
070.024	LÁCERA	8	CARBONATE	Folded sedimentary (Mesozoic and Cenozoic)
070.023	JUMILLA-YECLA	264	CARBONATE	Folded sedimentary (Mesozoic and Cenozoic)
070.010	PLIEGUES JURÁSICOS DEL MUNDO	985	CARBONATE	Folded sedimentary (Mesozoic and Cenozoic)
070.006	PINO	48	CARBONATE	Folded sedimentary (Mesozoic and Cenozoic)
070.011	CUCHILLOS-CABRAS	209	MIXED	Carbonate and detrital
070.027	SERRAL-SALINAS	97	CARBONATE	Folded sedimentary (Mesozoic and Cenozoic)
070.017	ACUIFEROS INFERIORES DE LA SIERRA DE SEGURA	1524	CARBONATE	Folded sedimentary (Mesozoic and Cenozoic)
070.021	EL MOLAR	288	CARBONATE	Folded sedimentary (Mesozoic and Cenozoic)
070.022	SINCLINAL DE CALASPARRA	332	MIXED	Carbonate and detrital
070.025	ASCOY-SOPALMO	369	MIXED	Carbonate and detrital
070.026	EL CANTAL-VIÑA PI	40	MIXED	Carbonate and detrital
070.029	QUIBAS	137	CARBONATE	Folded sedimentary (Mesozoic and Cenozoic)
070.028	BAÑOS DE FORTUNA	86	CARBONATE	Folded sedimentary (Mesozoic and Cenozoic)
070.020	ANTICLINAL DE SOCOVOS	751	MIXED	Carbonate and detrital
070.030	SIERRA DEL ARGALLET	6	CARBONATE	Folded sedimentary (Mesozoic and Cenozoic)
070.031	SIERRA DE CREVILLENTE	20	CARBONATE	Folded sedimentary (Mesozoic and Cenozoic)
070.036	VEGA MEDIA Y BAJA DEL SEGURA	705	DETRITAL	Alluvial, litoral and other Pliocuaternary deposits
070.035	CUATERNARIO DE FORTUNA	19	DETRITAL	Alluvial, litoral and other Pliocuaternary deposits
070.034	ORO-RICOTE	66	CARBONATE	Folded sedimentary (Mesozoic and Cenozoic)
070.032	CARAVACA	677	CARBONATE	Folded sedimentary (Mesozoic and Cenozoic)
070.033	BAJO QUÍPAR	61	CARBONATE	Folded sedimentary (Mesozoic and Cenozoic)
070.040	SIERRA ESPUÑA	630	CARBONATE	Folded sedimentary (Mesozoic and Cenozoic)
070.019	TAIBILLA	69	CARBONATE	Folded sedimentary (Mesozoic and Cenozoic)

070.042	TERCIARIO DE TORREVIEJA	169	DETRITAL	Tabular detrital from Neogene basins
070.041	VEGA ALTA DEL SEGURA	27	DETRITAL	Alluvial, litoral and other Pliocuaternary deposits
070.039	BULLAS	279	CARBONATE	Folded sedimentary (Mesozoic and Cenozoic)
070.018	MACHADA	43	CARBONATE	Folded sedimentary (Mesozoic and Cenozoic)
070.038	ALTO QUÍPAR	181	MIXED	Carbonate and detrital
070.051	CRESTA DEL GALLO	25	CARBONATE	Folded sedimentary (Mesozoic and Cenozoic)
070.053	CABO ROIG	62	DETRITAL	Alluvial, litoral and other Pliocuaternary deposits
070.052	CAMPO DE CARTAGENA	1240	MIXED	Carbonate and detrital
070.037	SIERRA DE LA ZARZA	17	CARBONATE	Folded sedimentary (Mesozoic and Cenozoic)
070.050	BAJO GUADALENTÍN	324	DETRITAL	Alluvial, litoral and other Pliocuaternary deposits
070.055	TRIÁSICO DE CARRASCOY	108	CARBONATE	Folded sedimentary (Mesozoic and Cenozoic)
070.047	TRIÁSICO MALÁGUIDE DE SIERRA ESPUÑA	30	CARBONATE	Folded sedimentary (Mesozoic and Cenozoic)
070.048	SANTA-YÉCHAR	42	CARBONATE	Folded sedimentary (Mesozoic and Cenozoic)
070.043	VALDEINFIERNO	152	CARBONATE	Folded sedimentary (Mesozoic and Cenozoic)
070.049	ALEDO	73	MIXED	Carbonate and detrital
070.046	PUENTES	121	MIXED	Carbonate and detrital
070.054	TRIÁSICO DE LOS VICTORIA	110	MIXED	Carbonate and detrital
070.045	DETRÍTICO DE CHIRIVEL-MALÁGUIDE	93	MIXED	Carbonate and detrital
070.044	VÉLEZ BLANCO-MARÍA	72	CARBONATE	Folded sedimentary (Mesozoic and Cenozoic)
070.057	ALTO GUADALENTÍN	275	DETRITAL	Alluvial, litoral and other Pliocuaternary deposits
070.058	MAZARRÓN	284	CARBONATE	Metamorphic
070.063	SIERRA DE CARTAGENA	66	CARBONATE	Metamorphic
070.061	ÁGUILAS	379	MIXED	Carbonate and detrital
070.056	SIERRA DE LAS ESTANCIAS	7	CARBONATE	Folded sedimentary (Mesozoic and Cenozoic)
070.059	ENMEDIO-CABEZO DE JARA	50	CARBONATE	Metamorphic
070.060	LAS NORIAS	18	DETRITAL	Alluvial, litoral and other Pliocuaternary deposits
070.062	SIERRA DE ALMAGRO	20	CARBONATE	Folded sedimentary (Mesozoic and Cenozoic)

Table 3.1. Groundwater bodies in the SB system.

- ***Surface water bodies***

The River Segura is the main stream of the basin together with its tributaries Mundo, Argos, Quípar, Mula and Guadalentín. Traditionally, surface water in this basin has been strongly regulated due to the water scarcity in the region and the extreme events (such droughts as floods) that historically have afected it. A complex network of reservoirs and canals has been set up in the system to regulate internal and external water resources (water transfer from Tagus basin), and more recently to also incorporate desalination resources.

So the flow series measured at most gauges are in altered regime, and only in the upper basin can be found a natural regime. However the series have been restored to natural regime by the River Basin Authority and in some IGME project.

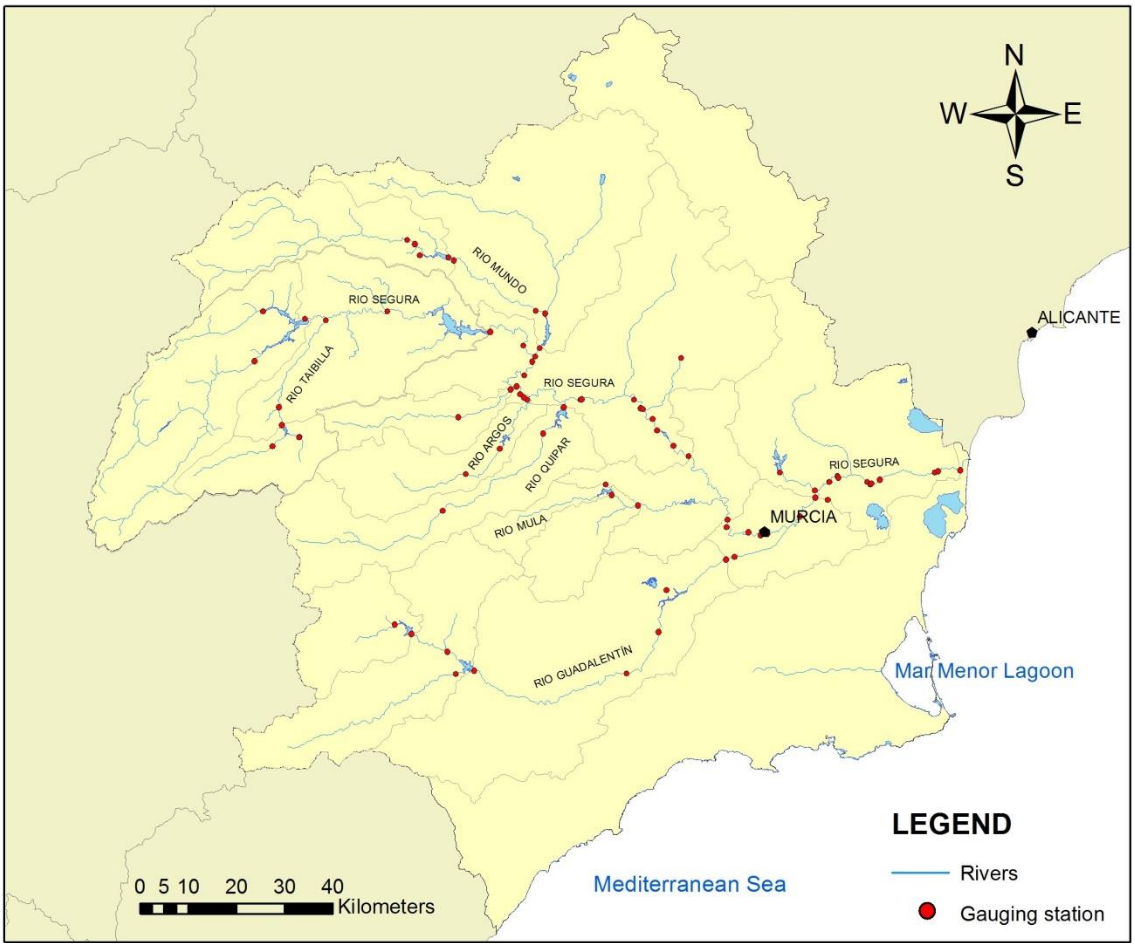


Figure 3.3. Surface water bodies and stream gauges.

- ***Climate***
    - *climate type*

      The general predominant climate in the Segura Basin is Mediterranean, with specific tipologies in different areas. So half of the basin, the highest lands at the North and West, has a temperate Mediterranean climate. At middle altitudes the climate becomes continental Mediterranean, and at the rest of the territory (second in extension) it is subtropical Mediterranean, except in a coastal strip at the South where it is semi-arid subtropical Mediterranean (CHS, 2018).

- *precipitation, temperature and evapotranspiration*
  The annual average rainfall in the basin is 382 mm according to historical series (1940/41-2005/06) and 362 mm considering the short period (1980/81-2005/06). The regime of precipitation is extremely variable in space and time, with clear differences between the upper and lower basin.

  The mean potential evapotranspiration is around 700 mm and the mean real evapotranspiration is estimated about 328 mm for the long period series. The overall mean runoff has been calculated as 13% of the overall mean precipitation, which is the lowest in the Iberian Peninsula.

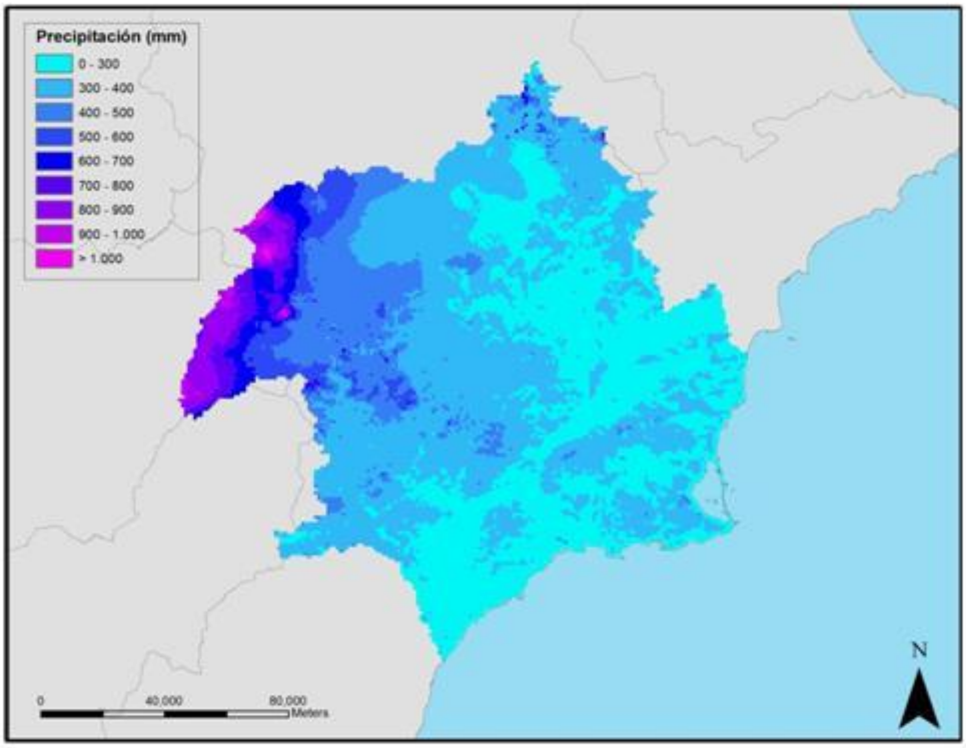


Figure 3.4. Mean annual precipitation distribution in the Segura Basin District (CHS, 2018)

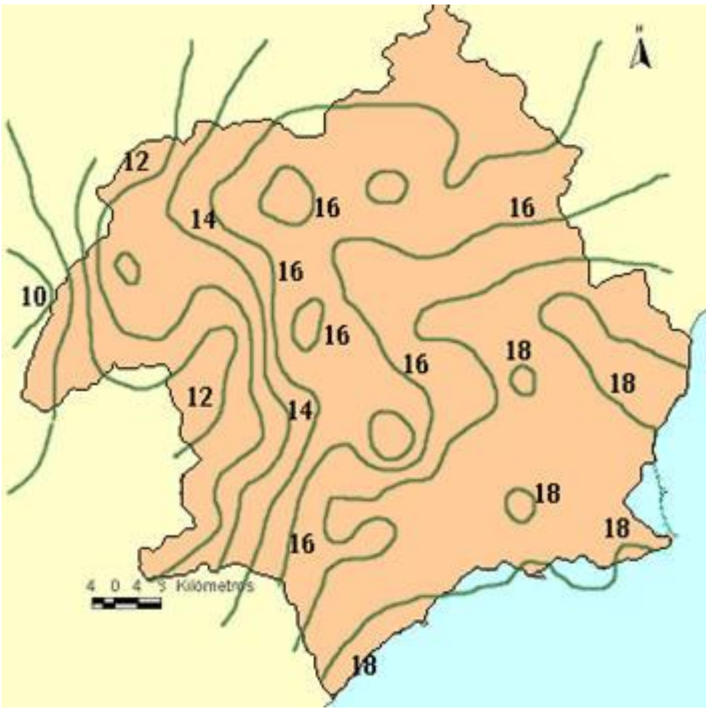


Figure 3.5. Mean annual temperature distribution in the Segura Basin District (CHS, 2018)

- Land use

The main socioeconomic activity is irrigated agriculture, traditionally concentrated in the alluvial and coastal plains. The main crops are citrus and fruit trees, and also green and other vegetables.

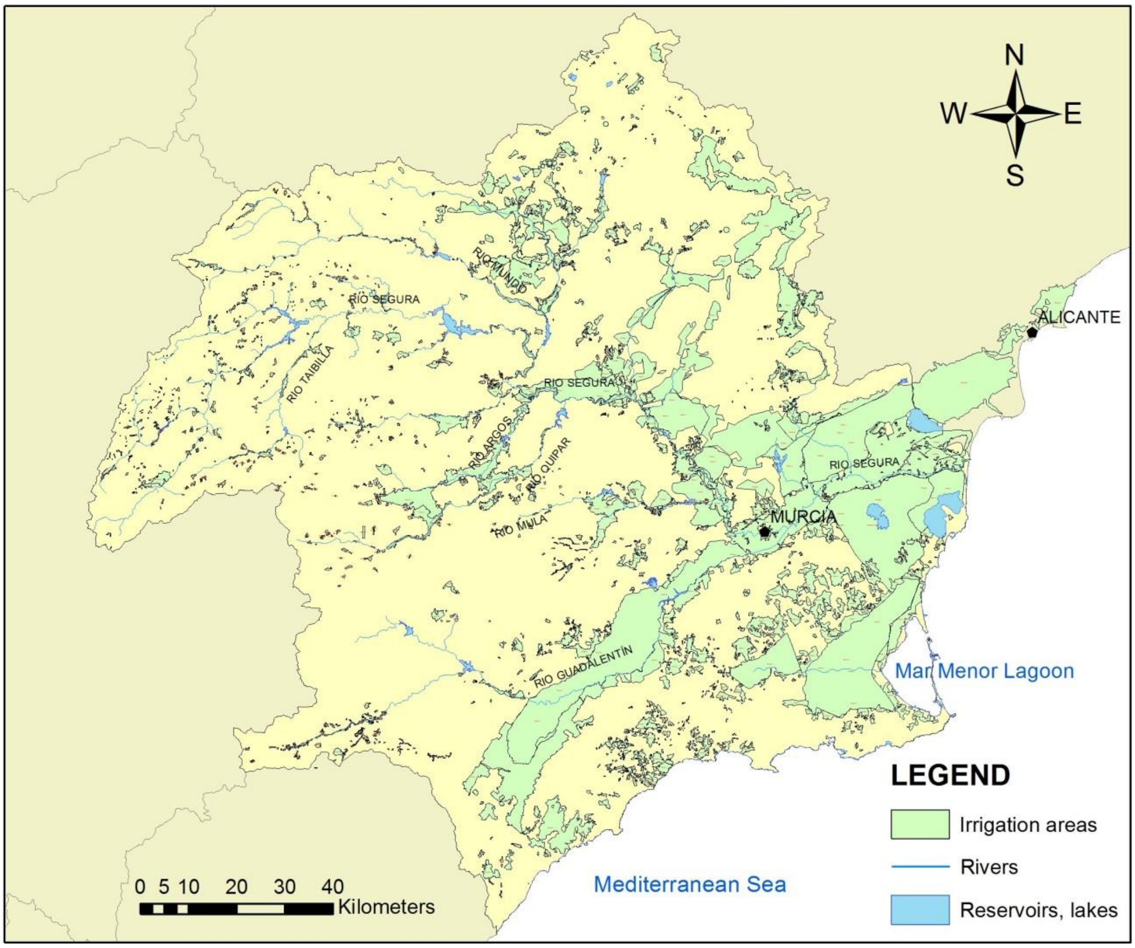


Fig. 3.6 Irrigation areas

- ***Management scheme***

This complex conjunctive use system includes different types of water resources such as groundwater, surface water, external water transfer from Tagus basin (Central Spain) and unconventional resources (wastewater reuse and desalination). The system integrates a network of reservoirs and canals in order to regulate and distribute such resources and meet the different demands. The simplified topologic scheme of the lower part of the system shows such complexity (see Fig. 3.7).

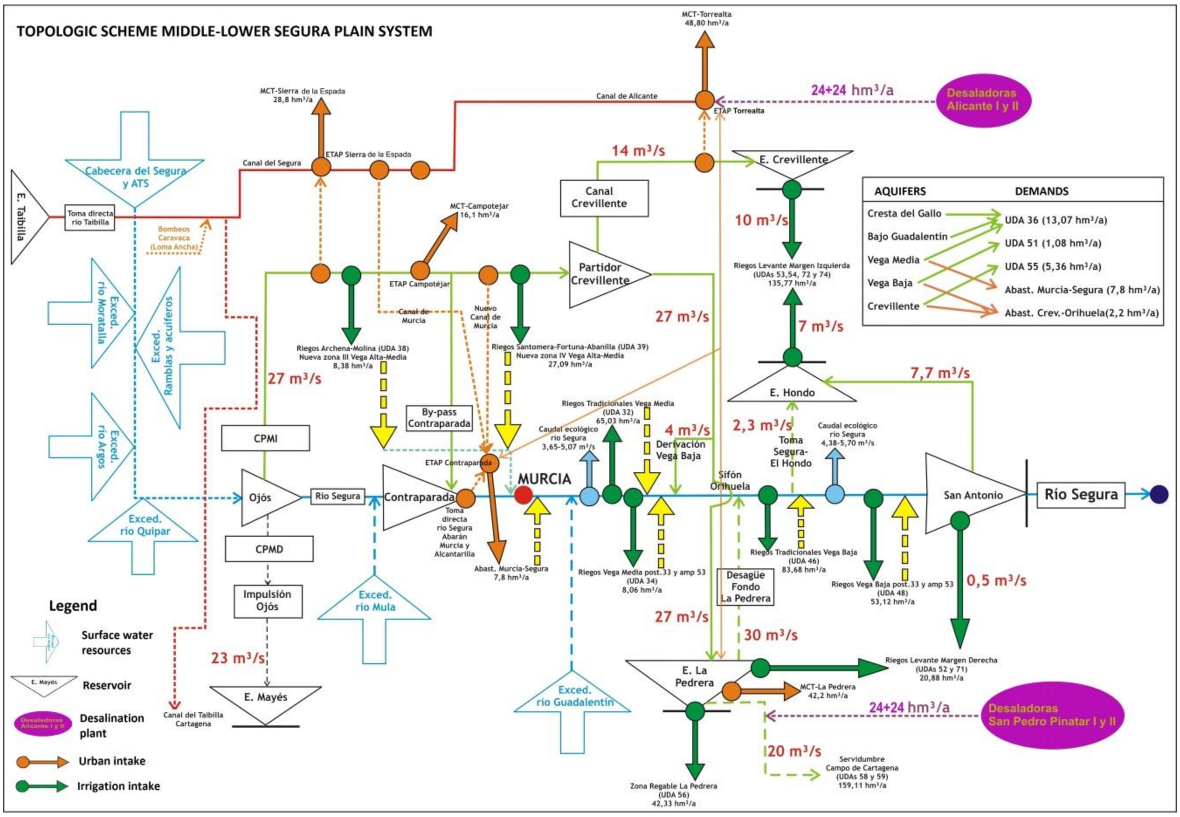


Fig. 3.7 Topologic scheme of the water management system (modified from Gómez-Gómez et al., 2016)

3.2 Climate change challenge

In accordance with the EEA map the main expeted issues due to climate change in this case study are those described in the Figure 8 for the 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 aquifer recharge in the area (see Pulido-Velazquez et al., 2018)

The main challenge is to find adaptation measures to maintain a sustainable use of groundwater bodies and the other water resources with a balance between supply and water demands (different uses) under future climate change conditions.

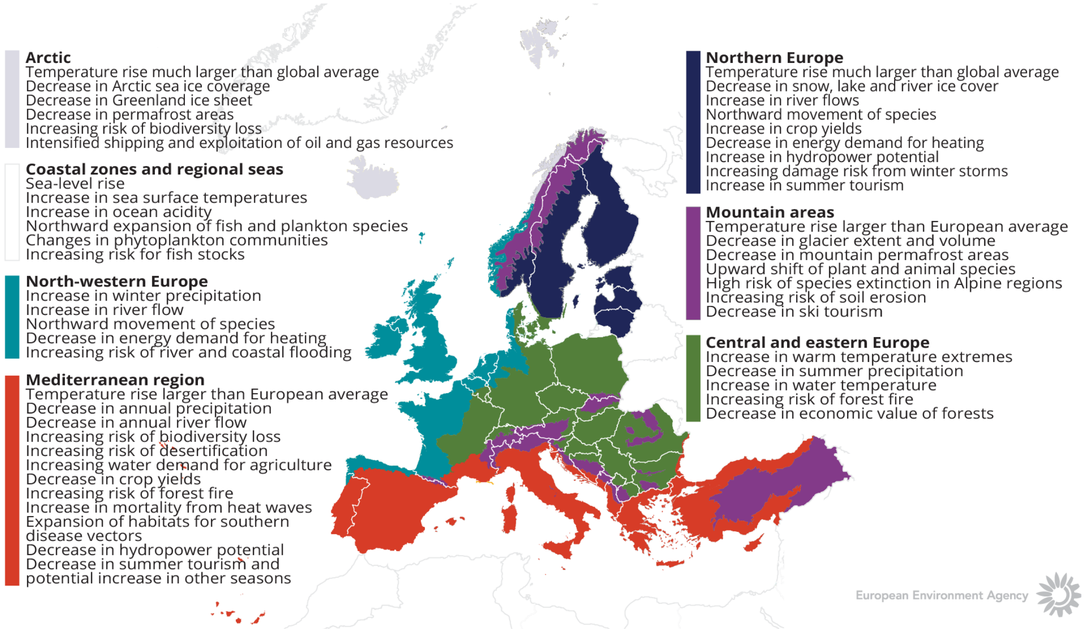


Figure 3.8. How is climate expected to change in Europe. The European Environment Agency map

4 METHODOLOGY

The assessment of climate change impacts on the Segura basin water resources management system (groundwater, surface water and alternative water sources) have been performed using the climate change scenarios from Euro-Cordex (RCP8.5 emission scenario) and the integrated hydrological management model of the basin. The Segura Basin management model is based on the AQUATOOL code, coupled with a rainfall-runoff model (Temez) and a CROPWAT model for irrigation demands assessment (TACTIC toolbox reference).

4.1 Climate data

The present pilot study relies on the Euro-CORDEX regional climate models to reflect future climate conditions. The TACTIC standard CC scenarios have not been used for this pilot.

4.1.1 Euro-CORDEX climate change scenarios

Future climatic series (temperature and rainfall) have been generated applying a statistical downscaling technique for the period 2071-2100. The applied method have been "delta-change" type. It intends to obtain series considering the differences between control and future of the regional climate models and to apply them to the historical series (Fowler et al., 2007). More specifically we have been followed the methodology proposed by Pulido-Velazquez et al., 2011.

The regional information about climate change has been got from CORDEX project, which has resolution about 12,5x12,5 Km for version EUR-11. In this project four emissions scenarios are considered. They are called Representative Concentration Pathways (RCP) and they are related to a possible range of radiative forcing (FR) values in the year 2100 depending on CO2 concentration values. The most pessimistic scenario (RCP8.5) has been considered in this study.

Nine regional climate models nested to different global climate models (see Table 4.1), with RCP 8.5 emission scenario, were used to assess future conditions for the Segura Basin pilot area.

Table 4.1. Euro-CORDEX climate change ensemble.

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

We tested several statistical techniques to generate local scenarios from the considered RCMs (correction of first- and second-order moments, regression approach, quantile mapping) under two different conceptual approaches: bias correction and delta change techniques. The bias corrections intend to apply a perturbation of the control series obtained with the RCM

simulations to reduce their statistical differences with the historical ones. Future series will be generated by assuming that this bias with the real values will be maintained invariant also in the future. The delta change corrections are defined by using the relative difference in the statistic of future and control of the RCM simulations to perform a perturbation of the historical series in accordance with these estimated changes. It assumes that the RCM simulation approach properly the deltas due to climate change, but not the absolute values.
We considered four options to define the most representative future scenarios by applying different ensembles of the potential scenarios deduced from the available climate models. Two ensemble scenarios were considered by combining, as equi-feasible members, all the future series (that correspond to different RCM simulations) generated by delta change (E1) or bias correction (E2). Two other options were defined by combining only the non-eliminated models (E3) (in delta change approach) or the non-eliminated combinations of models and correction techniques (E4) (bias correction techniques), assuming that we do not trust on the eliminated ones. We eliminated the projections considered as 'inferior' in terms of goodness of fit (see detail of the method in Collados-Lara et al., 2018). The criteria employed to identify the inferior approaches is the next one: An approach is inferior if any other approach provides approximations significantly better for all the statistics (basic and drought statistics).

4.1.2 Differences between the TACTIC standard CC scenarios and the used Euro-CORDEX climate change scenarios

The methodology of the assessment of climate change impacts on groundwater conditions are slightly different between the TACTIC standard scenarios and the Euro-CORDEX ensemble. Whereas the TACTIC scenarios apply four selected scenarios representing a 1 and 3 degree temperature change in the 2nd most dry and 2nd most wet scenario, the Euro-CORDEX uses a larger ensemble with no specific attention to most wet or dry scenario. Furthermore, the TACTIC scenarios are not targeted to a specific future time-period but to a specific temperature rise relative to the reference period, of 1 and 3 degrees, respectively. The Euro-CORDEX scenarios targets the specific time-period of 2071-2100, or the changes between this future period and the reference period. The reference period for the CORDEX approach has been 1971-2000.

There are also additional differences in the application of climate model scenario data in forcing of the hydrological models. The TACTIC scenarios apply local datasets of precipitation, temperature and reference evapotranspiration to which the delta change factors are multiplied (or added) to generate the dataset representing the future conditions. Therefore, the dynamics between different events (e.g. numbers of rainy days) in the historical dataset are transferred to the dataset representing the future. With the approach for applying the Euro-CORDEX ensemble, the output from the climate models, is used for both the reference and future periods, and thus dynamics of the input may be projected differently.

4.2 Integrated hydrological management modelling of climate change

The Segura Basin management model is based on the AQUATOOL code, coupled with a rainfall-runoff model (Temez) and a CROPWAT model for irrigation demands assessment (TACTIC toolbox reference).

It is based in a previous integrated model developed for the Vega Baja del Segura system (Gomez-Gomez et al. 2016), and subsequently updated and extended to the whole Segura basin.

4.2.1 Model description

The decision support system of Segura Basin (SB) was developed using the code AQUATOOL, and specifically its module SIMGES (Andreu et al. 1996).

This is a software for integrated management modelling of water resources at a basin scale (similar to MIKE BASIN), appropriate for simulation of the river-aquifer interaction, regulation elements such as reservoirs and aquifers, and many other elements involved in water management such as river flows, demands, return flows, ecological flows, canals and other conections, pumpings and artificial recharge. The simulation uses a monthly time step.

The Segura alluvial plain (Fig. 4.1) aquifer has been integrated in the conjunctive use model by means of a flow model made with the code AQUIVAL, which simulate transient state groundwater flow by the eigenvalues method (Pulido-Velazquez et al. 2007).

The activities carried out to develop the model can be grouped into three phases:

- Characterisation of the SB hydrological system, setting and describing the different elements to be considered, available resources (surface water, groundwater and alternative resources), demands to be met and current hydraulic infrastructures.

- Once the integrated management model was set up with SIMGES, the current management scenario was calibrated and simulated for the historical period.

- The generated future CC scenarios were applied to the model to analyse the impacts on the different elements of the hydrological management system (aquifers, satisfaction of demands, river flows…), with special focus on drought propagation.

Different types of water resources such as groundwater, surface water, external water transfer from Tagus basin (Central Spain) and unconventional resources (wastewater reuse and desalination) have been considered in the model. The system integrates a network of reservoirs and canals in order to regulate and distribute such resources and meet the different demands. The simplified topologic scheme of the lower part of the system shows such complexity (see Fig. 3.7).

A total of 60 GW bodies are included in the Segura Basin integrated management model, with a complex geology and different lithologies such detrital as carbonate and mixed (see Fig. 3.2). Special attention has been paid to the Middle-Lower Segura Plain, a Plioquaternary aquifer located in the lower part of the basin partially connected to the sea, which concentrates most of the urban and agricultural water demands of the system.

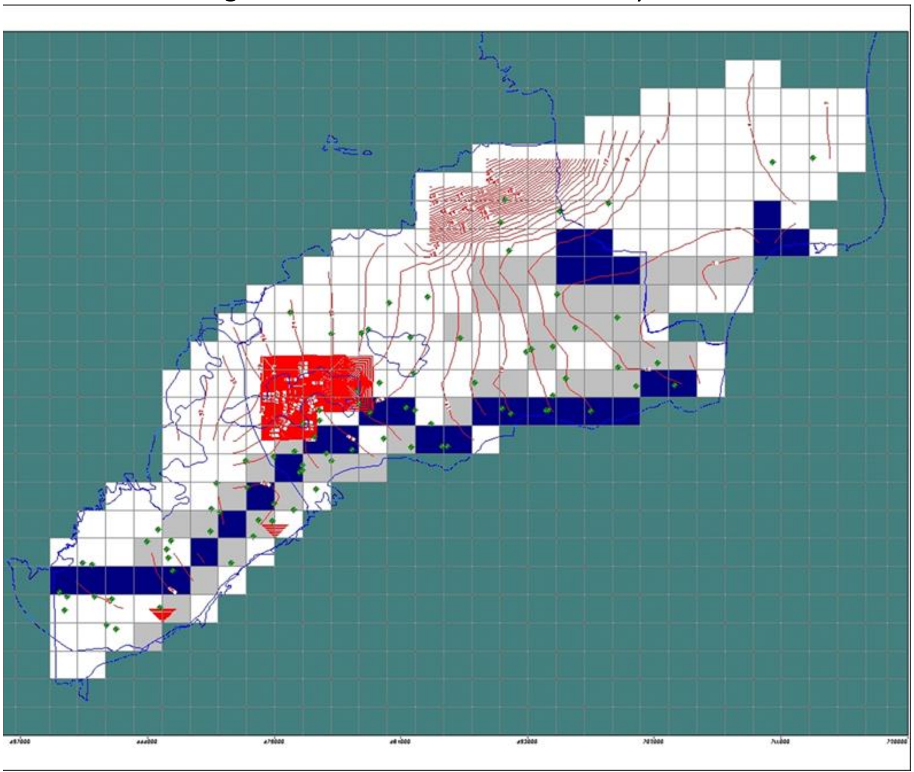


Figure 4.1. Discretization of the Segura alluvial plain aquifer

The basin has been divided into 11 subbasins for different Segura reaches and tributaries: Guardamar, Beniel, Contraparada, Paso de los Carros, Puentes, Baños de Mula, Cenajo, Camarillas, Alfonso_XIII, Argos and Archena. A rainfall-runoff model (Témez) has been developed to calculate river flow series for the subbasins.

Figure 4.2. River subbasins and gauge stations to calibrate TEMEZ model.

A total of 103 demand elements have been included in the model considering urban, industrial, agricultural, environmental and golf demands. Irrigation areas corresponding to agricultural demands are shown in figure 3.6.

Table 4.2. Total annual demands by uses (Mm3)

Urban	Agricultural	Environmental	Industrial	Golf
244.31	1582.38	273.36	10.79	6.20

Surface water regulation infrastructure has also been considered. 15 reservoirs have been included in the model.

4.2.2 Model calibration

The integrated model has been calibrated with a total of 70 gauge stations (Fig. 4.2) for the surface water flow (Temez rainfall-runoff model) and 82 observation wells for the Vega Media-Baja del Segura aquifer (Fig. 4.3).

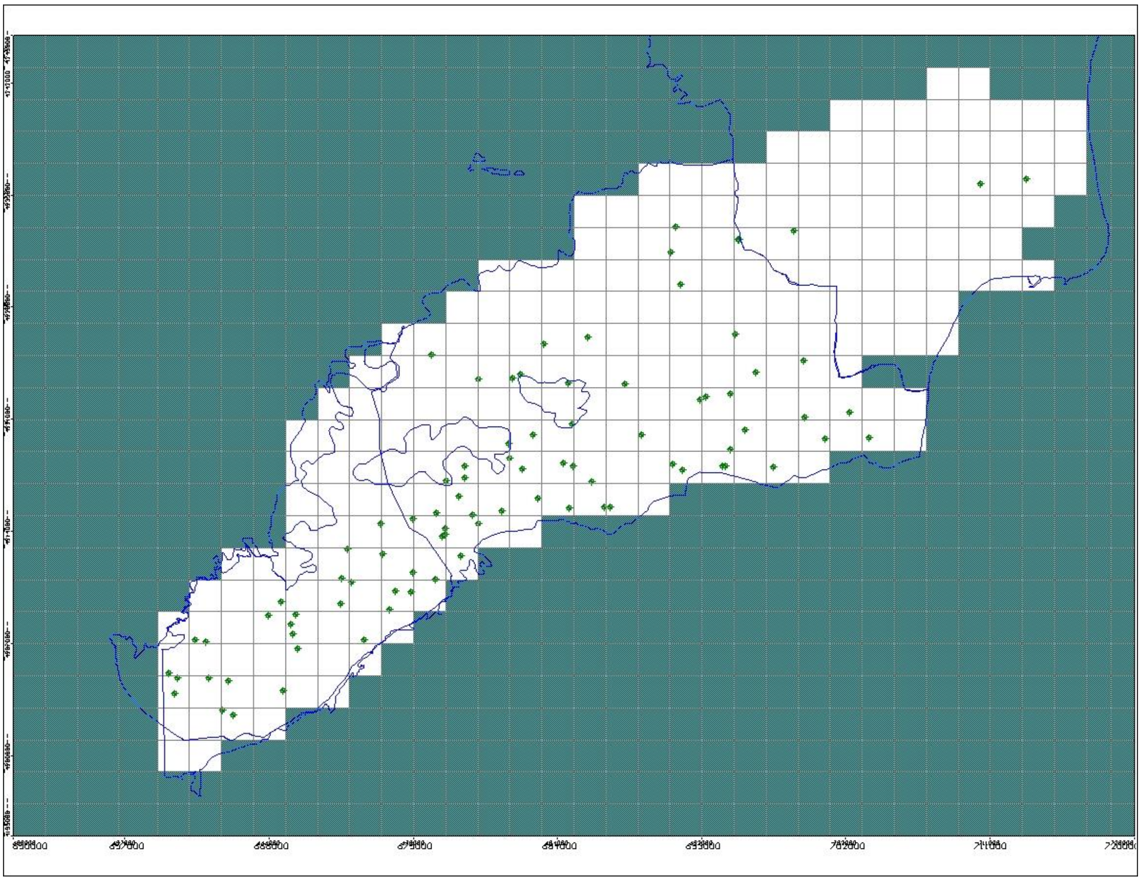


Figure 4.3. Observation wells in Vega Media-Baja del Segura aquifer.

The calibration period was 1994-2010 for the groundwater flow model of Vega Media-Baja del Segura aquifer and 1972-2001 for the rainfall-runoff model of the basin.

Fog 4.4 shows the simulated pezometric levels for September-2010 in Vega Media-Baja del Segura aquifer.

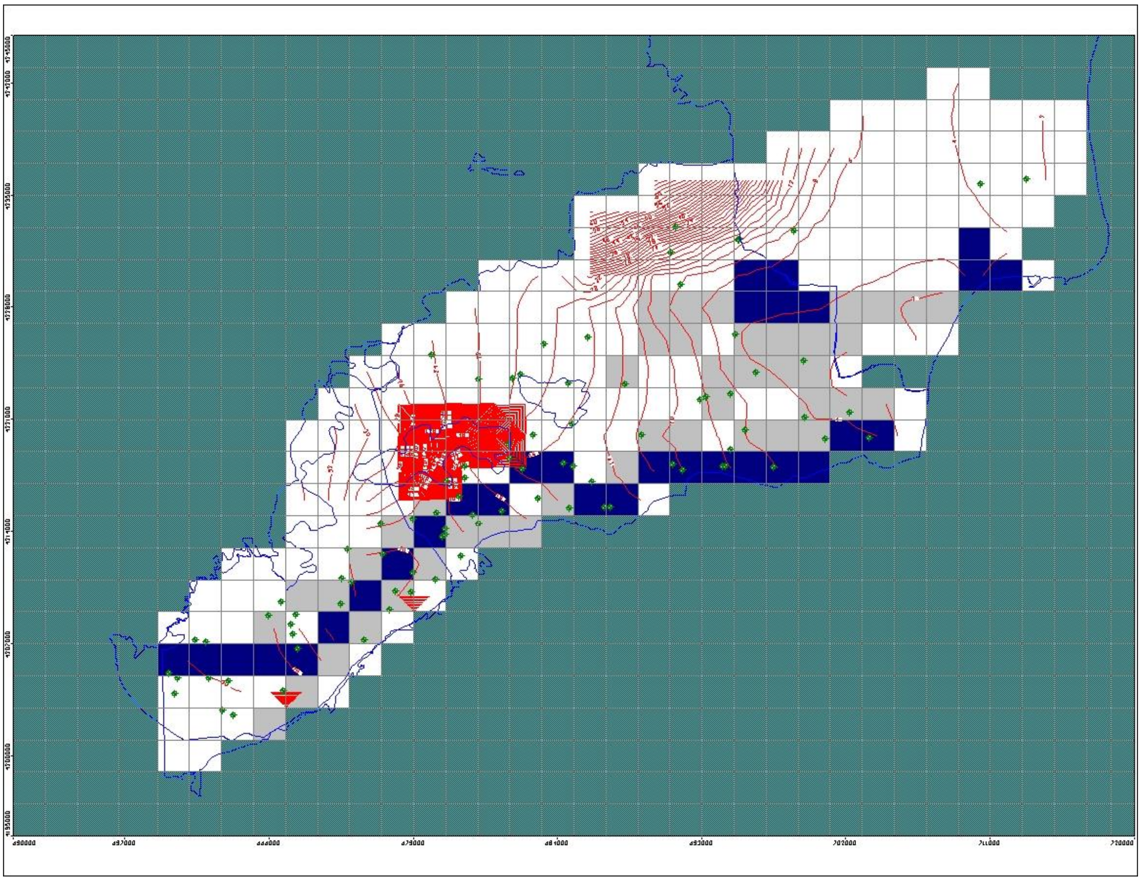


Figure 4.4. Calculated piezometric levels for sep-2010 in Vega Media-Baja del Segura aquifer.

4.3 Assessment of droughts and their propagation

In order to assess meteorological, agricultural and hydrological droughts we will employ the next series of inputs and outputs of the hydrological models: precipitation, humidity and streamflow. The operational drought was assessed by considering a "demand satisfaction index", which is obtained for each month dividing the total supply by the total demand.

The first step needed to assess droughts from the series of outputs of the model is to aggregate them at a yearly scale for each proposed spatial homogeneous unit. For all these aggregated series of results (precipitation, humidity, streamflow, and satisfaction indices) we propose to apply the same statistical procedure, the standard precipitation index (SPI), in order to identify and assess the main statistical properties (duration, magnitude or intensity) of the different types of droughts in each spatial unit. Note that the probability of occurrence of precipitation for the SPI calculation, in the control and future simulations, was obtained using parameters calibrated from the observed series, in order to perform an appropriate comparison. From the SPI series, the statistics (number of droughts, duration, magnitude and intensity) were obtained by applying run theory

We also studied the temporal correlation of different kinds of drought assuming different time lags. We intend to identify which is the time lag that provides the best correlation between the meteorological drought and the other types of droughts (agricultural, hydrological and operational). It allows us to estimate the inertial or time lags between each type of droughts and the meteorological ones.

We also propose to perform a sensitivity analysis to the spatial scale, assessing droughts and temporal correlations also for the whole basin that integrates different homogeneous units.

