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

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Geological Survey of Spain (IGME)

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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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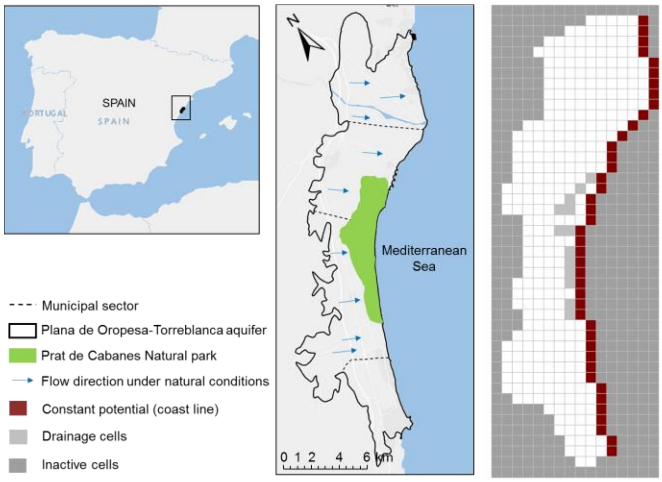
1 EXECUTIVE SUMMARY

Pilot name	Plana de Oropesa-Torreblanca	
Country	Spain	
EU-region	Mediterranean region	
Area (km^2)	89 km^2	
Aquifer geology and type classification	Coastal sedimentary plain (gravel and sand levels in a silty clay matrix). Porous aquifer.	
Primary water usage	Irrigation / Drinking water	
Main climate change issues	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.	
Models and methods used	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.	

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).

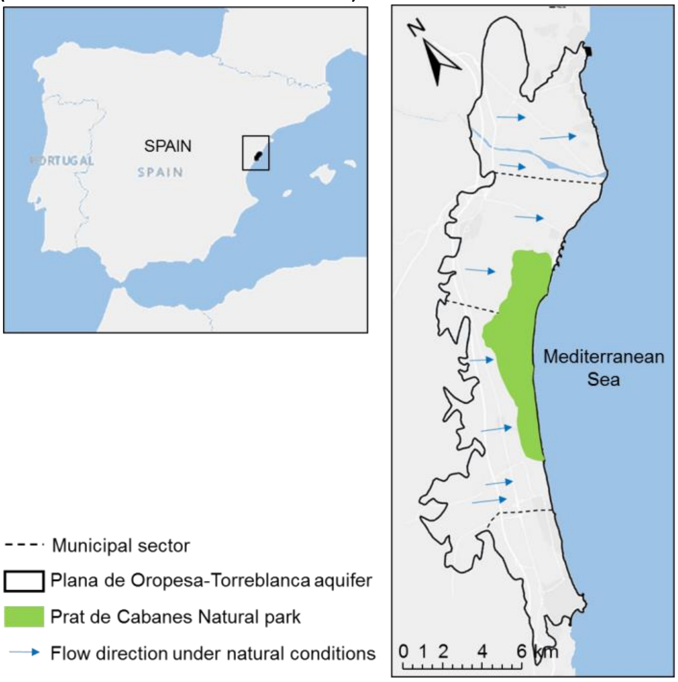


Fig. 1. Location of the pilot area

- 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 m^2/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.

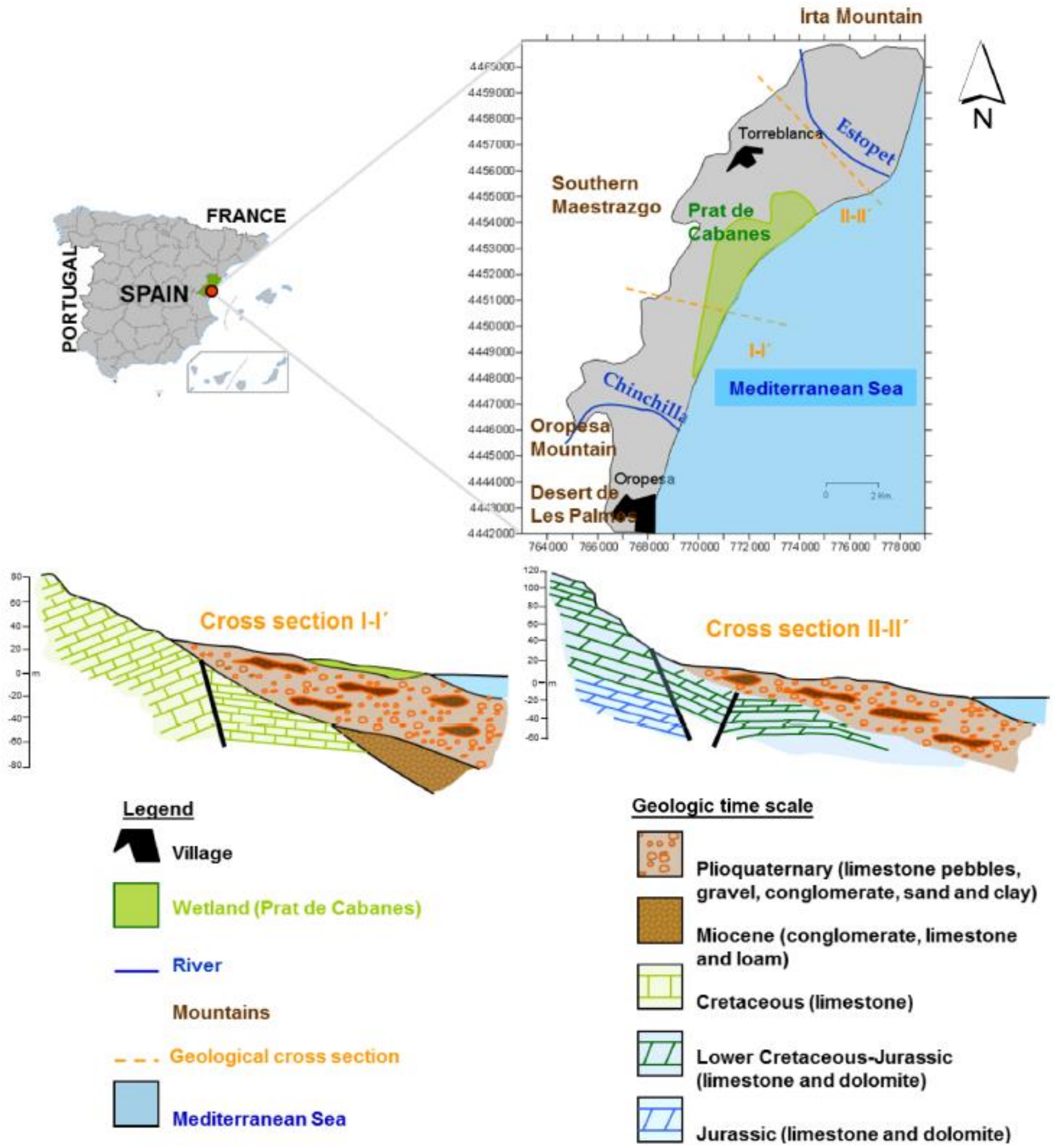


Fig. 2 Geological map and cross sections (Pulido-Velazquez et al. 2018)

