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Integrated assessment of future potential global change scenarios and their hydrological impacts in coastal aquifers. A new tool to analyse management alternatives under uncertainty in the Plana Oropesa-Torreblanca aquifer.

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Abstract. Any change in the components of the water balance in a coastal aquifer, whether natural or anthropogenic, can alter the fresh water-salt water equilibrium. In this sense Climate change (CC) and Land Use and Land Cover (LULC) change might significantly influence the availability of groundwater resources in the future. These coastal systems demand an integrated analysis of quantity and quality issues to obtain an appropriate assessment of hydrological impacts using density-dependent flow solutions. The aim of this work is to perform an integrated analysis of future potential global change scenarios and their hydrological impacts in a coastal aquifer, the Plana Oropesa-Torreblanca aquifer. It is a Mediterranean aquifer that extends over a 75 Km2 in which important historical LULC changes have been produced and are planned for the future. Future CC scenarios will be defined by using equi-feasible and non- feasible ensemble of projections based on the results of a multi-criteria analysis of the series generated from several Regional Climatic Models with different downscaling approaches. The hydrological impacts of these CC scenarios combined with future LULC scenarios will be assessed with a chain of models defined by a sequential coupling of rainfall-recharge models, crop irrigations requirements and irrigation returns models (for the aquifer and its neighbours that feeds it), and a density dependent aquifer approach. This chain of models, calibrated using the available historical data, allow testing the conceptual approximation of the aquifer behaviour. They are also fed with series representatives of potential GC scenarios in order to perform a sensitivity analysis regarding future scenarios of rainfall recharge, lateral flows of the hydraulically-connected neighbouring aquifer, agricultural recharge (taking into account expected future LULC changes) and Sea Level Rise (SLR). The proposed analysis is valuable to improve our knowledge about the aquifer and so comprise a tool to design sustainable adaptation management strategies taking into account the uncertainty in future global change conditions and their impacts. The results show that CC and LULC scenarios produce significant increase in the variability of flow budget components and in the chloride salinity concentration. They also show a low sensitivity to the SLR scenarios, especially in terms of hydraulic head.

1. Introduction

Certain coastal regions simultaneously suffer scarce surface water resources and significant water demand. As a result, the reliability of supplying the demand depends on groundwater resources, which therefore play an important role in the management of these systems (Sola et al., 2013; Renau et al., 2016). The analysis of coastal aquifer management problems is an important and complex issue in which water quantity and quality have to be considered together to predict the salinization process, which depend on aquifer stratigraphy and other hydrodynamic factors (precipitation regime, tides, wave setup and storm surges, etc.) (Vallejos et al., 2015). Due to the interaction between freshwater and seawater, coastal aquifers have important hydrodynamic and hydrogeochemical peculiarities (Custodio, 2010). Any change in the components of the water balance can modify the fresh water-salt water equilibrium that defines the seawater intrusion processes (Yechieli and Sivan, 2011; Arslan and Demir, 2013). In the future, the difficulty of meeting demand in coastal systems will increase due to the impact of GC, which will reduce freshwater recharge, raise sea level and increase irrigation demand (Fujinawa, 2011; Unsal et al., 2014). Therefore, GC impacts will challenge the current water supply management of coastal aquifer (Rasmussen et al., 2013).

In recent years the number of studies of CC impacts focus on aquifers has grown fast (Green et al., 2011; Molina et al., 2013). A few of these also studied quality impacts, though groundwater quality can be affected by GC in many different ways (Pulido-Velazquez et al., 2014; Dragoni and Sukhija, 2008). Even fewer research papers have been published on the impacts of GC on coastal aquifers (Yechieli et al., 2010). Though coastal aquifers warrant greater attention since they are more vulnerable to GC (due to their connection with the sea and the interaction between fresh water and seawater) they have not been extensively studied (Rasmussen et al., 2013). To assess the salinization process and possible adaptation strategies properly, coastal aquifers require that water quantity and quality issues are analysed in an integrated way.