5 RESULTS AND CONCLUSIONS

5.1 Results based on the integrated hydrological modelling

Once the model was calibrated, the generated future series (P, T) of four climatic scenarios for the period 2071-2100 were applied. Results were obtained for the whole Segura Basin system in terms of lower resources available to meet the different demand elements, which means higher deficits for that demands.

Results were also obtained and analysed with a monthly step on water volumes stored in reservoirs and aquifers, river flows, piezometric levels in Vega Media-Baja aquifer, pumpings, demands and supplies. Propagation of drought events were also analysed for the four future scenarios. All these results were aggregated by subbasins to be analysed.

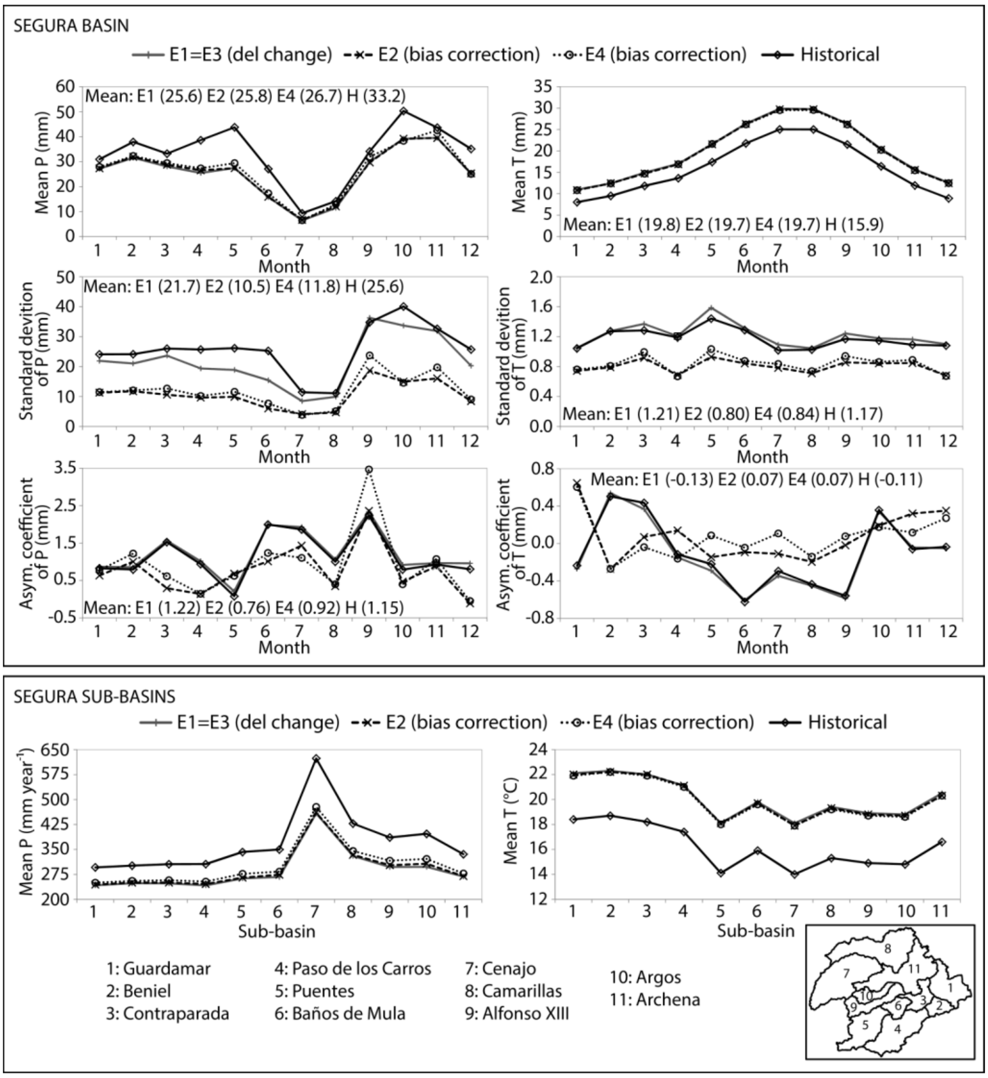


Figure 5.1. Future P and T series for the four ensembles

Statistics of precipitation and temperature for the four scenarios (E1 to E4) are shown in figure 5.1. Main statistics on runoff and demands are also reflected for these four scenarios and compared to historical data (Fig. 5.2) both for the whole Segura Basin and for the subbasins.

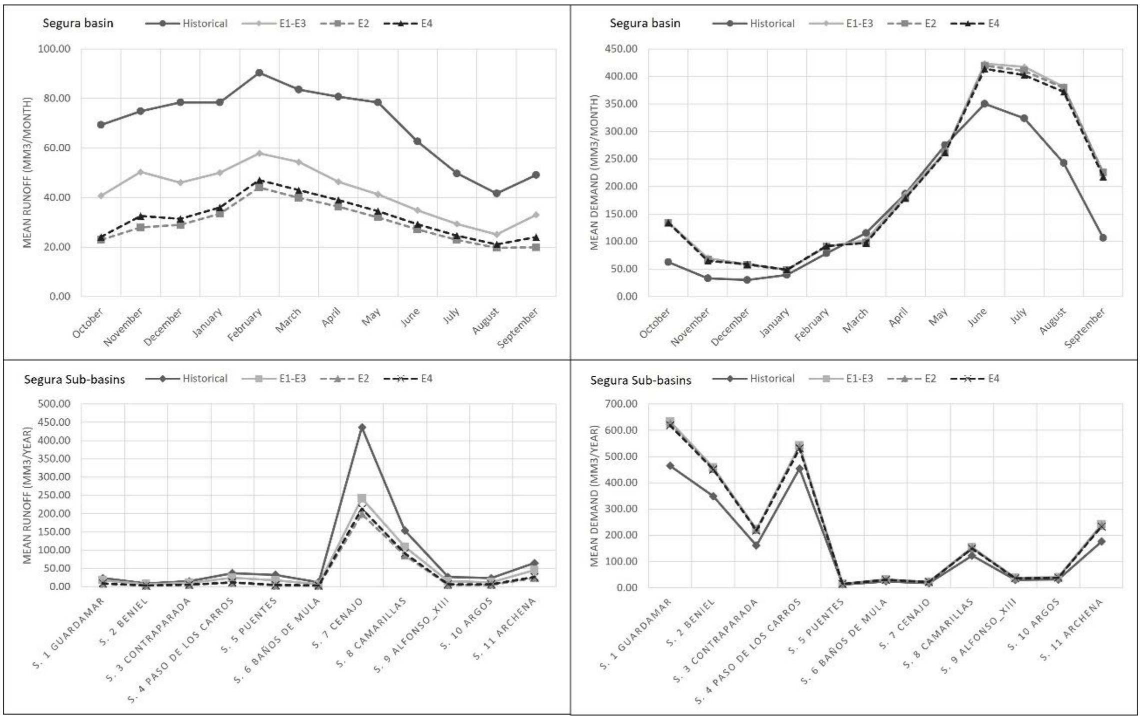


Figure 5.2. Runoff and demand for the four scenarios

A summary of results respect to guarantees of satisfaction of demands are reflected in table 5.1. Once again, these results are aggregated for the whole Segura Basin and the different subbasins. We can observe how guarantees are estimated to decrease significantly for the three future scenarios. The worst scenario is E2 with more than 21% of reduction of guarantee for the whole basin.

Table 5.1. Mean monthly volumetric guarantees (supply/demand)

Basin-Subbasin \ Scenario	**Historical**	**E1=E3**	**E2**	**E4**
Total Basin	**96.25%**	**77.61%**	**75.02%**	**76.04%**
S. 1 Guardamar	99.58%	86.28%	86.02%	86.59%
S. 2 Beniel	98.89%	92.32%	91.52%	92.10%
S. 3 Contraparada	95.83%	62.87%	55.40%	56.95%
S. 4 Paso de los Carros	90.36%	66.35%	63.84%	65.15%
S. 5 Puentes	70.35%	55.79%	51.30%	52.69%
S. 6 Baños de Mula	83.46%	67.20%	66.19%	66.71%
S. 7 Cenajo	95.36%	62.48%	56.58%	59.35%
S. 8 Camarillas	96.35%	67.98%	61.61%	63.09%

S. 9 Alfonso_XIII	95.55%	68.07%	64.66%	66.17%
S. 10 Argos	83.46%	52.71%	47.20%	48.90%
S. 11 Archena	96.23%	73.25%	68.26%	69.50%

Future CC scenarios would also have a negative impact in aquifers according to the results obtained on groundwater pumpings (table 5.2). For the worst scenario (E2) there would be an increase of 275 Mm3 in groundwater exploitation for the whole basin.

Table 5.2. Mean annual pumping in aquifers (Mm3)

Basin-Subbasin \ Scenario	Historical	E1	E2	E4
Total Basin	**645.84**	**880.84**	**921.47**	**908.29**
S. 1 Guardamar	63.99	134.27	134.56	133.39
S. 2 Beniel	84.06	137.99	137.15	136.20
S. 3 Contraparada	56.42	62.48	64.12	63.45
S. 4 Paso de los Carros	126.85	126.63	127.86	127.33
S. 5 Puentes	10.41	10.53	10.53	10.53
S. 6 Baños de Mula	19.25	19.72	19.77	19.70
S. 7 Cenajo	0.00	0.00	0.00	0.00
S. 8 Camarillas	41.26	59.11	64.33	63.32
S. 9 Alfonso_XIII	3.33	3.73	3.83	3.76
S. 10 Argos	51.33	71.91	80.10	77.75
S. 11 Archena	188.96	254.48	279.22	272.86

Finally figures 5.3, 5.4, 5.5 and 5.6 show a summary of results obtained for the propagation of droughts according to different parameters: meteorological, agricultural, hydrological and operational respectively. These results are showed for the different Segura basins and homogeneous areas. We observe important increases of the number of droughts and its duration, magnitude and intensity for the period 2071-2100 with respect the historical period for the different series studied (precipitation, humidity, streamflow and demand satisfaction index).

We also studied the correlation between the different types of droughts (Figure 5.7). Meteorological droughts show a good correlation with hydrological and operational droughts. The maximum correlations are reached for different gaps in each case. In the case of hydrological the maximum correlation is obtained without gap and in the case of operational the gap is 3-4 months.

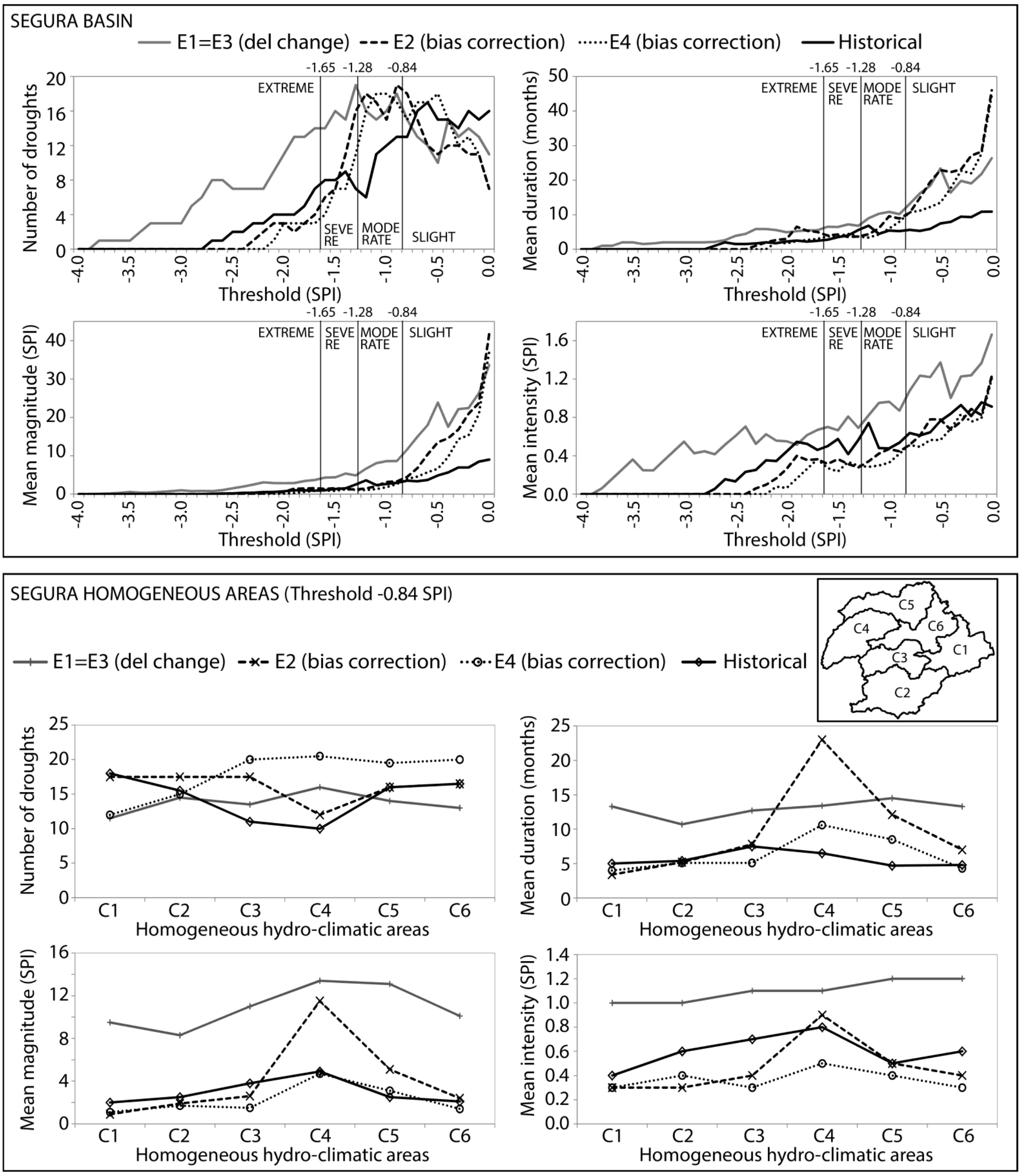


Figure 5.3. Statistics of meteorological droughts (Precipitation)

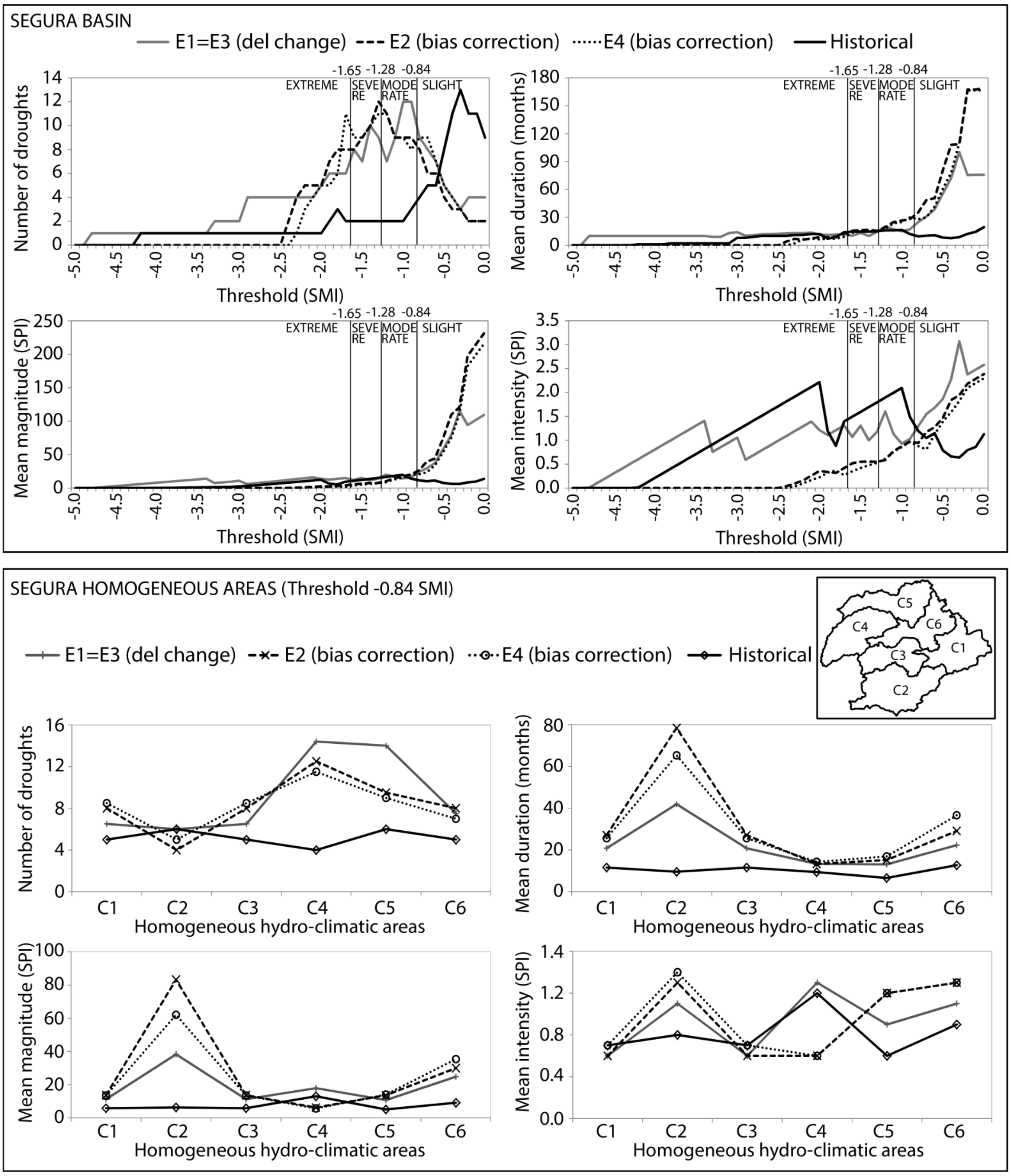
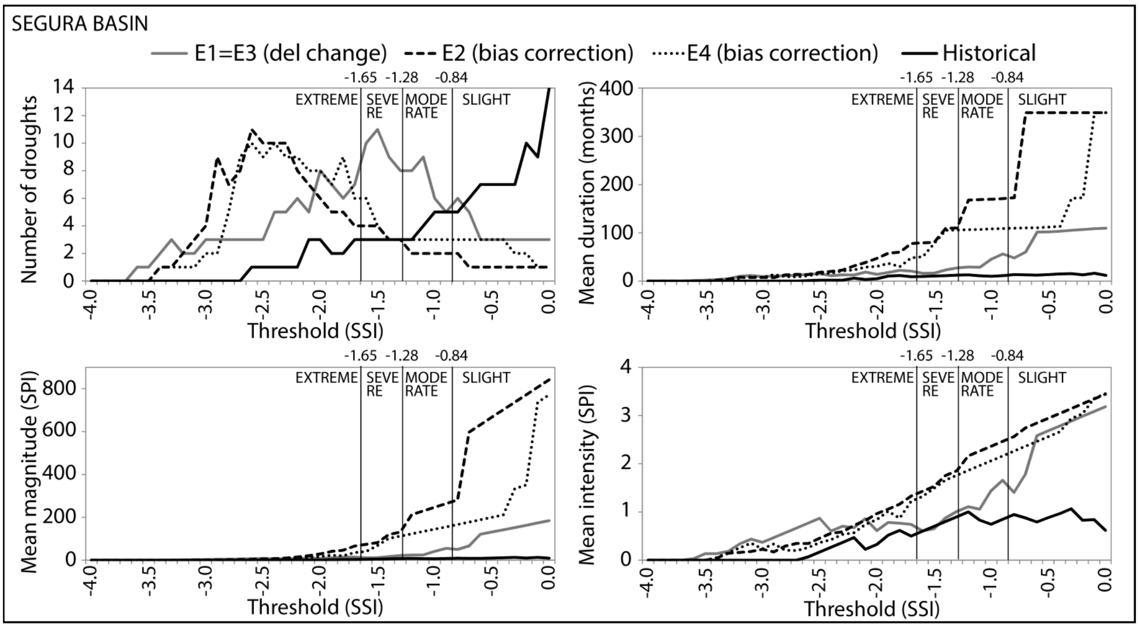


Figure 5.4. Statistics of agricultural droughts (Moisture)



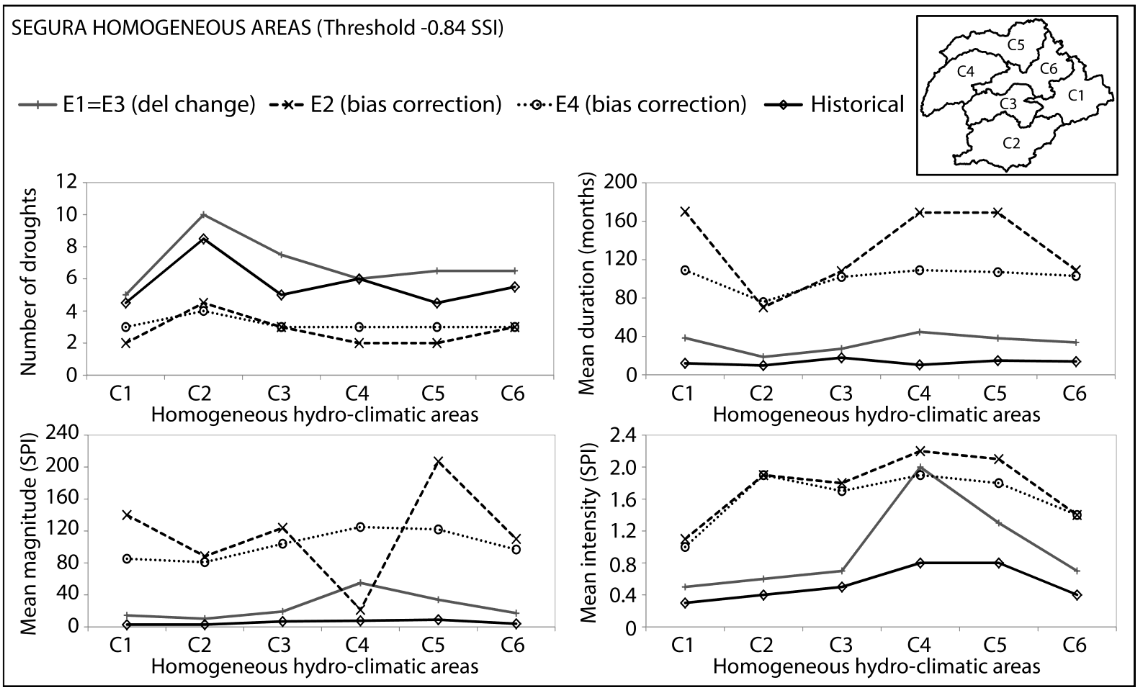


Figure 5.5. Statistics of hydrological droughts (Streamflow)

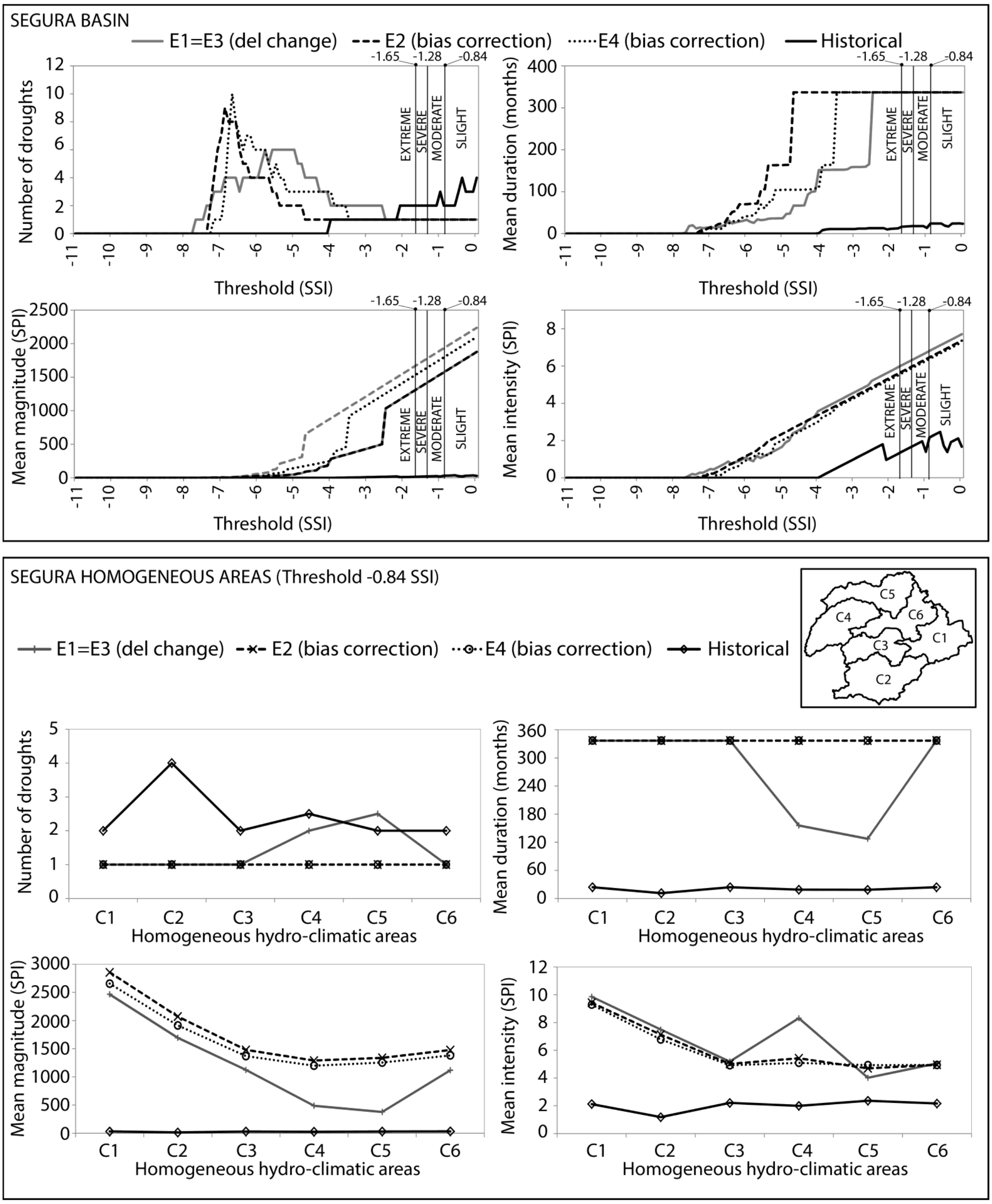


Figure 5.6. Statistics of operational droughts (Satisfaction)

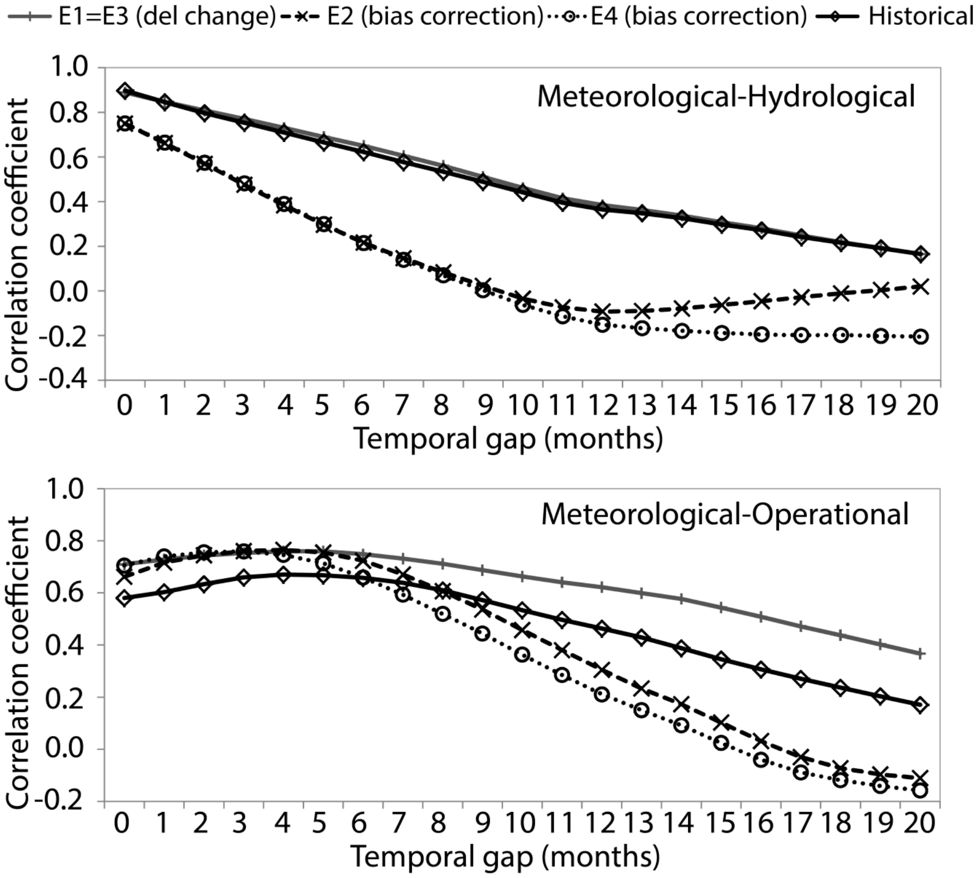


Figure 5.7. Droughts correlation

5.2 Conclusions of the assessment based on integrated hydrological modelling

This method has been applied to assess impacts of future potential climate change scenarios on the Segura Basin management system and on meteorological, agricultural, hydrological and operational droughts providing consistent pictures of monthly plausible future scenarios taking into account basic and drought statistics of the historical series and the climatic model simulations.

Results observed for the whole Segura Basin system with the four climatic scenarios for the period 2071-2100 show lower resources available to meet the different demand elements, which means higher deficits for that demands. Higher pumping rates in aquifers are estimated for future scenarios and the impacts would also be reflected on lower guarantees to meet demands. Scenario E2 has the worst impacts on the system according to this assessment.

The four studied scenarios show important reduction of precipitation and increase of temperature and large increments of the number, duration, intensity and magnitude of droughts. The study of the correlation of hydrological and meteorological droughts shows significant correlations for a gap from 0 to 2 months in E2 and E4 cases and for a gap from 0 to 6 months in historical and E1=E3 cases. However the correlation of meteorological and operational droughts shows a maximum of correlation for a gap around 4 months for all cases.

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TACTIC GROUNDWATER

GeoERA

Establishing the European Geological Surveys Research Area to deliver a Geological Service for Europe

Deliverable 3.2 and 6.2

PILOT DESCRIPTION AND ASSESSMENT

Storåen-Sunds, Denmark

Authors and affiliation:

Jacob Kidmose

Geological Survey of Denmark and Greenland

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	*D3.2, D6.2*
Dissemination level	Public
Deliverable name	*Pilot description and assessment*
Work package	WP3, WP6
Lead WP/Deliverable beneficiary	*GEUS*
Deliverable status	
Version	*2*
Date	28/02/2021

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LIST OF ABBREVIATIONS & ACRONYMS

MSL	Main Stationary Line
GCM	Global Circulation Model
RCP	Representative Concentration Pathway
RCM	Regional Climate Model
DMI	Danish Meteorological Institute
GEUS	Geological Survey of Denmark and Greenland
Jupiter	Danish borehole archieve, hosted by GEUS at www.geus.dk

TABLE OF CONTENTS

1 EXECUTIVE SUMMARY

Pilot name	Storåen-Sunds	
Country	Denmark	
EU-region	NW	
Area (km^2)	1052	
Aquifer geology and type classification	Sand and gravel	
Primary water usage	Drinking	
Main climate change issues	Rising shallow groundwater table causing groundwater-introduced flooding	
Models and methods used	Hydrological integrated model	
Key stakeholders	Herning municipallity, Central Region of Denmark	
Contact person	Jacob Kidmose (GEUS)	

The pilot of storåen and Sunds include Miocene and glacial sand aquifers. These aquifers constitutes by far the most impotant, qualitively as well as quantitatively. In the Sunds pilot study, focus are on the shallow groundwater conditions and how the shallow aquifer – surface water interaction are affected by climate change and possible climate change adaptation.

In the context of TACTIC, a climate change impact asssesment on the shallow groundwater have been performed by the use of a local scale hydrological model with 25 m simulation cells. The model is an integrated hydrological model based on MIKE SHE and MIKE HYDRO. To assess future groundwater conditions in Denmark, the TACTIC standard scenarios representing a future one and a three degree temperature change have been used to force the hydrological models. Furthermore, a number of adaptation strategies to soften the impacts of climate change has been investigated with the hydrological model.

Predictions of the future groundwater conditions are not clear in terms of the direction of change looking at the most dry and wet of the one and three degree scenarios, respectively. Depending on the scenarios choosen, e.g. 1 degree wet or dry, 3 degree wet or dry, groundwater levels of the shallow groundwater aquifer either increases or decreases. The adaptation scenarios illustrates that unwanted climate change effects can be counteracted by adaptation measures. Based on the different scenarios tested, the most effective measure is to lower the groundwater table in the urban part of the City of Sund is by implementation of a

“3rd pipe”, an urban drainage system installed along the existing sewer system. The scenarios also show that especially renovation of an old sewer system and increasing the rainwater infiltration will increase the upper groundwater table and potentially introduce groundwater flooding.

The combination of deferent scenarios illustrated that different interventions can either work for or against the goal of preventing future groundwater flooding. Comparing the unclear signal of climate change on groundwater conditions with the possible interventions of climate change adaptation measures, it is obvious that special care should be taken in designing the future hydrological conditions within the urban area.

2 INTRODUCTION

Climate change (CC) already have widespread and significant impacts in Europe, which is expected to increase in the future. Groundwater plays a vital role for the land phase of the freshwater cycle and have 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. In order 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 infra structure 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 Storåen and Sunds pilot represents one of the small scale pilots in TACTIC where the impacts from climate change on groundwater will be adressed. The general challenge of the pilot is to define if and where most upper groundwater levels will increase or descrease in the future as a result of climate change and adaption measures.

3 PILOT AREA

Storåen and Sunds pilot is located in the western part of Jutland, Denmark. In this area several events with high groundwater table have caused flooding in both rural as well as urban areas. Especially, around the area at the city of Sunds, groundwater conditions have been under investigation because of a believed connection between high shallow groundwater and surface water flooding. The groundwater table in focus is the shallow groundwater table, which is here defined as the upper and most horizontally hydraulic connected groundwater table. In addition, the high groundwater table is believed to interact with the urban sewer system. This has significant economic consequences for the local sewer cleaning facilities.

With high groundwater tables, areas with inflow of groundwater into sewer systems are widespread because the saturated soil zone is above sewer level. In this situation, leaky sewers will not discharge sewerage to the adjacent soils, but groundwater will enter the sewer and increase the cost of cleaning sewer water. In general, the Storåen river catchment, Figure 3.1, are often flooded by a high groundwater table or indirectly by increased groundwater discharge to surface waters. An example of this is the flooding of the city of Holstebro in 1970, 2007, 2011 and 2015. Storåen flows through Holstebro.

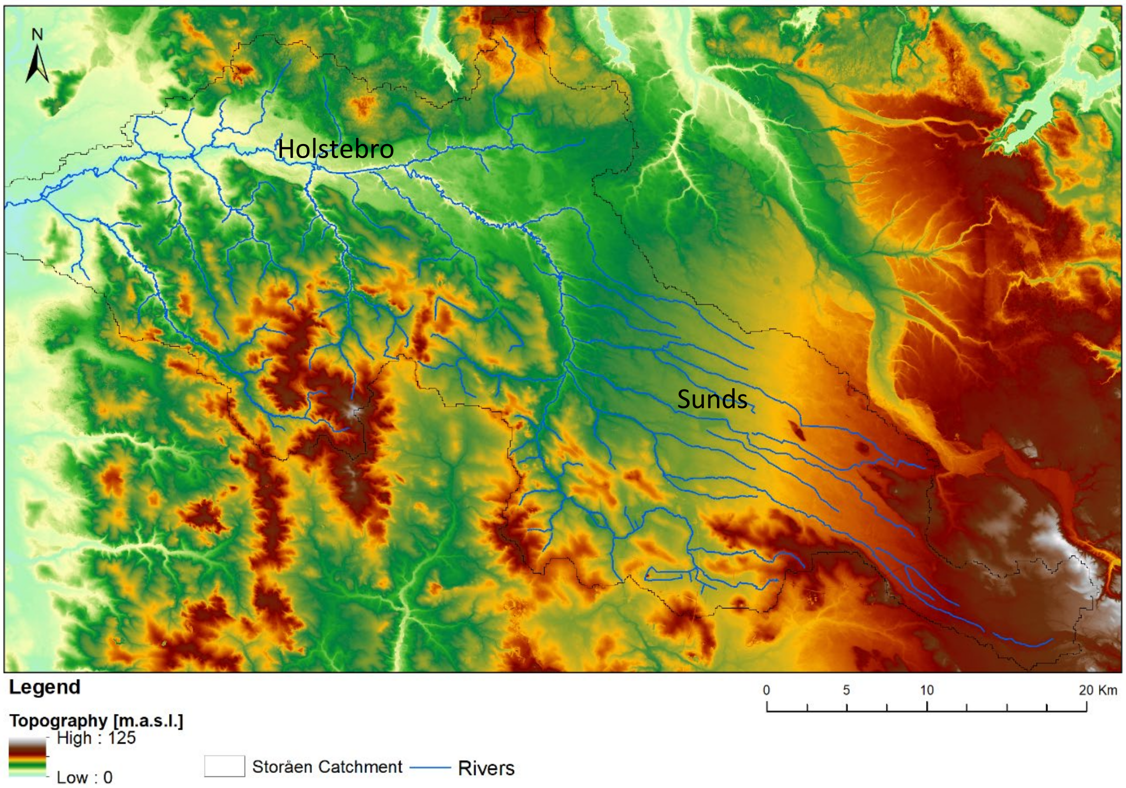

Figure 3.1 Storåen catchment. Sunds city is located in the upper part of the Storåen catchment. Topography in the Storåen catchment varies from 110 m a.s.l. (meters above sea level) to 0 m a.s.l. at Nissum Fjord, where Storåen discharges to, which is connected to the sea.

The Storåen-Sunds pilot will focus on the challenges at the city of Sunds and the Sunds Lake. The lake is an important surface water for the pilot because of its vicinity to Sunds and because it has a hydraulic connection to the aquifer below the city.

3.1 Site description and data

3.1.1 Climate

Denmark and the studied pilot lies in the temperate climate zone. At Sunds, the yearly precipitation is 900 mm and varied in the years 2011 to 2018 between 693 and 1056 mm/yr. The yearly average temperature is just below 9 ^{0}C, and peaks in July with daily average of 16.5 ^{0}C and coldest in February of 1.1 ^{0}C. Potential evapotranspiration is 591 mm/yr. Precipitation is available from 1989 to present with daily values in 10 by 10 km grids. Temperature and potential evapotranspiration calculated by a modified Makkink equation are available in 20 by 20 km grids, also with daily values. Both datasets are from DMI (Danish Meteorological Institute).

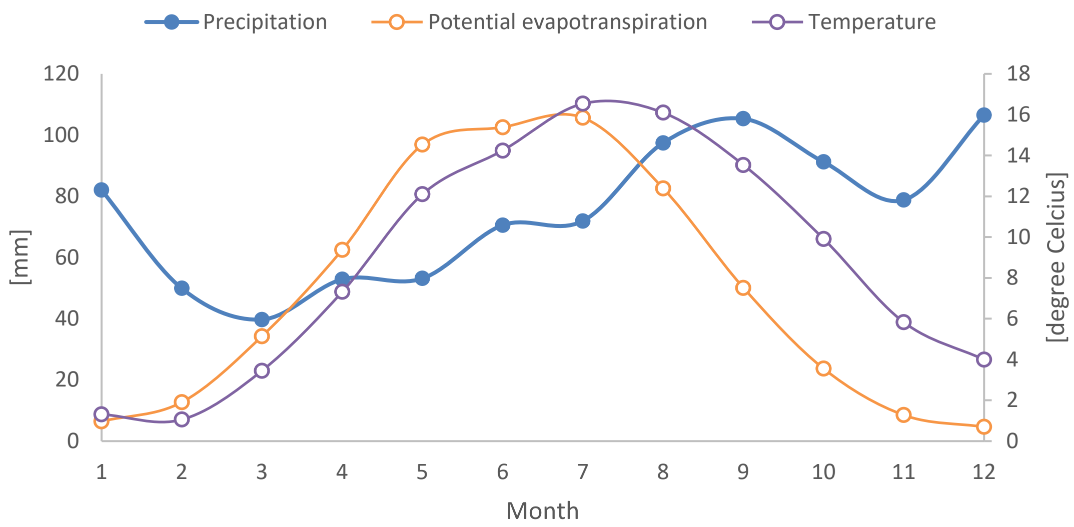

Figure 3.2 Monthly variation in precipitation, potential evapotranspiration and temperature. Average monthly values are derived from the grid-based dataset for the period of 2011-2018.