- 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)

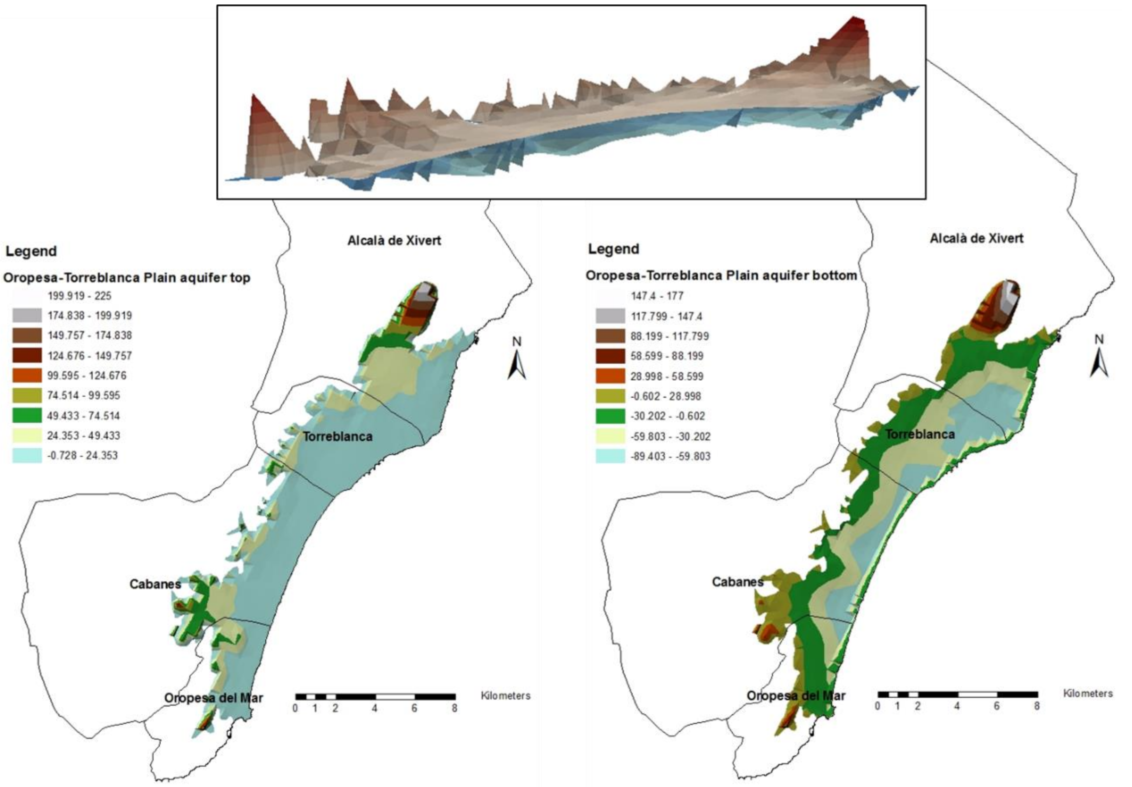


Fig. 3 Aquifer Geometry (top and bottom of the aquifer)

- ***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.

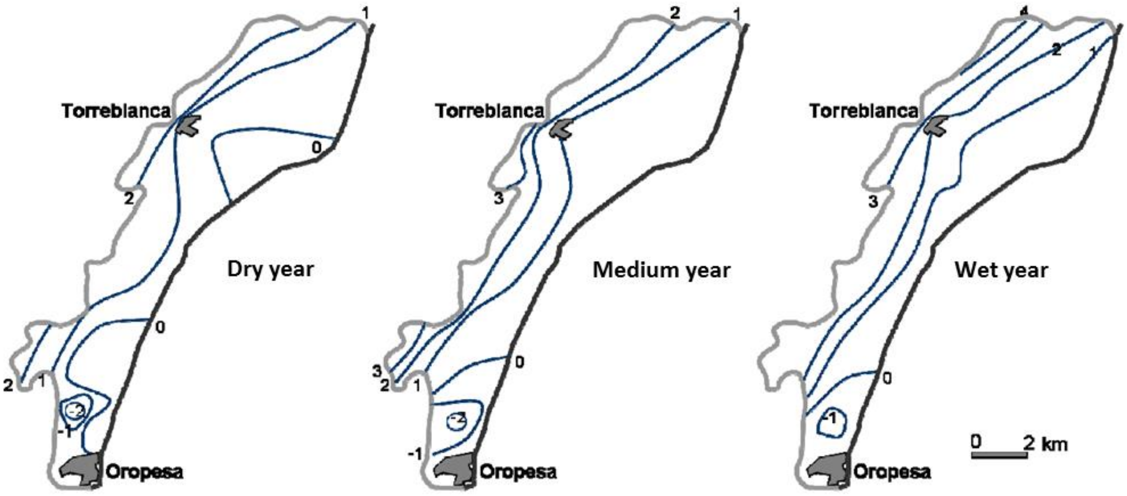


Fig. 4. Hydraulic head in dry, medium and wet years (modified from Renau-Pruñonosa 2013)