In order to analyse the potential impacts of future scenarios of CC on any hydrological system, we need to generate time series of climate variables and to feed previously calibrated hydrological models with them.

In coastal aquifers there is another important issue that needs to be considered when analysing CC impacts, namely any change in sea level (Ketabchi et al., 2016;). A number of authors have studied the impacts of SLR in various coastal aquifers. Chan et al. (2011) showed that in a synthetic confined coastal aquifer in which recharge in unchanged there is no long-term impact on seawater intrusion. Werner and Simmons (2009) showed that in unconfined aquifers the influence of the inland boundary condition can be significant to its sensitivity to SLR. Rasmussen et al. (2013) analysed an inland coastal aquifer and found that minor SLRs did not seem to affect seawater intrusion as much. There are also reports by the IPCC (Church et al., 2013) and the European Environment Agency (EAA 2014), which focus on the analysis of historical and potential future SLR scenarios.

In addition, urban and agricultural development forces appropriate management rules to be applied if groundwater resources under different LULC scenarios are to be exploited sustainably (Robins et al., 1999; Grundmann et al., 2012;). A certain degree of overpumping usually occurs in Mediterranean coastal aquifers, particularly in summer, which encourages salinization processes (Rosenthal et al., 1992). This could be exacerbated by the future LULC scenarios.

Few studies have been published that analyse global change in an integrated way –along with its impacts on future LULC change scenarios – to produce an overall analysis of GC (e.g., Pulido-Velazquez et al., 2014; Guo et al., 2015); some address cases of coastal aquifers (Benini et al., 2016; Gorelick and Zheng, 2015).

From a methodological point of view, the study of the impacts of potential GC on groundwater using an integrated and holistic climatic-agronomical-hydrological model that includes water quantity and quality continues to be a big challenge. From an operational point of view, research aimed at solving these problems has focussed on sequential coupling of models. The assessment of these impacts requires models that can predict the evolution of the fresh water-salt water interface. In order to obtain an accurate representation of the physical process involved in saltwater intrusion, flow and transport need to be coupled and solved simultaneously for each time step. Such an approach gives density-dependent solutions (e.g., Shammas and Thunvik, 2009; Doulgeris and Zissis, 2014) that take the salinization process into account. Simplified sharp interface models would provide a less accurate approach with a fewer number of parameters and lower computational requirements (e.g., Llopis-Albert and Pulido-Velazquez, 2014, 2015).

The objective of this work is to perform an integrated analysis of future potential global change scenarios (including CC, LULC change and SLR) and their hydrological impacts in a coastal aquifer, the Plana Oropesa-Torreblanca aquifer. We simultaneously consider water quantity and quality in order to approach the salinization process. Section 2 describes the aquifer and the available data, while Section 3 presents the methodology. We propose a method to analyse and generate potential future global change scenarios involving different sources of uncertainty (Section 3.1). An integrated modelling framework is defined to assess hydrological impacts on the coastal aquifer based on a sequential coupling of rainfall-recharge models, crop irrigations requirements and irrigation-return models, and a density-dependent solution that couples the resolution of flow and transport calculations for each time step (Section 3.2). Section 4 presents the results and their discussion. It includes an analysis of the sensitivity to potential future changes in rainfall recharge, LULC and sea level. We consider the limitations of this study and propose future research. Lastly, Section 5 presents the main conclusions of this research.