3.1.2 Area use

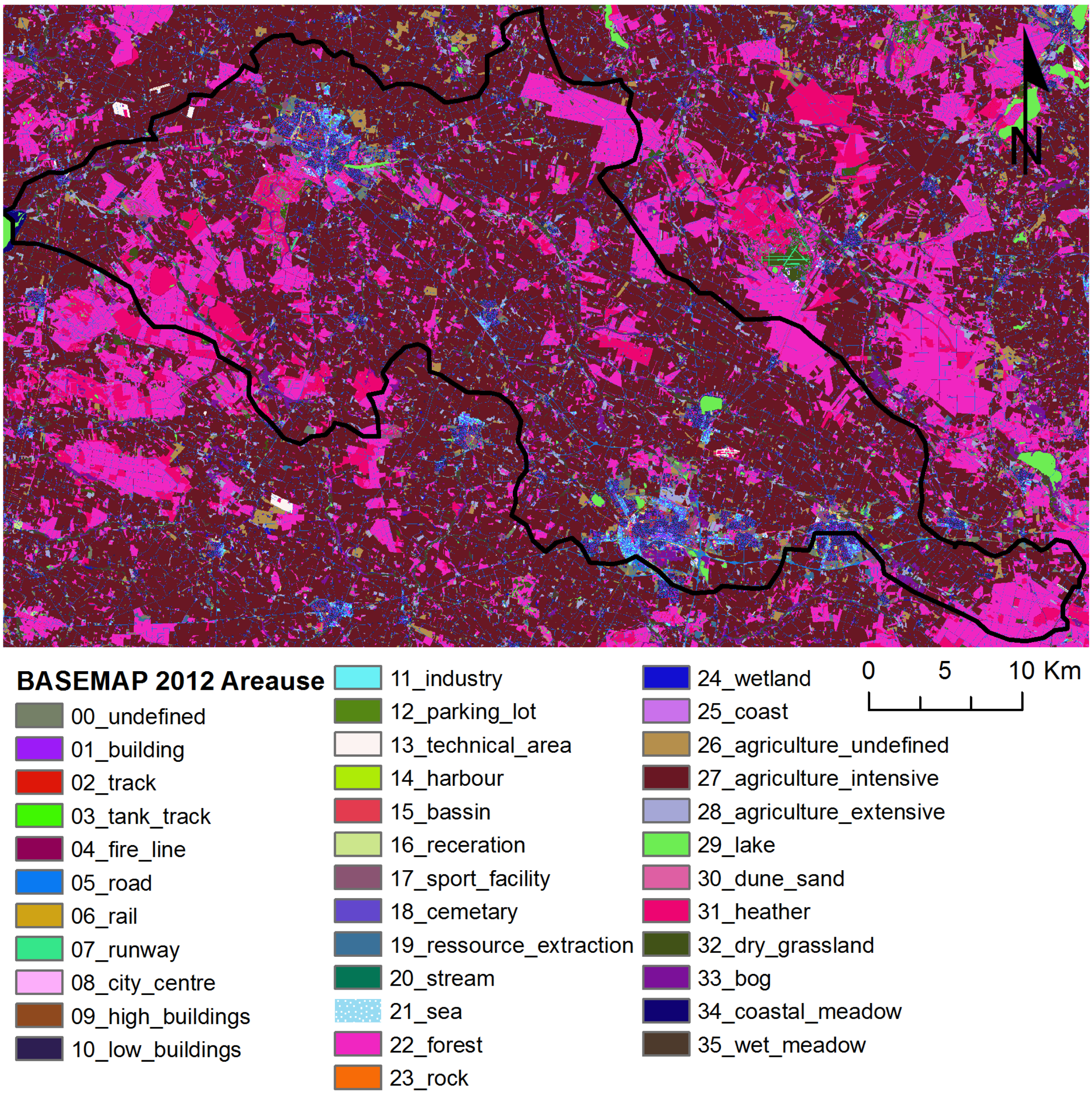

Figure 1.3 Area use in Storåen-Sunds (datasource: Danske Miljøportal 2018).

Area use in Storåen-Sunds is defined by the Basemap 2012 for Denmark by Levin et al. 2012. Basemap 2012 are a 10 by 10 m raster dataset with 35 different area classes, figure 3.3. The dominating area uses in the pilot are agriculture and forest. Other area uses as building, road, industry, heather, wetlands and surface water are also widespread in the Storåen catchment. The 10 m resolution makes even spatial small features as roads and buildings visible in the dataset. The Basemap 2012 are freely available in GIS formats. Hence, the dataset can be manipulated to a reasonable number of classes for hydrological modelling purposes. For instance, the classes building, road, city center, high building, low building, industry and technical area could be merged to describe paved areas.

3.1.3 *Geology*

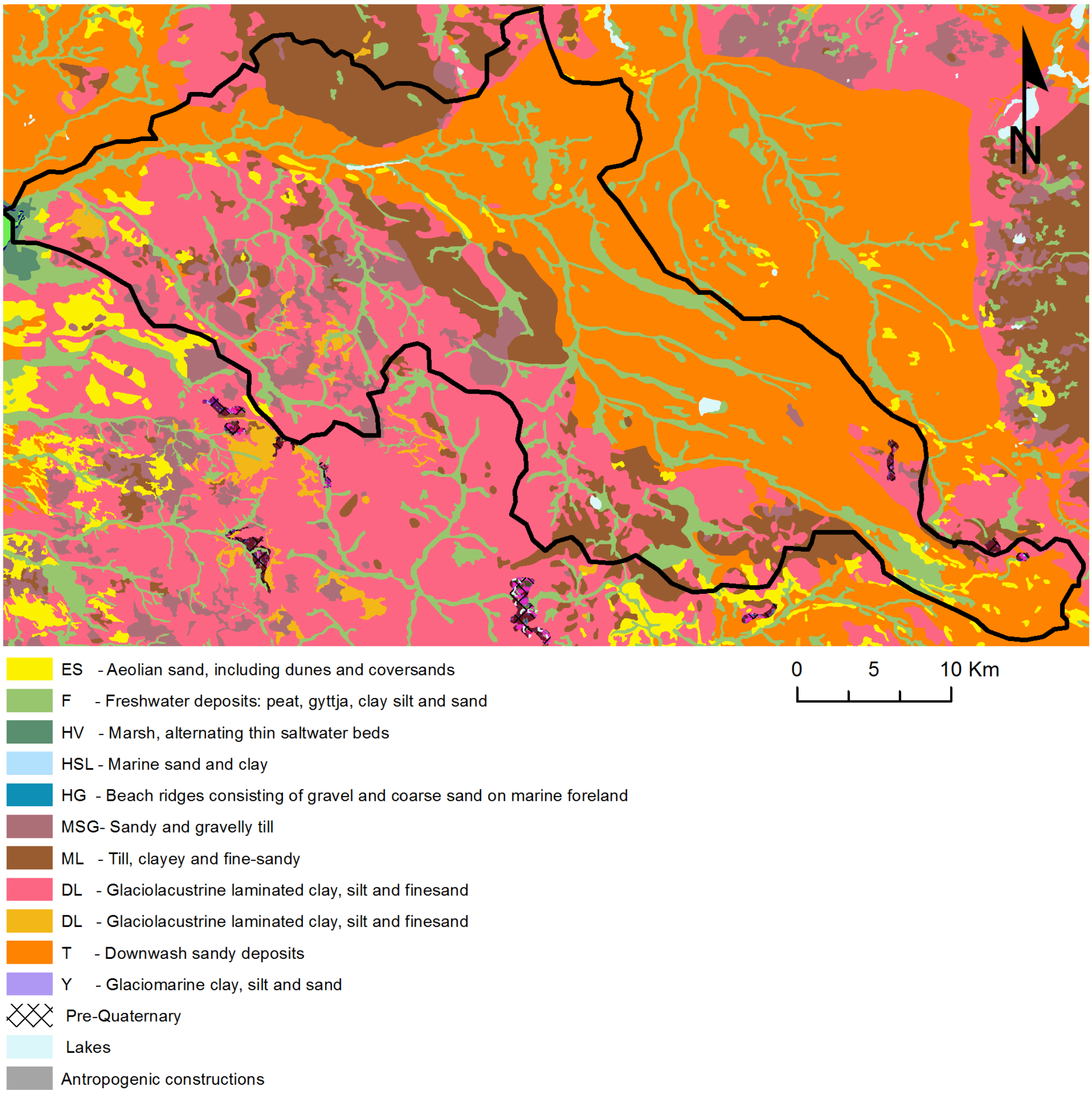

Figure 3.2 Geology at the surface (datasource: GEUS).

At the surface, geology primarily consists of glacial, e.g. sand and clay, and post-glacial sediments, e.g. freshwater sediments as peat, gyttja, sand and clay. Only a few small areas have pre-quaternary sediment outcropping at the surface. The pre-quaternary surface consists of Oligocene un-cemented sediments. The pre-quaternary aquifers are of Oligocene and Tertiary age and unconsolidated in general. The aquifers in the Storåen-Sunds pilot can therefore be characterized as porous and consisting of sand and gravel. Figure 3.4 shows the surface geology and figure 3.5 is a profile of the geology from Nissum Fjord to the most eastern part of the Storåen catchment.

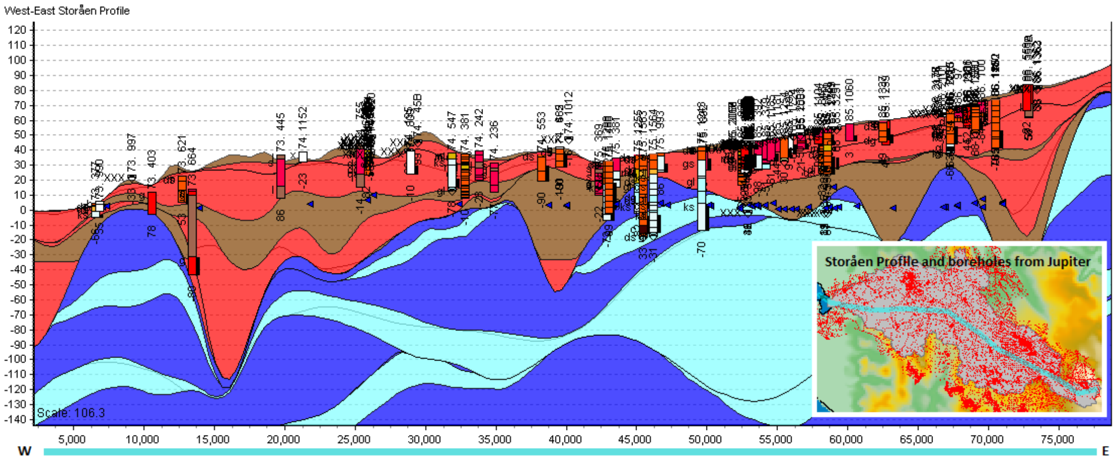

Figure 3.3 Geological profile of the Storåen catchment. Upper quaternary clays (brown), sands (red), and pre-quaternary sands (light blue) and clays (blue).

The geological layers shown in figure 3.5 are shown as hydrogeological units ready to use in a hydrological model. A 3D geological model of the full Storåen catchment are hosted by GEUS on the Danish model database (GEUS model database 2018).

3.1.4 Surface water bodies

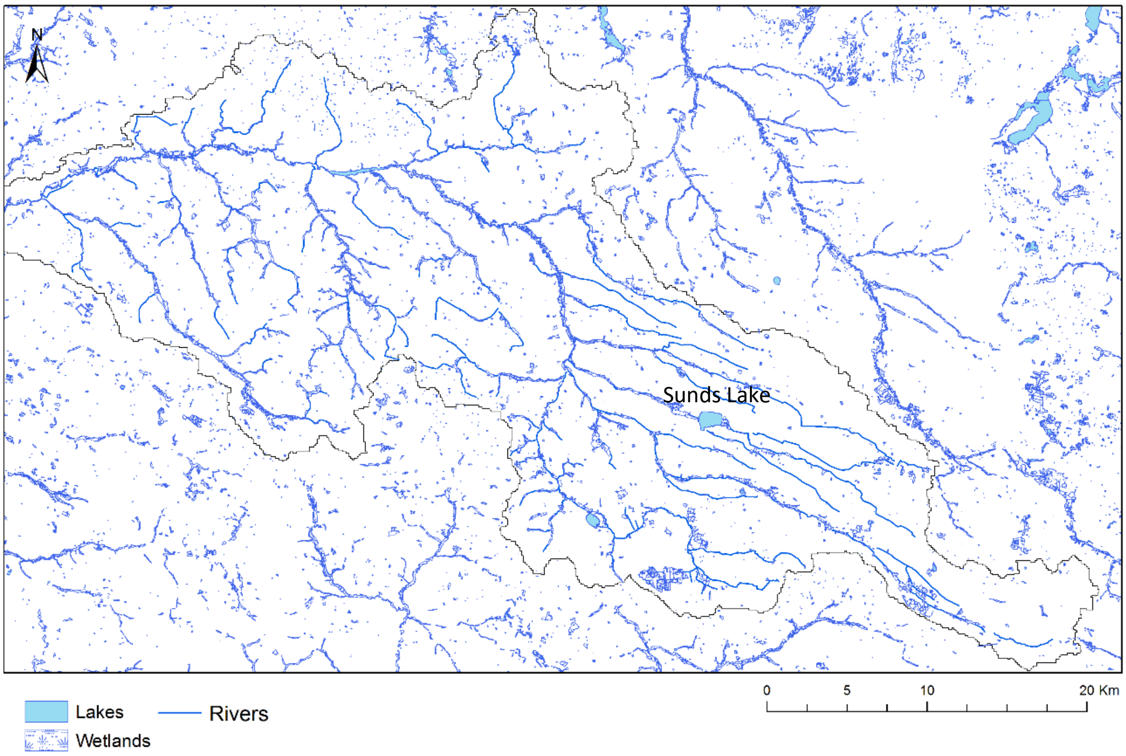

Figure 3.4 Surface waters at Storåen catchment (datasource: Dansk Miljøportal 2018).

The position of shallow groundwater close the surface results in many lake, wetlands and streams. In addition to these water bodies interacting with local groundwater, hanging or purged water tables forming wetland and smaller lakes are also widespread in the catchment. Data are freely available at www.danskmiljøportal.dk (Dansk Miljøportal 2018).

3.1.5 *Groundwater table observations and pumping*

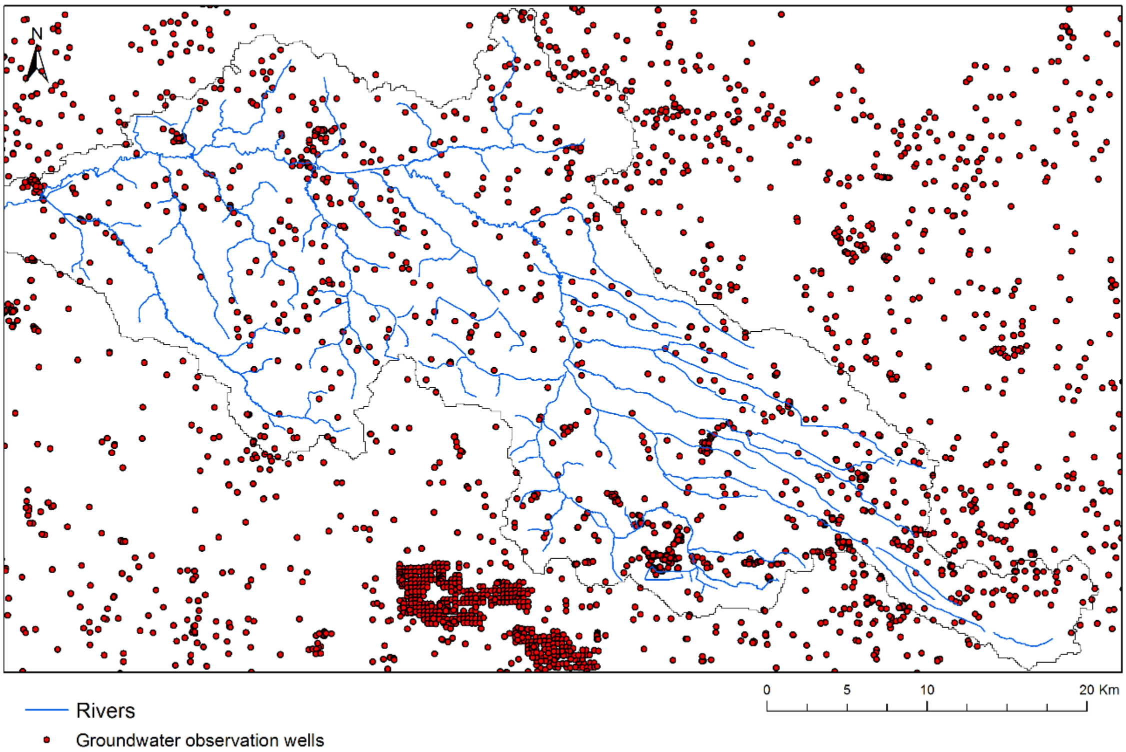

Figure 3.7 Wells with groundwater-level observations at Storåen Catchment.

Well data, observations of groundwater level, permissions for groundwater abstraction, monitored water chemistry and basic borehole data are in Denmark stored in Jupiter, the Danish Borehole archive. Data from Jupiter are freely available and can be downloaded from www.geus.dk. Jupiter are hosted and maintained by GEUS. Figure 3.7 shows the boreholes with groundwater head data between the years 2000-2010. Temporal resolution of observations at the different wells differs significantly (between single observations and one every minute during the analysed period).

Groundwater abstraction data are also reported to Jupiter but often records are incomplete.

3.2 Climate change challenge

The climate change challenge at the Storåen-Sunds pilot is the increasing risk of groundwater-introduced flooding because of future changing climate conditions. At the pilot, relevant climate change aspects for the North-Western Europe are: Increase of winter precipitation, increase in river runoff and, because of increased winter precipitation potentially higher groundwater levels. If true, these conditional changes will strengthen and enhance the already occurring threat of flooding. The pilot will investigate these issues at a local urban scale where anthropogenic effects (man made) on hydrology and groundwater conditions are strong.

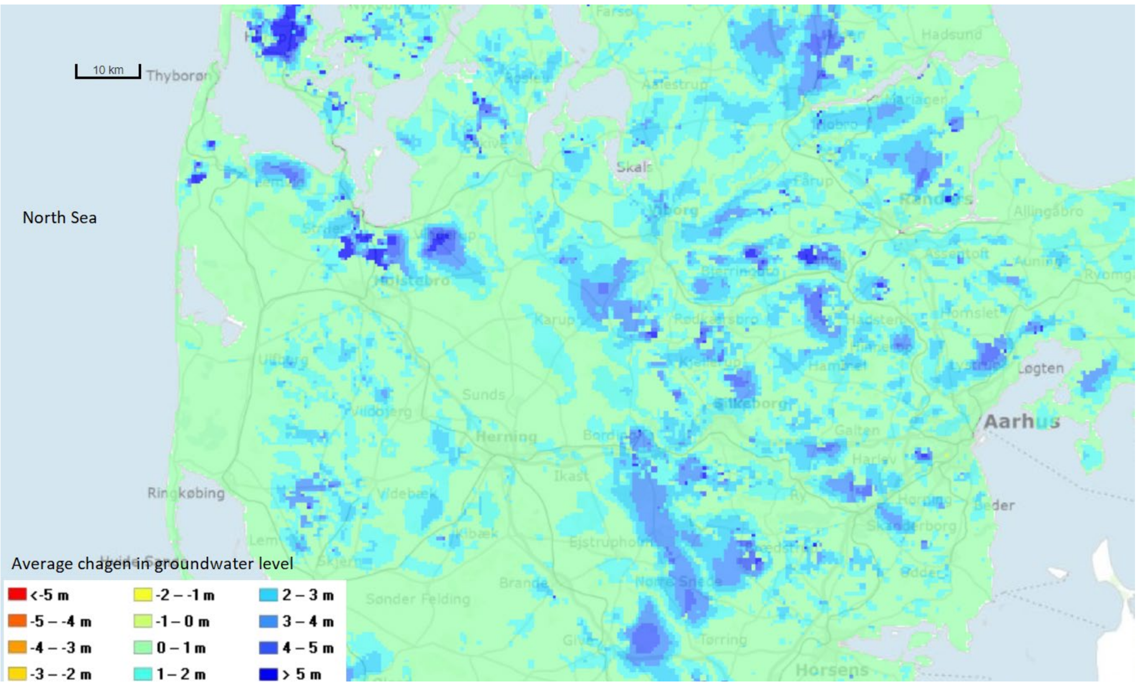

Figure 3.5 Climate change impact on groundwater. Groundwater changes between the historic period of 1961-1990 and the future period of 2021-2050. Results are shown from Central Jutland in meter of change between present and future mean groundwater table (Source: Klimatilpasning.dk 2011).

4 METHODOLOGY

The assessment of climate change and adaptation measures on groundwater conditions at Storåen and Sunds are performed using the TACTIC standard climate change scenarios and an local scale integrated hydrological model around the City of Sunds in the larger Storåen catchment, Western Denmark. The model is based on the MIKE SHE code, coupled with MIKE HYDRO code (TACTIC toolbox). Figure 4.1 illustrate the location of the Sunds model in Denmark (left), the model boundary, the City of Sunds within the model, and Lake Sunds.

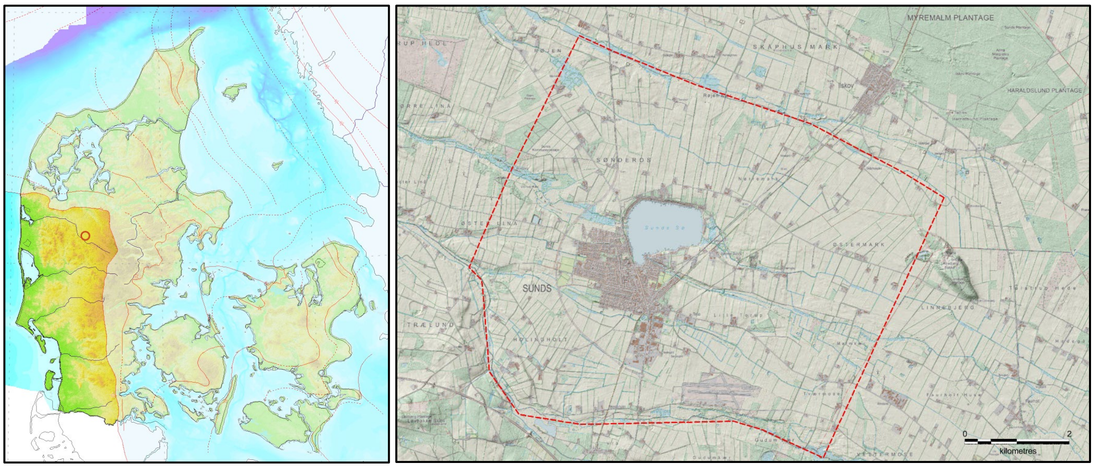

Figure 4.1 Location of Sunds in Denmark (left), and model boundary (red polygon to the right)

4.1 Methodology and climate data

The present study relies on the TACTIC standard climate change dataset to reflect future climate conditions, which include a “wet” and a “dry” climate for a +1 and +3 degree global warming scenario.

4.1.1 TACTIC standard Climate Change scenarios

The TACTIC standard scenarios are developed based on the ISIMIP (Inter Sectoral Impact Model Intercomparison Project, see www.isimip.org) datasets. The resolution of the data is 0.5°x0.5°C global grid and at daily time steps. As part of ISIMIP, much effort has been made to standardise the climate data (a.o. bias correction). Data selection and preparation included the following steps:

1. Fifteen combinations of RCPs and GCMs from the ISIMIP data set where selected. RCPs are the Representative Concentration Pathways determining the development in greenhouse gas concentrations, while GCMs are the Global Circulation Models used to simulate the future climate at the global scale. Three RCPs (RCP4.5, RCP6.0, RCP8.5) were combined with five GCMs (noresm1-m, miroc-esm-chem, ipsl-cm5a-lr, hadgem2-es, gfdl-esm2m).
2. A reference period was selected as 1981 – 2010 and an annual mean temperature was calculated for the reference period.

3. For each combination of RCP-GCM, 30-years moving average of the annual mean temperature where calculated and two time slices identified in which the global annual mean temperature had increased by +1 and +3 degree compared to the reference period, respectively. Hence, the selection of the future periods was made to honour a specific temperature increase instead of using a fixed time-slice. This means that the temperature changes are the same for all scenarios, while the period in which this occur varies between the scenarios.
4. To represent conditions of low/high precipitation, the RCP-GCM combinations with the second lowest and second highest precipitation were selected among the 15 combinations for the +1 and +3 degree scenario. This selection was made on a pilot-by-pilot basis to accommodate that the different scenarios have different impact in the various parts of Europe. The scenarios showing the lowest/highest precipitation were avoided, as these endmembers often reflects outliers.
5. Delta change values were calculated on a monthly basis for the four selected scenarios, based on the climate data from the reference period and the selected future period. The delta change values express the changes between the current and future climates, either as a relative factor (precipitation and evapotranspiration) or by an additive factor (temperature).
6. Delta change factors were applied to local climate data by which the local particularities are reflected also for future conditions.

For the analysis in the present pilot the following RCP-GCM combinations were employed:

Table 4.1. Combinations of RCPs-GCMs used to assess future climate

		RCP	GCM
1-degree	"Dry"	4.5	noresm1-m
	"Wet"	6.0	miroc-esm-chem
3-degree	"Dry"	6.0	hadgem2-es
	"Wet"	8.5	miroc-esm-chem

4.2 Integrated hydrological modelling of climate change

The MIKE SHE/ MIKE HYDRO model framework that the Sunds-model is based on, simulates overland flow, evapotranspiration, flow in the unsaturated zone, the saturated zone with drainage routing, and river flow, Figure 4.2, for the area around the city and lake of Sunds, Figure 4.3.

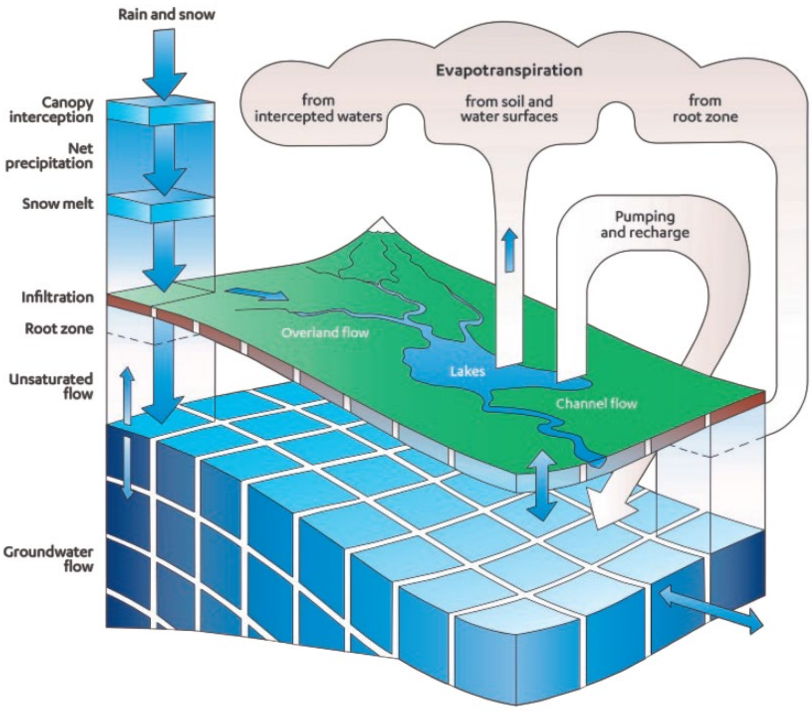

Figure 4.2 MIKE SHE model: Simulated hydrological water fluxes.

The geology of the Sunds model is sketched in figure 4.3 and is based on geophysical measurements. Numerical layers follow the principal layers of the geology, besides near the surface, where additional numerical layers are inserted. From the surface, the geology is glacial and post-glacial with important aquifers of glacial meltwater. Deeper, a Miocene sandy aquifer is separated from the upper glacial meltwater aquifer by a Miocene clay layer. The deepest horizon of the model consists of relatively impermeable clay from the Arnum Formation, also of Miocene origin, Figure 4.3.

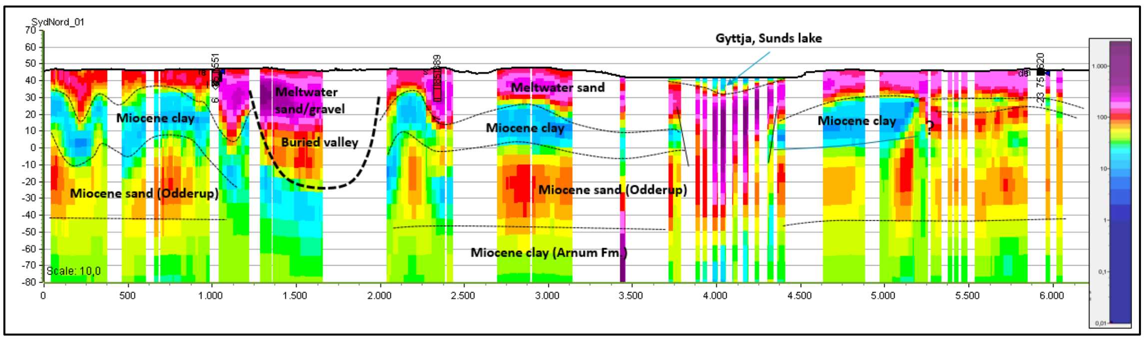

Figure 4.3 The geology of the Sunds model is based on geophysical measurements, Rasmussen et al. 2020.

In the assessment of climate change for the future periods or levels of temperature change, the model structure and parametrization are not changed for simulating the future period. The only model differences are the forcing climate states, precipitation, temperature and reference evapotranspiration. Besides these, nothing is changed within the model setup for simulation the future conditions. In reality, it is expected that most of the physical descriptions represented in the model will actually change; this could be inputs such as land use, field crops, morphology of surface waters and others. This means that the model runs only simulates the effect from the change of climate.

In the assessment of adaptation measures, other model elements different the climatic states are also changed and can be summed up in the following adaptation scenarios:

1. Groundwater drainage, a dedicated groundwater drainage pipe installed together with the existing sewer system (the 3rd pipe) in urban areas, Sunds City.
2. Plantation of coniferous forest on 395 ha west, south, and east of the City of Sunds.
3. Changed groundwater abstraction close to the City of Sunds.
4. Application of local area recharge, forced infiltration of surface water into the shallow aquifer from 25% (today) to 50% (possible future) of the stormwater.
5. Renovation of sewers. The sewer do not act as groundwater drainage because the leakage are reduced.
6. Keeping the Lake water stage fixed to the summer water stage (lowering the water table in Sunds Lake to a constant elevation of 41.6 m).

The adaptation measures are tested under historic climatic conditions and compared with business as usual run for the same historic period with change maps.

4.3 Model calibration

The hydrological model for Storaa was calibrated against groundwater heads and river runoff using the parameter estimation software PEST. The hydrological observations used include observations of groundwater levels, water level in Sunds Lake and discharge from rivers.

Data from a synchronous groundwater measuring campaign ultimo October 2012 included 68 shallow boreholes with a maximum depth of 5 m. The campaign also included measurements of water levels at 33 locations in the river systems, and water levels measured at 107 locations around the rim of Sunds Lake.

Time series of groundwater level from eight boreholes have been available for the hydrological model. The time series are from seven shallow boreholes and from one deeper borehole. The longest time series was started in 2012. At the western outlet of Sunds Lake the water level of the lake is measured continuously. In the creek, Møllebæk, east of Sunds Lake the river discharge is measured continuously.

Figure 4.4 shows an overall good match between observed and computed groundwater heads with a difference of less than 0.5 m. At a few locations towards the west of the area, a difference of more than 1 m between observed and computed groundwater heads is seen.

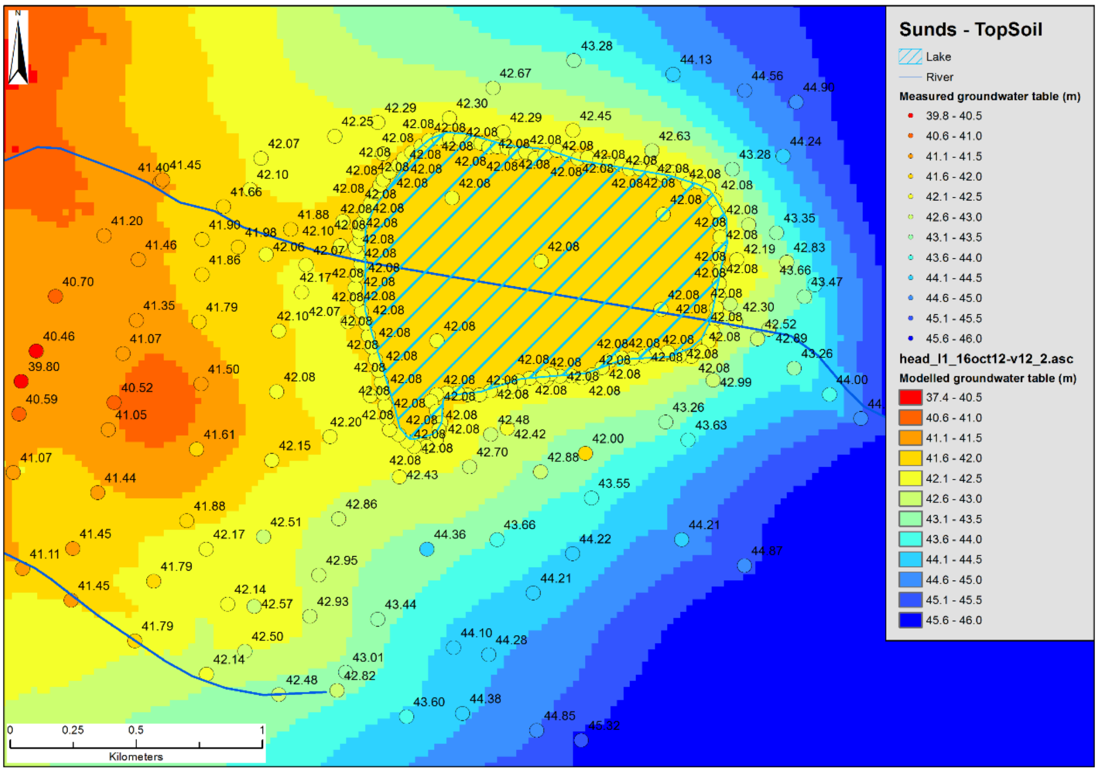

Figure 4.4 Groundwater head elevations from the calibrated hydrological model (colour contours) and the observed groundwater heads and water levels of Sunds Lake (coloured circles and numbers). Rasmussen et al. 2020.

Figure 4.5 Show simulated and observed times-series for som groundwater well within the model.

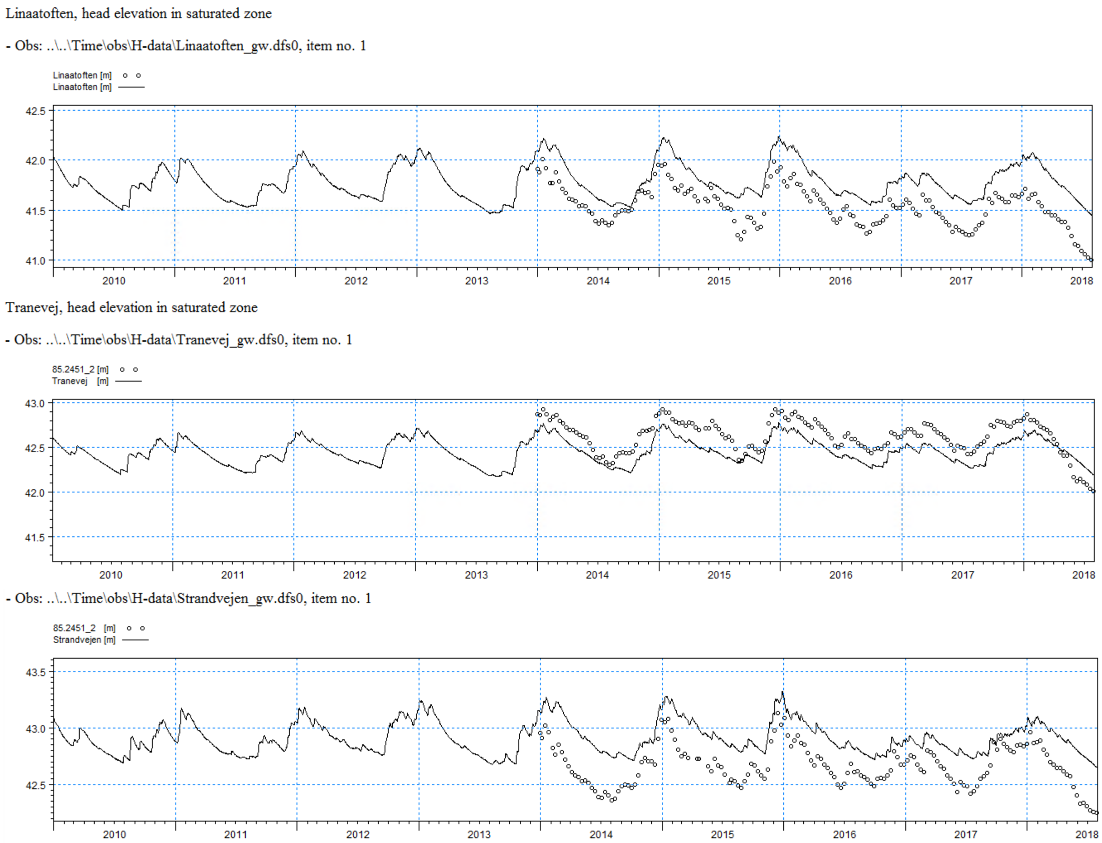

Figure 4.5. Modelled (solid lines) and observed groundwater head (circles) at station Linaatoften, Tranevej, and Strandvejen. Rasmussion et al. 2020.

Based on the calibration results, the model is qualified to be used for the climate change assessment and assessment of adaptation strategies.

5 RESULTS AND CONCLUSIONS

5.1 Integrated hydrological modelling of climate change

The TACTIC standard climate change scenarios simulated in the sunds model show changes in average groundwater levels for a 30 year historic, reference period, and future 30 year periods representing a 1 and 3 degree increase in temperature of the future. Figure 4.6 illustrate changes in groundwater levels between the reference and future periods. Areas with changes below zero (negative numbers), figure 4.6, have rising groundwater levels (blue colours) and areas with values above zero have a decreasing groundwater table (yellow-red colours).

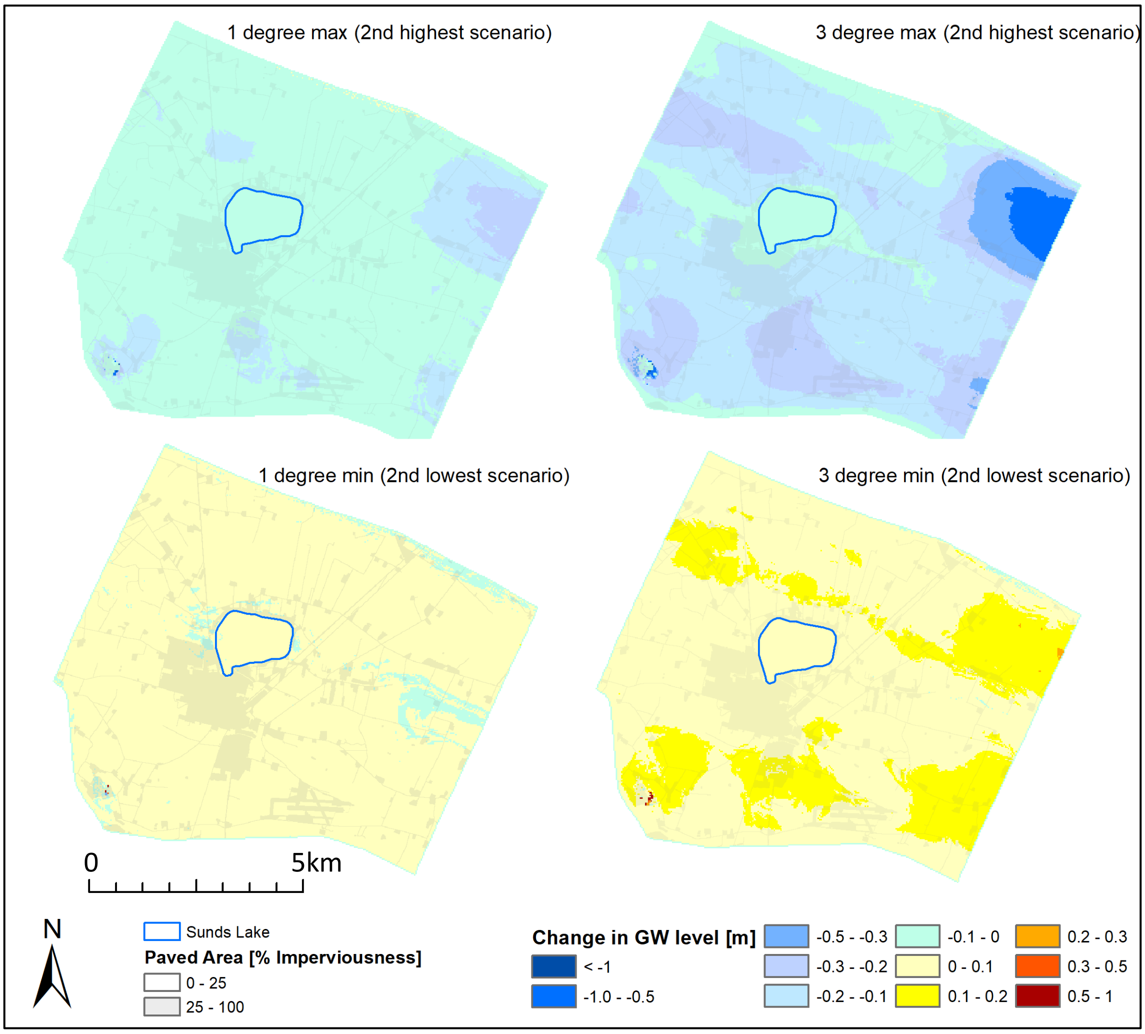

Figure 4.6 Change in groundwater levels for the four TACTIC climate change standard scenarios. The lower ones are the dry scenarios where groundwater levels mostly decrease (yellow-red colour) and the upper ones are the wet where groundwater levels increase (blue colour). Negative numbers (-) indicate an increase groundwater levels. Positive numbers indicate a decrease of the groundwater levels.

Average change for the entire model domain are for the 1 and 3 degree wet scenarios -6 cm and -17 cm, respectively. This shows a phreatic surface in 6 and 17 cm closer to the surface for the scenarios. The 1 and 3 degree dry scenarios show a increasing depths to the upper most groundwater table of 2 and 7 cm. Average of the four scenarios is a 4 cm decrease, a 4 cm lower groundwater surface in the future.

5.1.1 Conclusions of the assessment based on integrated hydrological modelling

Based on the 4 investigated scenarios of a possible 1 or 3 degree temperature change, groundwater levels can either increase or decrease. Average change of all the 4 models show a small increase of the upper most unconfined groundwater of 4 cm.

5.2 Assessment of climate change adaptation strategies

The following section shows selected results for the simulated 5 adaptation scenarios, Figure 4.7-12. The effects in the shallow groundwater table can be divided into measures lowering the groundwater table. The measures lowering the groundwater table and thereby reducing risk of groundwater flooding of infrastructure and building are: Installing the 3rd pipe, (the groundwater drain) along the sewer system, plantation of coniferous forest in the vicinity of the City, and maintaining the lake water stage at the summer level the whole year around. From these interventions, installing the 3rd pipe (groundwater drain) are clearly the most efficient one to decrease the groundwater levels. The measures increasing the groundwater levels include: renovation of the leaky sewer system, increasing the rainwater infiltration to the groundwater aquifer (local area recharge, forced infiltration), and stopping drinking water abstraction close to the city.