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

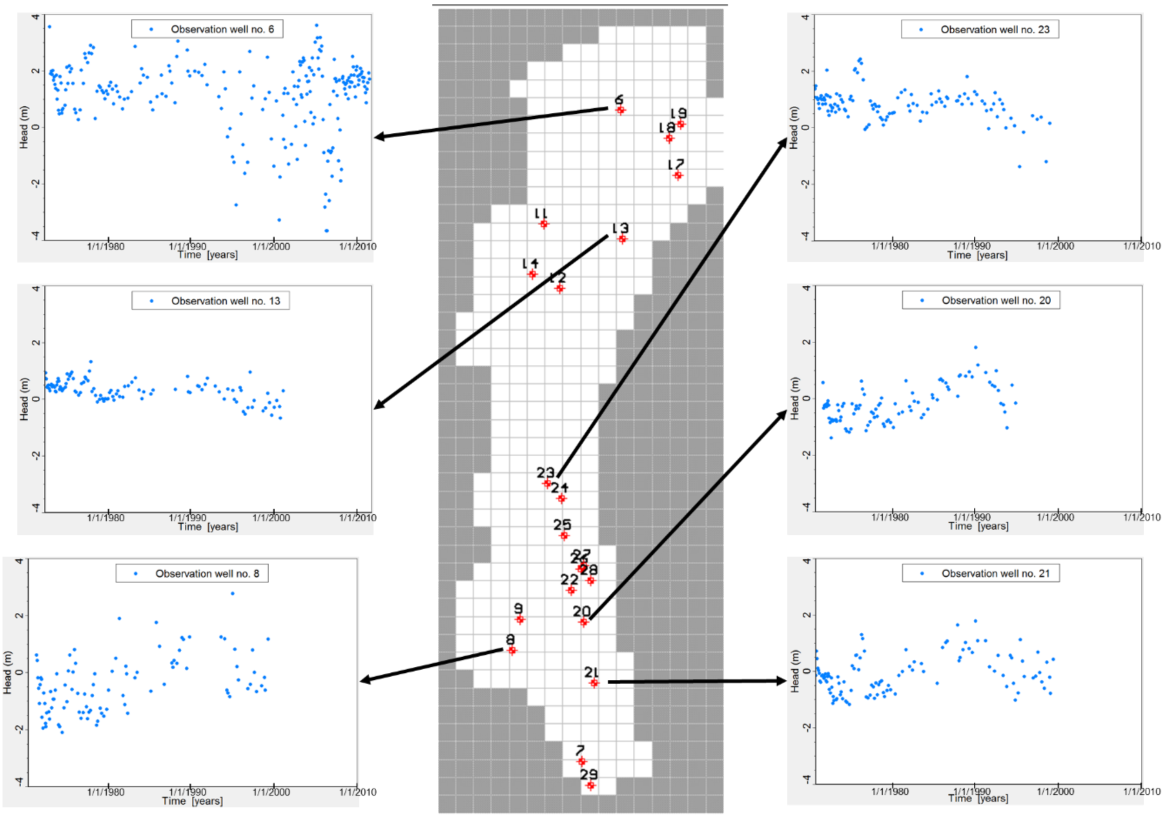


Fig. 5. Historical evolution of hydraulic head at some observation points

- ***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.

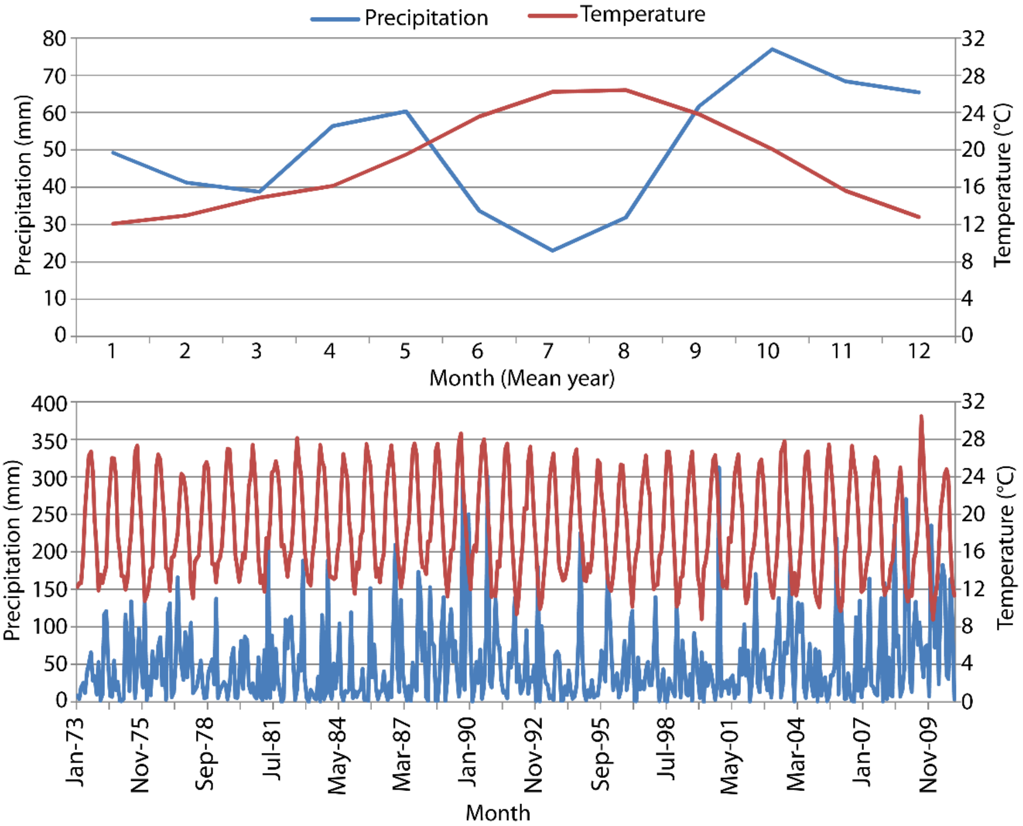


Fig. 6. Historical rainfall and temperature in Plana de Oropesa-Torreblanca aquifer (modified from Pulido-Velazquez et al. 2018)

- 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).

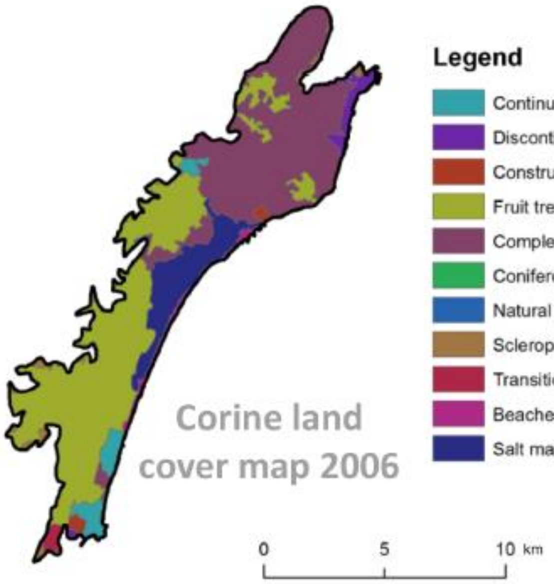


Fig. 7 CORINE Land use maps in 2006 (modified from Pulido-Velazquez et al. 2018)

- ***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.

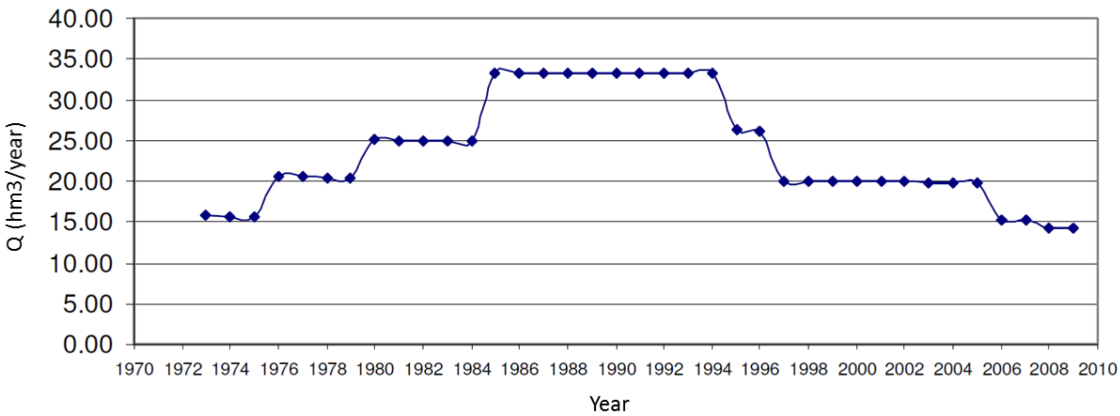


Fig. 8 Historical temporal evolution of pumping (Mm^3/y). (modified from Renau-Pruñonosa 2013)

- ***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.