2. Materials: Description of the aquifer and the data available

2.1 Location and hydrogeology

The Plana Oropesa-Torreblanca is a shallow heterogeneous detrital aquifer that extends over approximately 75 km^2. It is oriented NE-SW, parallel to the Mediterranean coast, with a length of 21 Km and a width of between 2.5 and 6 Km. The ground surface over the aquifer comprises a gentle relief, steepening towards the surrounding limestone massifs (Figure 1).
Geographically, the Plana Oropesa-Torreblanca aquifer borders the Irta Mountain to the north (Cretaceous-Jurassic limestone), which is in hydraulic connection with the Plana. To its south lie the Oropesa Mountains (Cretaceous limestone). The western border (southern Maestrazgo) is formed by the Aptian and Gargasian limestone massif, which is in hydraulic connection with the Plana Oropesa-Torreblanca aquifer (except in the immediate vicinity of the Chinchilla and Estopet rivers where the impermeable Miocene base appears; Morell and Giménez, 1997; Renau-Pruñonosa et al., 2016).
The Plana Oropesa-Torreblanca is composed of 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 of facies and the overall distribution is irregular. The aquifer is overlain by more recent alluvial fans, colluviums, dunes and peatlands. Its geometry is lenticular – it is thinnest in the interior and thickest near the coast, exceeding 80 metres at the mouths of the Estopet and Chinchilla rivers. Several studies have demonstrated how the transmissivity of the aquifer varies over a wide range: from 5000 m^2/day to 100 m^2/day; the calculated effective porosity varies from 2% to 12% with the highest porosity nearest to the coastline. Inflows to the system consist of lateral groundwater transfers from adjacent aquifers, infiltration from precipitation and irrigation returns. Outflows comprise the pumped abstractions, together with groundwater discharges to sea and seeps/springs in the Prat de Cabanes wetland. Under natural conditions, groundwater flows NW-SE, perpendicular to the coastline (Morell and Giménez, 1997; Renau-Pruñonosa et al., 2016).
The Prat de Cabanes is a wetland located in the centre of the Plana. It extends approximately 9 km2, parallel to the coastline with an elongated shape. It is separated from the sea by a coastal bar some 8 km long, 20 m wide and 3 m high, consisting of sorted pebbles. It is composed of brown and black silt and loam, with a recognized peat level some 3 to 4 metres thick, which is commercially exploited.

2.2 Historical LULC changes and climatic-hydrological data

In the 1960s and early 1970s the Oropesa-Torreblanca Plain was sparsely populated and land was dedicated mostly to non-irrigated cropping. From 1975-1995 there was a significant transformation from dry to irrigated lands, especially in the period 1985-1995. From 1995 to 2010, marked changes occurred in LULC, with a generalised overhaul of the irrigation systems used and a conversion from agricultural to residential LULC, particularly along the coastal belt (Oropesa del Mar, Amplaries and Torre la Sal).

The following historical data for the period 1973-2010 were used to define the inputs of the integrated modelling framework described in Section 3:

1) Changes in LULC (Figure 2), 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 irrigation returns, following the procedure described in Section 3.1.2.

A comparison of the land cover maps for 1990 and 2006 shows that the main change in LULC classes was an increase (+227%; from 182 ha in 1996 to 592 ha in 2006) of artificial surfaces (transport infrastructure, urban sprawl, tourism and recreation facilities), mainly at the expense of agricultural areas (-5.5 %; from 7420 ha in 1996 to 7015 ha in 2006). According to the Júcar River Basin Management Plan (CHJ, 2015), the percentage LULC for major crops are: citrus fruits 72.4%, vines 12.9%, outdoor vegetables 7.9% and others 6.8%. As for irrigation techniques, drip irrigation supplies 65.5% of the total irrigated area, flood irrigation provides 34% and spray irrigation provides 0.5%, with an overall irrigation efficiency of 60.1%.

2) Historical rainfall and temperature for the Plana Oropesa-Torreblanca and Maestrazgo aquifers (See Figure 3) were taken from the Spain02 project dataset (Herrera et al., 2016). They were used to estimate rainfall-recharge (see Section 3.1.1.)

3) Historical evolution of total pumping in the Plana Oropesa-Torreblanca aquifer was deduced from historical data.

   The transformation from dry to irrigated croplands led to an increase in pumped abstractions that extended over two 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.

   A graphical representation of this series is included in Figure 9 in Section 3.1.3 (density-dependent flow model).