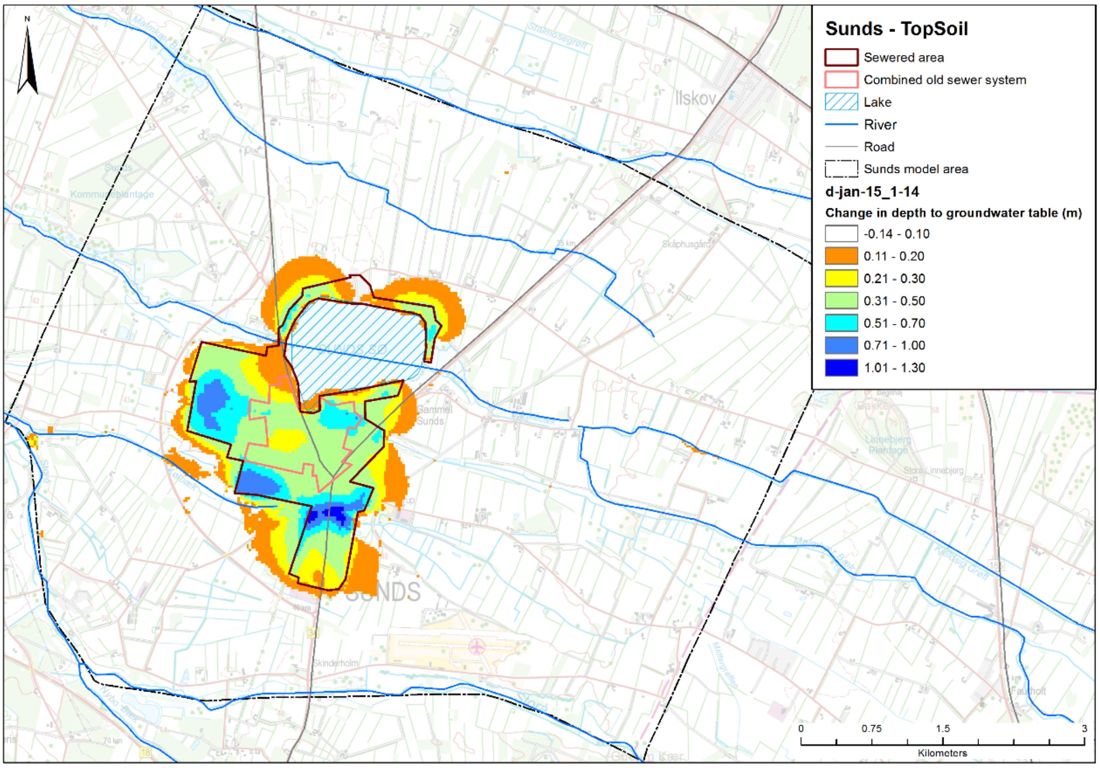

Figure 4.7 Effect on depth to groundwater table if establishing drains (3rd pipe) in the whole town. The figure shows the situation for a January situation with high groundwater table. Rasmussen et al 2020.

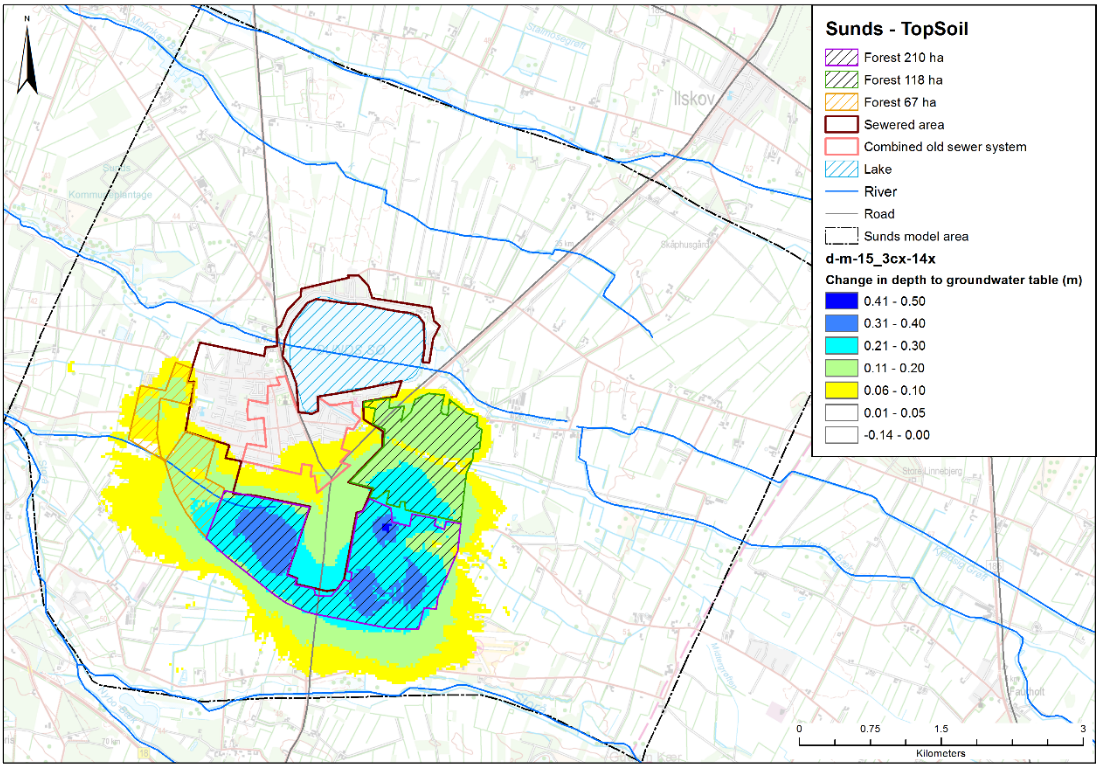

Figure 4.8 Effect on groundwater table with plantation of coniferous forest on 395 ha west, south, and east of town. Rasmussen et al 2020.

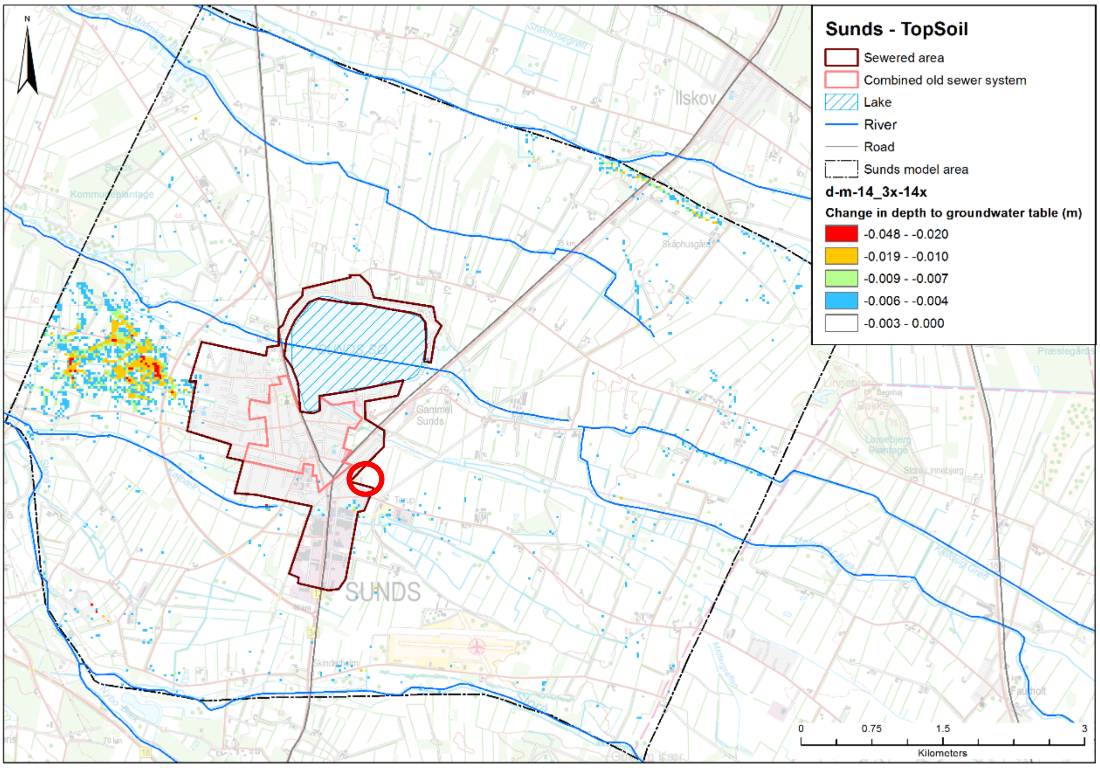

Figure 4.1 Effect on depth to groundwater table if groundwater abstraction for Sunds Waterworks stops. Minus in the numeric scale indicates a rise in groundwater table. Red circle shows the location of the waterworks wellfield. Rasmussen et al 2020.

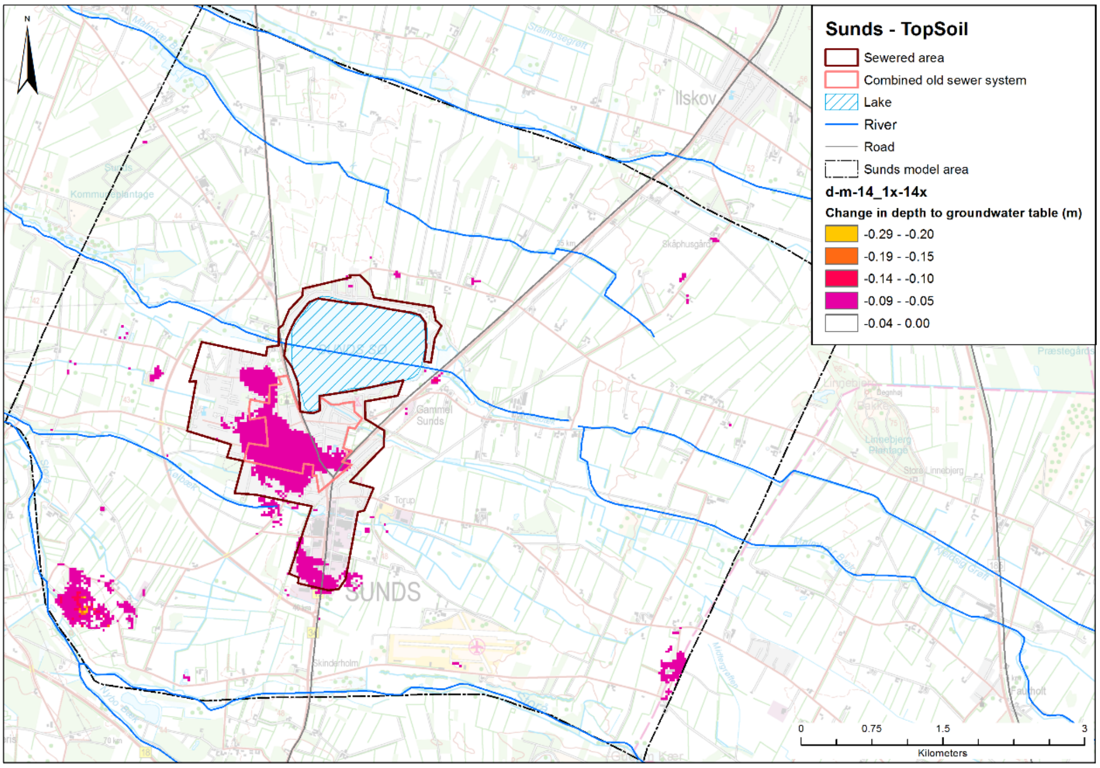

Figure 4.10 Change in depth to groundwater for the scenario with an increase of local rainwater infiltration in the whole town from 25% to 50%. Rasmussen et al 2020.

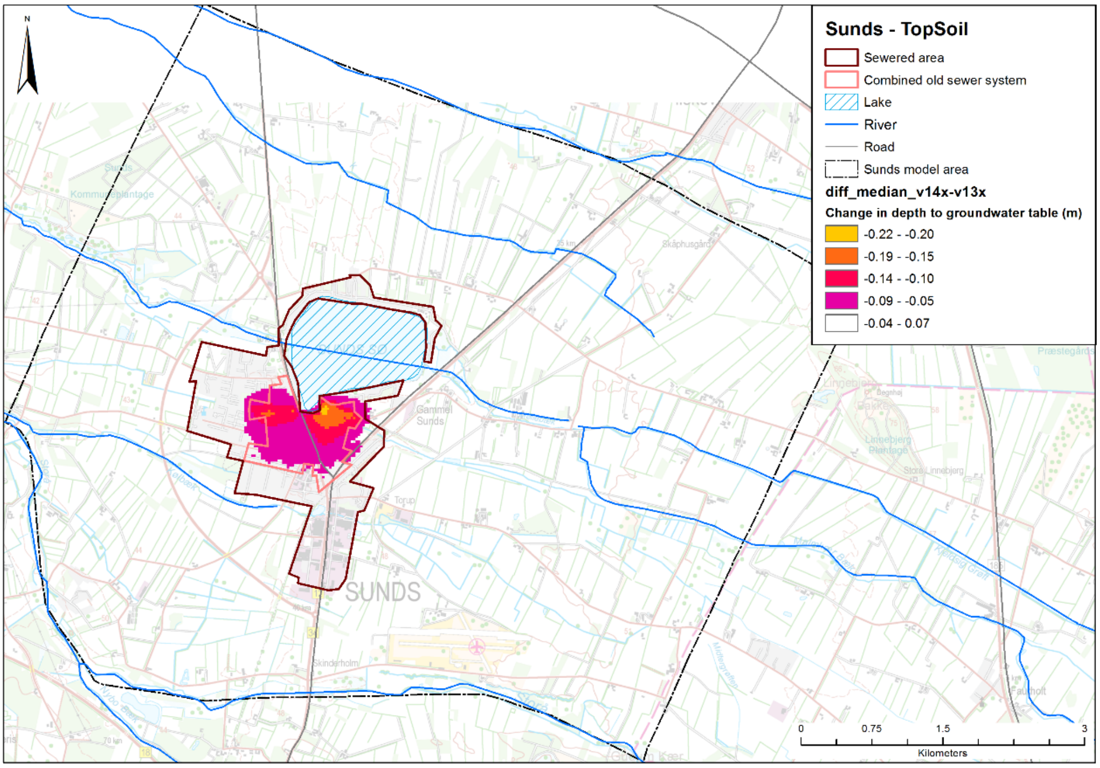

Figure 4.11 Change in depth to groundwater table after renovation of sewers in the centre of town (area inside light red lines). Rasmussen et al 2020.

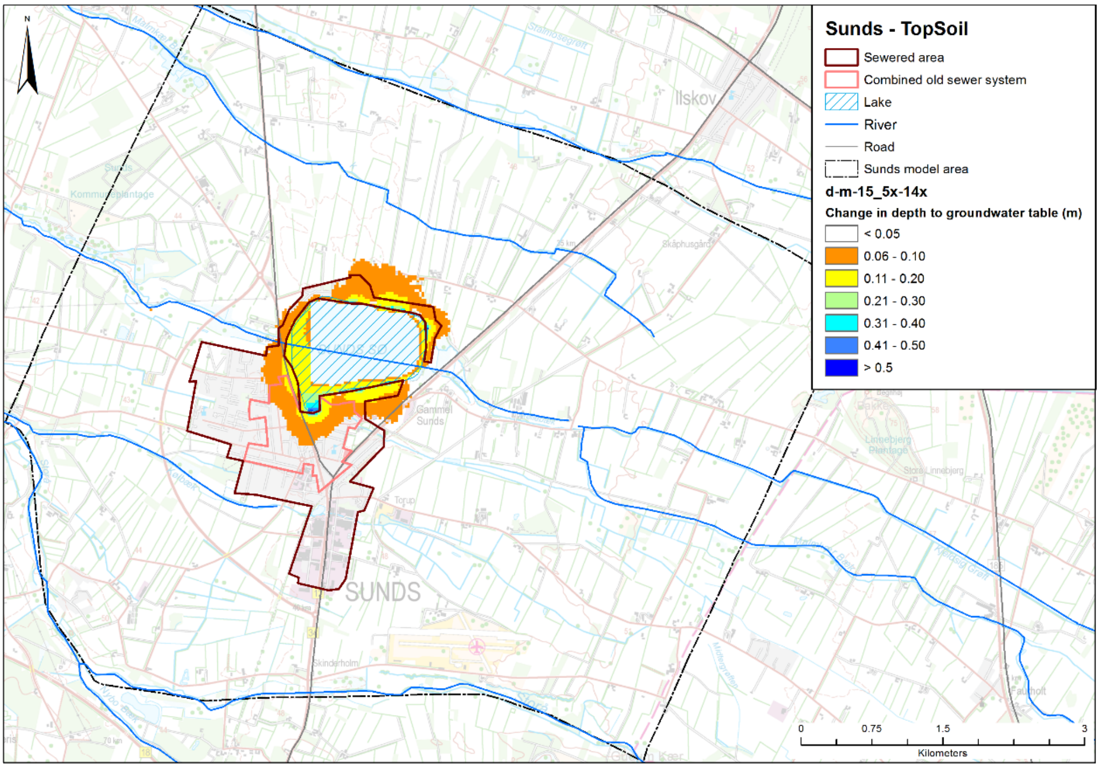

Figure 4.12 Lowering the water table in Sunds Lake to a constant elevation of 41.6 m, "the summer level". The figure shows the situation for a median groundwater table. Rasmussen et al 2020.

5.2.1 Conclusions of the assessment of climate change adaptation strategies

Based on the different scenarios tested, the most effective measure is to lower the groundwater table in the urban part of the City of Sund is by implementation of a "3rd pipe", an urban drainage system installed along the existing sewer system. The scenarios also show that especially renovation of an old sewer system and increasing the rainwater infiltration will increase the upper groundwater table and potentially introduce groundwater flooding.

The combination of deferent scenarios illustrated that different interventions can either work for or against the goal of preventing future groundwater flooding.

6 REFERENCES

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Establishing the European Geological Surveys Research Area to deliver a Geological Service for Europe

Deliverable 3.2 & 6.3

PILOT DESCRIPTION AND ASSESSMENT

Upper Guadiana Basin (Spain)

Authors and affiliation:

David Pulido-Velazquez, Leticia Baena-Ruiz, Africa de la Hera Portillo, Miguel Mejias, AJ. Collados-Lara, Juan de Dios Goméz-Gómez.

Geological Survey of Spain (IGME)

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Deliverable Data	
Deliverable number	D3.2 & D6.3
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Deliverable name	Pilots description and assessment report for groundwater-surface water/ Pilots description and assessment report for adaptation
Work package	WP3 & WP6
Lead WP	GEUS (WP3), IGME (WP6)
Deliverable status	
Version	Final version
Date	09/03/2021

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LIST OF ABBREVIATIONS & ACRONYMS

CC	Climate Change
FAO	Food and Agriculture Organization of the United Nations
GSOs	Geological Survey Organisations
MS	Management scenario
SAC-SMA	Sacramento Soil Moisture Accounting
UGB	Upper Guadiana Basin

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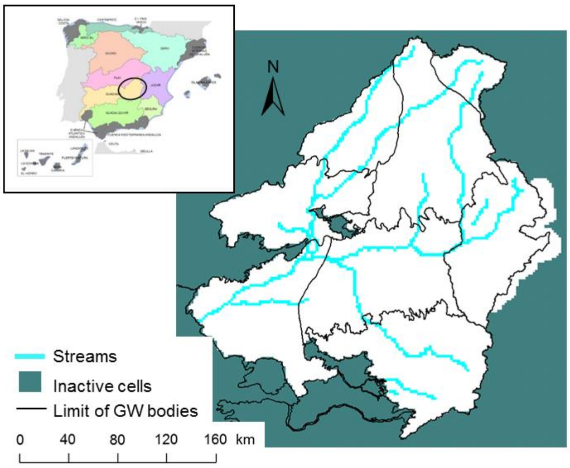
1. EXECUTIVE SUMMARY



Pilot name	UPPER GUADIANA BASIN
Country	Spain
EU-region	Mediterranean region
Area (km^2)	14000 km^2
Aquifer geology and type classification	Detrital and carbonated. Sedimentary & karstic.
Primary water usage	Irrigation / Drinking water / Industry
Main climate change issues	Decrease in piezometric levels and some negative environmental impacts upon groundwater-dependent wetlands, streams and rivers. Identify and assess climate change adaptation measures for a sustainable management of the Basin.
Models and methods used	Generation of local future climate change scenarios and definition of adaptation scenarios (by applying top-down and bottom-up approaches). Propagation with a chain of auxiliary models (recharge, agricultural) to generate inputs for a distributed flow model defined with the MODFLOW code; Propagation of impacts on laggoons by using regression models that include climatic and hydrological explanatory variables.
Key stakeholders	Guadiana River Basin Authority, farmers associations (farmers are a highly heterogeneous group, whose interests often cannot be generalised; this implies a wide range between those associations working at institutional level and those working at political scale representation), water supply companies, Environmental Conservation Groups.
Contact person	L. Baena, D. Pulido, A. de la Hera, M. Mejias, JD Goméz, Aj Collados-Lara. IGME (Spain), l.baena@igme.es; d.pulido@igme.es; a.delahera@igme.es; m.mejias@igme.es; j.dedios@igme.es; Aj.collados@igme.es

Eight groundwater bodies compose the Upper Guadiana Basin (UGB), including detrital and carbonated aquifers with a complex geology. The intensive groundwater use mainly for irrigation has trigger abundant social and economic benefits; however, it has also produced a significant decrease in piezometric levels and some negative environmental impacts upon groundwater-dependent wetlands, streams and rivers. The Basin shows strong natural interaction between groundwater and surface water gives rise to over one hundred wetlands that make up UNESCO's Mancha Húmeda Biosphere Reserve; under semi-natural conditions wetlands totalled about 25000 ha. However, this area is now reduced to only 7000 ha. In addition, some rivers and streams that were naturally fed by the aquifers now have become net losing rivers. Some climate change (CC) predictions forecast an increase in temperature and a decrease in precipitation, which will cause a decrease in water contributions and an increase in the magnitude and frequency of extreme phenomena such as floods and droughts. In front of these scenarios it will be necessary to design adaptation strategies able to be impemented with the acceptation and support of all groundwater users.

The overall objective of this study is to assess and summarise impacts of potential future CC scenarios on the quantitative status of aquifers and groundwater depend lagoons. This assessment will require the generation of local future CC scenarios. Their impacts are assessed by propagating them with a chain of auxiliary models (recharge, agricultural) that generate inputs for a distributed flow model defined with the MODFLOW code. A regression model is also applied to estimate impacts on laggoons. Finally, we identify and analyse potential adaptation strategies by applying top-down and bottom-up approaches.

Results show that some CC scenarios would imply a reduction in the recharge due to higher temperature and lower precipitation. This entails an increase in pumping to maintain the irrigation area. These scenarios will produce a decrease of the water table regarding the reference year (2015), producing a reduction of the discharge and therefore, a smaller surface water in wetlands. Other scenarios estimate a slightly increase in both precipitation and temperature. It will imply an increase in groundwater recharge. For those scenarios, although the increase in pumping to maintain irrigated area (due to the higher temperature) will produce groundwater depletion in some areas, the groundwater discharge could increase regarding the mean historical discharge.

2. INTRODUCTION

CC already have widespread significant impacts in Europe, which are expected to increase in the future. Groundwater plays a vital role for the land phase of the freshwater cycle and have 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 CC 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. In order 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, identification, and analyses of potential adaptation strategies.

TACTIC is centred on 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 infra structure 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 UGB pilot (Spain) represents one of the pilots in TACTIC where the impacts from CC on groundwater and dependent ecosystems will be adressed. The general challenge of the pilot is to assess future potential groundwater levels and changes in the surface of groundwater dependet lagoons. We will also study potential adaptation strategies by using a mixed top-down and bottom-up approach.

3. PILOT AREA

In the UGB strong natural interactions between groundwater and surface water are observed, which gives rise to over one hundred wetlands that make up UNESCO's Mancha Húmeda Biosphere Reserve. This pilot area also highlights the strong conflict between groundwater-dependent ecosystems and groundwater pumping to supply demands (mainly irrigation demands). This problem might be exacerbated in the future due to CC impacts. In this project we intend to assess potential future impacts, considering different potential CC scenarios and adaptation strategies.

3.1 Site description and data

3.1.1 Location and extension of the pilot area

The case study cover and area of near 14000 km^2 located in the Mediterranean region of EU (See Figure 3.1 and Table 3.1). It has traditionally been one of Spain's most intensively pumped groundwater systems, due to a predominantly dry climate and to the prevalence of irrigated agriculture, as well as to the fact that it stores large amounts of accessible groundwater (Martínez-Santos et al., 2018). It represents a unique example of a semiarid region where groundwater use has helped transform a largely poor rural region into a prosperous agricultural and industrial center (Hernández-Mora, 2002; Llamas, 2005).

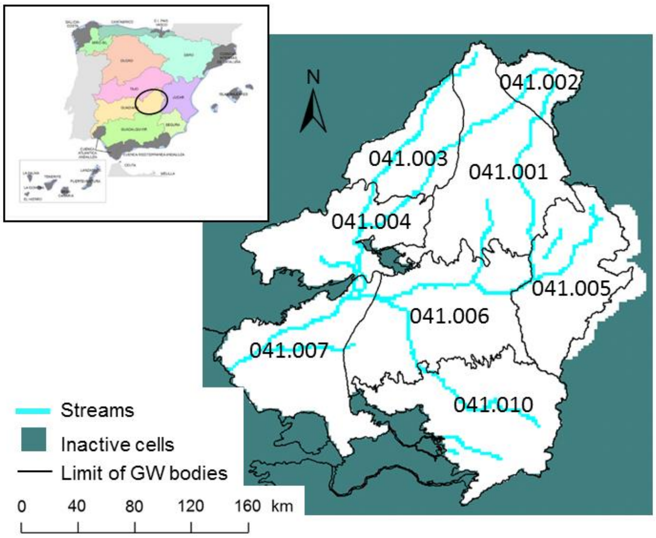


Fig. 3.1: Location of the pilot area.

Table 3.1: Groundwater bodies in the UGB according to UGB (2018, 77).

Name	Code	Extension (km^2)
Sierra de Altomira	041.001	2575
La Obispalía	041.002	490
Lillo-Quintanar	041.003	1102
Consuegra-Villacañas	041.004	1606

Rus-Valdelobos	041.005	1459
Mancha Occidental II	041.006	2536
Mancha Occidental I	041.007	2003
Campo de Montiel	041.010	2200

3.1.2 Geology/Aquifer type

The geology of the UGB is complex including detrital and carbonated aquifers (see Figure 3.2). One of the main groundwater bodies is the Mancha Occidental Aquifer, located in the central part of the UGB. Groundwater connectivity between the different aquifers in the UGB is structurally complex, however, the Mancha Occidental Aquifer is known to be on the receiving end of the system (IGME, 2004; Martínez-Cortina, 2003; Martínez-Santos et al., 2008) and it has been thoroughly described from the hydrogeological viewpoint in several works (IGME, 2004, 2005; ITGE, 1989; Martínez-Santos et al., 2008).

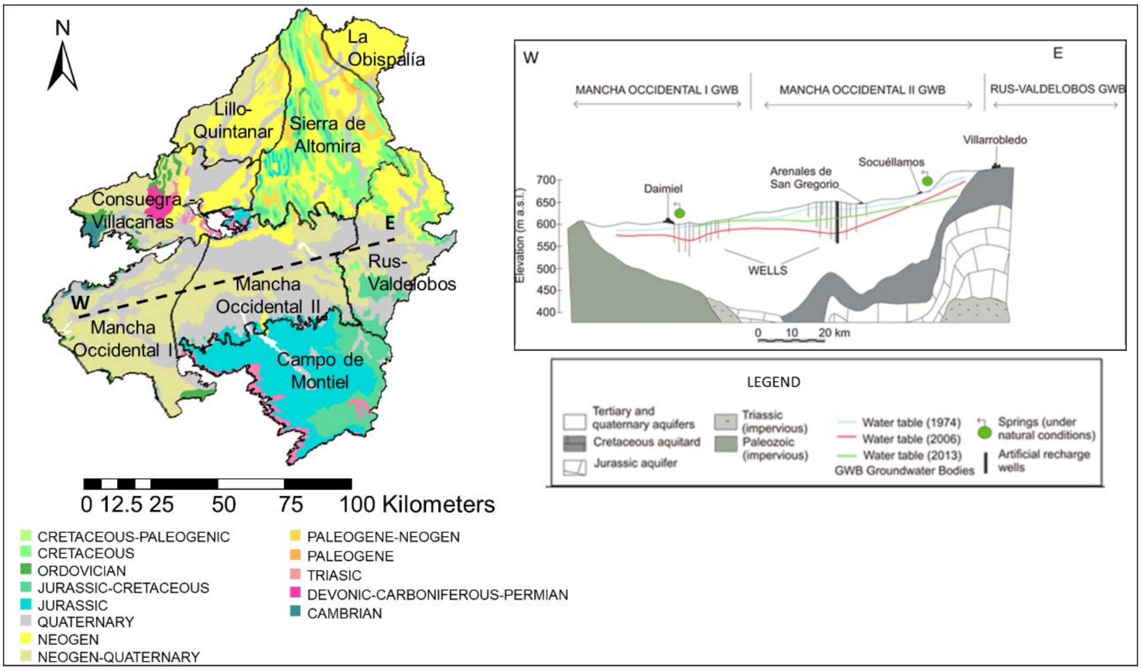


Fig. 3.2: Geological map and cross sections.

3.1.3 Topography and soil types

The area is predominantly flat, sloping gently over 150 km, from the northeast (elevation 730 m.a.s.l.) to the southwest (600 m.a.s.l.) (Figure 3.3, left). The soils (Figure 3.3, right) in the basin mainly belong to the calcisol group according to the FAO classification (1998). It also be found Regosol and others such as luvisol and podzol can be found in the southeast area (Conan et al. 2003).

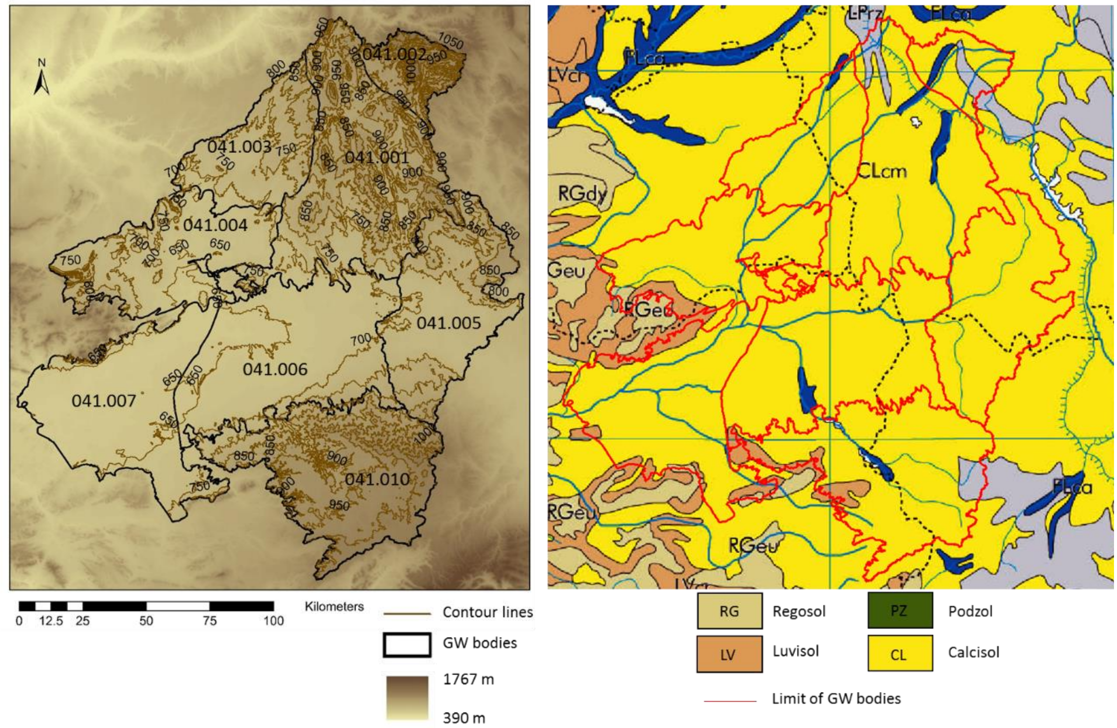


Fig. 3.3: Left: Topography (Digital Elevation Model map with a resolution of 100m); right: soil map from IGN (E 1:3000000).

3.1.4 Surface water bodies

The Basin shows strong natural interaction between groundwater and surface water which gives rise to over one hundred wetlands that make up UNESCO's Mancha Húmeda Biosphere Reserve (see Figure 3.4); under semi-natural conditions wetlands totalled about 25000 ha. However, this area is now reduced to only 7000 ha (De la Hera, 2003) due to intensive groundwater pumping. The most part of them are groundwater-dependent wetlands. The current groundwater management implies that a good number of them are at risk to survive. Intensive groundwater withdrawal depleted the water table by more than 20 m between the mid-1970s and the first decade of the new century (IGME, 2004). Although an important and unexpected recovery of the Mancha Occidental aquifer has occurred recently, there are still uncertainties with regard to ecosystems functionality and provision of ecosystem services.

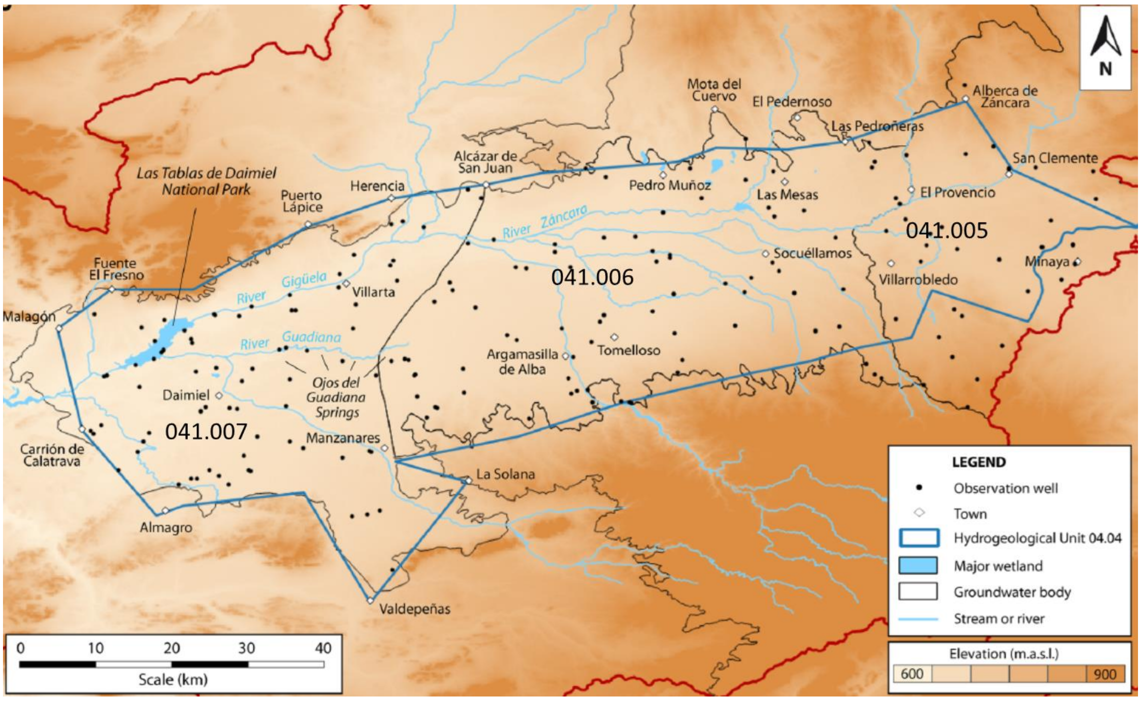


Fig. 3.4: Wetlands that make up UNESCO's Mancha Húmeda Biosphere Reserve.

There are some flow gauges in which the streamflows of some sub-basins are measured even in nearly natural conditions. The location, resolution and period covered by them are represented in Table 3.2 and Figure 3.5.

Table 3.2: Statistics of the flow gauges.

Flow gauges	Average Q(m^3/s)	Period	Temporal resolution	Surface (km^2)
4004	2.17	1973-2015	Daily	847
4101	0.44	1973-1996	Daily	674
4201	1.22	1973-2012	Daily	1080
4202	1.01	1973-2015	Daily	3120
4224	0.67	1975-2015	Daily	2090

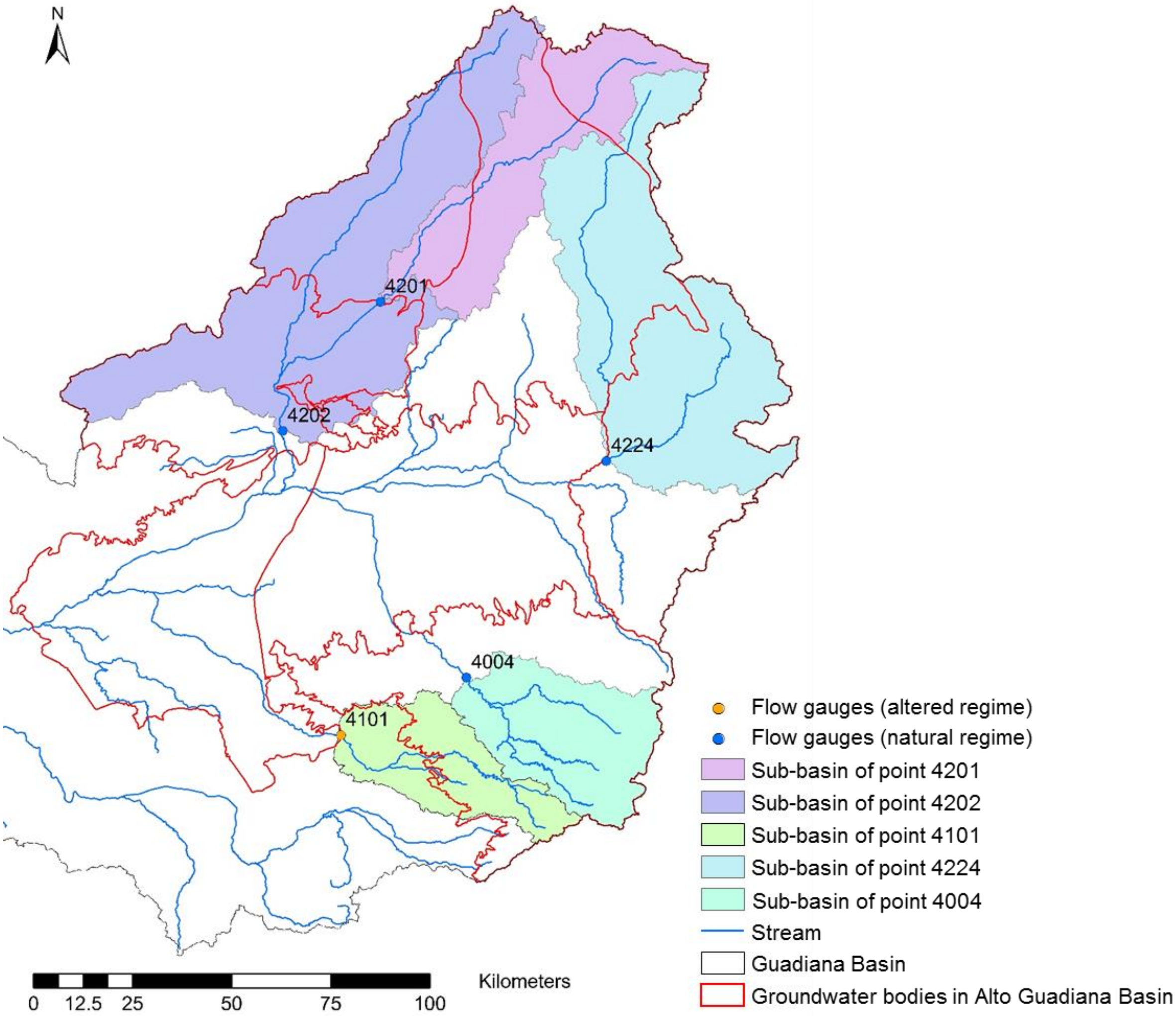


Fig. 3.5: Flow gauges distribution.

3.1.5 Hydraulic head evolution

The intensive groundwater withdrawal depleted the water table by more than 20 m between the mid-1970s and the first decade of the new century (IGME, 2004). In Figure 3.6 we represent the location of the observation points, the maximun observed drawdowns and the temporal evolution in some relevant observation wells.

Aquifers located in the central part of th UGB (Mancha Occidental I and Mancha Occidental II) have experienced a spectacular recovery of its piezometric levels in recent times; in fact, it is currently close to full storage, to the point that its wetlands, artificially maintained for decades, have experienced natural groundwater discharge again for the first time since the early 1980s (Martínez-Santos et al., 2018).

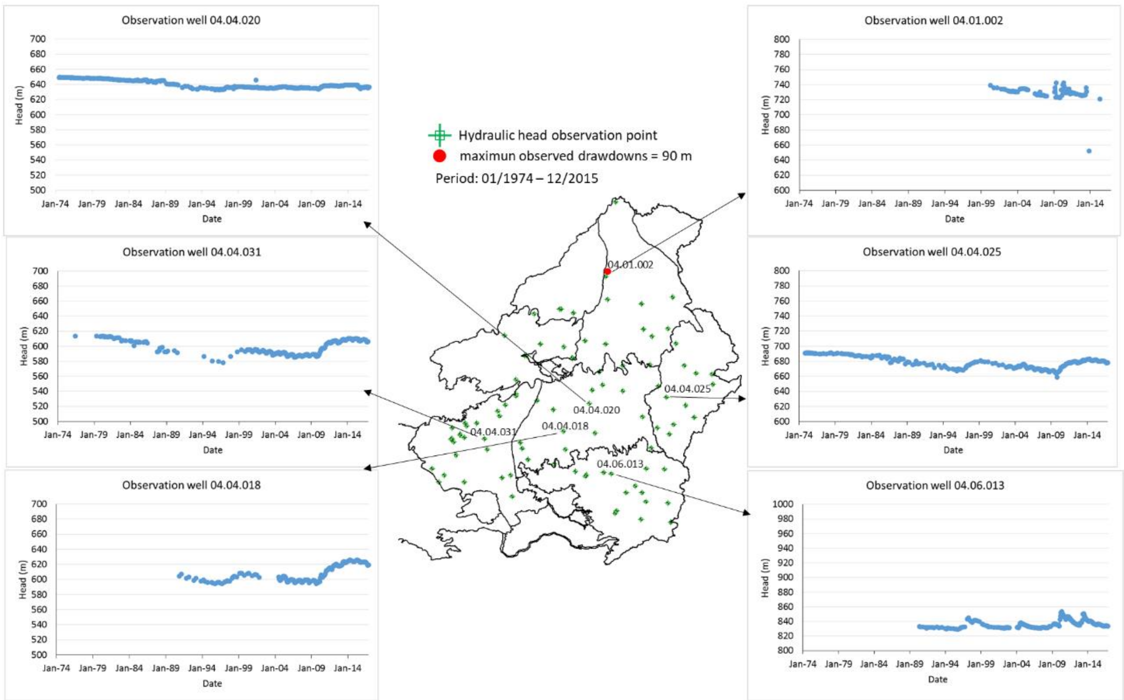


Fig. 3.6: Location of hydraulic head observation points.