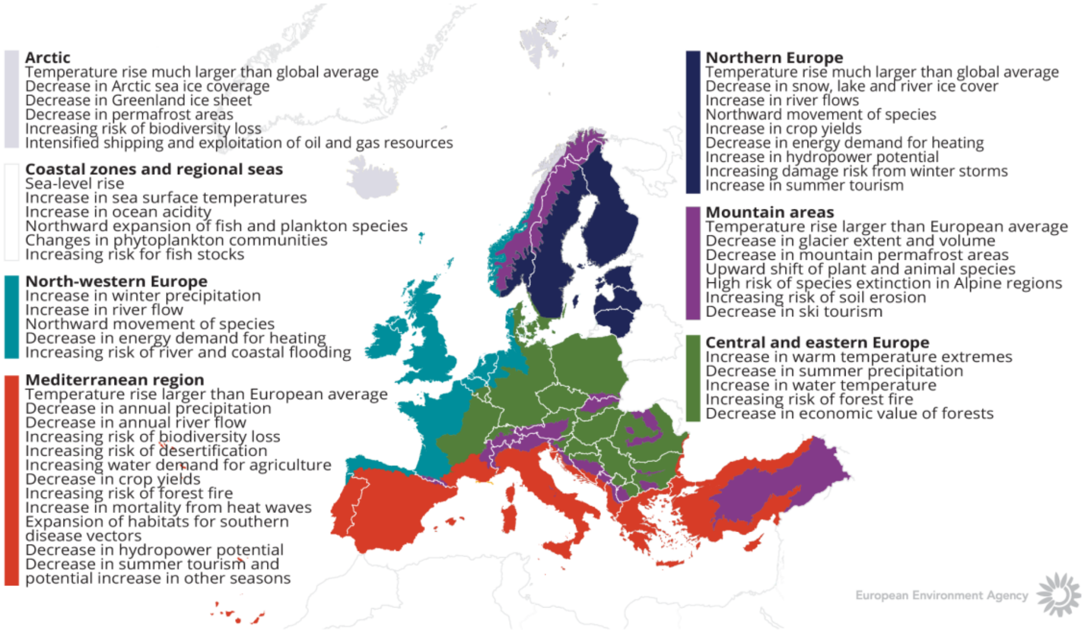


Figure 9. How is climate expected to change in Europe. The European Environment Agency map

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).

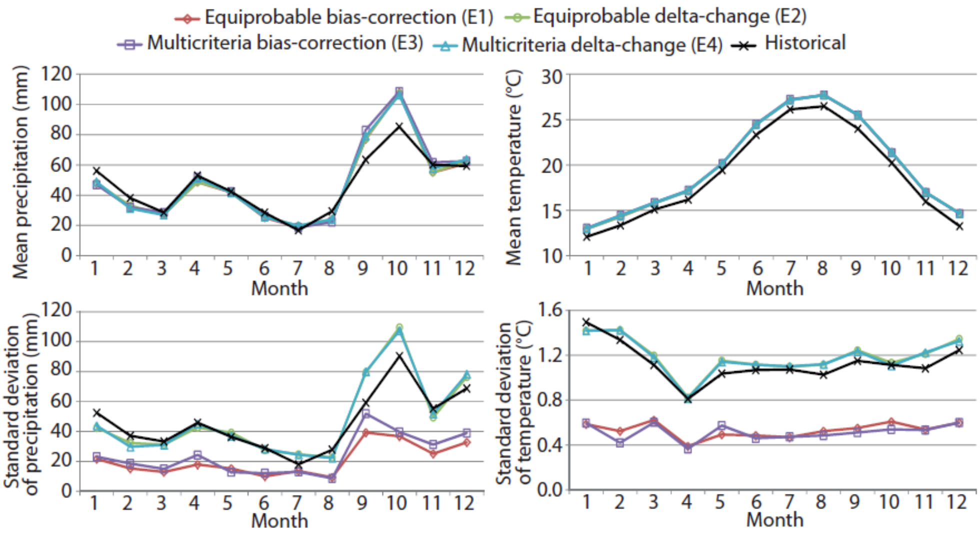


*Figure 10. Monthly mean and standard deviation of future temperature and precipitation for the f*our ensemble scenarios (taken from Pulido-Velazquez et al., 2018)

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).