Other hydrological information used to calibrate the models are:

1) An infiltration rate coefficient of 14% for the historical period, which was obtained from previous lysimiter readings from a neighbouring aquifer (Plana de Castellón; Tuñon, 2000). The mean historical recharge (85 mm/year) obtained from this infiltration rate coefficient is quite similar to the mean (89 mm/year) estimated by other authors who applied an atmospheric chloride mass balance (Alcalá and Custodio, 2014).

2) Hydraulic heads and concentrations in different observation wells.

The available observation network (21 points of hydraulic head and 31 points for chloride concentration) yielded good distributed information on aquifer state from both, quantitative and qualitative points of view. The location of the observation wells and the evolution of the variables at some of these points are represented in Figure 8 in Section 3.1.3 (density-dependent flow model). We have used the information available for the period 1973-2010.

2.3 Future LULC change scenarios

The predicted future changes in LULC over the Plana Oropesa-Torreblanca are of greater magnitude and could drastically modify the rural and urban landscape. 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 create different water demands to the present ones, which could mean substantial changes to 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.

The General Town Plan for Torreblanca (PGOU Torreblanca, 2009) approves the conversion of 70% of the municipality's area included in the plan, which is currently used for citrus agriculture, into land classified as buildable residential or

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industrial. Even along the coast, to the north of Prat de Cabanes, is the projected urbanisation – included in the so-called 'Integrated Activity Plan' (PAI) – of Doña Blanca Golf (Figure 4).

The municipalities of Cabanes and Oropesa in the southern inland part of the Plana de Oropesa-Torreblanca have approved PAIs for the Marina d´Or Golf, which will include three golf courses, private residential developments, hotel complexes and associated garden areas. Once all these planned constructions are completed, they will cover some 16 Km^2 (Figure 4). Two of the conditions that the Valencian Government imposed before it approved the PAI Marina D´Or Golf are that the whole of the area that requires irrigation (both golf course and garden areas) must use recycled residential water from the wastewater treatment works; and that all water destined for urban supply must be sourced from a desalination plant. Thus, as the various individual projects are built, the groundwater abstractions in the area are falling, until they will cease completely at the end of the PAI development period.

Over the neighbouring Maestrazgo aquifer, we will assume that there are no changes in LULC.

2.4 Climate model simulation data. Control and future scenarios.

In this work we have focused on the information available for the most pessimistic emission scenario (RCP8.5) We analyse the information coming from EU CORDEX project (2013), where we find nine climate-change scenarios (see Table 1) defined with the simulations (control and future series) obtained with five Regional Climate Models (CCLM4-8-17, RCA4, HIRHAM5, RACMO22E and WRF331F) nested with some GCMs (4 GCM were available).

We have obtained representative lumped series of these simulations for our system, by weighting the values in each CORDEX cell according to its surface in the domain. In Figure 5 shows a significant bias between the historical data and the control simulation that will forces us to apply a correction technique to generate future scenarios (see Section 3.2).

In Figure 6 we also observe important differences between the statistic of future (2011-2035) and control (1976-2000) series (rainfall and temperature) for each RCM.

2.5 Sea Level Rise (SLR) scenarios

Based on the European Environment Agency analysis (EAA 2014) of historical and potential future SLRs, we propose a SLR scenario to study the sensitivity of our GC simulations to a potential SLR. The EAA report states that, over the last two decades, satellite measurements have indicated a mean rate of SLR of more than 3.2 mm/year. If we assume that this rate remains constant then, by the end of a future horizon of 25 years, we would have a rise in sea level of 0.08 m. On the other hand, model simulations for the RCP8.5 emission scenario show a rise in sea level for 2081-2100 in the range 0.45-0.81 m. If we assume a constant rate of SLR from now until 2100, the sea level would rise a maximum of 0.19 m (more than double the observed rate over the last two decades). This value (a rise of 0.19 m by the end of the future horizon) was used to define a very pessimistic scenario of maximum SLR. A linear SLR was considered during the future horizon (2011-2035).