3.1.6 Climate

Although this pilot is located in the Mediterranean Region in accordance with the EEA maps, the climate conditions are typically continental and semiarid. Summers are hot and dry, and winters are short and generally mild (Martinez-Santos et al., 2018).

The precipitation is irregularly distributed in the time (see Figure 3.7). The annual average value in the period 1904-2014 is 405 mm (Martinez-Santos et al., 2018). The mean annual temperature is 14.7 °C, oscillating between a maximum mean value of 25.5 °C in July and a minimum of 5.4°C in January. The mean potential evapotranspiration is 700 mm/year. Rainfall is the main source of aquifer recharge.

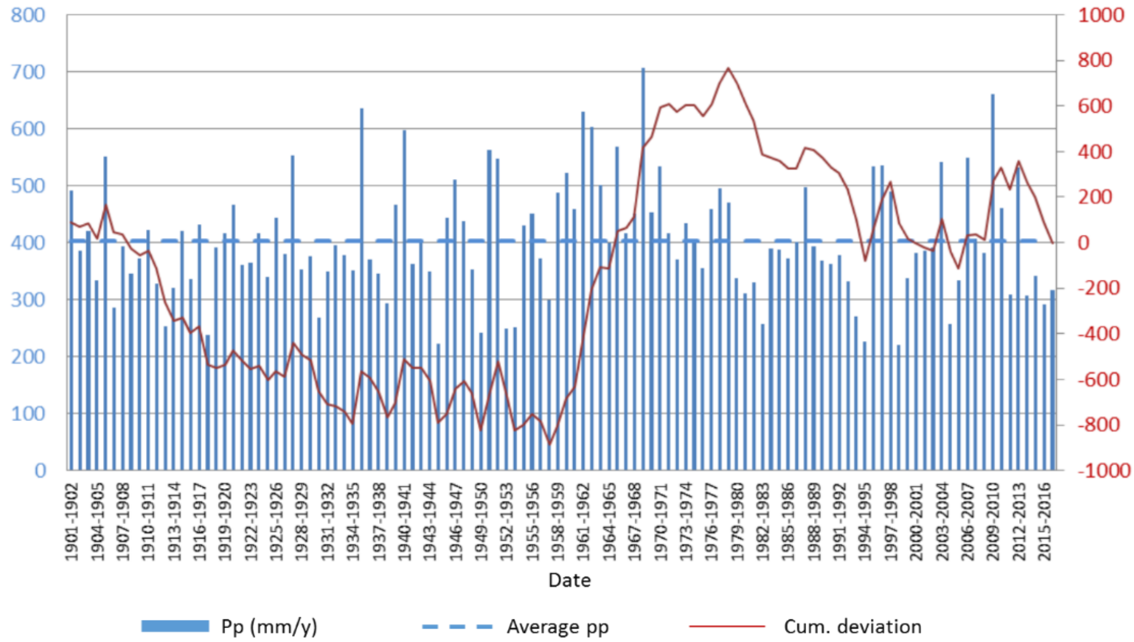


Fig. 3.7: Temporal evolution of the Precipitation (mm/year).

3.1.7 Land use

The main land use is agriculture (see Figure 3.8), which has been expanded in this area since early seventies. The main crops are winter cereals, vineyards and olives (Conan et al. 2003). Although non-irrigated agriculture is the most extensive, there are important irrigation areas mainly located in the central part of the basin.

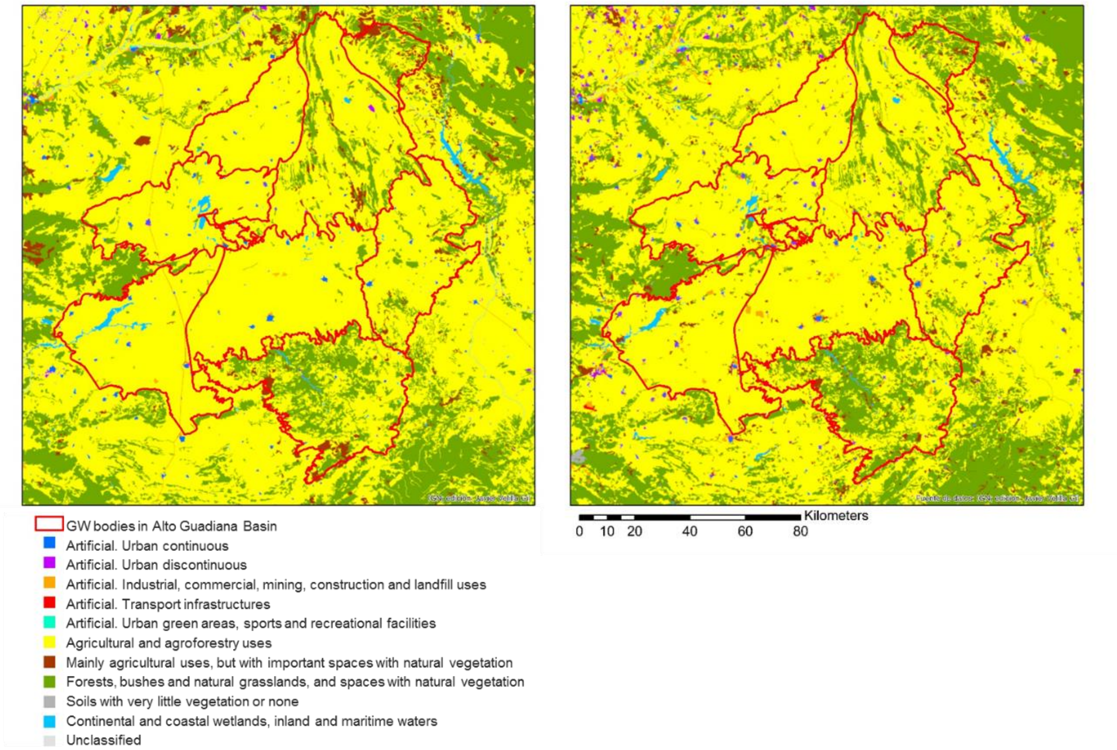


Fig. 3.8: Land use maps from CORINE (1990 and 2012).

3.1.8 Abstractions/irrigation

Currently, pumping-based irrigation accounts for over 90 % of the total water uses. The intensive groundwater pumping in turn led to the desiccation of most groundwater-dependent ecosystems, including Ramsar-listed Las Tablas de Daimiel National Park (Castaño-Castaño et al., 2008), and triggered a series of measures to constrain irrigation. This intensive groundwater pumping is partly due to inadequate management and partly to the presence of thousands of illegal wells. Figure 3.9 and Figure 3.10 show the annual historical temporal evolution of the pumping applied in the MODFLOW model and the spatial distribution in the UGB.

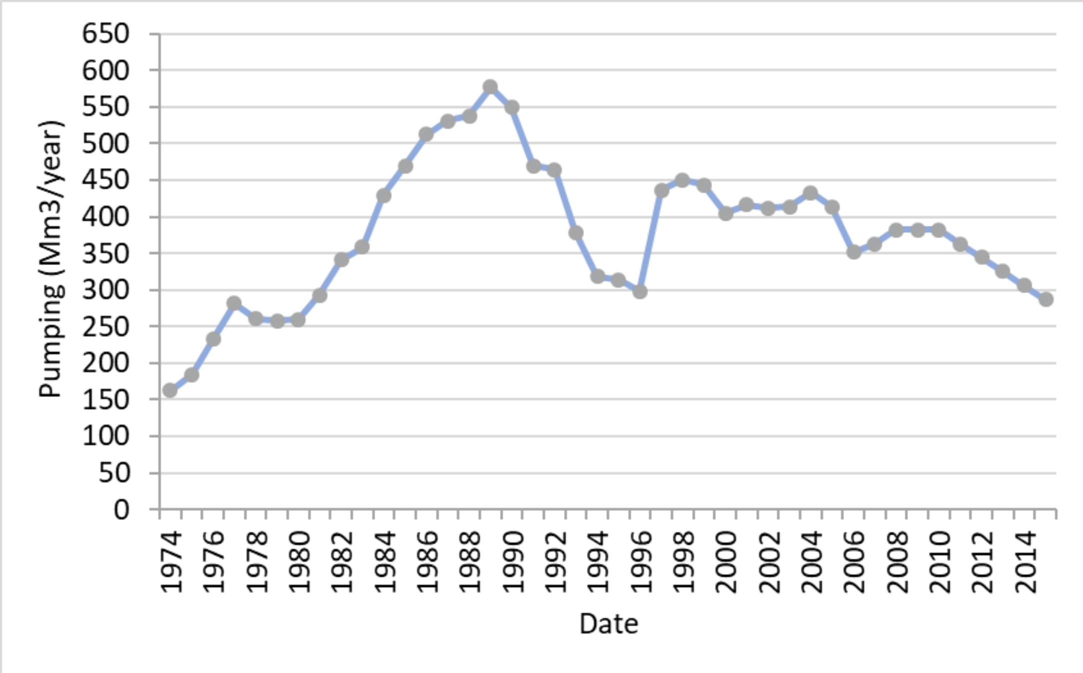


Fig. 3.9: Historical temporal evolution of pumping (Mm^3/y).

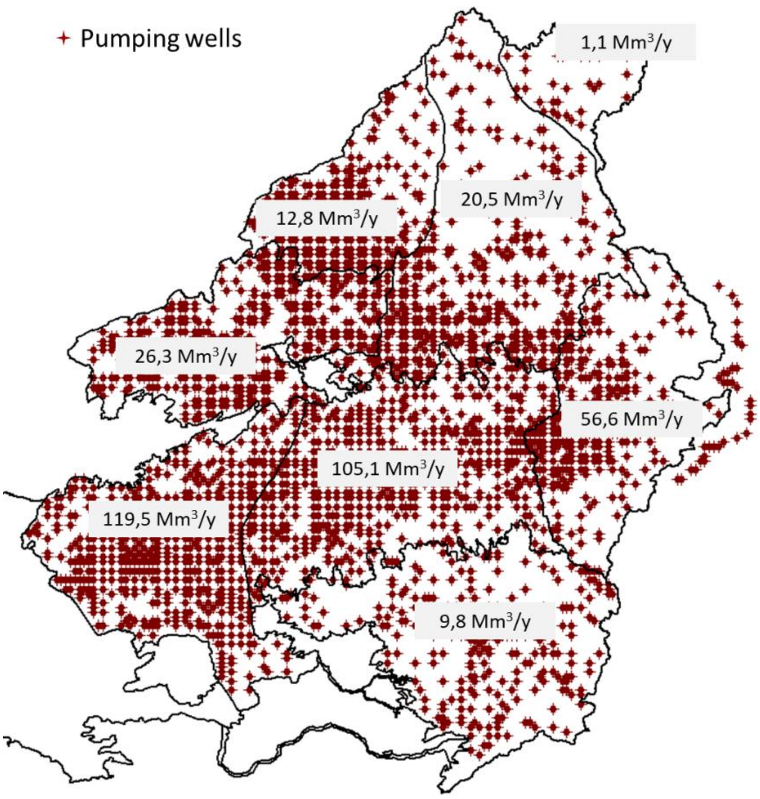


Fig. 3.10: Spatial distribution of the pumpings and mean pumping rates in each GW body in the period (2006-2015).

3.1.9 Flow balance components

The evolution of the main components of the flow balance in the UGB is sumarized in (Table 3.3).

Table 3.3. Approximate water balance in the Upper Guadiana Basin.

Inflow/outflow	Inflows (Mm^3/y)		Outflows (Mm^3/y)			
Date	Rainfall recharge	Recharge from streams	Groundwater pumping	Evapotranspiration from the water table	Discharge to rivers	Lateral transfer to Júcar
1976-1980	771.8	29.3	244.6	985.2	411.8	-19.5
1981-1985	481.2	31.6	347.9	279.5	148.0	18.9
1986-1990	628.5	32.7	489.1	177.4	123.4	47.2
1991-1995	237.4	22.6	328.7	80.2	79.9	52.4
1996-2000	742.6	31.6	336.2	180.5	127.5	68.5
2001-2005	484.0	27.8	340.9	116.1	100.2	72.9
2006-2010	620.6	29.7	375.5	93.5	87.8	0.9
2010-2015	591.1	31.4	327.8	163.1	126.3	0.3
1976-2015	**569.7**	**29.6**	**348.8**	**259.4**	**150.6**	**30.2**

3.2 Climate change challenge

In accordance with the EEA map the main expeted issues due to CC in this case study are those described in the Figure 3.11 for the 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 aquifer recharge in the area (see Pulido-Velazquez et al., 2017).

The main challenge is to find adaptation measures to maintain a sustainable use of the groundwater bodies with a balance between supply water demands (different uses) under future CC conditions and maintaining a good status in the related ecosystem.

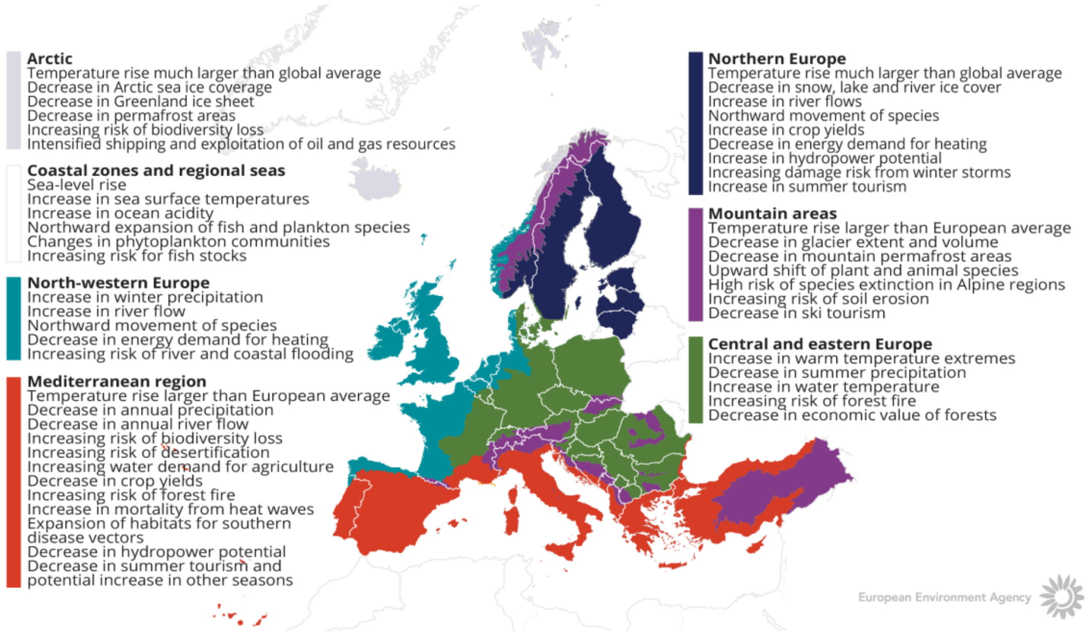


Figure 3.11: European Environment Agency map of projected CC for Europe.

4. METHODOLOGY

The assessment of CC impacts on groundwater and dependent wetlands in the UGB are performed using the TACTIC standard CC scenarios and a chain of hydrological, agricultural and groundwater flow models.
On the other hand, the monitoring and estimation of the water surface in wetlands (groundwater dependent ecosystems) is an important issue in the UGB due to the high environmental value that these lagoons have in the ecosystem functionality. A regression model is applied to estimate the impacts of CC on laggoons.
Finally, we identify and analyse potential adaptation strategies by applying top-down and bottom-up approaches through a participatory process involving groundwater users and skateholders.
The modelling framework is summarised in Figure 4.1.

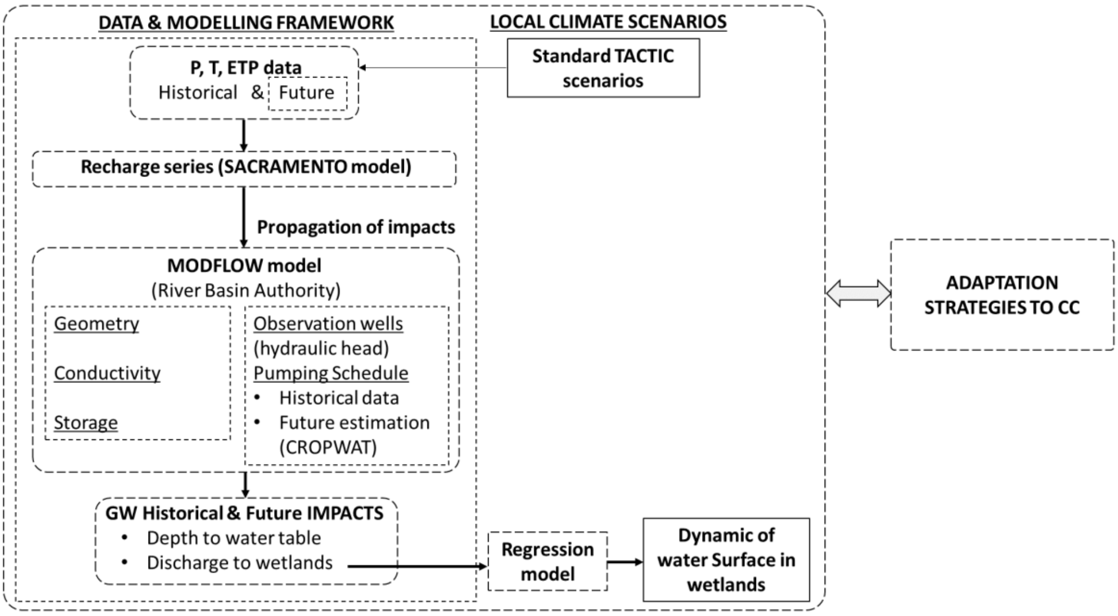


Figure 4.1: Modelling framework.

4.1. Climate data

The present study relies on the TACTIC standard CC dataset to reflect future climate conditions, which include a “wet” and a “dry” climate for a +1 and +3 degree global warming scenario.

4.1.1. TACTIC standard CC scenarios

The TACTIC standard scenarios are developed based on the ISIMIP (Inter Sectoral Impact Model Intercomparison Project, see www.isimip.org) datasets. The resolution of the data is 0.5°x0.5°C global grid and at daily time steps. As part of ISIMIP, much effort has been made to standardise the climate data (a.o. bias correction). Data selection and preparation included the following steps:

1. Fifteen combinations of RCPs and GCMs from the ISIMIP data set where selected. RCPs are the Representative Concentration Pathways determining the development in greenhouse gas concentrations, while GCMs are the Global Circulation Models used to

simulate the future climate at the global scale. Three RCPs (RCP4.5, RCP6.0, RCP8.5) were combined with five GCMs (noresm1-m, miroc-esm-chem, ipsl-cm5a-lr, hadgem2-es, gfdl-esm2m).

2. A reference period was selected as 1981 – 2010 and an annual mean temperature was calculated for the reference period.
3. For each combination of RCP-GCM, 30-years moving average of the annual mean temperature where calculated and two time slices identified in which the global annual mean temperature had increased by +1 and +3 degree compared to the reference period, respectively. Hence, the selection of the future periods was made to honour a specific temperature increase instead of using a fixed time-slice. This means that the temperature changes are the same for all scenarios, while the period in which this occur varies between the scenarios.
4. To represent conditions of low/high precipitation, the RCP-GCM combinations with the second lowest and second highest precipitation were selected among the 15 combinations for the +1 and +3 degree scenario. This selection was made on a pilot-by-pilot basis to accommodate that the different scenarios have different impact in the various parts of Europe. The scenarios showing the lowest/highest precipitation were avoided, as these endmembers often reflects outliers.
5. Delta change values were calculated on a monthly basis for the four selected scenarios, based on the climate data from the reference period and the selected future period. The delta change values express the changes between the current and future climates, either as a relative factor (precipitation and evapotranspiration) or by an additive factor (temperature).
6. Delta change factors were applied to local climate data by which the local particularities are reflected also for future conditions.

For the analysis in the present pilot the following RCP-GCM combinations were employed:

Table 4.1: Combinations of RCPs-GCMs used to assess future climate.

		RCP	GCM
1-degree	“Dry”	4.5	gfdl-esm2m
	“Wet”	4.5	noresm1-m
3-degree	“Dry”	8.5	miroc-esm-chem
	“Wet”	6.0	ipsl-cm5a-lr

4.2. Integrated hydrological modelling of CC (method 1)

The assessment of impacts of CC is performed by propagating the local climate scenarios within a chain of auxiliary models (recharge, agricultural) that generate the inputs for a distributed flow model defined with the MODFLOW code.

The numerical groundwater flow (Modflow) model was developed by the River Basin Authority in 2010 and it has been has been updated until 2015 (SURGE, 2018). The Modflow model simulates the groundwater flow and river-aquifer relationship in the eight groundwater bodies that compose the UGB. It covers a total area around 14000 km^2 and the cell size is 1000x1000

m. The model is discretized into three layers to simulate the different hidraulic properties in some areas of the model.
The model was calibrated against hydraulic head data from the River Basin Authority and the Spanish Geological Survey (IGME) in the period 1974-2015. It was not possible to perform an automated model optimization (with PEST calibration tool) probably due to the complexity of the model. The groundwater levels were adjusted in 23 piezometers (of the 91 available in the UGB) by varying hidrogeological parameters (within reasonable ranges) through a trial-error procedure. Figure 4.2 shows some xamples of results of the calibration of the Modflow model in the UGB in terms of groundwater levels.

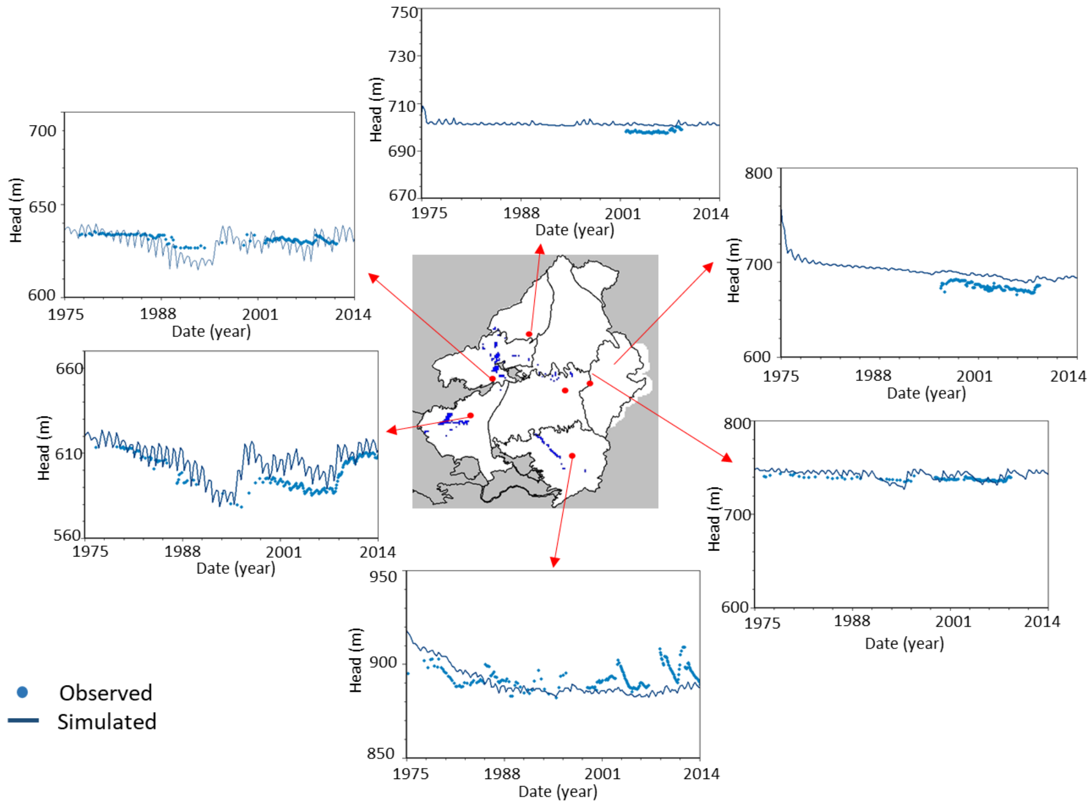


Figure 4.2: Examples of observed and simulated groundwater levels in the Modflow model (UGB).

The flow model requires recharge series as input, which are obtained from a calibrated Sacramento Soil Moisture Accounting (SAC-SMA) model of the US National Weather Service River Forecast System. This model uses precipitation and evapotranspiration time series as input, along with parameters on soil moisture states and the basin's relative permeability to estimate the amount of water that enters, is stored in, and leaves the basin. Five SAC-SMA models were calibrated in the historical period (1974-2015) by a trial and error process to fit the simulated flow rates to the observed ones from five flow gauges in the UGB (see Figure 3.5). Climate series of precipitation came from Spain02 (Herrera et al., 2016) and evapotranspiration series were calculated by using Hargreaves formulation. The period of calibration for each subbasin varied depending on the data availability. The Nash-Surcliffe and R^2 were used to compare the simulated and observed flow for the five subbasins.

Figure 4.3 shows the results of calibration of SAC-SMA model in subbasin EA4004.

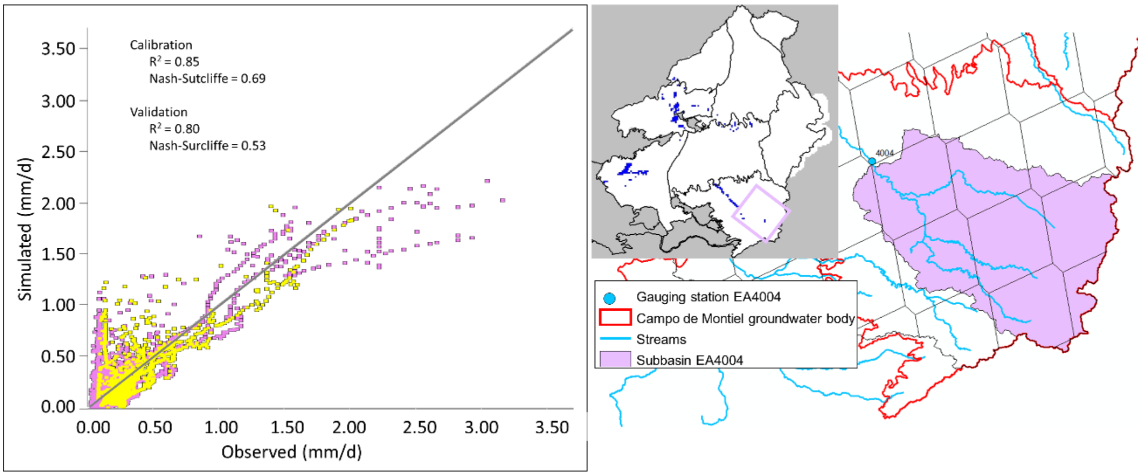


Figure 4.3: Results of SAC-SMA model calibration in subbasin EA4004 in the UGB.

The calibrated SAC-SMA models are used to propagate the impacts of CC on recharge, which is used as input data in the Modflow model.

The future pumping schedule in the Modflow model is generated by using the CROPWAT model (Smith, 1992) to calculate net irrigation demands according to the CC scenario. This tool allows estimating water requirements for each kind of crop from precipitation and temperature data. Thus, the future climatic series has been applied to two management scenarios (MS) with different objectives:

- Maintaining the current (2015) pumping schedule in the future (MS 1).
- Maintaining the current (2015) spatial crop distribution in the future (MS 2);

The Modflow model is used in this study to propagate the impacts of CC on groundwater levels and discharges to wetlands.

4.3. Estimation of the dynamic of surface water in wetlands (method 2)

The monthly dynamic of surface water in Lagunas de Ruidera wetlands in Campo de Montiel (South of UGB) has been estimated from an ensemble of regression models that were calibrated by using satellite data and hydro-climatological variables. Figure 4.4 shows the location of Lagunas de Ruidera in the UGB.

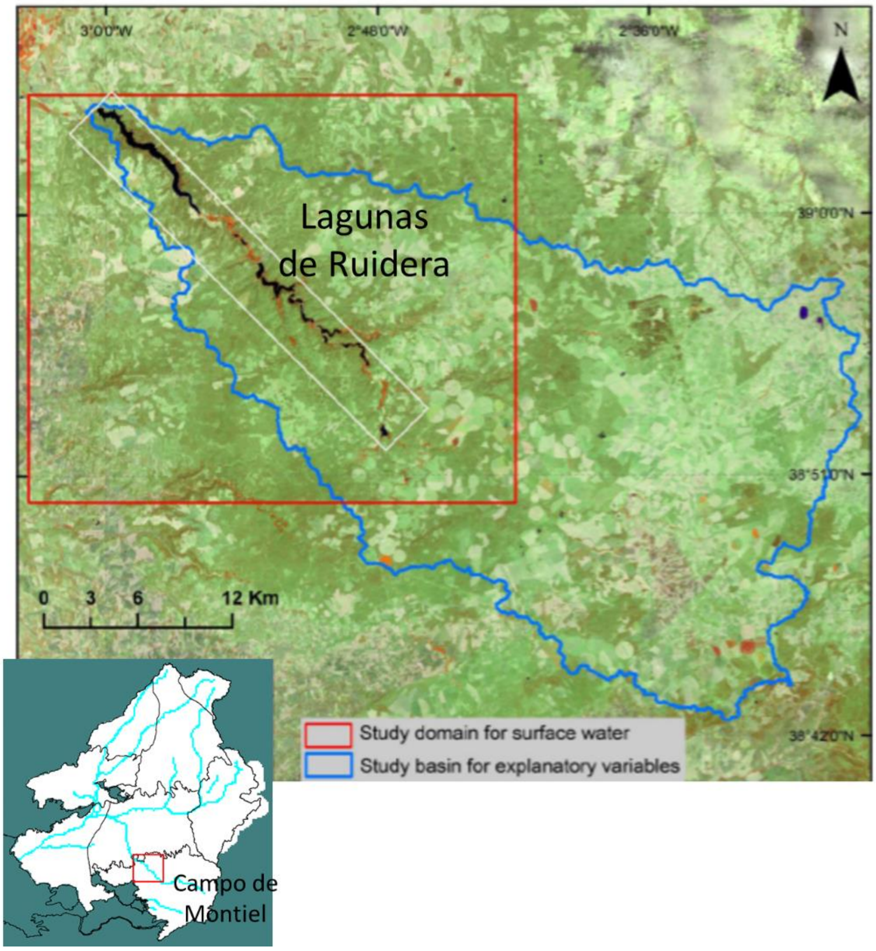


Figure 4.4: Location of the pilot area for the estimation of the dynamic of surface water in the UGB.

The purpose of these regression models is to complete the information provided by satellite data in order to obtain long monthly series of surface water in small lagoons that require high spatial resolution information. This ensemble of regression models also allows estimating future changes in surface water on lagoons due to CC.

The explanatory variables used for the calibration of the multiple regression model were: precipitation; effective precipitation; temperature; potential evapotranspiration; and aquifer discharge in the period 1984 to 2015.

4.4. Adaptation strategies to CC (method 3)

In this project, a participatory method has been designed to define local future socio-economic scenarios, establish adaptation strategies and validate the model developed in the pilot area. This participatory process involves local agents of agricultural communities in the UGB including farmers, the Guadiana River Basin Authority, the General Directorate of Agriculture and Natural Environment of Castilla La Mancha, local municipalities, national environmental officers and environmental organizations.

Three local scenarios were defined and presented in a workshop that was held in the study area (Bolaños de Calatrava), were some exercises were carried out to elicit their knowledge in relation to the previous results obtained with the physical flow model. The three socio-economic scenarios are:

1) Business as usual: a vision of future evolution with current trends;
2) Innovation and globalization: trend to globalization and opening of borders and markets with reinforcing economic subsidies, promoting environmental practices and crops and a high rural innovation;
3) Fragmentation and protectionism: the European Union promotes market protectionism and the economic subsidies support for productivity.

5. RESULTS AND CONCLUSIONS

Results from the work in the UGB pilot (Spain) will focus on changes on shallow groundwater levels and the impacts on dependent ecosystems. This pilot area reveals the strong conflict between groundwater-dependent ecosystems and groundwater pumping to supply demands (mainly irrigation demands). This problem will be exacerbated in the future due to CC impacts, although some CC scenarios show hopeful results.

The ensemble of regression models calibrated to estimate the water surface in wetlands are useful to understand the impacts of CC in groundwater dependent ecosystems.

The knowledge of these impacts (groundwater levels and dependent ecosystems) allows us to establish and assess adaptation measures, which are defined in the framework of a participatory process that includes all groundwater users of the area.

5.1. Climate data: TACTIC standard CC scenarios

The TACTIC standard scenarios show differences in the mean value of climatic variables. The mean annual precipitation in the historical period (1974-2015) was 433 mm/year and the mean annual temperature was 14.6 ºC (Herrera et al., 2016). All the CC scenarios estimate an increase in the mean temperature (between 0.8 and 3.1 ºC). The minimum change scenarios (1 and 3 degree) show a decrease in mean annual precipitation (drier conditions) whereas the maximum change scenarios (1 and 3 degree) show an increase in this variable (wetter conditions).

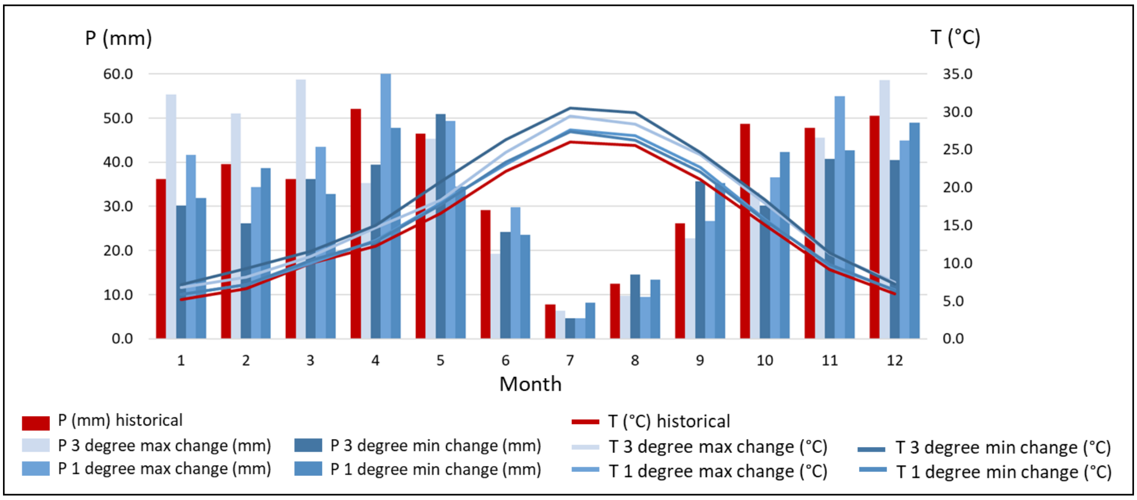


Figure 5.1: Monthly mean historical and future estimated climatic variables (precipitation P (mm) and temperature T (ºC)) for the four TACTIC standard CC scenarios.

5.2. Integrated hydrological modelling of CC (method 1)

The results generated by the TACTIC standard scenarios are consistent for the minimum and maximum changes between the 1 and 3 degree scenarios. The minimum change shows "drier" conditions in the future and the maximum changes show "wetter" conditions in the future. As expected, the 3 degree minimum scenario is the most extreme and therefore, it will cause a higher decrease in rainfall recharge (figure 5.2).

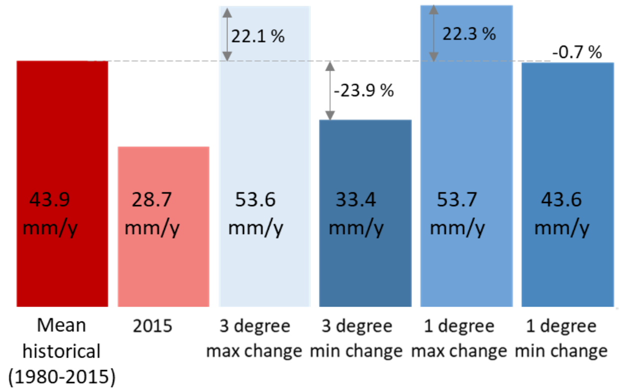


Figure 5.2: Recharge obtained by SAC-SMA models and change (Δ%) caused by CC scenarios regarding to the mean historical recharge.

The MS simulated by using CROPWAT model also show different results depending on the CC scenario (Figure 5.3), although all of them move in the same direction regarding the reference year (2015).

Although maximum change scenarios (1 and 3 degree) estimate an increase in groundwater recharge, the increase in the mean annual temperature will produce higher crop water requirements. If the pumping schedule is maintained in the future as in the year 2015 (MS 1), the CC will led to decrease the irrigation area. The reduction in the irrigation area will be larger in the most extreme CC scenario (3 degree, minimum change) and it will be smaller under the 1 degree maximum change scenario.

The MS 2 will require an increase of groundwater abstractions in order to maintain the irrigation area as in 2015. Under this MS, 3 degree minimum change CC scenario will mean the highest increase in pumping whereas 1 degree maximum change CC scenario will imply the smallest increase in pumping.

Although the 3 degree maximum change scenario estimates a significant increase in future groundwater recharge, the strong increase in mean temperature (2.3 °C above the historical mean temperature) will imply a drastic reduction in the irrigation area (MS 1) or a large increase in pumping (MS 2), depending on the MS. On the contrary, the 1 degree minimum change scenario estimates a slight reduction in future groundwater recharge (regarding the mean historical) and the small increase in the mean temperature (0.8 °C above the mean historical temperature) will contribute to moderate changes in both irrigation area and pumping in the future.

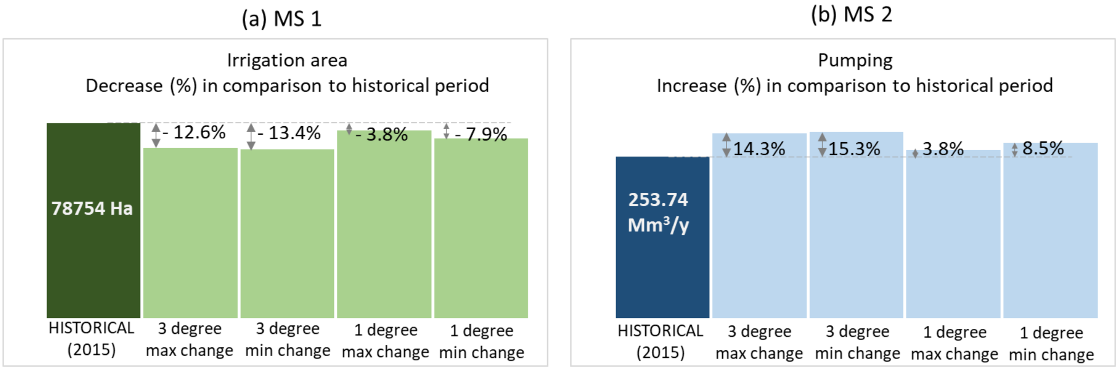


Figure 5.3: Changes (%) in irrigation area (a) and pumping (b) regarding to the reference year (2015) caused by CC scenarios.

Figure 5.4 shows the distributed impacts of the most adverse CC scenario (3 degree minimum change) on the pumping and/or the irrigated area under the two MS. All the groundwater bodies will experiment similar changes in irrigation area and pumping except La Obispalía, which will require a large increase in pumping to maintain the irrigation area as in 2015.

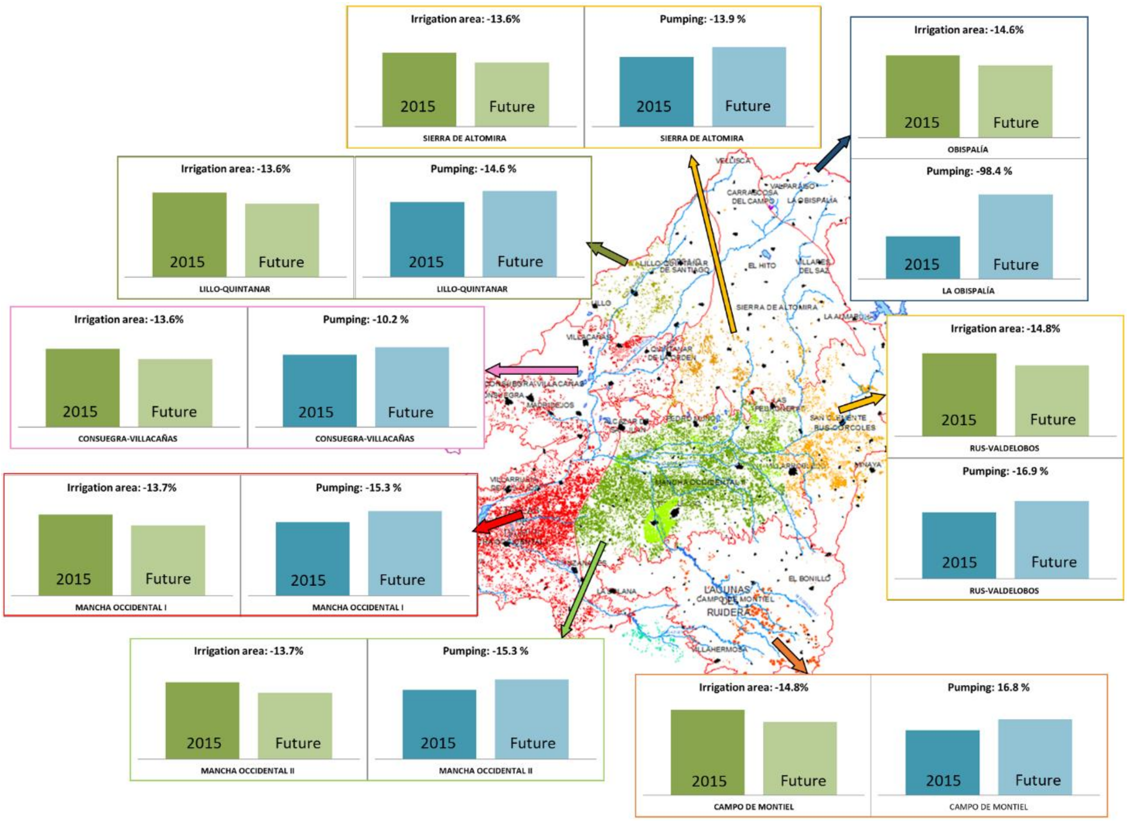


Figure 5.4: Impacts of 3 degree, minimum change CC scenario on irrigation area and pumping regarding the reference year (2015).