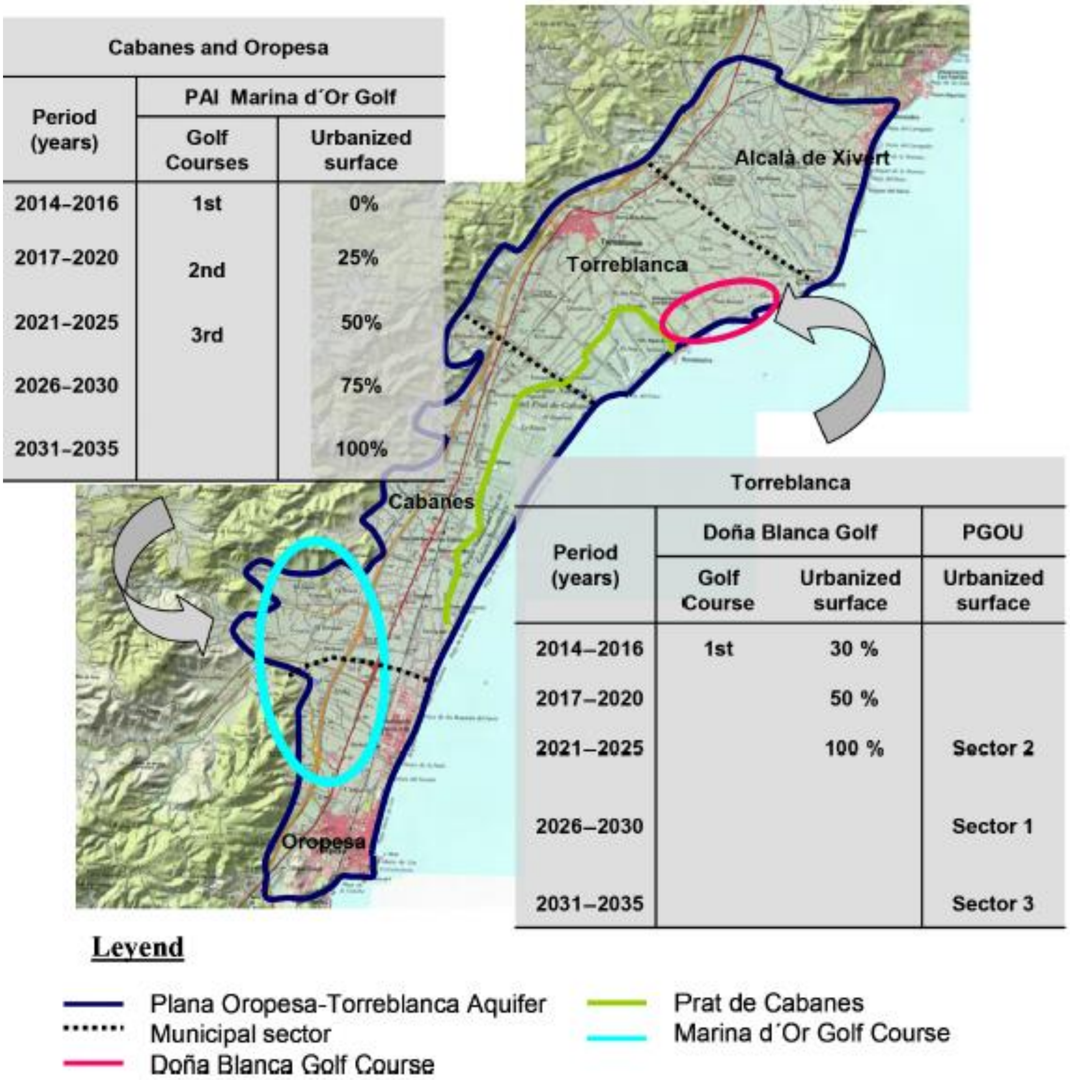


Figure 11. Future land use scenarios in 2035. (taken from Pulido-Velazquez et al., 2018)

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).

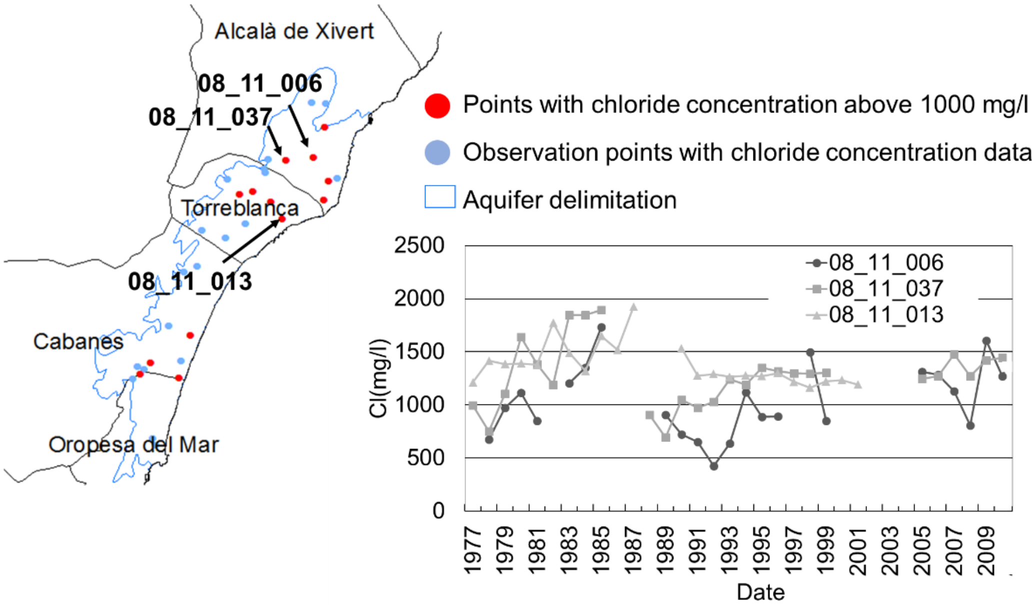


Figure 12 Location of the observation points in Plana de Oropesa-Torreblanca and evolution of the chloride concentrations in monitoring points (modified from Baena-Ruiz et al., 2018)

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).

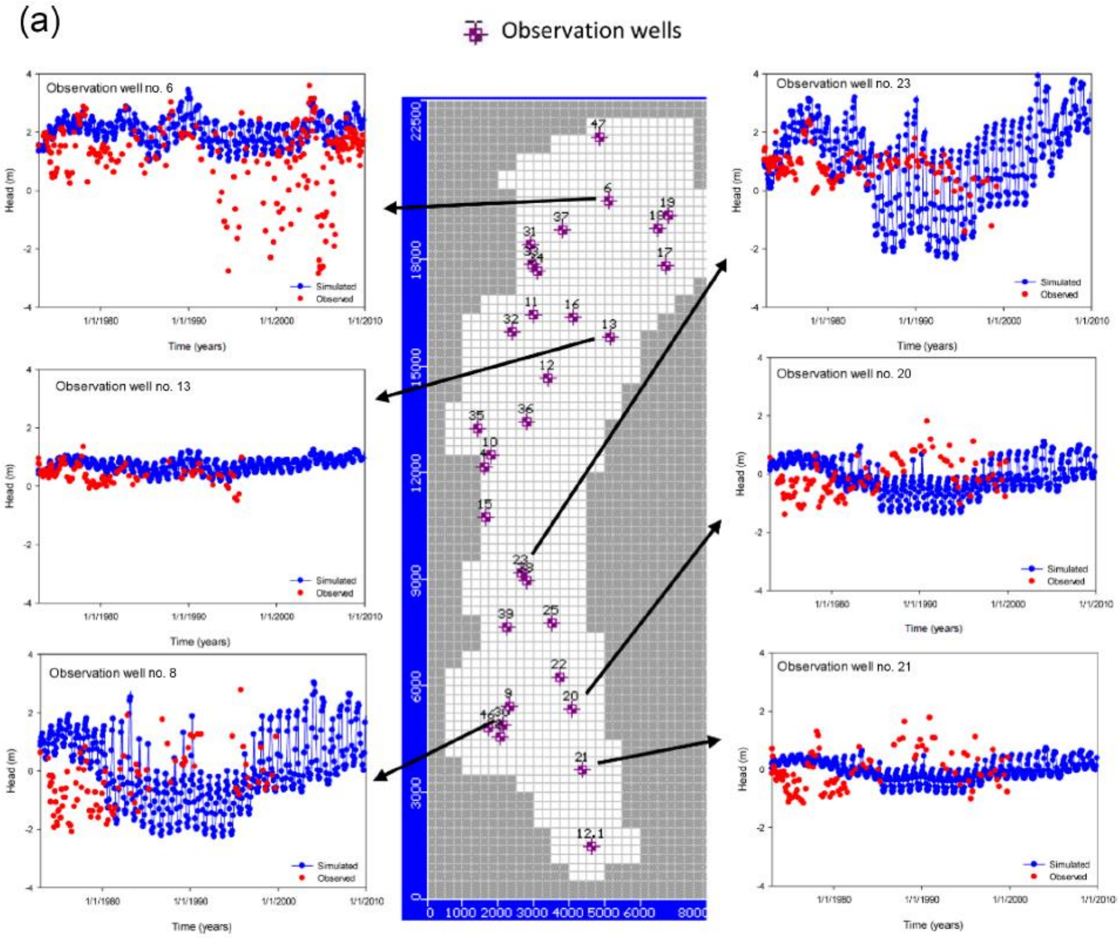
The chain of models were employed to assess the information required by the proposed **method/tool (Deliverable 5.2) in order to assess and summarize the status and vulnerability** to SWI through visual pictures and time series. The **inputs** of this method have been taken from the outputs and data 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.