These MS and CC scenarios will reflect their impacts in the groundwater levels producing changes of different magnitude and direction (Figure 5.5).

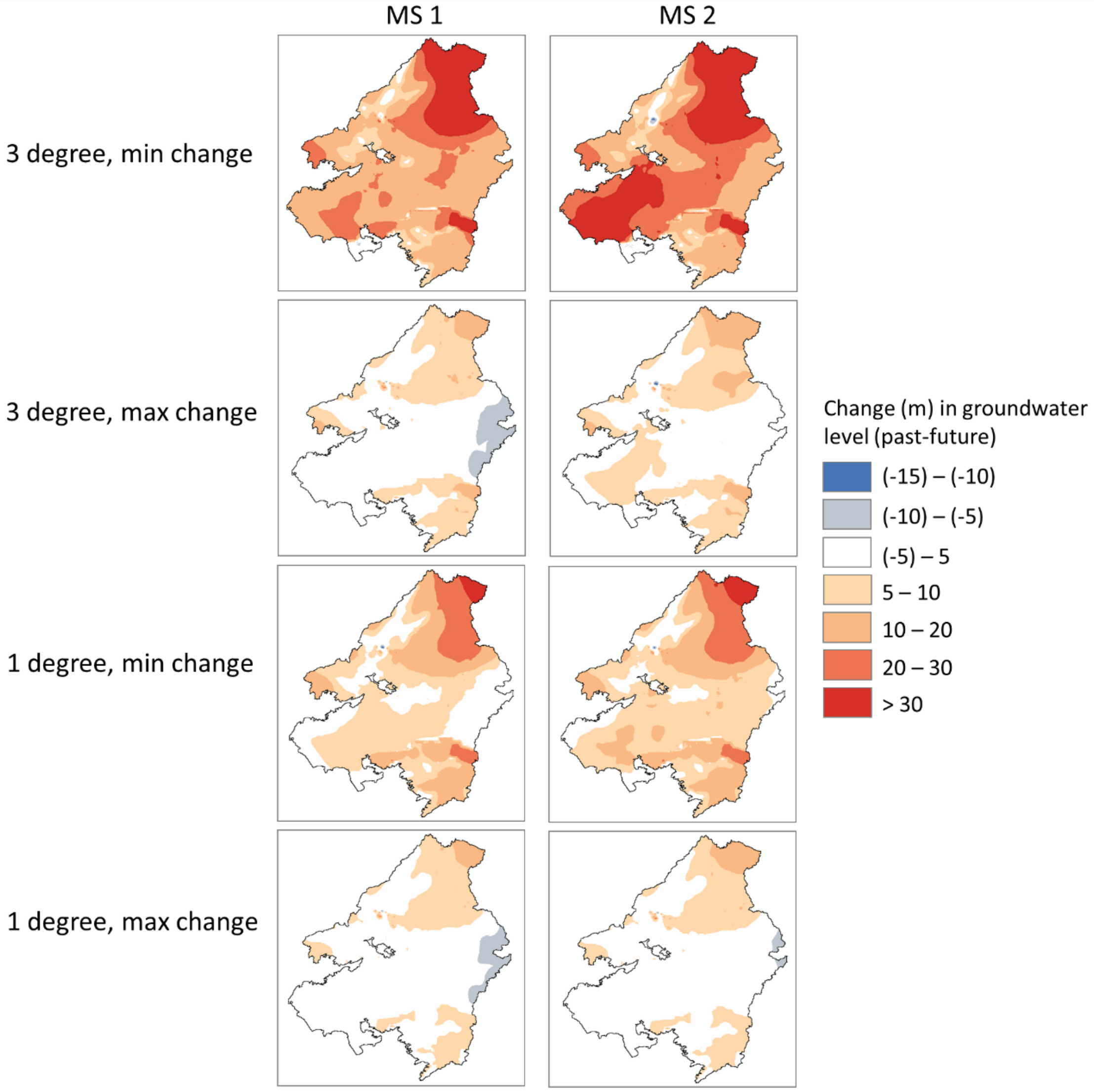


Figure 5.5: Maximum changes regarding 2015 in groundwater levels simulated with the 4 TACTIC standard scenarios

The minimum change scenarios shows "drier" conditions (lower groundwater levels) in the future regarding the maximum change scenarios (1 degree and 3 degree). Maximum change scenarios show "wetter" conditions (higher groundwater levels) in the future in some zones in the pilot area. As expected, the 3 degree scenarios are more extreme for both the minimum and maximum change than the 1 degree scenarios.

In general, the most adverse scenario would be 3 degree maximum change CC scenario in combination with the MS 2. On the contrary, the MS 1 under the 1 degree maximum change scenario would be the most favourable. For this scenario, a large area will maintain the groundwater level as the past (or it will experiment slight changes, between (-5) – 5 meters).

Under this scenario, some aquifers mainly in northern and southern areas will decrease the groundwater level and a small area in the east will increase the groundwater level.

5.3. Estimation of the dynamic of surface water in wetlands (method 2)

The ensemble of regression models calibrated in Lagunas de Ruidera wetland area (Campo de Montiel, UGB) is used to estimate the water surface under CC scenarios. Figure 5.6 shows the future estimation for the most extreme CC scenario (3 degree, minimum change). The water surface is expressed in pixels with a resolution of 30x30 m. This CC scenario will involve a decrease of the water surface of 12.6% regarding the mean historical water surface. It might lead the disappearance of the smallest lagoons in this area.

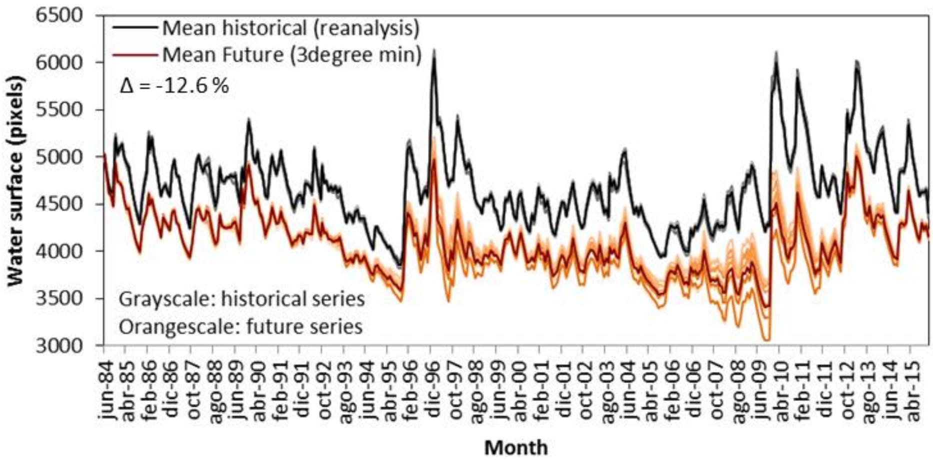


Figure 5.6: Monthly time series of the surface water for the historical period and future estimation

5.4. Adaptation strategies to CC (method 3)

In the workshop held with skateholders in the UGB, the participants discussed the main environmental, social, economic characteristics and the expected evolution of some indicators of the three proposed local scenarios. Most of the participants were aware of the need to preserve the groundwater status and dependent ecosystems and they revealed the importance of the wetlands to the region development.

Some of the most valued adaptation strategies in the workshop were the land use change through the development of other activities and the improvement of the control of the extractions, among other measures (innovation, optimization of crop water use, etc).

Some of these measures will lead to a reduction of the irrigation area, which could be materialized through the MS 1 described in Sections 4.2 and 5.2.

Figure 5.5 shows that MS 1 will help to counter the CC impacts and it will be possible to maintain and/or increase the groundwater levels in some areas in the UGB.

The impacts of the reduction of the irrigated area are also analysed in terms of discharge to wetlands in Figure 5.7.

These results are also consistent for the minimum and maximum changes between the 1 and 3 degree scenarios. Two CC scenario (3 degree, minimum change and 1 degree, minimum change) show a decrease in groundwater discharge to wetlands regarding the discharge in the reference year (2015). Although the recharge in 2015 was notably lower than the mean historical, the groundwater bodies have experimented a recovery due to the decrease in pumping since 2010 (see Figure 3.9). However, in the past (1980-2015), the overexploitation in the UGB lead to some wetlands to disappear due to the reduction in the discharge.

Under the MS1, the CC scenarios with higher recharge will experiment also an increase in discharge to wetlands.

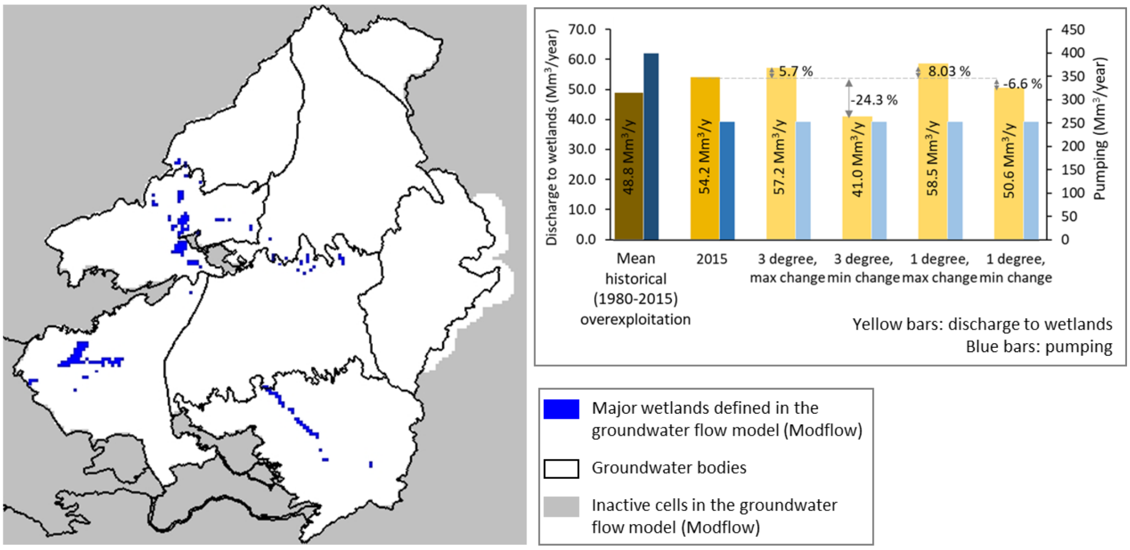


Figure 5.7: Location of the major lagoons in the UGB and mean future groundwater discharge to wetlands simulated with the 4 TACTIC standard scenarios

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Establishing the European Geological Surveys Research Area to deliver a Geological Service for Europe

Deliverable 5.3 and 6.3

PILOT DESCRIPTION AND ASSESSMENT

Vrana lake, Croatia

Authors and affiliation:

Andrej Stroj

Croatian geological survey (HGI-CGS)

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	D5.3 & D6.3
Dissemination level	Public
Deliverable name	Pilot description and assessment
Work package	WP5: **ASSESSMENT OF SALT-/SEA WATER INTRUSION STATUS AND VULNERABILITY**; WP6: **GROUNDWATER ADAPTATION STRATEGIES**
Lead WP/Deliverable beneficiary	IGME
Deliverable status	
Version	*Version 3*
Date	*1/4/2021*

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LIST OF ABBREVIATIONS & ACRONYMS

CC	Climate Change
GC	Global Change
LULC	Land Use and Land Cover
SWI	Sea Water Intrusion
GSO	Geological Survey Organisations
PET	Potential evapotranspiration

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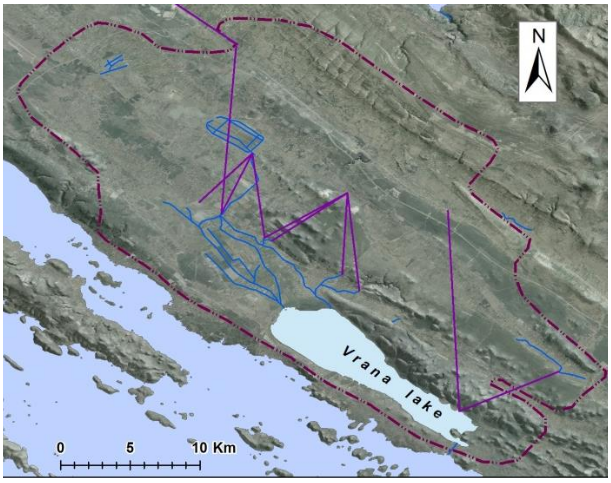
1 EXECUTIVE SUMMARY

Pilot name	Vrana lake	
Country	Croatia	
EU-region	Mediterranean region	
Area (km^2)	516 km^2	
Aquifer geology and type classification	Karstic limestones, Fissured aquifer	
Primary water usage	Drinking, irrigation	
Main climate change issues	Vrana lake is situated in the close vicinity of Adriatic Sea coast in highly karstified terrain (Dinaric Karst region). The lake is declared as a nature protection area. Permeable terrain between the lake and the sea enable underground inflow of sea water into the lake during dry periods when lake level is low. Therefore, the lake eco system is highly vulnerable to increasing duration of draughts as well as sea level rising. Pumping of groundwater for public water supply and irrigation in the catchment presents additional pressure on the lake system.	
Models and methods used	Time series analysis, conceptual and lumped model (GARDENIA-BRGM, METRAN-TNO)	
Key stakeholders	Vrana lake nature park (public institution), water supply company, private farmers	
Contact person	Andrej Stroj, Croatian Geological Survey, astroj@hgi-cgs.hr	

Vrana lake is situated in Croatian coastal region Dalmatia, separated from the Adriatis Sea by a narrow carbonate ridge less than 1 km wide in its narrowest parts. The lake and its immediate surrounding is declared as a nature protection area. Carbonate ridge, which separates the lake from the sea, is intensely karstified, i.e. permeable for groundwater flow. This enables sea water intrusion (SWI) to the lake through permeable subsurface during the low lake water levels. Lake water level above the sea level is the main factor that prevent SWI. Although occasionally slightly brackish lake water is natural characteristic of the lake, inflow of a sea water during prolonged draught periods, which are generally concurrent with summer seasons in the area, produce excessive salinization of the lake and a major threat to the ecosystem. The most important cause for lowering the lake water levels during relatively hot summer seasons is direct evaporation from the lake. High water and air temperatures, together with large lake surface area (approx. 30 km^2) and shallow depth (up to a few meters) produce very high rates of evaporation. Lake level and salinization dynamics shows significant inertia, so major lake salinization events typically occur when the lake was not sufficiently replenished during preceding wet season, resulting in low water level and increased salinity at the beginning of summer/draught periods.

The lake is fed solely by groundwater from the extensive karstic catchment with approx. area of 500 km^2. Pumping of groundwater for public water supply and irrigation in the catchment presents additional pressure on the lake system, as sufficient fresh water inflow is essential to control SWI to the lake. Additional unfavourable factor presents presence of artificial channel for evacuation of the lake water during high water levels. The channel was firstly built in 18^{th} century, reconstructed additionally several times afterwards, with the aim to drain the extensive wetlands in the area upstream from the lake. Before the channel construction the lake was drained naturally through the permeable subsurface, but channel considerably fastens that process resulting with lower water levels at the beginning of dry summer periods, when lake water losses continue by strong evaporation. Intensive agriculture is still present in the area upstream from the lake, and closing of the channel during the wet seasons would cause flooding of the agricultural lands. This prevents restoration/closing of the channel in order to re-establish natural conditions.

As already explained, SWI feed lake during low lake water levels, resulting in lake level stabilization at levels slightly below sea water level despite high evaporation and low fresh water inflow during prolonged draughts. Therefore, CC, which results in increasing temperature and prolonged draughts in the area, presents major thread to the lake ecosystem. Increasing trend of the sea water level, which is also a consequence of CC and GC, would additionally amplify lake salinization processes in the future. In depth understanding and significance estimation of all processes, influencing the lake SWI is necessary to predict future CC scenarios, as well as to consider potential adaptation and mitigation strategies.

All available data time series, related to the historical lake level and salinity dynamics, were collected: over 70 years of the lake level data; almost 60 years of rainfall, air temperature and relative humidity data which served also for calculation of potential evapotranspiration (PET) data based on Turc method (Etp Turc software developed by BRGM); data on direct evaporation from the lake surface; and 18 years of monthly lake salinity measurements. Preliminary time series analysis was carried out including descriptive statistics, autocorrelation and cross correlation functions to examine system inertia and interdependence of different parameters. After the preliminary time series analysis, lumped modelling tools were used to model lake level dynamics based on precipitations, PET and direct lake evaporation. GARDENIA (developed by BRGM), METRAN (developed by TNO) and AQUIMOD (developed by BGS) lumped modelling tools were tested for modelling purposes. Although all used tools were principally developed for modelling groundwater levels in aquifers, they were tested for modelling lake level, which is in strong connection with the surrounding karst groundwater. Water fluxes to the lake are happening mainly dispersedly through the karst subsurface, and consequently impossible to be directly measured and monitored. This prevents modelling the lake level based on direct inflow, outflow and lake geometry. Lumped groundwater modelling tools were used as an option to overcame this problem. GARDENIA and AQUIMOD models enable level modelling based on precipitations and additionally pumping dynamics, which was used as equivalent process to direct evaporation from the lake. METRAN model is pure transfer function model which can use several input time series in order to model output series. Simple transfer function was also used to model lake salinity response to the low lake levels.

Best results for lake level modelling were obtained by GARDENIA software due to effective way to take evaporation effect into account as a pumping. GARDENIA software calibrates pumping influence with pumping coefficient, determined automatically through calibration. AQUIMOD software also has option to include pumping to the model, but its influence is not calibrated through coefficient, resulting in largely overestimated effect when it was expressed in recommended units. Therefore, pumping/direct evaporation was not included in the AQUIMOD model, resulting with low final model efficiency. Moreover, we experience additional problems with automatic calibration process: final parameters for the model were calibrated manually. METRAN software succeeded to produce relatively efficient model based by two input series: precipitations and air temperatures. Direct lake evaporation is strongly correlated to air temperature, and together with the precipitation is main controlling factor for the lake level dynamics. This enables good efficiency of the METRAN model. Main problem with the METRAN is that it is not user friendly in the present form, so all the modelling work had to be done by TNO expert who developed the tool.

The second considered model for the lake salinity study was dependence of the lake salinity on the lake levels. First, critical lake level was determined, below which salinity start to increase. Afterwards, only levels below critical level were taken as a input series, and lake salinity values as an output. Simple transfer function that summed influence of 10 months historical period of lake levels below threshold value produced good agreement with the observed vales. Finally, usage of lake level model and lake salinity model together enabled possibility for prediction of future lake salinity, based on predicted precipitations and air temperature from various CC scenarios.

2 INTRODUCTION

Climate change (CC) already have widespread and significant impacts in Europe, which is expected to increase 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. In order 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 infra structure 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 present document reports the TACTIC activities in the pilot Vrana lake located in the Adriatic Sea coast of Croatia, in Dalmatia province. The lake is declared as a nature protection area (Nature Park) because of its rare natural habitats and biodiversity. It has been included in the list of Important Bird Areas in Europe and became Ramsar site. Lake is fed mainly by a groundwater from a large karstic catchment. The lake is separated from the sea by relatively narrow (in places less than 1 km wide) carbonate tidge. Carbonate ridge is intensely karstified, what enables SWI to the lake during low lake water levels through the permeable subsurface. Although occasionally brackish lake water is natural characteristic of the lake, more and more pronounced draught periods, increasing temperatures and sea level rising due to a CC and GC are the main thread for the vulnerable lake ecosystem. Detailed knowledge of all processes, influencing the lake SWI, is necessary to assess and summarise impacts of potential future CC and GC scenarios, and to identify potential measures for mitigation of adverse consequences and to estimate their impact. Therefore, the Vrana pilot was included in TACTIC WP5: *Assessment of salt-/sea water intrusion status and vulnerability* and WP6: G*roundwater adaptation strategies* in order to examine potential future CC scenarios for the lake SWI, as well as to consider potential adaptation and mitigation strategies. Within the TACTIC project different modelling tools were used and tested for modelling the lake level based on historic climatic measurements, as well as future CC predictions, which were developed and provided by partner GSOs (GARDENIA by BRGM, AQUIMOD by BGS and METRAN by TNO).

3 PILOT AREA

3.1 Site description and data

3.1.1 Location and extension of the pilot area

The pilot area is located in the western part of Croatia (Dalmatia) beside the Adriatic Sea coast (Fig 1). It is located within the broader Dinaric Karst region which spreads across the several countries (Slovenia, Croatia, Bosnia and Herzegovina, Montenegro, northern Albania) parallel to the eastern Adriatic sea coast. Vrana lake catchment area belongs to Mediterranean region and covers approx.. 515 km^2 (Fig. 1).

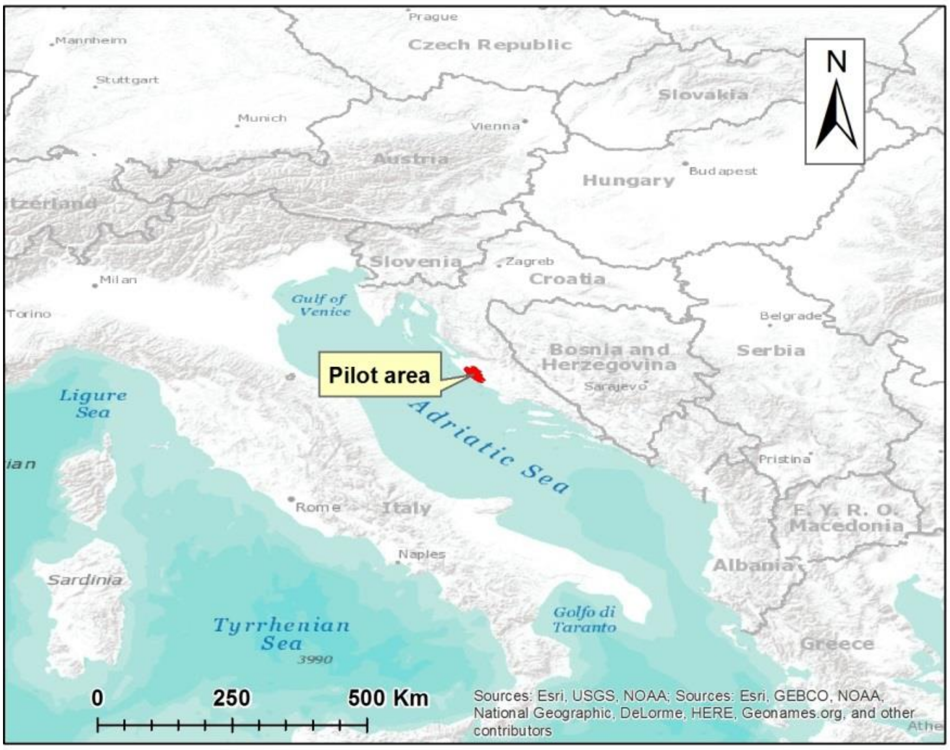


Figure 1. Location of the pilot area

Vrana lake is situated in the close vicinity of Adriatic Sea coast in highly karstified terrain (Dinaric Karst region). It is located in a shallow kryptodepression with the bottom at –3.5 m a.s.l. Lake water levels vary annually approx. in the range 0–2.5 m a.s.l. Permeable terrain between the lake and the sea enable underground SWI into the lake during dry periods, in conditions when the lake level drop close or even slightly below sea level. Therefore, the lake eco system is highly vulnerable to increasing duration of draughts as well as sea level rising.

Upstream of the lake, within the same karstic catchment, there is agricultural lowland area called Vrana polje (45 km^2). Agricultural activities include groundwater abstractions for irrigation purposes (mostly uncontrolled). Public Water Supply Company also use groundwater from the catchment with pumping stations located on the major freshwater springs upstream from the lake, mostly at the NE edge of the Vrana polje.

In the SE part of the lake, across the narrowest part of the carbonate ridge that separates the lake from the sea, there is an 850 m long artificial channel for evacuation of the lake water during high water levels. The channel was firstly excavated in 18th century, additionally reconstructed and deepened afterwards, with the aim to drain the extensive wetlands in the area upstream from the lake (Vrana polje, agricultural area that was marshy area prior the channel). Before the channel construction the lake was drained only through the permeable (karstified) subsurface, and channel considerably fastens that process. Although the channel bottom is slightly above average sea water level, fast drainage through the channel in high lake level conditions results with lower water levels at the beginning of dry summer periods. During low lake levels, when drainage through the channel ceases, lake water losses continue by strong evaporation. As intensive agriculture is present in the area upstream from the lake, closing of the channel during the wet seasons would cause flooding of the agricultural lands. This prevents restoration/closing of the channel as a measure to re-establish natural conditions.

3.1.2 Climate

Climate in the area of Vransko Lake is typically Mediterranean, with mild, considerably short and rainy winter periods, and dry, hot summers. By Köppen, this type of climate is called "Olive tree climate". Holm oak forests, maquis (Mediterranean scrubland) and dry grasslands on rocky karst terrain characterize its vegetation.
Mean annual temperature varies within the watershed in the range 12-15°C, and average annual precipitation amounts 950 mm/y (Zaninović et al. 2008). Warmest months of the year are July and August (21-24°C monthly averages), and January and February are the coolest (5-8 °C). October and November have the highest precipitation (approx. 120 mm monthly average), and June and July are the driest months (approx. 50 mm monthly average). Infiltration coefficient is estimated to be approx. 0.2-0.3. Based on the estimated infiltration coefficient, mean annual recharge is approx. 250 mm, which equals 129×10^6 m^3/y.

3.1.3 Topography and soil cover

Water catchment of Vrana Lake consists of levelled surfaces of karst poljes, separated by moderately elevated hills and ridges. All the morphological features are elongated in NW-SE direction, known as a Dinaric strike direction. Elevation of the area ranges from 0-300 m a.s.l. (Fig. 2), generally rising in NE direction. Soil cover of variable thickness covers levelled surfaces, while on elevated hilly areas soil cover is almost absent with bare limestone rock outcrops on the surface.

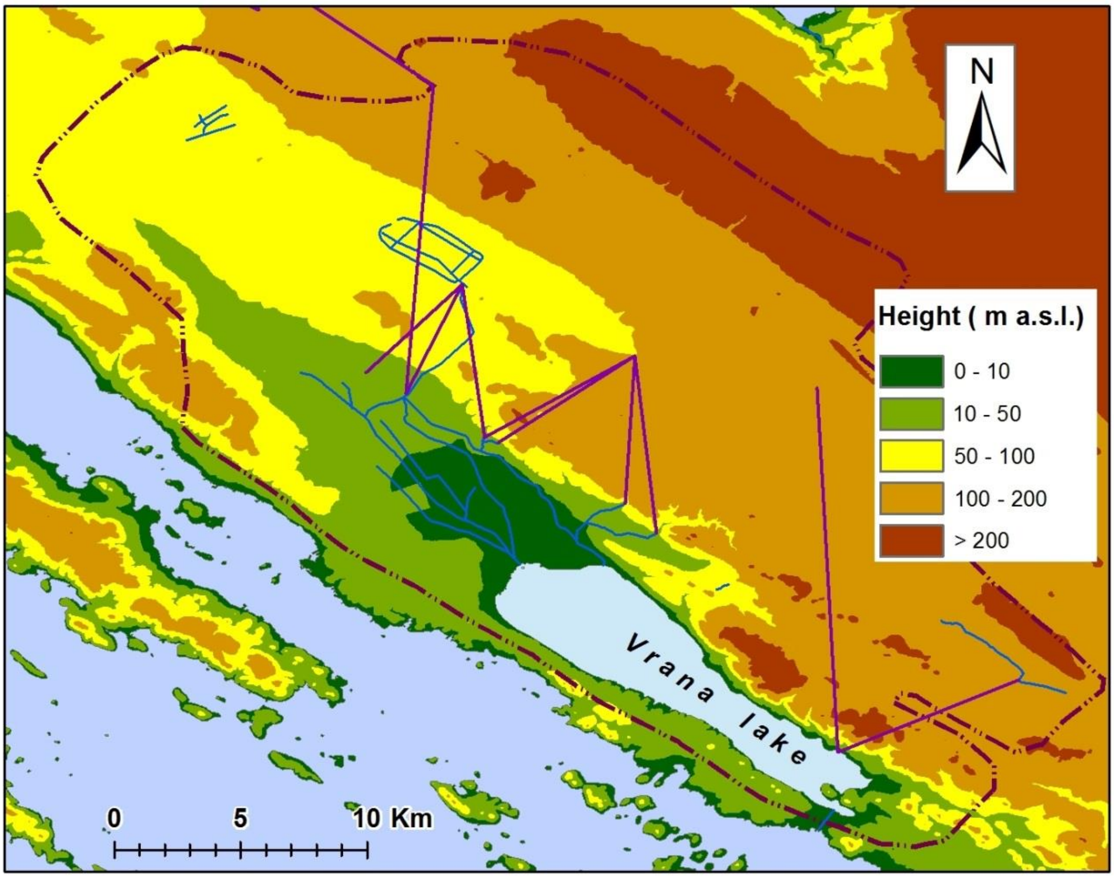


Figure 2. Topography of the pilot area.

3.1.3 Land use

Vrana lake and its immediate surrounding is declared as a nature protection area (Nature park) because of its rare natural habitats and biodiversity. It has been included in the list of Important Bird Areas in Europe and became Ramsar site. Lake is fed mainly by a groundwater from a large karstic catchment (>500 km^2). Nature protected area, which is in natural condition, presents only a small part of the catchment (approx. 57 km^2, of which 30 km^2 is extent of the Lake).

Vrana polje area was historically occasionally flooded swampy area upstream from the lake. Artificial drainage of the Vrana polje begun in 18th century with construction of the channel connecting the lake with the sea. The Channel serve for evacuation of the lake water during high water levels up to present day. Additional network of drainage channels across the polje area converted wetland to arable land. Today Vrana polje is agricultural area which is both drained and partly irrigated during dry seasons.

There are additional agricultural areas in the catchment area, typically situated within the elongated shallow valleys and levelled surfaces (karst poljes), separated with rocky hills and ridges. Rocky carbonate hills are covered with shrubs and Mediterranean woods. Larger settlements are located at the see coast (downstream from the lake), while inner parts of the catchment are relatively sparsely inhabited, without larger individual settlements.

3.1.3 Geology/Aquifer type

Study area is dominantly built of limestones (karst rocks) of Cretacious and Paleogene age, and in lesser extent of flysch rock complex of Paleogene age (Fig. 3). Flysch rocks are generally covered by soil cover, while soil cover is almost absent on limestones (Fig. 3). Area is tectonically folded and thrusted, with dominant NW-SE strike of the structures (faults and fold axes). The Flysch rocks, representing the stratigraphically youngest rocks, are situated in the core areas of the synclines. Thrust faults often intersect and deform continuation of synclines and anticlines in the area.

Limestones are well karstified, proven by a number of tracing tests performed in the area (Fig. 3). Surficial water flows are mostly absent on the limestone areas, and precipitations quickly infiltrate into the epikarst (surficial most intensively karstified zone, usually few to ten meters thick). Infiltrated water is partly transported from epikarst further to the deeper karst conduit networks, but it is also partly lost through evapotranspiration processes as epikarst zone is typically within the reach of plant roots.

Ground water flow in karst terrains is concentrated within karst conduits, while surrounding rock mass usually have very low porosity and consequently low permeability. Low permeability of the rock mass is reflected by general unproductiveness of wells that failed to intercept significant conduits. Storage of water is mainly related to shallow epikarst zone, as well as fractured rock mass within the deeper vadose and phreatic zone. Exact significance of epikarst zone and deeper zones for water storage is still relatively unclear. However, storage and regulation capacity of the karst system is limited, resulting in typical extreme oscillation of spring discharges during dry and wet seasons. This causes occasional floods of low lying karst terrains during wet seasons, as well as water scarcity in dry seasons.

Flysch rock complex consist of intercalation of marl, sandstone and limestone beds. In contrary to limestone terrains, flysch terrains are generally non-karstified and impermeable, forming hydrogeological barriers in the subsurface. Therefore, in flysch areas water flow mostly on the terrain surface. Position of flysch rocks above limestones within synclines often form “hanging” groundwater flow barriers which enable deep karstic flows beneath them (Fig. 4).

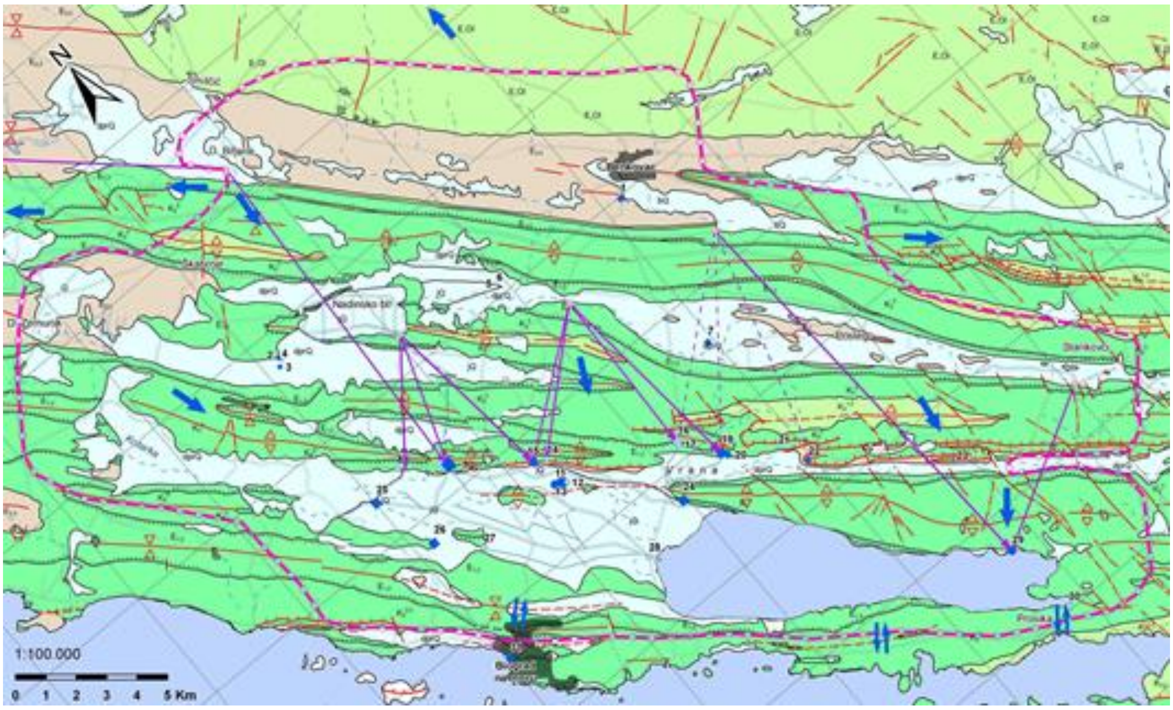


Figure 3. Hydrogeologic map of the Vrana lake catchment (karst rocks in green colors, low permeable flysch rocks in brown, unconsolidated sediment cover in light blue, ground water tracing connections are marked with purple lines, groundwater flow directions with blue arrows, adapted from Stroj 2012).

While majority of the karstic springs in the Vrana polje area discharges fresh water, there are also a few springs discharging brackish water. SWI on the springs is not controlled directly by their distance from the sea coast, but rather by depth of water circulation (Fig. 4). More precisely, springs that are fed by the water from deep lying karst conduits, which are situated below fresh water-brackish water interface, discharges brackish water. Seawater share in the spring water is variable depending on hydrological conditions, i.e. inflow of fresh water to the conduit system.

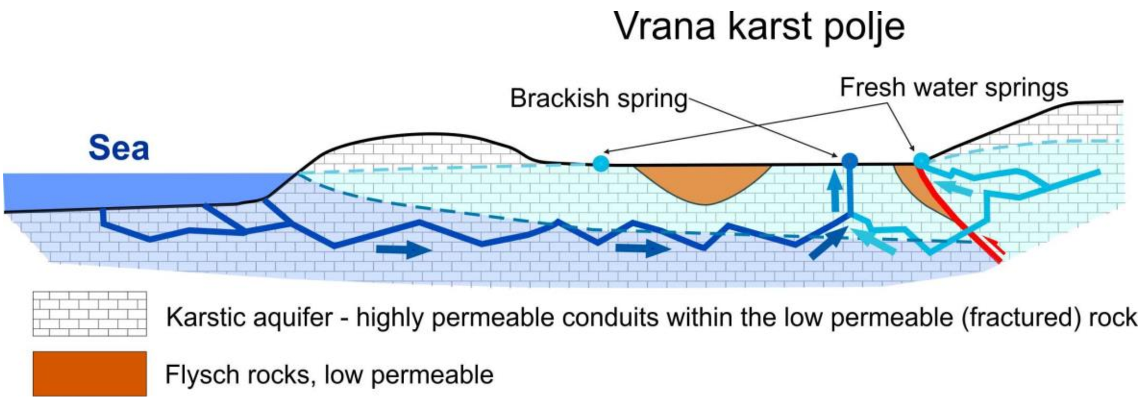


Figure 4. Conceptual model of sea water intrusion affecting some of the inland springs on the Vransko polje area (upstream/NE from the lake, Fig. 2).

Vrana Lake is separated from the sea by karstified limestone ridge, on the narrowest part slightly less than 1 km wide. This allows fast drainage of fresh water from the lake to the sea during wet periods, both through the artificial surface channel for high water evacuation and karstified subsurface. On the other hand, lowering of the lake level near or even slightly below the sea level due to the high evaporation during summer draught periods enable direct SWI through the karstified subsurface into the lake (Fig. 5). This direct SWI to the lake is the main cause for the major lake salinization events, as salinity of the brackish springs are below the lake salinity in such periods. In addition, highest salinity is typically measured in the lake area closest to the Sea coast (SE part of the lake). Therefore, the main factor for prevention of excessive salinization of the lake is sufficiently high lake level above the sea level, what directly prevents SWI.

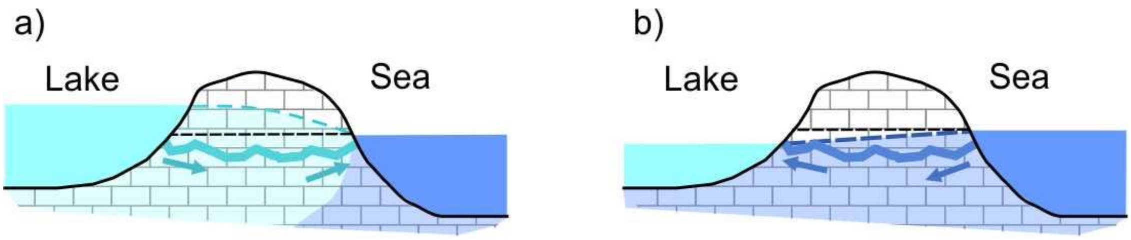


Figure 5. Conceptual model of sea water/fresh water dynamics between the lake and the sea: a) high lake water level during wet season; b) low lake water level during draught periods.

3.1.3 Surface water bodies

Vrana lake with its surface of approx. 30 km^2 and average depth of 1-2 m is major surface water body in the area. It is separated from the Adriatic Sea by a narrow land stretch. The lake is fed by karstic springs, majority located across Vransko polje area and its edges, and some located immediately at the lake coast (Fig. 3). Springs located upstream in the Vrana polje area form relatively short and intermittently dry watercourses which inflow to the lake. Watercourses are mostly modified and incorporated in a network of artificial drainage channels, which spreads across the Vrana polje area.

3.1.3 Abstractioms/irrigations

Major fresh water karst springs in the Vrana polje area are captured and pumped for the public water supply. During dry season water level in the spring pools (and shallow wells, digged or drilled at spring locations) are pumped bellow the terrain surface, drying the watercourses downstream. Estimated mean annual pumping rates are approx. 100 l/s, with maximum pumping capacity of 180 l/s.

Groundwater is additionally pumped for irrigation purposes on a number of shallow digged wells in the polje area, typically excavated at intermittent spring locations. Irrigation pumping quantities are mostly uncontrolled. Estimated yearly mean abstraction for irrigation is approx. 200-300 l/s.

Both abstractions for agriculture and drinking water supply are most intensive during relatively dry and hot summer seasons. Pumping of groundwater in the catchment presents additional pressure on the lake system, as it lowers fresh water supply to the lake during draughts.

3.2 Climate change challenge

In accordance with the EEA map, the main expected issues due to CC in the broader area are those described in Fig. 9 for the Mediterranean regions. Main expected changes are increasing temperatures, especially during summer season (Croatian Meteorological and Hydrological service, www.meteo.hr). In addition, draught periods during summer seasons are expected to be more frequent and severe. Increasing temperatures will intensify direct evaporation from the lake, resulting in decreased lake levels in summer periods. This, together with rising trend of the sea level, will enhance SWI to the lake, what presents major threat for the lake ecosystem. Fresh water inflow to the lake during summer season is also expect to lower due to a combination of expected decrease of groundwater recharge within the karstic catchment and increase in demands for water abstractions for irrigation during summer seasons.