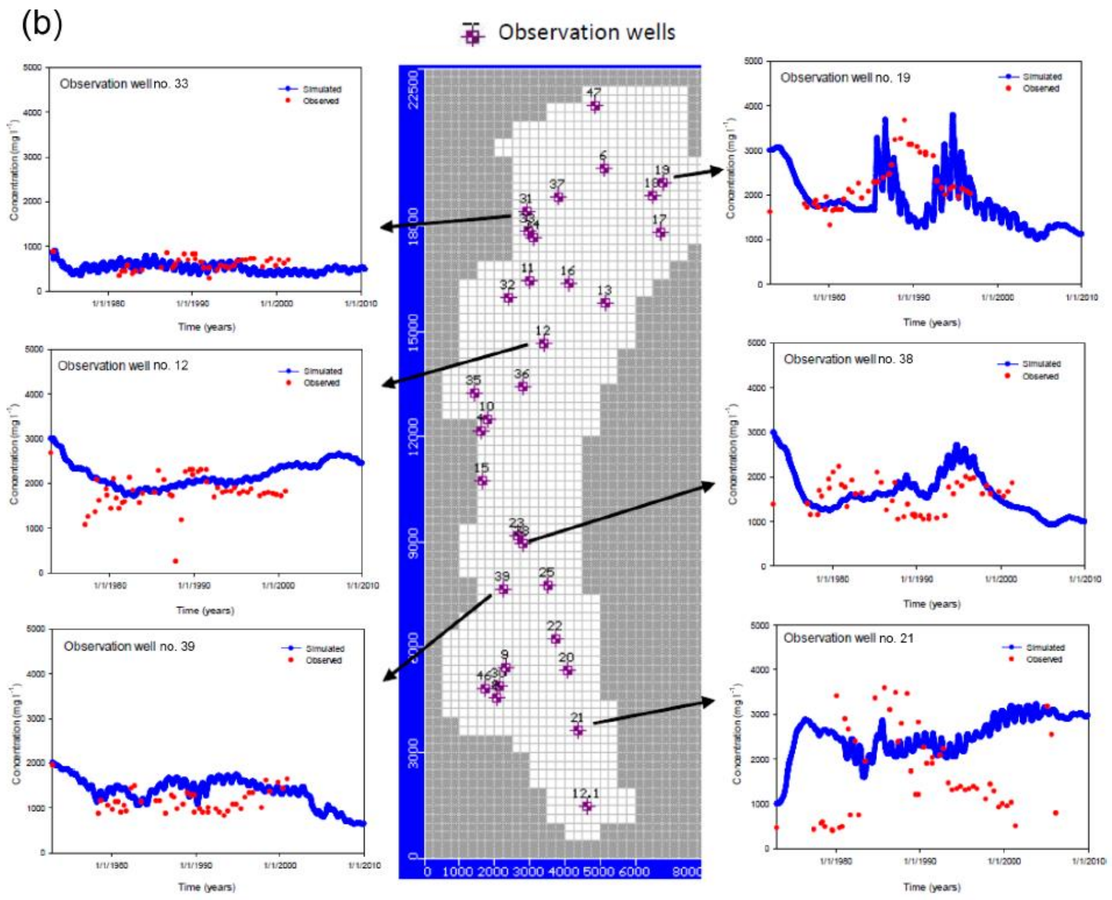


Figure 13. (a) Hydraulic head obtained with the models vs. data at some observation points. (b) Salinity obtained with the models vs. Data at some observation points. (Figure taken from Pulido-Velazquez et al., 2018)

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.

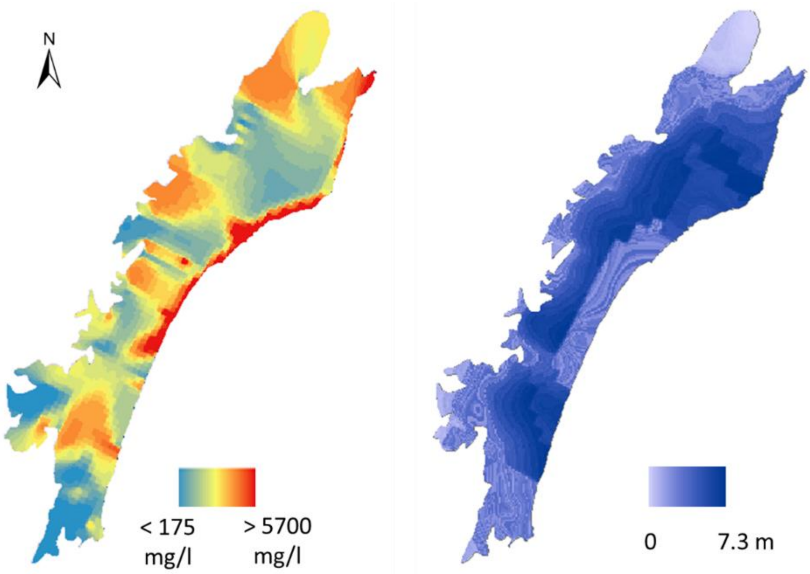


Figure 14. Historical maps of chloride concentration (left) and groundwater resources (right) (October 1985)

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.

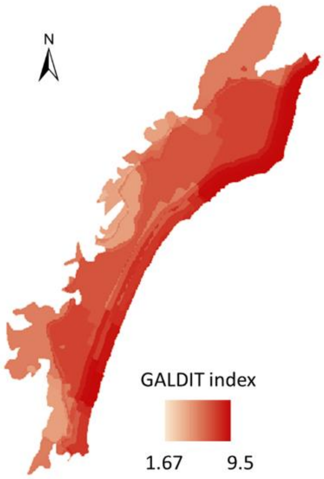


Figure 15 Historical maps of vulnerability (October 1985)

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.