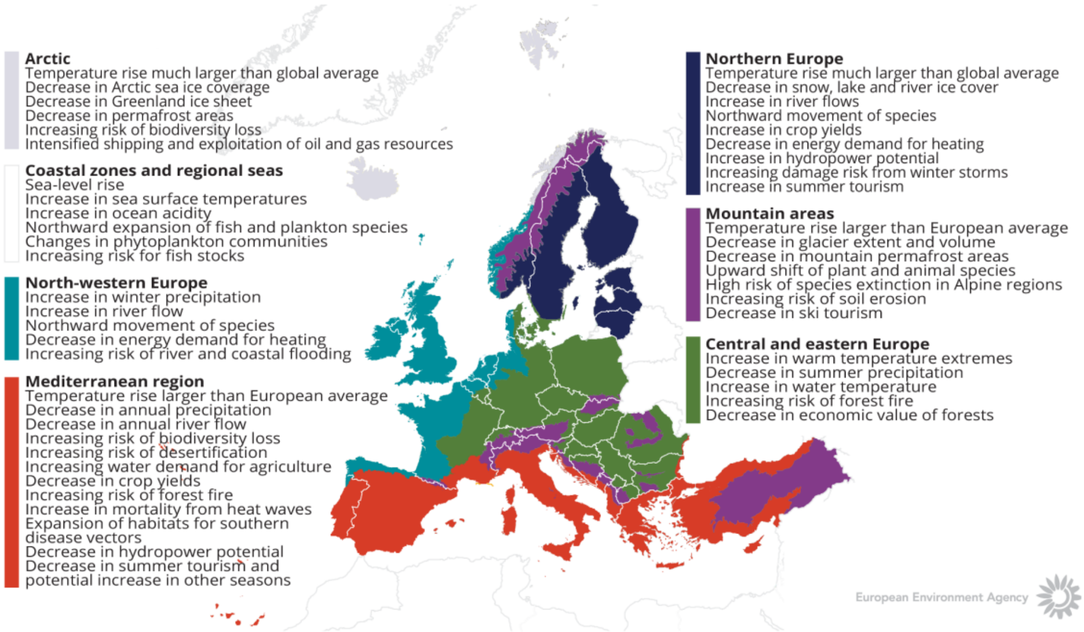


Figure 6. How is climate expected to change in Europe. The European Environment Agency map

4 METHODOLOGY

4.1 Methodology and climate data

4.1.1 Tools/ model description

Assessment of Vrana lake pilot area was done using several lumped modelling softwares/tools: GARDENIA (including EtpTurc module), METRAN and AQUIMOD modelling tools, all included in the TACTIC Toolbox (WP2). Prior to modelling, preliminary analysis of available data time series was done by usage of common statistical softwares (Excel, XLSTAT). Lumped modelling was used to model lake level response to precipitation and temperatures in the catchment, as well as lake water salinity in response to critically low lake levels. Modelling lake levels based on precipitations and temperatures within the catchment as a first step, and lake salinity based on lake levels as a second step enabled analysis how CC future scenarios will affect SWI to the lake. Very heterogeneous nature of karstic subsurface, together with generally scarce data on subsurface parameters, especially regarding karst conduits geometry, prevents usage of spatially distributed groundwater flow models.

GARDENIA is a lumped hydrological model for the simulation of relationships between series of stream or spring flow data at the outlet of a watershed, and/or groundwater level data at an observation well situated in the underlying aquifer and the rainfall received over the corresponding watershed. Withdrawals by pumping groundwater can be considered if necessary. The calibration phase of the model is done automatically by the software under control of the user.
GARDENIA enables to set a hydrological balance for the basin: actual evapotranspiration, runoff, infiltration, recharge. The hydrological balance can be used for the evaluation of natural groundwater recharge of aquifers. GARDENIA gives the extension of river flow, groundwater level or recharge data over a long period for which precipitation and potential evaporation data are known.
EtpTurc module, installed with the GARDENIA, allows the calculation of the potential evapotranspiration at daily, ten-weekly or monthly time steps by using the monthly Turk formula (1961). Calculated PET is further used in GARDENIA together with precipitation as an input file.

AQUIMOD is a simple, lumped-catchment groundwater model. It simulates groundwater level time-series at a point by linking simple algorithms of soil drainage, unsaturated zone flow and groundwater flow. It takes time-series of rainfall and potential evapotranspiration as input, and produces a time-series of groundwater level. Hydrographs of flows through the outlets of the groundwater store are also generated, which can potentially be related to river flow measurements.

METRAN is transfer-noise modelling tool for time series modelling, mostly used with piezometric heads as explained variable and precipitation and reference evaporation as explanatory variables.
Tool can also perform factor analysis of residuals of multiple time series models. Simple parametrization of transfer functions, which allows spatial correlation and interpretation of the physical system.

All described tools were used for modelling Vrana lake level based on historic, and predicted future precipitation and temperature data. METRAN was also used to model lake salinity based on precipitations data. It should be emphasized that described modelling tools are primarily developed for modelling groundwater level instead of surface water level in the lake. However, Vrana lake is situated within the karstic environment, and the lake level is strongly influenced by groundwater recharge from the extensive karstic catchment, as well as by discharge through the permeable subsurface to the sea. Groundwater recharge and discharge are largely happening dispersedly along the lake shores and below lake level, so direct measurements of total inflow and outflow are not available nor possible to measure. Usage of lumped groundwater modelling tools enabled to solve the problem of non-measurable total inflow and outflow by modelling level based on lumped values of precipitation and air temperatures over the catchment, as well as lumped values of subsurface permeability and local base level. However, due to specifics related to modelling lake, i.e. surface water instead of groundwater level, several approximations and unrealistic parameter settings in the modelling process were necessary (GARDENIA and AQUIMOD modelling tools).

4.1.2 Climate data

The TACTIC standard scenarios are developed based on the ISIMIP (Inter Sectoral Impact Model Intercomparison Project, see www.isimip.org) datasets. The resolution of the data is 0.5°x0.5°C global grid and at daily time steps. As part of ISIMIP, much effort has been made to standardise the climate data (a.o. bias correction). Data selection and preparation included the following steps:

1. Fifteen combinations of RCPs and GCMs from the ISIMIP data set where selected. RCPs are the Representative Concentration Pathways determining the development in greenhouse gas concentrations, while GCMs are the Global Circulation Models used to simulate the future climate at the global scale. Three RCPs (RCP4.5, RCP6.0, RCP8.5) were combined with five GCMs (noresm1-m, miroc-esm-chem, ipsl-cm5a-lr, hadgem2-es, gfdl-esm2m).
2. A reference period was selected as 1981 – 2010 and an annual mean temperature was calculated for the reference period.
3. For each combination of RCP-GCM, 30-years moving average of the annual mean temperature where calculated and two time slices identified in which the global annual mean temperature had increased by +1 and +3 degree compared to the reference period, respectively. Hence, the selection of the future periods was made to honour a specific temperature increase instead of using a fixed time-slice. This means that the temperature changes are the same for all scenarios, while the period in which this occur varies between the scenarios.
4. To represent conditions of low/high precipitation, the RCP-GCM combinations with the second lowest and second highest precipitation were selected among the 15 combinations for the +1 and +3 degree scenario. This selection was made on a pilot-by-pilot basis to accommodate that the different scenarios have different impact in the various parts of Europe. The scenarios showing the lowest/highest precipitation were avoided, as these end members often reflects outliers.

5. Delta change values were calculated on a monthly basis for the four selected scenarios, based on the climate data from the reference period and the selected future period. The delta change values express the changes between the current and future climates, either as a relative factor (precipitation and evapotranspiration) or by an additive factor (temperature).
6. Delta change factors were applied to local climate data by which the local particularities are reflected also for future conditions.

For the analysis in the present pilot the following RCP-GCm combinations were employed:

Table 1. Combinations of RCPs-GCMs used to assess future climate

		RCP	GCM
1-degree	"Dry"	rcp4p5	hadgem2-es
	"Wet"	rcp6p0	noresm1-m
3-degree	"Dry"	rcp4p5	hadgem2-es
	"Wet"	rcp6p0	hadgem2-es

4.2 Tool(s) / Model set-up

After the preliminary time series analysis, lumped modelling tools were used to model lake level dynamics based on precipitations, potential evapotranspiration (PET) and direct evaporation from the lake surface. GARDENIA (developed by BRGM), METRAN (developed by TNO) and AQUIMOD (developed by BGS) lumped modelling tools were tested for modelling purposes.
Although all used tools were principally developed for modelling groundwater levels in aquifers, they were tested for modelling lake level, which is in strong connection with the surrounding karst groundwater. Water fluxes to the lake are happening mainly dispersedly through the karst subsurface, and consequently impossible to be directly measured and monitored. This prevents modelling the lake level based on direct inflow, outflow and lake geometry. Lumped groundwater modelling tools were used as an option to overcome this problem. GARDENIA and AQUIMOD models enable level modelling based on precipitations and additionally pumping dynamics, which was used as equivalent process to direct evaporation from the lake. METRAN model is pure transfer function-noise model which can use several input time series in order to model output series. Additionally, manually adjusted simple transfer function was also used to model lake salinity response to the low lake levels.

4.3 Tool(s)/ Model calibration/ test

4.3.1 Observation data

58 years (1961-2018.) of monthly average lake level, sea level, air temperature and relative humidity measurements were available for the historical modelling of the Vrana lake level dynamics. Potential evaporation (PET) was calculated based on Turc method (EtpTurc modelling tool, developed by BRGM). Data of direct evaporation from the lake was available only for two

shorter periods (few years in total). High correlation of monthly evaporation with air temperature enabled calculation of direct evaporation from the lake for the whole period based on air temperature measurements solely.

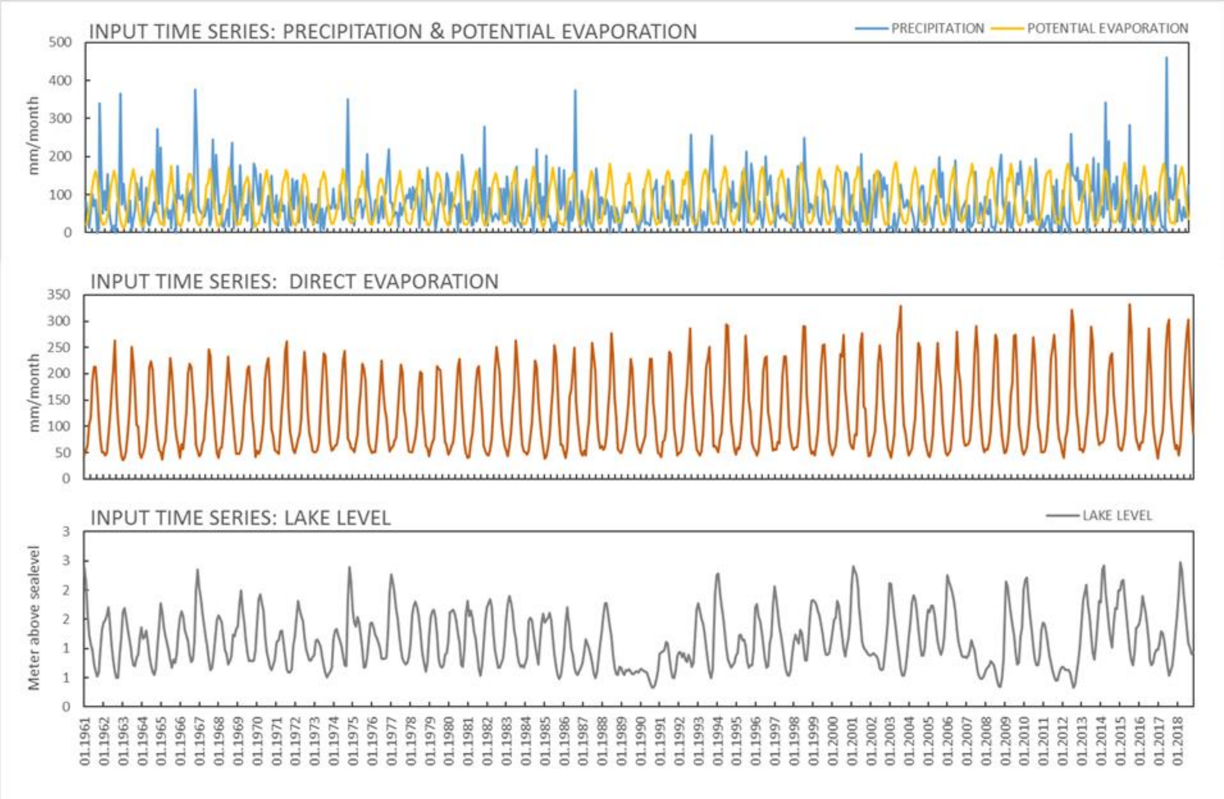


Figure 7. Input time series used for modelling the Vrana lake level dynamics.

4.3.2 Model calibration/adjustment

GARDENIA

GARDENIA modelling tool has a large number of parameters that can be calibrated automatically, or fixed at certain values. Initial calibration attempts, with all parameters non fixed/calibrated ended at unrealistically low effective recharge, accompanied by unrealistically low efficient porosity. Therefore, efficient porosity was fixed at 5%, which is realistic value for the karstified limestone in the area. Base level was also fixed at 0.5 m, as this was average sea level measured close to the Lake, and sea level presents base level for the lake subsurface outflow. Direct lake evaporation was included in the model as pumping. Evaporation was expressed in m^3/s units, converted from monthly evaporation height multiplied by the lake area. GARDENIA model optimize pumping influence on modelled water level by calibration, which enabled efficient inclusion of direct evaporation from the lake surface to the model.

AQUIMOD
Aquimod modelling tool was adjusted in similar way as GARDENIA. The main difference between GARDENIA and AQUIMOD is that AQUIMOD is not able to optimize pumping influence, and therefore inclusion of direct evaporation from the lake in the model resulted with largely exaggerated lowering of the modelled water level. Therefore, direct evaporation could not be included in the model, which resulted in much lower model efficiency comparing to GARDENIA. Therefore, only GARDENIA was used for future climate assessment.

METRAN
Metran transfer-noise modelling tool was used both for modelling lake level based on measured precipitations and air temperatures, and for modelling lake salinity increases based on lake levels. As transfer-noise modelling is purely stochastic model, unlike GARDENIA and AQUIMOD which are physically based lumped models, modelling lake level in METRAN didn't require any approximations and manipulation of input parameters in order to model lake level with groundwater modelling tool. Also, as transfer-noise modelling can be used for modelling any output time serie based on one or more input time series, this model was also used to model lake salinity based on lake level. Prior to modelling lake salinity, critical lake level bellow which lake salinity start to increase was determined. Final model use only lake levels below this threshold value as an input serie.

4.4 Uncertainty

Main source of uncertainty for future CC predictions and scenarios is non-linearity of the processes involved both in lake level response to rainfall and temperature and lake salinity response to low lake levels. All modelling approaches assume linearity of the processes involved in transfer of input to output signal. However, modelled processes are probably not linear, especially lake salinity response in the case of extremely low lake level. Therefore, it can be concluded that presented models are relatively reliable within historically observed conditions, while uncertainty significantly rises in conditions outside them.

5 RESULTS AND CONCLUSIONS

5.1 Performance to historical data

Gardenia model of lake the level (Fig. 8) shows correlation coefficient of 0.83, and NSE of 0.684. However, the greatest importance was atributed to simulation in extremely low lake level conditions, as that are the critical conditions for the lake salinization process. Therefore, model performance is better simulation in drought periods in comparison to the whole modelling period.

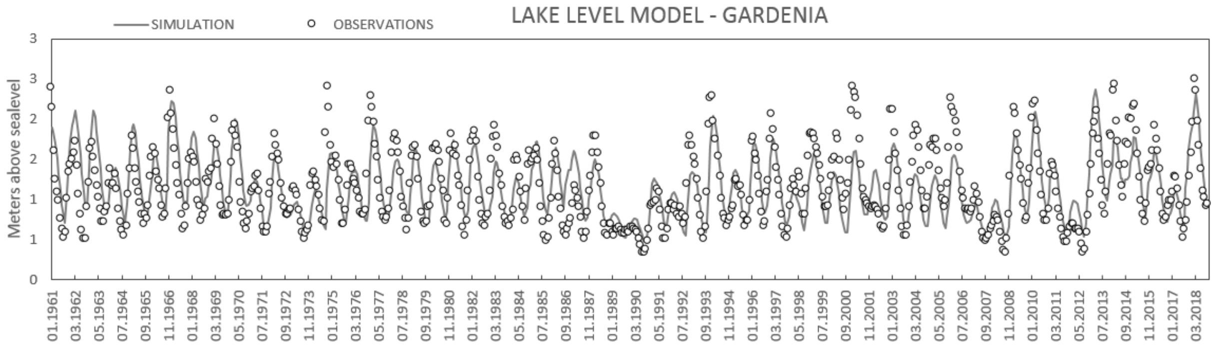


Figure 8. Historical modelling of the Vrana lake level with GARDENIA modelling tool.

As already explained, impossibility to efficiently integrate direct evaporation from the lake surface in the model, AQUIMOD model shows much lower efficiency in comparison to GARDENIA (Fig. 9). NSE of AQUIMOD lake level model is 0.42 wich is not acceptible for reliable lake level predictions. Furthermore, the model was not able to model extremely low lake levels, which are the most important for the lake salinity increases.

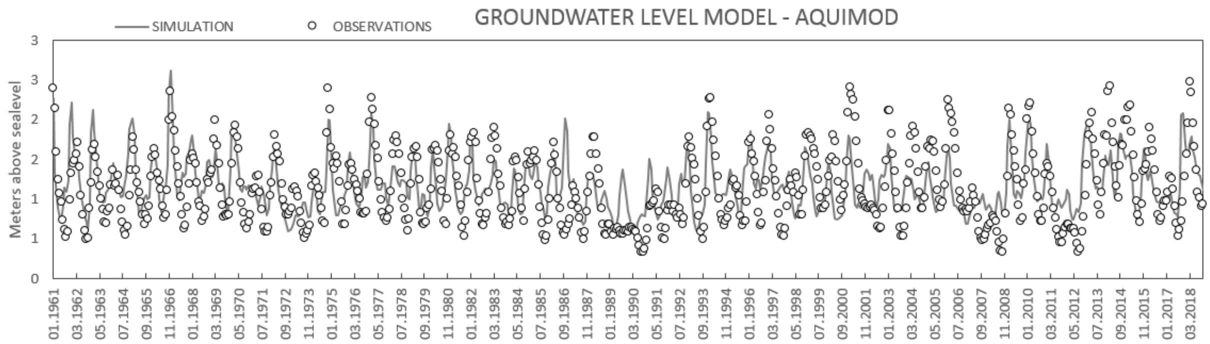


Figure 9. Historical modelling of the Vrana lake level with AQUIMOD modelling tool.

METRAN model shows relatively good efficiency (R^2 = 0.62), and it simulate extremely low levels very well (years 2008 & 2012 in Fig. 10). However, model is designed to work in daily timesteps, and montly timesteps (not exactly same timesteps in days) presented some problems. Adittional problem is related to non-applicability of the modelling with METRAN by non-modelling experts (modelling was done by TNO expert), which slightly reduced posibility to more extensive model modification and development. However, pure stochastic modelling with METRAN is probably the most correct approach to model Vrana lake level, despite slightly better modelling result obtained with GARDENIA tool.

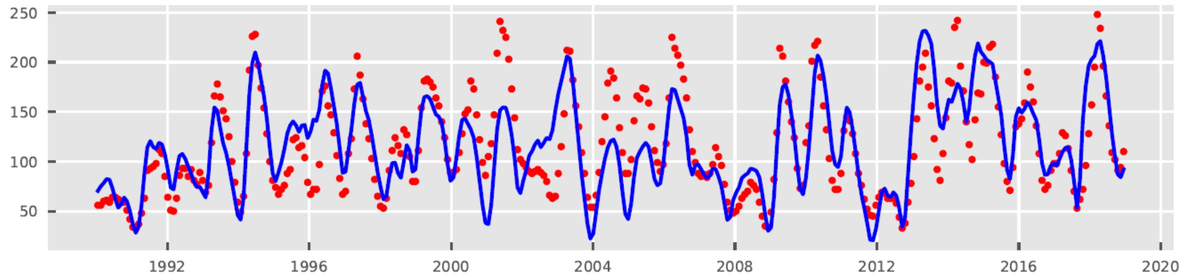


Figure 10. Historical modelling of the Vrana lake level with METRAN modelling tool.

METRAN stochastich transfer-noise model was also posible to used to model the lake salinity with the lake levels as an input. Model performed reasonably well ($R^2 = 0.76$), but it was not able to simulate extremely high salynity values (Fig. 11). If low values bellow natural lake water salinity background in normal conditions had been subsitiued by background values, model would show even higher efficiency.

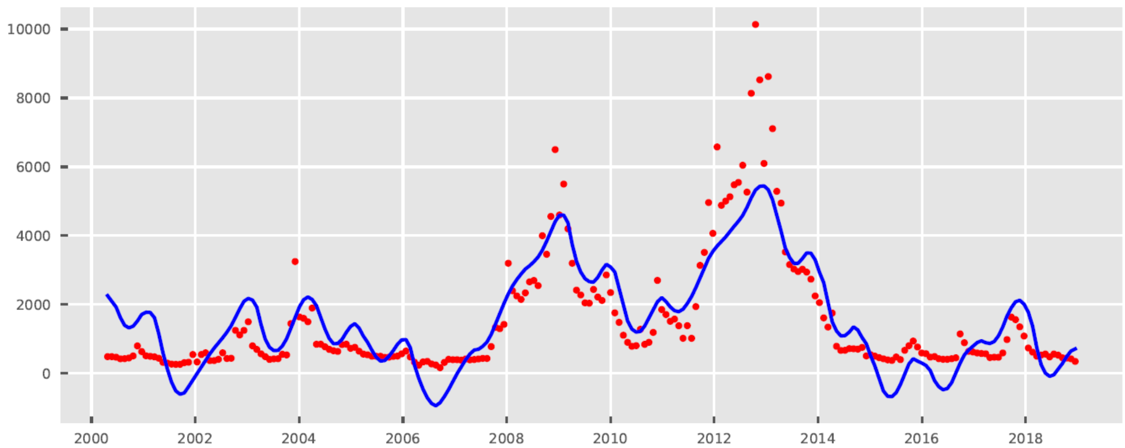


Figure 11. Historical modelling of the Vrana lake salinity with METRAN modelling tool.

Aditional approach to model the lake salinity based on lake level was done by using simple transfer function, manually adjusted in excel software. Simple model uses lake levels below threshold value, determined as a criticall value below which salinity starts to increase, as an input. The model simulate salinity dynamics very well ($R^2 = 0.78$).

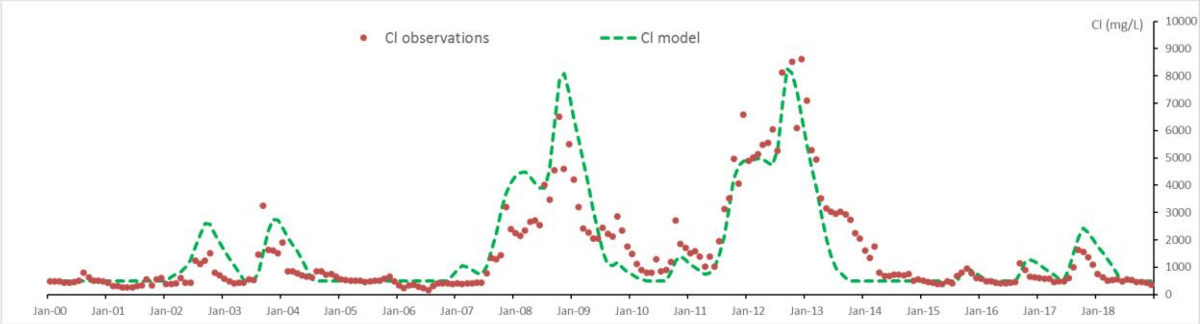


Figure 12. Historical modelling of the Vrana lake salinity with manually calibrated transfer function.

5.2 Results of assessments

Assesment of future CC scenarios, based on four selected scenarios (Table 1) was done with GARDENIA tool, as this tool provided best performance on modelling based on historical observations. Modelled future lake levels based on all four scenarios are considerably lower than historic levels (Figs. 13, 14). The most significant influence on lowering lake levels in GARDENIA model has largely increased direct evaporation from the lake (Fig. 15) due to significantly increased air temperatures in summer months according to all four considered CC scenarios. Moreover, the lake level below determined threshold value of 0.5 m a.s.l., in which case salinity of the lake start to significantly increase, historically appeared only in the cases of severely dry years, while according to the considered future CC scenarios it will appear regularly (Fig. 14). Also, all four CC scenarios ended with relatively close future lake level predictions.

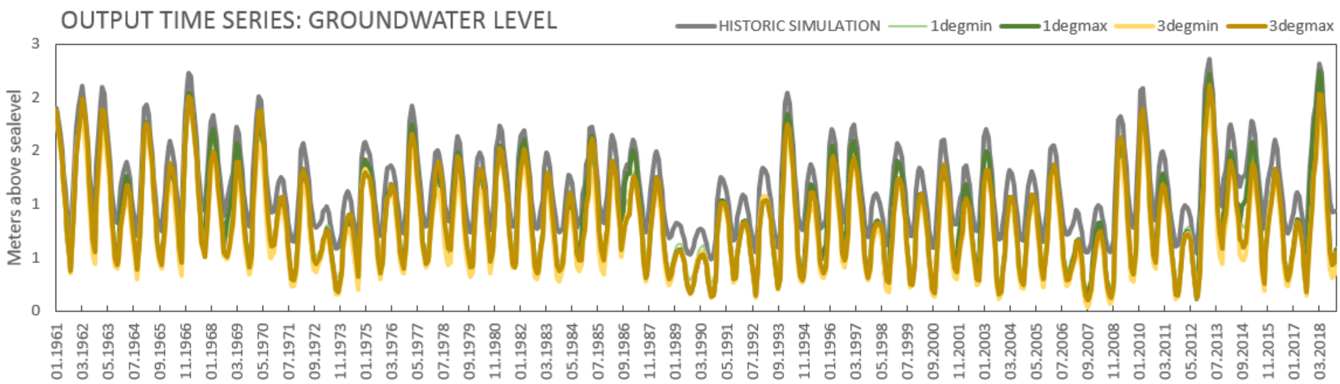


Figure 13. Future projection of the Vrana lake levels for four selected CC scenarios (Table 1), modelled with GARDENIA tool calibrated on historical observations.

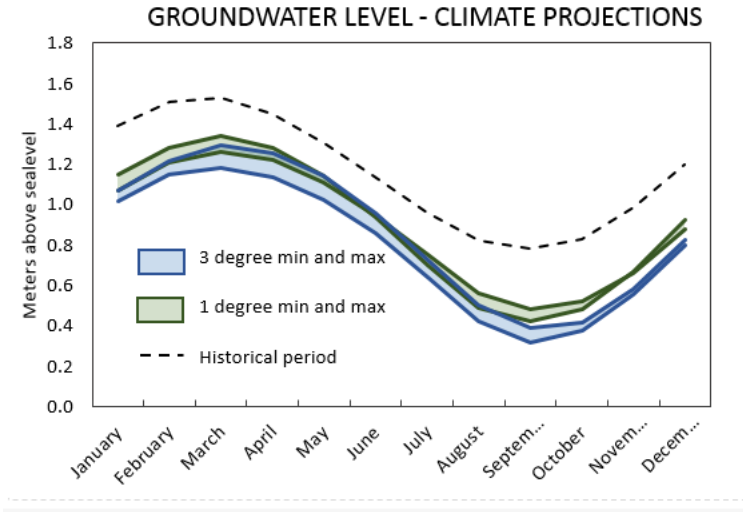


Figure 14. CC projection of the average monthly levels of the Vrana lake, modelled with GARDENIA tool calibrated on historical observations.

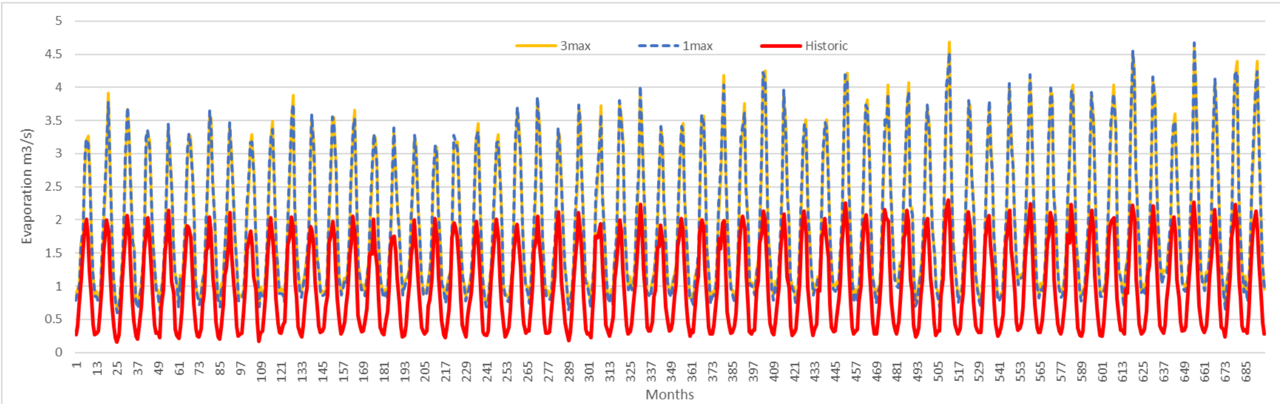


Figure 15. CC projection of direct evaporation from the Vrana lake (m^3/s), based on established relation to air temperatures on historic measurements.

On Figure 16. Future CC projection of the Vrana lake chloride content, based on 3deg max scenario is shown. Future CC projection is modelled by using a simple transfer function. Other future CC scenarios shows similar output, as future levels (input fore chloride model) modelled with GARDENIA (Figs. 13, 14) are relatively close. However, it should be noted that transfer function is linear model, while response of salinity to the low lake levels is probably non-linear. Therefore, modelled future CC salinity results should be regarded as very approximate. Regardless of exact values of expected future salinity increase due to CC, it is certain that generally large increase in the lake salinity is expected, which will result in transition of the system state from mostly fresh water lake with occasional brackish episodes to all the time brackish lagoon with variable salinity (maximum approaching seawater salinity).

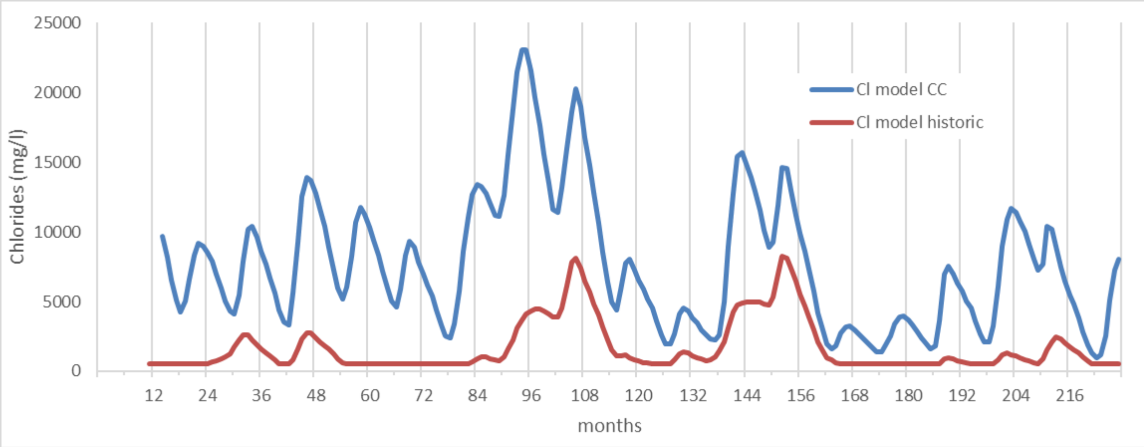


Figure 16. Future projection of the Vrana lake chloride content, modelled by using simple transfer function (Fig. 12).

5.3 Adaptation strategies

Permeable karst terrain separating the lake and the sea enable underground inflow of sea water into the lake during dry periods when lake level drops near (or even below) sea level. Excessive salinization of the lake presents a major threat to the lake ecosystem. The main preventing factor for lake salinization is sufficient lake water level, i.e. sufficient freshwater quantity within the lake. Major sink of the freshwater from the lake during hot and dry summer months is very high evaporation from the lake surface. Due to the large lake volume system has considerable inertia. Therefore, sufficiently high lake level at the beginning of dry period usually prevents subsequent excessive level drop. Also, sufficient inflow of freshwater into the lake during critically low lake levels prevents excessive lake salinization. Consequently, two main factors that can prevent excessive lake salinization are high lake level at the start of dry period, as well as sufficient inflow of fresh water to the lake during dry periods. Adaptation strategies applicable to Vrana lake ecosystem are therefore aimed at achieving these two goals.

Both pumping of groundwater for public water supply and irrigation within the lake catchment lower fresh water inflow to the lake. Therefore, adaptation measures that can be applied and tested include *Water transfer* from neighboring water supply systems and *Integrate water demands in conjunctive systems*. The local water supply system is already connected to the neighboring systems, but due to additional costs, water from other system is used only in the cases of water shortage from local sources. Nevertheless, effects of possible water transfer on reducing lake salinization should be analyzed in more detail. In addition, *improved planning, control and resources allocation* between public water supply, agriculture and freshwater depending ecosystem should be applied. *Improved monitoring and early warning system* should be eatablished in order to anticipate conditions leading to excessive lake salinization, and start applying the *Water transfer* measures.

Additional measures aimed at insuring high water level before start of the dry season include Create*/restore wetlands*, which were historically converted to agricultural lands by digging artificial evacuation channel for high lake waters. The channel can be partially blocked and actively managed in future, but some of agriculture lands in vicinity of the lake would probably be occasionally drowned (restoration of the wetlands) in order to have sufficiently high lake level in dry season.

Table 2. Adaptation strategies that applicable to Vrana lake system.

DEMAND
REDUCING ENVIROMENTAL IMPACTS
Increase water allocation for ecosystems
Create/restore wetlands
OFFER
COMPLEMENTARY RESOURCES
Water transfer
MIXED (improving resilence & adaptation capacity)
Improve planning, control and resources allocation
Improved monitoring and early warning
Integrate water demands in conjunctive systems

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Establishing the European Geological Surveys Research Area to deliver a Geological Service for Europe

Deliverable 5.3 and 6.3

PILOT DESCRIPTION AND ASSESSMENT

Falster, Denmark

Authors and affiliation:

Per Rasmussen, Klaus Hinsby, Denitza Voutchkova, Birgitte Hansen

[GEUS]

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Deliverable Data	
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Lead WP/Deliverable beneficiary	*IGME*
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LIST OF ABBREVIATIONS & ACRONYMS

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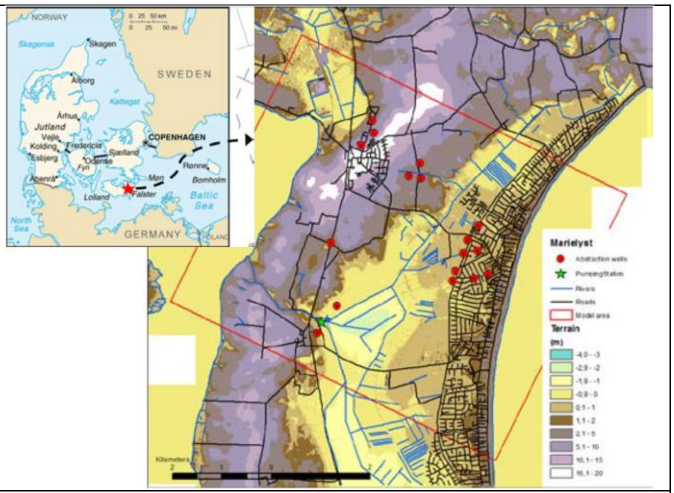
1 EXECUTIVE SUMMARY



Pilot name	Falster
Country	Denmark
EU-region	Central and eastern Europe
Area (km^2)	32
Aquifer geology and type classification	Chalk, fractured
Primary water usage	Drinking water supply
Main climate change issues	Increasing sea levels is expected to increase the risk of saltwater intrusion to the coastal confined chalk aquifer. Groundwater modeling studies have shown that a potential decrease in precipitation for extended periods may also increase the risk of saltwater intrusion to the local groundwater aquifer. Other effects of projected climate change impacts include an increase in the number and size of extreme rain events resulting in floodings along drainage canals if measures are not taken to avoid this.
Models and methods used	Geophysical measurements (e.g. electromagnetic, both airborne and groundbased, as well as geophysical borehole logging) have been conducted to find the existing fresh-saltwater boundary and support the development of a geological and an integrated groundwater-surface water model for climate change impact assessment and adaptation. Field tracer experiments were completed in order to estimated dual-domain flow parameteres for density dependent groundwater modelling using MODFLOW, MT3DMS and SEAWAT. Analyses of groundwater and surface water including age dating and emerging contaminants were performed for characterization of water qualities. Salinity sources were assessed by the use of self-organizing maps (SOM) for the analysis of the distribution of selected trace elements. Natural backgroundwater values were furthermore estimated by different methods and used to assess groundwater threshold values and chemical status according to the Water Framework Directive.
Key stakeholders	Marielyst Waterworks, Land Reclamation Society Bøtø Nor, Farmers, Dike Guild of Falster, Homeowners Association, tourist- and business associations, Gedser bird watching station.
Contact person	Klaus Hinsby (khi@geus.dk), Per Rasmussen (pr@geus.dk)

Saltwater intrusion to the coastal chalk aquifer on the southern part of the Falster island is a significant challenge and threat to water supply in the area in the near and far future (Rasmussen et al., 2013, 2015) as in many other coastal areas in Europe (Hinsby et al., 2011) and globally (Post and Abarca, 2010). The main climate change impact and adaptation issues with the Falster pilot area include potential saltwater intrusion from the Baltic Sea, deeper saline parts of the aquifer and other parts of the confined chalk aquifer and aquifer system (Hinsby et al., 2012), which locally seems not to have been completely freshened during the Pleistocene and Holocene (Knudsen et al., 2021). In addition flooding of low-lying areas and droughts during extreme events have occurred during recent years and is expected to increase in the area according to climate change projections for Northwestern Europe.

The upper part of the chalk aquifer at a depth between typically 15 – 25 meter below surface locally has elevated chloride contents to concentrations above the drinking water standard of 250 mg/l. Depending on location the observed elevated concentrations may originate from the aquifer itself as an old marine sediment, the Baltic Sea and Holocene marine sands above the aquifer (Hinsby et al., 2012, Rasmussen et al., 2013, Knudsen et al., 2021).

The understanding of the salinity sources and the migration of dissolved chloride in the chalk aquifer is important for developing efficient measures to control saltwater intrusion and protect water supply wells from increasing chloride e.g. by temporary groundwater storage / water banking and other subsurface water solutions (Hinsby et al., 2018), while potentially protecting the built environment in the area at the same time (Hinsby et al., 2015, 2016, 2019).

2 INTRODUCTION

Climate change (CC) already have widespread and significant impacts in Europe, which is expected to increase 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. In order 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 centered 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 Falster pilot area in Southeastern Denmark has been investigated for about a decade to improve the understanding of salinity sources (Hinsby et al., 2012, Knudsen et al., 2021), climate impacts on salt water intrusion to a coastal aquifer that secure water supply for a summer housing areas in the southeastern part of the Falster Island (Marielyst), which experiences increasing salinity and risk of flooding.

3 PILOT AREA

The local waterworks, Marielyst Waterworks, located in the Falster pilot area has experienced problems with increasing salt (chloride) concentrations in water supply wells during the last two to three decades (Fig. 1). The waterworks have had to close several existing water supply wells due to chloride concentrations above the drinking water standard in the coastal aquifer. The main aquifer in the area is a shallow chalk aquifer highly fractured in the upper 10-20 meter. The land use in the study area is dominated by agriculture and settlements of summer cottages, although a few small permanent villages have developed on top of the push moraine hills in the western part of the area. Today there are more than 5000 summer cottages. Although most of these are built on the original barrier islands in the eastern part of the investigated area, the most recent housing areas have spread into the reclaimed areas and some of these are therefore located at or below mean sea level. The freshwater supply for the villages and the summer cottages is based solely on groundwater.

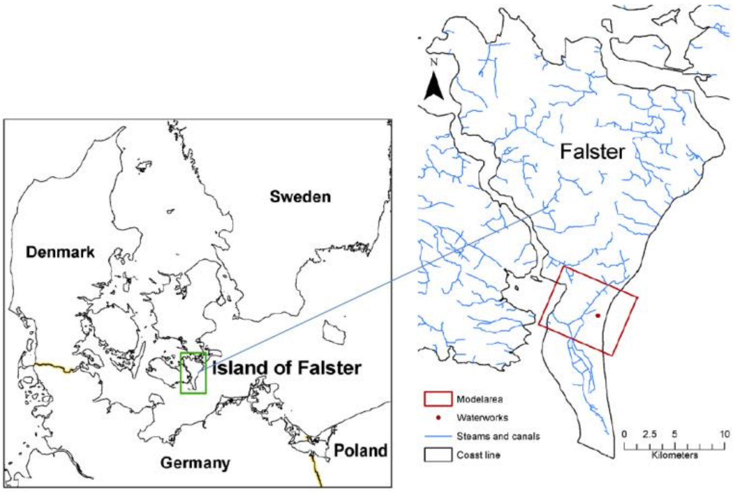


Fig. 1. Location of Falster pilot area

The Falster test site area was studied in the three previous EU and National research projects: "BaltCICA" (www.baltcica.org) was part-funded by the BONUS programme on the Baltic Sea (www.bonusportal.org), "Water4Coasts" was part-funded by the Ecoinnovation program of the Danish Ministry of Environment and Food (http://eng.ecoinnovation.dk/), and "SUBSOL" (www.subsol.org) received funding from the European Union's Horizon 2020 research and innovation programme (https://ec.europa.eu/programmes/horizon2020/en). Main results from the three projects can be found in Rasmussen et al. (2013), Hinsby et al. (2016), and Hinsby et al. (2018).

The main objective of the studies conducted in BaltCICA was to assess climate change impacts on the freshwater-saltwater boundary in the Chalk aquifer in the investigated area. Geophysical measurements (e.g. electromagnetic, both airborne (SkyTEM) and ground based, as well as geophysical borehole logging) were conducted to find the existing freshwater-saltwater boundary and to support the development of a geological and an integrated groundwater-surface water model for climate change impact assessment and adaptation (Fig 2 and 3).