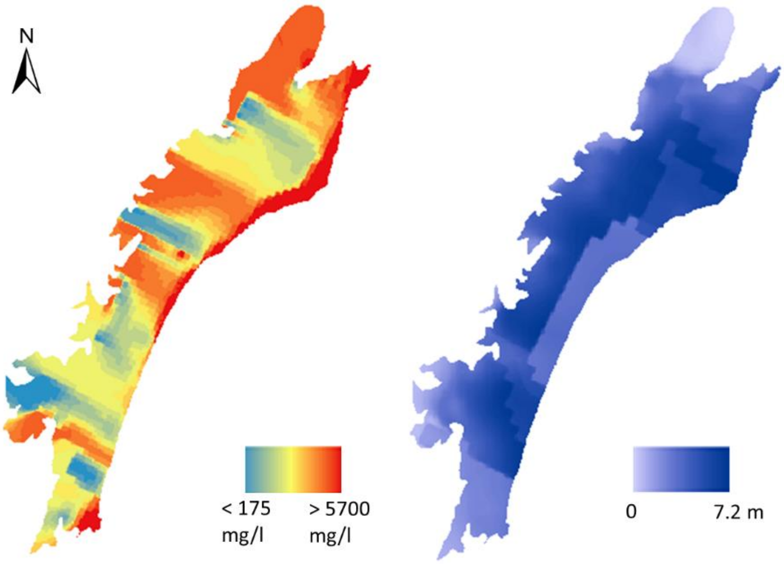


Figure 16. Maps of potential future chloride concentration and groundwater resources for the simulated scenario GC4 (September 2027)

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.

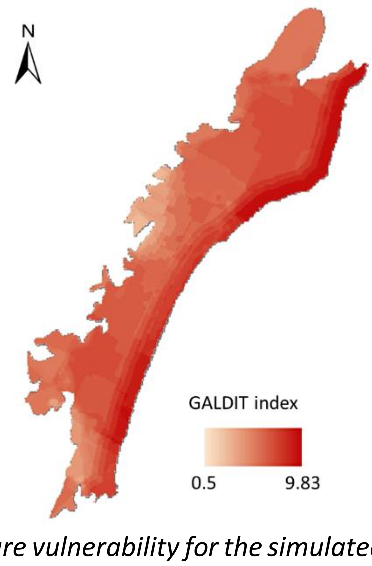


Figure 17 Maps of potential future vulnerability for the simulated scenario GC4 (September 2027)

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.

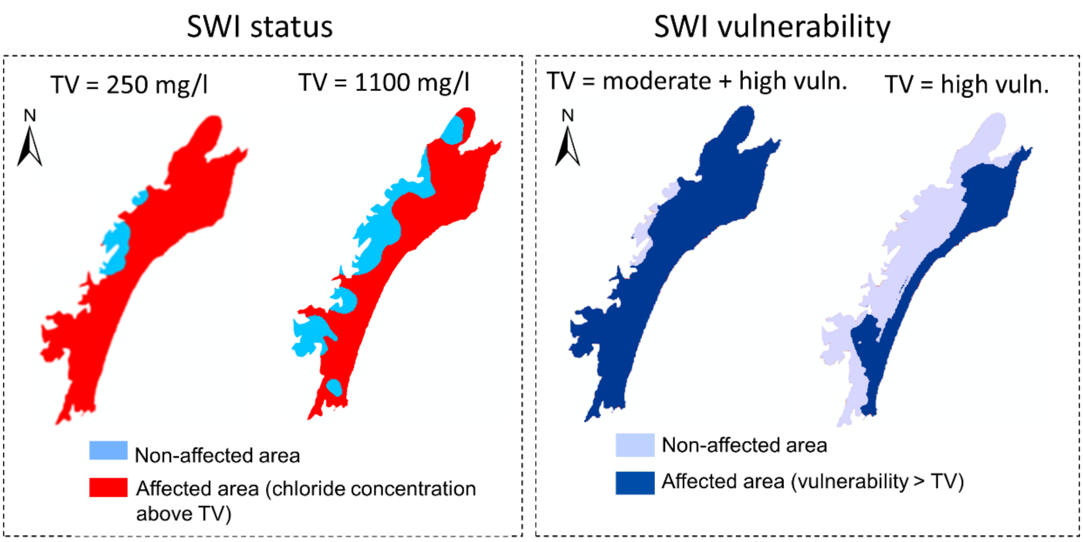


Figure 18. Maps of historical SWI status and vulnerability "affected volumes" (October 1985)

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.

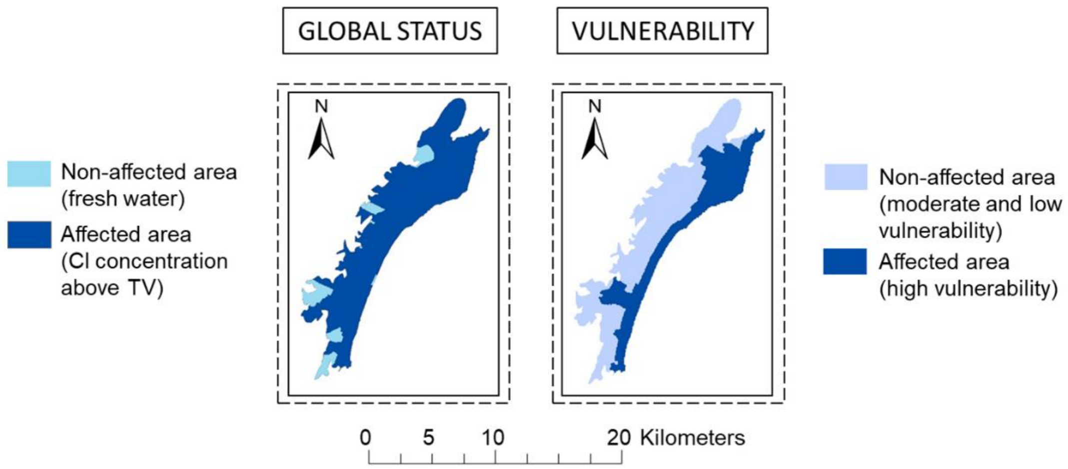


Figure 19. Maps of potential future SWI status and vulnerability "affected volumes" for the GC4 simulated scenario (September 2027)

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.

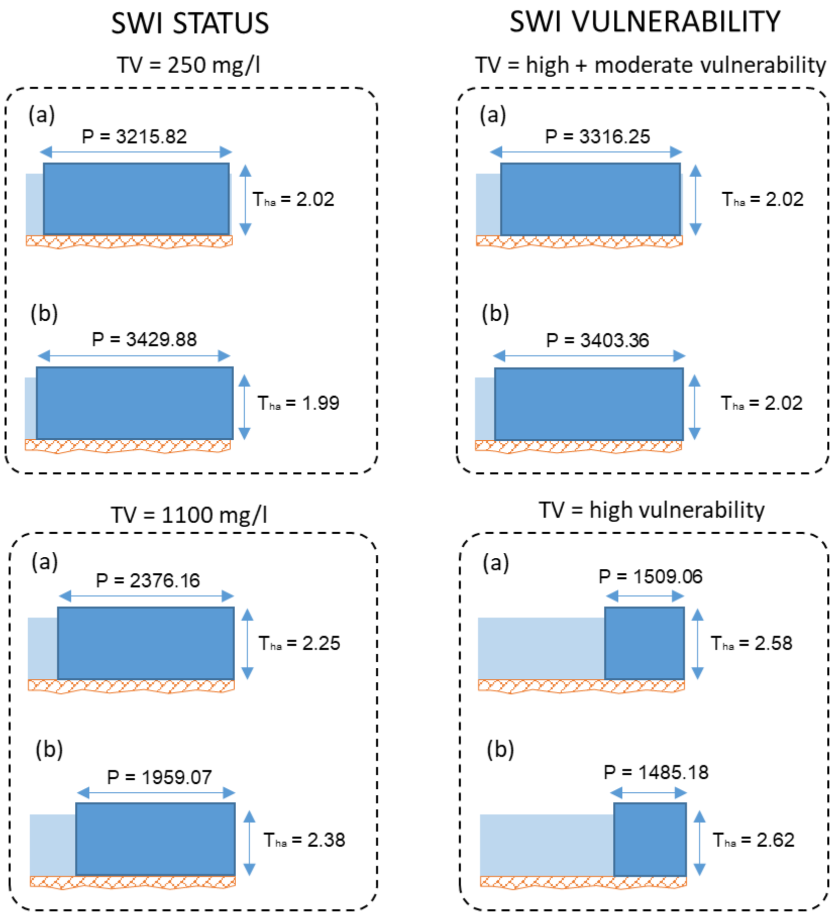


Figure 20. 2D conceptual cross-sections. Historical results in October 1985 (a) and mean values for the period 1973-2010 (b) (units in m)

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).

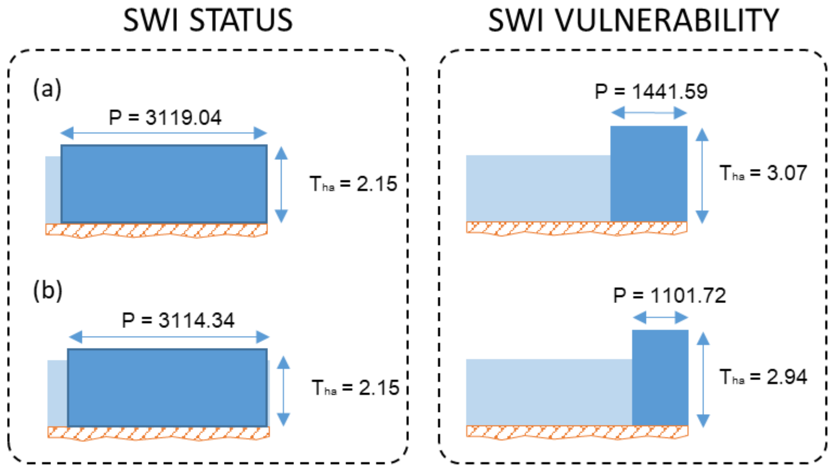


Figure 21. 2D conceptual cross-sections. Potential Future Results for the simulated scenario GC4 in September 2027 (a) and mean values for the period 2011-2035 (b) (units in m)

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).

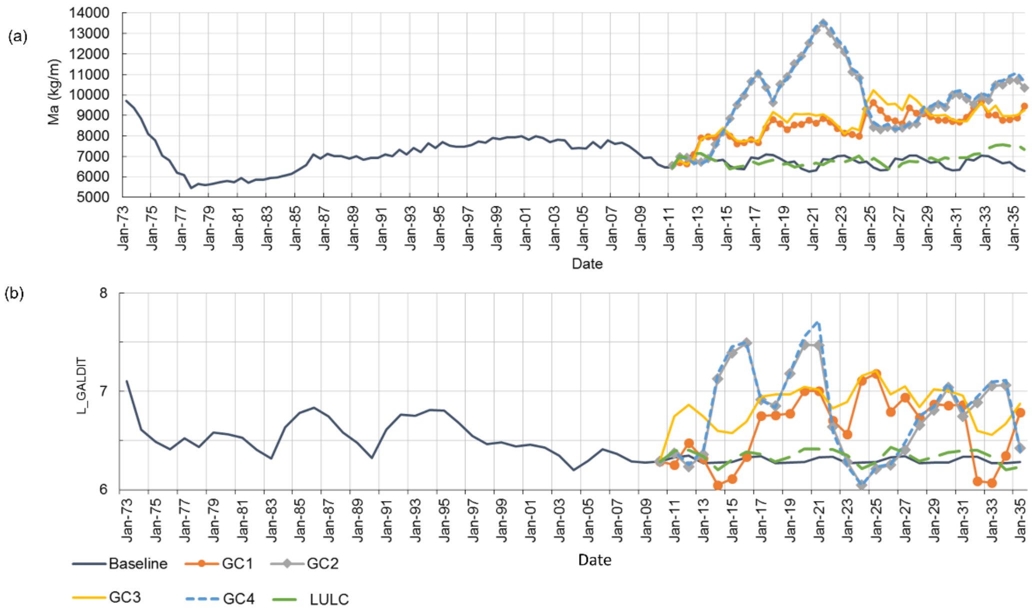


Figure 22. Time series of the indices Ma and L-GALDIT in the historical (1973-2010) and potential future results for the simulated scenarios in the horizon 2011-2035 (modified from Baena-Ruiz et al., 2020).

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).

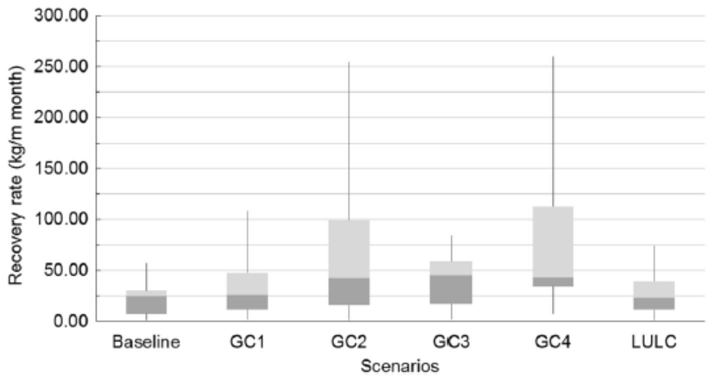


Figure 23. Statistics of recovery rate for all scenarios analyzed in the simulated scenarios in the horizon 2011-2035.

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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