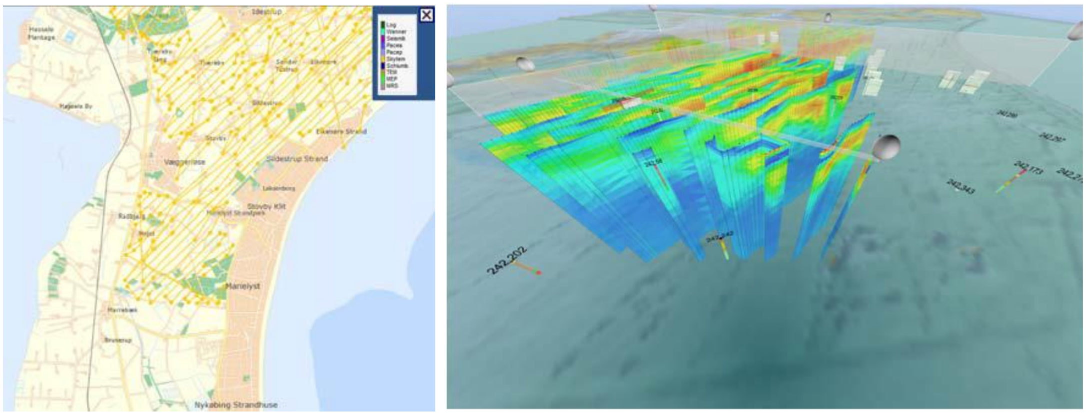


Fig. 2. SkyTEM flight lines (left). SkyTEM resistivities displayed in 3D (right)

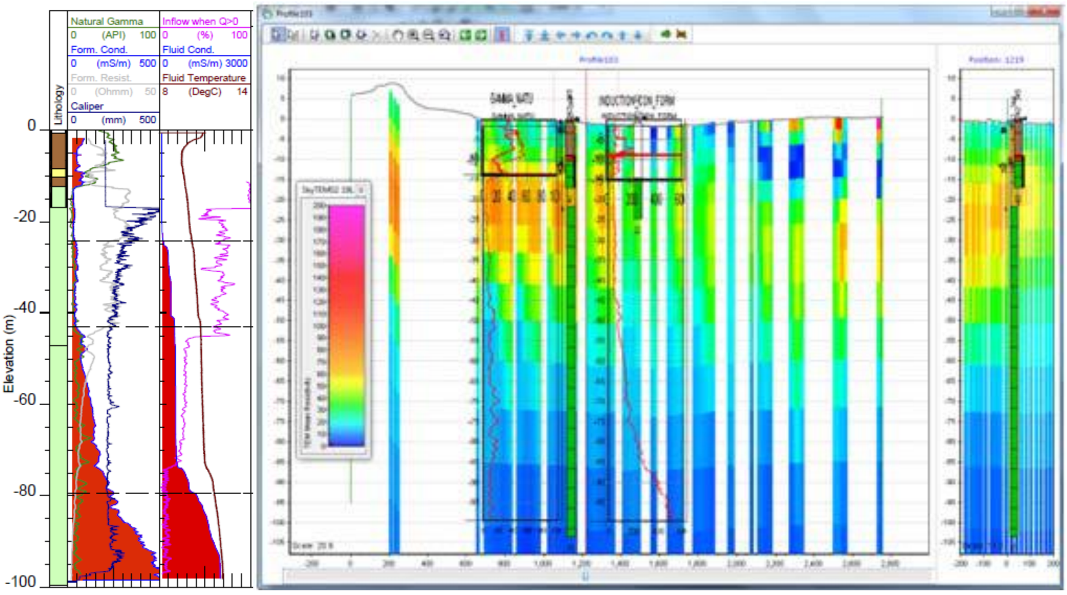


Fig. 3. Geophysical borehole logs (left). Combined plot of formation conductivity from wireline logging and SkyTEM resistivities (right)

The main objective of the Water4Coasts study was to initiate the assessment of the potential application of new innovative techniques to control saltwater intrusion and protect freshwater resources in the fractured Chalk aquifer of the Falster Island and similar settings, globally (Hinsby et al, 2016). The studies demonstrated that several issues needed to be investigated further before concrete solutions could be recommended. The recommendations included more detailed analyses of the hydraulic properties of the fractured chalk aquifer. Other suggestions dealt with further analysis of water quality of groundwater and surface waters. Surface water could potentially be used after treatment for injection and water banking e.g. between wet winter periods with low demands and abstraction and dry summer periods with high demands and abstraction.

In the SUBSOL project, the Falster area was selected as one of the areas to assess whether the subsurface water solutions (SWS) developed for single porosity granular aquifers in the Netherlands may be applied with similar success and designs in dual-porosity fractured carbonate aquifers. The conducted investigations indicate that dual porosity systems are very well suited for the application of SWS techniques, globally, but that fracture distributions and e.g. glaciotectonical impacts affects the hydraulic behaviour in complicated ways that require additional investigations and assessments (Fig. 4).

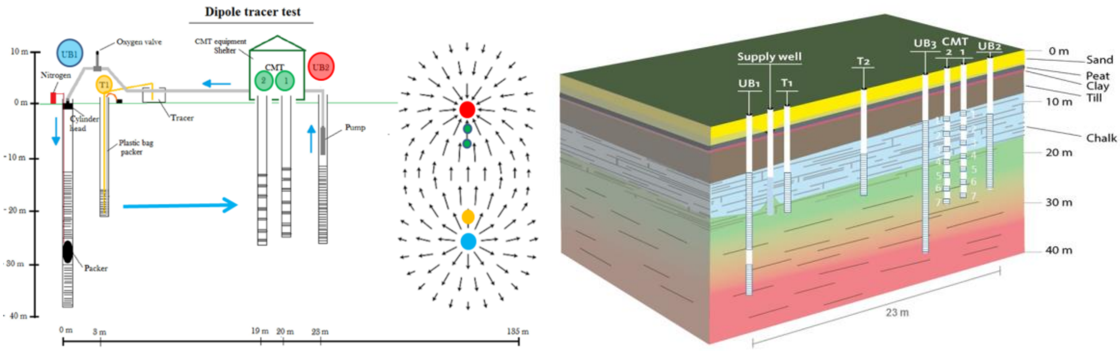


Fig. 4. The developed dipole tracer test setup in the SUBSOL project, blue arrows in the left diagram show the water movement. Tracer was injected in T1 or T2 (right diagram) and tracer breakthroughs were observed in the multi-level screens of CMT1 and 2

The aim of this case study was to further assess the salt-/seawater intrusion status and vulnerability in the shallow fractured chalk aquifer in Falster. The vulnerability assessments of the aquifer includeed effects of future climate predictions concerning risks of a drier climate with less precipitation resulting in reduced groundwater recharge, increased frequency and intensity of intense rainfall resulting in flooding. The aim was also to look at the possibility for using MAR (Managed Aquifer Recharge) as a tool for the long-term protection, sustainable management and improvement of local groundwater resources.

3.1 Site description and data

Location of pilot area

The pilot area is located in the south-eastern part of Denmark on the island of Falster. Towards the east the area is bounded by the Baltic Sea and towards the west of the strait of Guldborgsund (Fig. 5). The local waterworks are abstracting groundwater from the shallow Chalk aquifer overlain by quaternary and post glacial sediments of mainly clayey tills and sands. The well fields located closest to the Baltic Sea coast have seen an increasing chloride concentration in the abstracted groundwater during the last decades.

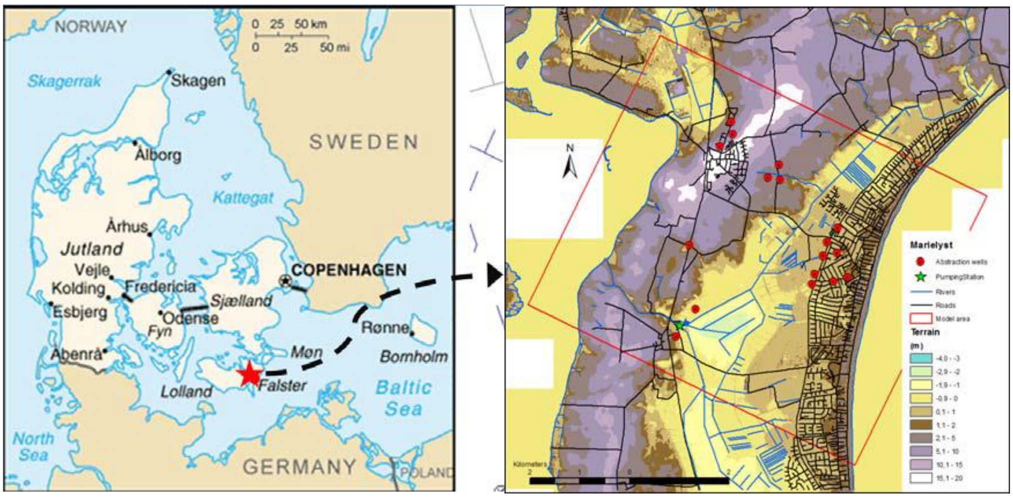


Fig. 5. Location of pilot area, abstraction wells, drainage canals and pumping station

Climate

The climate in Denmark is characterized by the country's close location to the Atlantic Ocean and the Gulf Stream. The predominant occurrence of western winds means that the coastal climate is dominant. The coastal climate and the location in the west wind belt mean that Denmark usually has relatively cool summers and mild winters. However, when the wind comes from the continent, periods of continental climate (hot summers and cold winters) can occur.

The sea is surrounding Denmark, which also means that the temperature difference between night and day is relatively small.

The average daily temperature in Denmark is around 15-16 degrees in summer and around or just above the freezing point in winter. Winters with a prolonged supply of cold air from the continent occasionally give rise to hard winters, where the inland waters freeze.

The average annual precipitation in the area is approximately 700 mm and the actual evapotranspiration is approximately 450 mm.

Topography

The elevation varies from 19 m a.s.l. (above sea level) in the west to -3 m a.s.l. in the central eastern part of the area. The landscape is mainly developed from north-south trending push moraine hills of clayey tills along the coast in the western part of the island, which were formed during the last glaciation by an east to west moving glacier. During the Holocene, small barrier islands with eolian sand dunes, which constitute the eastern part of the island and a lagoon developed in front of the glacial moraine hills. As the barrier islands grew it became possible to reclaim the low-lying wetland area between the push moraine and the barrier islands in the central part of the study area.

Land use

The land use in the study area is dominated by agriculture and settlements of summer cottages, although a few small permanent villages have developed on top of the push moraine hills in the western part of the area.

Soil types

The dominant soil types in the Falster pilot area are clayey till, marine sand, and eolian sand dunes (Fig. 6).

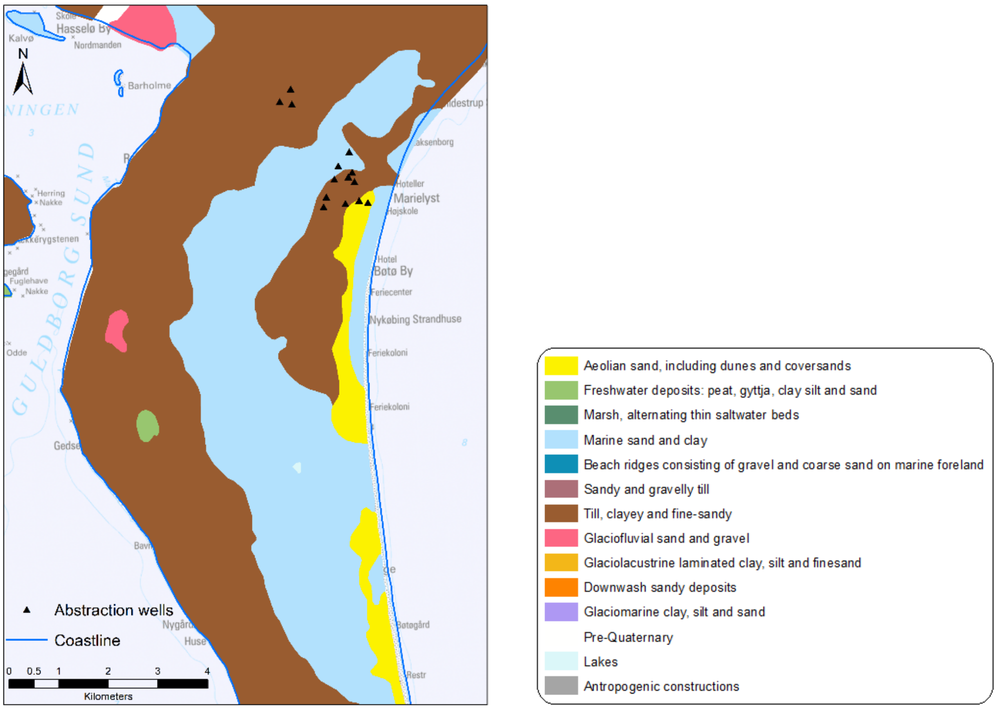


Fig. 6. Soil types (location map, see Fig. 7 A)

Geology/Aquifer type

In the pilot area, the top surface of the Upper Cretaceous chalk aquifer is situated at about 10 m below the surface. It is overlain by a 5 m thick unit of glacial sediments and 5 m marine sand. However, at a depth of 15 to 18 m there is a layer of chalk with gravel and pebbles of basement rocks.

Based on an evaluation of data from other wells in the area, it has become evident that another zone with basement gravel and pebbles existed even deeper at a level from 30 to 40 m below the surface. These findings have implications for the understanding of groundwater flow around the wells as the complexity of the hydraulic characteristics markedly changes the aquifer's behaviour. A model of the glaciotectonite occurrence was established based on a glaciodynamic concept of the area (Pedersen et al., 2018) (Fig. 7).

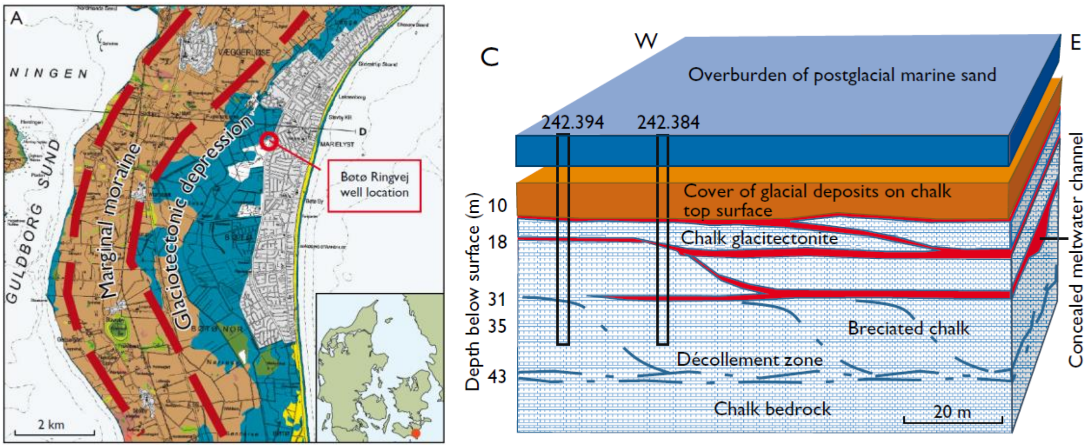


Fig. 7. Hydrogeological investigation site on Falster: A: geological map of the area demonstrating the glacial geological setting. C: block diagram illustrating the features and glacitectonites in the Upper Cretaceous beds (Pedersen et al., 2018)

The main aquifer for water supply in the area is the upper chalk. The Quaternary glaciations have caused fracturing of the upper 20–30m of the chalk. In this part, the chalk is fully or partly refreshed due to fast advective groundwater flow through the fractures. Previous studies of chalk aquifers in Denmark have shown that the residual saltwater typically is completely flushed out in the upper 50–80m of the chalk by infiltrating freshwater. Below this zone a mixing zone with elevated chloride concentrations is seen, where the number of fractures and the effective hydraulic conductivity is gradually decreasing compared to the fully refreshed zone above. Below this depth, matrix diffusion is the dominating transport process for saltwater. At depth below 150–200m the saltwater is of oceanic concentration with total dissolved solids (TDS) concentrations above 35 000 mg/l and chloride concentrations above 19 000 mg/l.

Surface water bodies

The surface water system is dominated by the artificial drainage canal system. A few minor creeks flow towards the drainage system or towards Guldborgsund. The drainage system is lowering the water table in the area where the ground surface has elevations between +1 and −3 m a.s.l. The pumping station is aiming at keeping a constant water level in the drainage canals.

Groundwater abstractions/irrigation

The Marielyst Waterworks supplies water to 5200 households. Due to the high percentage of summer cottages in the area, the groundwater supply varies considerably during the year with a maximum of 2000 m^3/day in July to a minimum of 300 m^3/day in January. The waterworks has 12 active abstraction wells, which are located in three separate well fields. The oldest well field is located about 0.5 km from the coast, a second group of wells are approximately 1 km from the coast (established 1975–1990) and both well fields are located on one of the former barrier islands. The newest well field is located in the central part of the island 2.5 km from the coastline. It was established in 2005 in or very close to the main groundwater recharge area in the push moraine hills.

All 12 groundwater abstraction wells of Marielyst Waterworks are drilled to a depth of 10–15m into the upper fractured chalk aquifer. Significant groundwater abstraction has taken place since the 1960s. The annual groundwater production reached its maximum around 470 000 m^3/year in the beginning of the 1980s and has since then decreased to the present level of around 250.000 m^3/year, mainly due to repair of leaky water pipes. Additionally, groundwater abstraction takes place from two other minor waterworks and a few irrigation wells, which add up to approximately 150.000 m^3/year.

3.2 Climate change challenge

The Falster pilot area is located in the Central and Eastern Europe climate zone (EEA map Fig. 8) where a decrease in summer precipitation is expected along with an increase in warm temperature extremes. In the Falster pilot area higher summer temperatures and lower precipitation will most probably result in a higher demand for groundwater, both for domestic use and for irrigation of e.g. golf courses. Lower summer precipitation will also affect the surface water bodies being subject to more water stress. A decrease in summer precipitation is not expected to affect the groundwater recharge that is mainly taken place from October to April.

The most likely climate scenario for the pilot area also predicts an increase in sea level, and an increase in winter precipitation, which will most probably result in an increase in groundwater recharge. Rising sea level will most probably result in further seawater intrusion into the coastal Chalk aquifer, causing a reduction in the available groundwater resource for the local freshwater supply. In addition, an increase in the frequency and the intensity rainfall is predicted, which might result in more severe flooding events.

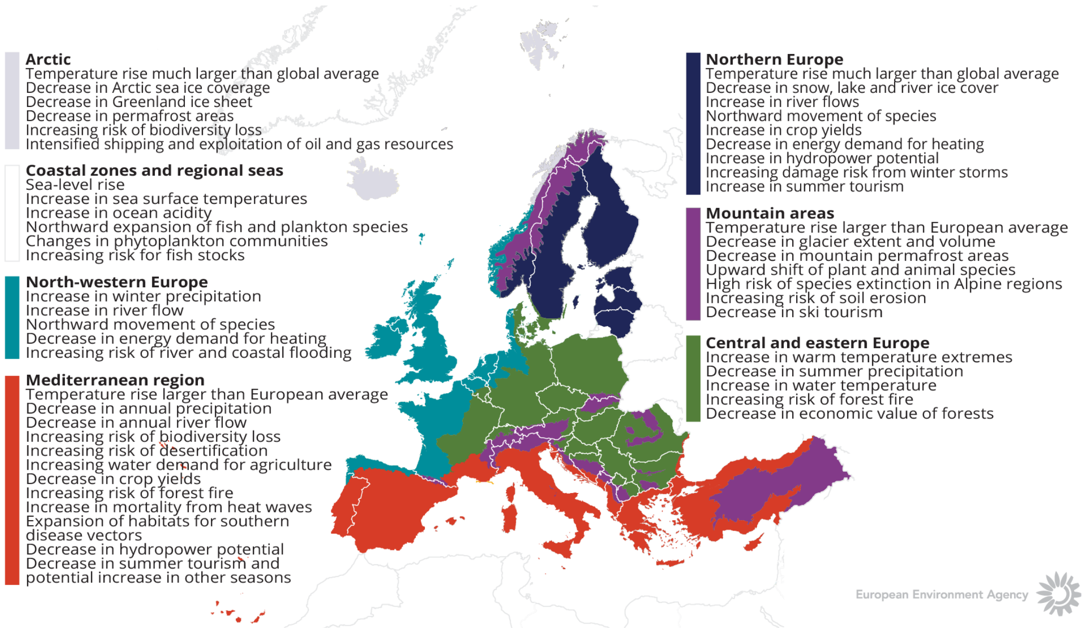


Fig. 8. Observed and projected climate change and impacts for the main biogeographical regions in Europe (European Environmental Agency)

4 METHODOLOGY

4.1 Methodology and climate data

4.1.1 Tools/ model description

For the pilot area on the island of Falster a 3D variable density groundwater model has been setup with the aim of analysing actual and future risk of saltwater intrusion to the local coastal aquifer. The modelling packages MODFLOW, MT3D, and SEAWAT were used. The setup of the MODFLOW/MT3D/SEAWAT model, its functionalities, applications and basic assumptions are described by Rasmussen et al. 2013, which can be found in a special issue of Hydrology and Earth System Sciences (Hinsby et al. 2011). Focus of the modelling were on 1) getting the initial saltwater concentrations right by modelling the transition of part of the pilot area, which over the last two to three centuries has changed from a saltwater lagoon to reclaimed land, 2) the increase in groundwater abstraction from the costal aquifer due to a significant development of summer cottages and the possible effect of seawater intrusion, 3) and impacts of climate change, change in precipitation and sea level rise, on seawater intrusion.

A minor local and simplified 3D variable density model based on the above described model has been setup with the purpose of analysing the applicability and effectiveness of subsurface water solutions (SWS) in a fractured chalk aquifer. The SWS “Freshkeeper” was tested, where freshwater is injected in to the aquifer with the aim of storing freshwater from winter to summer were, and at the same time prevent saltwater from entering the aquifer by creating a freshwater lens in the aquifer around the groundwater abstraction wells (Hinsby et al. 2018).

4.1.2 Climate data

The model scenarios on future risk of saltwater intrusion to coastal aquifer were based on predictions of sea level rise and on change in groundwater recharge due to projected changes in precipitation for the Danish area. The expected change in groundwater recharge for the Pilot Falster was based on the predicted change in groundwater recharge for a comparable area in Denmark (van Roosmalen et al. (2007). These studies used output from regional climate models representing IPCC (2000) scenarios A2 and B2.

The tested climate change effects of sea level rise and changes in groundwater recharge were gradually implemented in the groundwater model over a simulation period of 90 years. For an additional 200-year simulation period both recharge and sea level were kept constant in order to assess the long-term effects of the imposed climate changes (Rasmussen et al. 2013).

The groundwater model could be improved in a couple of ways, e.g. by including 1) an ensemble of the latest climate models for different emission scenarios including downscaling (see www.aquaclew.eu), 2) the latest predictions for expected sea level rise, and 3) the expected change in the demand for groundwater with predicted longer and warmer summer periods with less precipitation than today.

4.2 Tool(s) / Model set-up

The groundwater model was based on the large scale Danish national hydrological model, the DK-Model (Henriksen et al. 2003) with later updates. The geological information in the model was refined using data from geological soil maps, and from various types of borehole tests and borehole wireline logs. The canal and drainage system were refined using local maps and field surveys.

4.3 Tool(s)/ Model calibration/ test

The groundwater model was calibrated using groundwater head observations and discharge data from the main drainage canal. The variable density model simulations of saltwater intrusion were validated against groundwater chemical data and geophysical data (borehole logging data and data from both ground and airborne transient electromagnetic surveys).

4.3.1 Observation data

Time series of groundwater head, groundwater chemistry and river discharge were available for model calibration and validation. Some of the historical data series up to or more than 30 years long. During the resent project periods more intensive monitoring programmes were organised.

4.4 Uncertainty

The geological uncertainty was the major source of uncertainty for the groundwater density model. The knowledge in general and also site-specific knowledge about flow and transport characterises for the fractured and double porosity chalk aquifer was limited. The geological interpretation and the implemented geological model for the coastal zone was uncertain, there were only limit geological available in the coastal zone, few boreholes exist as groundwater interests are limited and geological information collected for exploration for off-shore raw material exist only further out in the sea. The degree and the extent of the refreshening of saline water in the chalk aquifer by fresh groundwater recharge was also a source of uncertainty.

These uncertainties were to some extent addressed by field campaigns including borehole wire logging, electromagnetic surveys, both airborne (SkyTEM) and ground based, and onsite field tracer tests. More investigations are needed to really improve the flow and transport processes in the double fractured chalk aquifer.

4.5 Saltwater intrusion and groundwater chemical status

The national Threshold Value (TV) for Cl is set to 250 mg/l, which is the same as the drinking water quality standard. The natural background levels (NBL) for Cl were estimated at the national scale for different types of aquifers and locations. However, because these NBLs were lower than the national TV, they were not used in the chemical status assessment of the Danish groundwater bodies.

The NBL for Cl relevant to Falster is for the carbonated aquifers on Sjælland, which was estimated to be 157.2 mg/l, based on the representative Cl values for 1283 sampling points. The representative value was determined as the mean of the annual mean concentrations for the period 2000-2018 (incl.).

5 MODELLING AND MONITORING RESULTS

5.1 Modelling results and climate change impact assessments

5.1.1 Performance to historical data

The calibration results for the groundwater heads for the steady-state models were are regarded as satisfactory with a RMS value of 1.53 m. The used groundwater heads for model calibration were all measured in boreholes with low salinity and density effects on hydraulic heads are insignificant. For the transient calibration a R^2-value (the Nash–Suthcliffe coefficient) of 0.88 was found for the drainage canal main gauging station based on monthly data, which in general is an acceptable calibration result (Rasmussen et al. 2013).

A comparison between the modelled saltwater distribution and SkyTEM surveys showed both good agreement in some areas and areas with some discrepancy (Fig. 9). See Rasmussen et al. 2013 for further discussions of the model validation and the electromagnetic surveys.

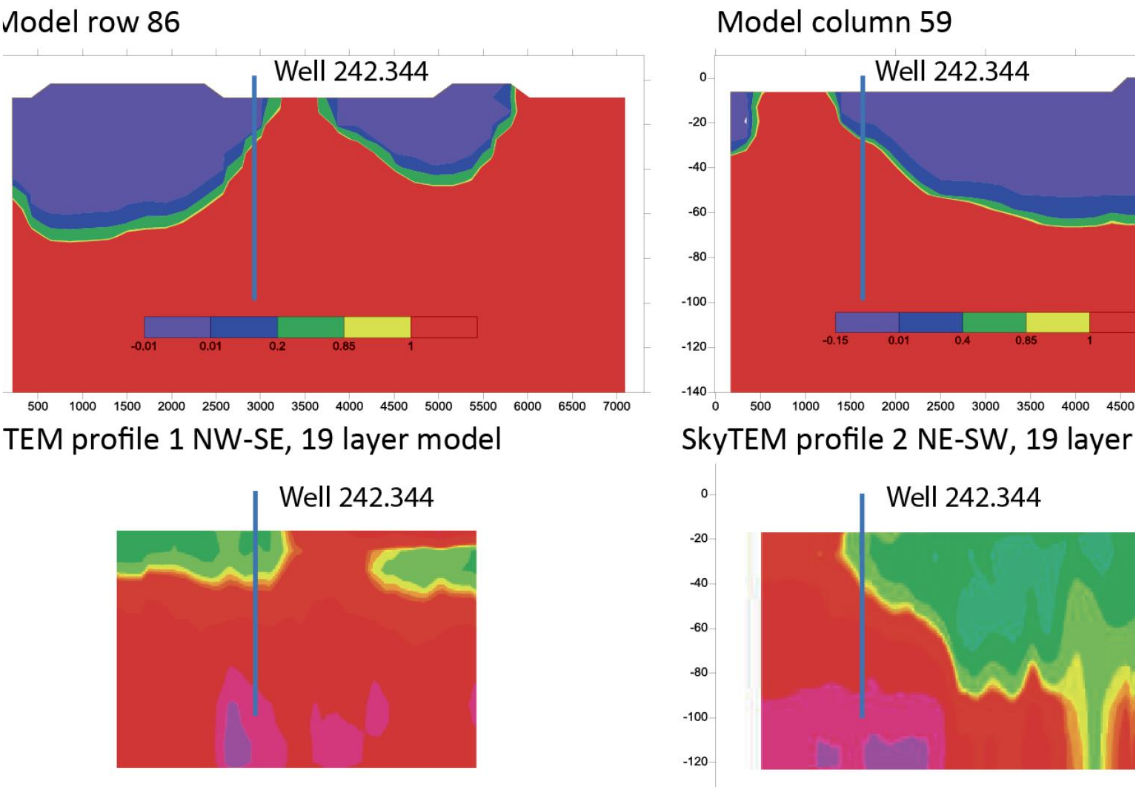


Fig 9. Comparison between the results of model simulations (upper cross sections) and SkyTEM surveys (lower cross sections). The colour scales are defined such that blue/green colours indicate freshwater of drinking water quality ([Cl−]<250 mg L−1). Yellow is breaching a threshold value of 150 mg L−1, and red breaches the drinking water guideline (Rasmussen et al. 2013)

5.1.2 Results of assessments

The study shows that saltwater intrusion in the Falster Pilot is sensitive to changes in sea level, groundwater recharge and stage of the drainage canals. The changes in recharge were found to be the most important factor, whereas minor sea level rises do not seem to affect the sea water intrusion as much. For the abstraction wells at risk the model studies show that the chloride concentrations are most sensitive to the stage of the drainage canals and to the groundwater recharge. However, the combination of significant changes in groundwater recharge, sea level rise, groundwater abstraction, and canal maintenance are crucial for the development of the groundwater quality (Rasmussen et al. 2013).

5.2 Monitoring data and chemical status assessments

5.2.1 Time series of chloride concentrations

The dataset covers the period 1985 to 2020 and includes groundwater Cl samples taken at 14 abstraction wells used by Marienlyst Vandværk for drinking water production (Table 1 and Figure 10 and 11). In addition, the Cl samples of the treated drinking water taken at the exit of Marienlyst Vandværk (after all treatment) are also presented for comparison purposes.

Table 1. Summary statistics for the Cl dataset with information on the number of samples, the sampling period, the minimum, 10th and 50th percentiles (p10 and p50 respectively), maximum, mean and standard deviation (SD)

Sampling point		**Samples**	**Period**		**Cl concentrations (mg/l)**					
DGU number	VV Boring	n	y_1	y_n	min	p10	p50	max	mean	SD
242. 172	3	115	1985	2020	60	120	160	**260**	156.8	39.3
242. 178	2	115	1985	2020	190	208	**280**	**300**	**262.8**	33.2
242. 189	5	115	1985	2020	40	70.8	176	250	162.2	55.4
242. 190	4	57	1985	**2005**	156	238	**270**	**316**	**267.2**	29.2
242. 212	9	112	1985	2020	76	110	140	236	148.4	34.5
242. 213	10	57	1985	**2005**	195	204	220	**260**	221.5	15.1
242. 230	6	115	1985	2020	39	54	80	144	86.3	30.2
242. 231	7	115	1985	2020	60	70	104	180	102.1	28
242. 239	11	107	**1993**	2020	11	39.2	78	160	74.7	33.1
242. 317	new 4	58	**2005**	2020	32	35	40	50	40.7	5.1
242. 319	12	58	**2005**	2020	34	38	40	60	42.1	5.3
242. 320	new 10	58	**2005**	2020	26	30	40	52	39.7	7.7
242. 332	8	115	1985	2020	76	116	148	180	144.7	21.7
242. 44B_1	1	59	1985	**2006**	130	239	**280**	**320**	**271.3**	37.9
242. 44B_2	1	44	**2009**	2020	20	32	40	80	41.9	13.9
Marielyst Vandværk		115	1985	2020	40	105	124	186	126.5	26

Seven of the wells have been used in the entire period (1985 – 2020). Two (242. 190 and 242. 213) were used until 2005 and after that they were replaced by other two new wells (242. 317 and 242. 320) (Figure 10)

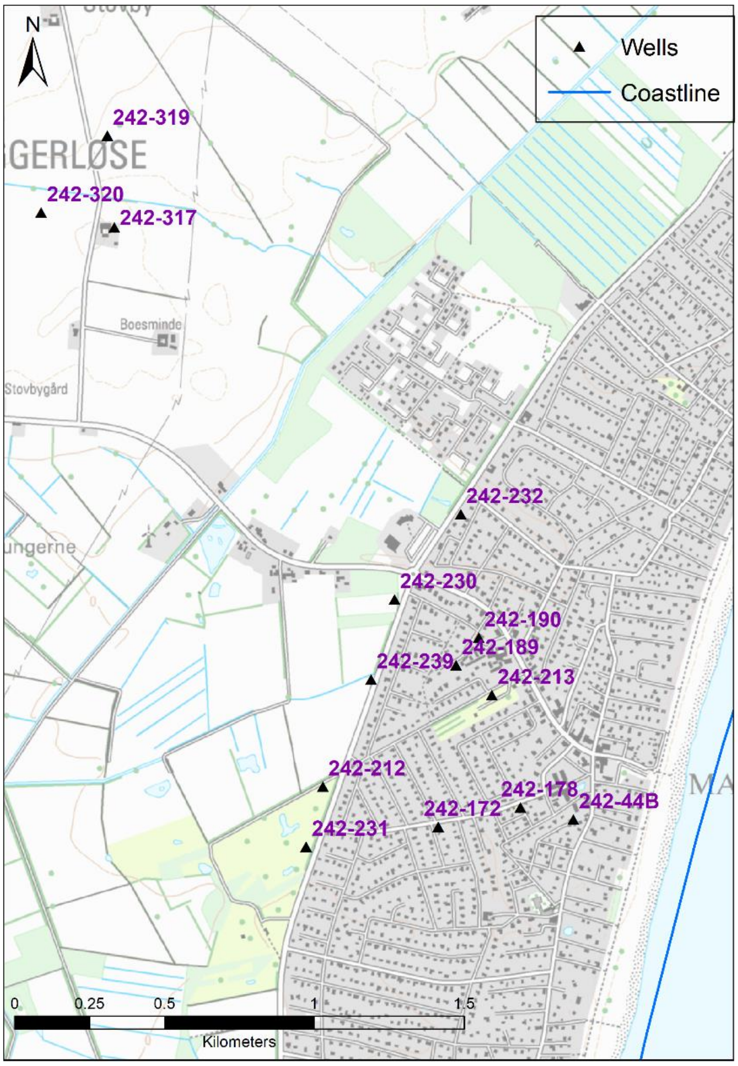


Fig. 10. Location of sampling wells

Well 242. 44B was re-established (deepened) in 26 Jan 2007, so the time-series have a gap from 2006 to 2009. The concentration before and after this intervention differ significantly, so in both Table 1 and Figure 11 those are shown separately and are treated as different sampling points. In the first period, the Cl concentrations were showing an increasing trend with concentrations exceeding the national TV of 250 mg/l, while after the intervention the median Cl concentration was 40 mg/l (max concentration 80 mg/l).

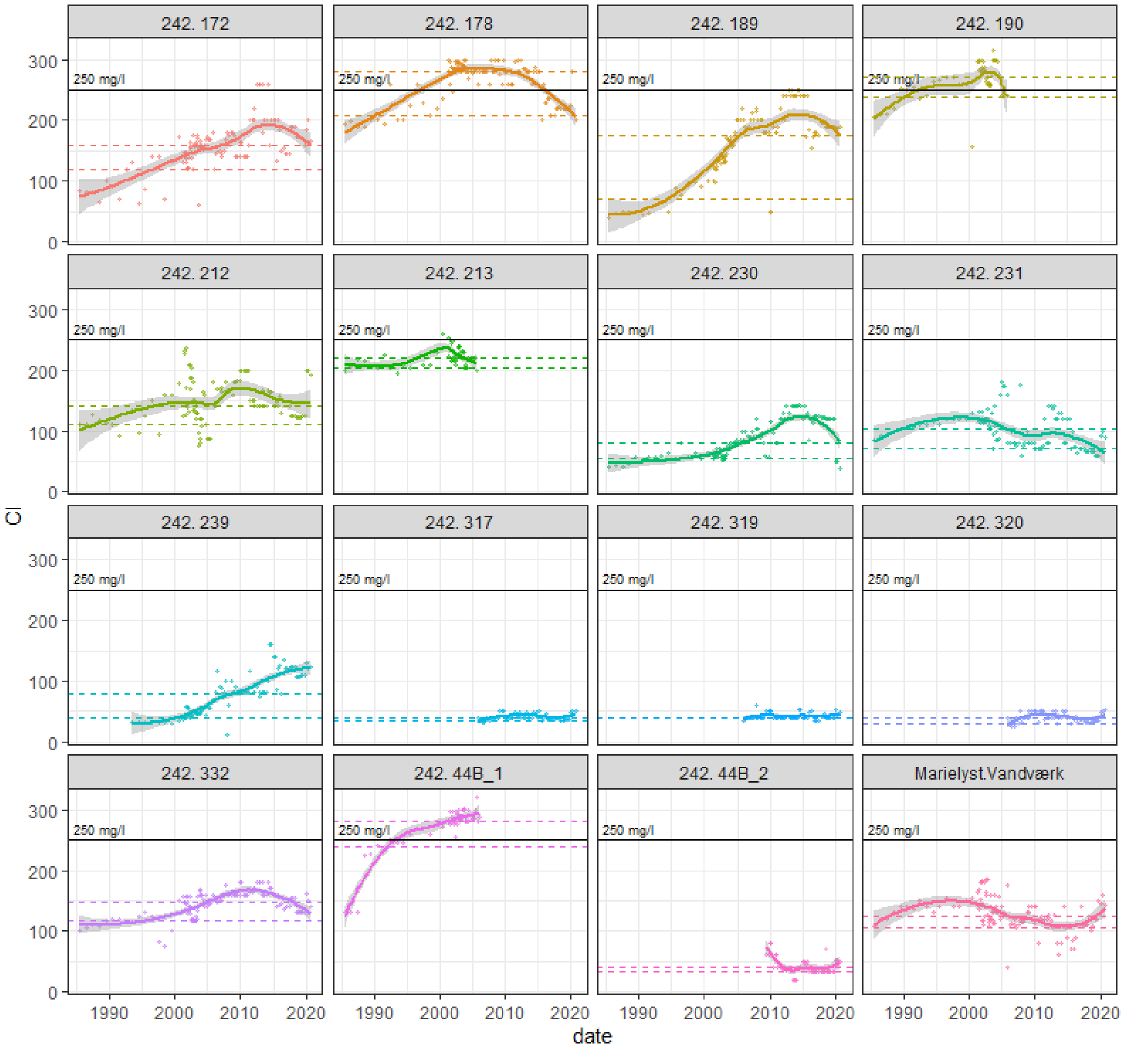


Fig. 11. Time-series of Cl concentrations (mg/l) (y-axis) in groundwater samples for the period1985-2020 at the abstraction wells of Marielyst Vandværk; Each measurement is visualized with a point, the trend is shown with a loess (local polynomial regression) and its 95% confidence interval. The DGU numbers of the abstraction wells are provided above each panel. The Marielyst Vandværk panel shows the Cl concentrations in the treated drinking water at exit waterworks. The national Threshold Value (250 mg/l) is drawn with a black horizontal line, while the representative value for each sampling point based on the 10th and 50th percentiles are shown with dashed lines; DGU n. 242.44B was re-established (deepened) in 26 Jan 2007, so the time-series are split for the two periods (before and after)

5.2.2 Natural background levels (NBLs) for Chloride based on time series data

In order to calculate NBLs (based on the 90th percentile), first a representative concentration level should be chosen for each sampling point. The representative concentration level for a specific period can be calculated based on different summary statistics. For example, in the River Basin Management Plan, the mean of the annual mean concentrations is used to account for the irregularity of the time-series, so each year is weighed equally. The mean is however very sensitive to outliers, so the median has been suggested by the BRIDGE method. In the recent work done in TACTIC, both the median (50th percentile, p50) and the 10th percentile were tested. Table 1 presents both p10 and p50 for each of the sampling points, both of which are considered here as "representative" levels. These sampling-point specific levels are also shown in Figure 11 together with the time-series and the national TV level.

The p10 representative level for all abstraction wells is below the national TV (250 mg/l). Two sampling points have high p10 (238-239 mg/l), but both of these are no longer in use (242. 190 was replaced, and 242. 44B was deepened).

The p50 representative level, however, is higher than the TV (250 mg/l) for:

- DGU n. 242. 178 (1985-2020), p50 is 280 mg/l and the max Cl concentration is 300 mg/l
- DGU n. 242. 190 (1985-2005), p50 is 270 mg/l and the max Cl concentration is 316 mg/l
- DGU n. 242. 44B (before intervention, 1985-2006), p50 is 280 mg/l and the max Cl is 320 mg/l

The NBL (90th percentile) calculated based on the abstraction wells of Marienlyst Vandværk (15 sampling points with data in the study period) are:

- 226 mg/l with p10 as a representative value
- 276 mg/l with p50 as a representative value (> national TV of 250 mg/l)

Both of these NBLs are higher than the NBL calculated for the carbonated aquifers on Sjælland as part of the River Basin Management Plan (157.2 mg/l). This could indicate that the Cl concentrations observed in these sampling points are influenced by saltwater intrusion due to groundwater abstraction. However, the time-series also show that for most of these sampling points there is a trend-reversal in the last 5-10 years. The new wells established after 2005 have generally low median Cl concentrations (40 mg/l), which could be considered as the natural background at this part of the aquifer.

It could be argued that in general p10 represents better the "natural" background at each of the sampling locations, because the medians at some of the sampling points are influenced by the increasing trends or the trend-reversals. Future work should include detrending of the time-series before estimating NBLs.

Even though the Cl concentrations at some of the abstraction wells of Marienlyst Vandværk are elevated, the drinking water produced at the waterworks has relatively low levels of Cl (median 124 mg/l) which has never exceeded the drinking water standard (250 mg/l) in the study period.

6 CLIMATE CHANGE ADAPTATION STRATEGIES

Saltwater intrusion in coastal aquifers is an increasing problem, and increasing sea levels increase the concern and need for protecting groundwater resources in coastal regions, globally. Hence, efficient adaptation strategies are of increasing importance for projection of the water supply of small cities as well as metropolis in coastal areas around the world. Managed aquifer recharge and other subsurface water solutions provides many options for protecting coastal freshwater resources and temporarily store water e.g. from wet winters to dry summers (Hinsby et al. 2015, 2016, 2018; Zuurbier et al., 2014, 2015, 2017). Sources of fresh water to be stored in groundwater reservoirs / aquifers include desalinized deep brackish groundwater (less energy demanding than seawater desalinization) and purified rain and drainage waters.

The Falster pilot area with its test site facilities for tracer test studies provide excellent opportunities for studying and analysing the efficiency and impact of temporarily storing different types of freshwaters in fractured carbonate aquifer to control salt water intrusion and protect groundwater resources in coastal regions. Studies of climate change impacts in the area (Rasmussen et al., 2013; Hinsby et al., 2018) indicate that such subsurface water solutions may be the only efficient way to protect groundwater resources in similar areas. Hence, such solutions should be more widely tested and optimized in coastal areas around the world.

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