3. Methods

The flowchart of the method has been represented in Figure 1. It summaries the steps that we propose to follow in order to perform an integrated assessment of potential scenarios of climate and land use change in the aquifer. A modelling framework (Section 3.1) was defined to assess hydrological impacts on the coastal aquifer based on a density-dependent simulation whose inputs are defined by sequential coupling of different models. It was used to simulate potential future global change scenarios (Section 3.3) by feeding it with LULC, CC and SLR scenarios that we have previously generated (Section 3.2) by applying a method to obtain consistence pictures taking into account different sources of uncertainty.

3.1 Definition of an integrated modelling framework

In order to assess quantity and quality impacts on groundwater systems we needed to calibrate a density-dependent model that simulates flow and transport within the porous aquifer medium. We propose a sequential coupling of three 'auxiliary models' (rainfall-recharge models and crop irrigation requirements and irrigation returns models) with this density-dependent model, in which the output of the auxiliary models is used as input to the groundwater model (see Figure 7). The models were calibrated with the available historical data (1981-2010). Historical data for the period 1973-1981 were used to validate them. These models were then used to simulate the impacts of future LULC and CC scenarios.

3.1.1 Rainfall-recharge models

Previously published detailed lysimeter readings (Tuñon, 2000) were examined to estimate actual diffuse recharge into the Plana de Castellón aquifer. An infiltration rate coefficient was calibrated so as to obtain a good fit to the mean recharge when applied to the historical rainfall series. Based on the results obtained in that study (located in a neighbouring coastal area with very similar climate and hydrological conditions to our case study) we defined a simple empirical rainfall-recharge model at a yearly scale. We consider that rainfall is not the only climate variable that influences total recharge, but that temperature also can affect it; thus changes in temperature could also be important in future climate scenarios. As temperature increases, the evapotranspiration (ETR) will also rise, so reducing the water available from other components in the water balance equation, including recharge. For this reason, instead of defining an infiltration coefficient that relates rainfall and recharge, we propose a transformation function (a modified infiltration rate) that calculates recharge as the difference between precipitation and ETR. In order to obtain this modified infiltration rate we propose calculating the mean annual ETR by applying the simple empirical method proposed by Turc (1954), depending on the series of mean yearly climate conditions defined by rainfall and temperature.

The annual rainfall recharge values obtained using the simplified model were divided between the 12 months, maintaining the historical pattern of recharge calculated from the infiltration rates deduced by Tuñon (2000). We assume that recharge from a rainfall event will reach the aquifer in less than one month, so working with stress periods of one month means there is no delay between the rainfall and the aquifer recharge.

Two simplified rainfall recharge models were developed, one for the Plana de Oropesa-Torreblanca aquifer and the other for the Maestrazgo aquifer. The first one calculates potential future rainfall recharge (RRi) scenarios by simulating future climate conditions (Ei).

The other, the Maestrazgo aquifer model, was used to assess lateral inflows (LI) from the Maestrazgo to the Plana Oropesa-Torreblanca aquifer under various potential GC scenarios. It requires simulated future climate conditions and assumes a constant ratio between lateral inflow to the Plana Oropesa-Torreblanca and aquifer recharge (including rainfall and agricultural recharge). The historical evolution of this rainfall recharge (RR), used as input to the groundwater model, is represented in Figure 9 (Section 3.1.3).

The future series of rainfall recharge (RRi) linked to the potential future climate conditions (Ei) are described in Section 4 (Results).

3.1.2 Modelling crop irrigation demands and irrigation returns

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). This approximation was applied in previous CC impact research studies (e.g., Escriva-Bou et al., 2016). The irrigation values added to the rainfall constitute the total inflows coming from the surface system. A modified version of the Turc model (1954) was employed to estimate the total ETR in the area considering not only rainfall but also irrigation water. The difference between the total ETR and the

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ETR for the rainfall allows us to determine the ETR related to irrigation, taking into account the climate conditions (rainfall and temperature).

Detailed fieldwork was also performed to assess irrigation returns in the Plana de Castellón aquifer by using lysimeter measurements (Tuñon, 2000). From Tuñon's study, irrigation return coefficients in the area were identified according to the irrigation techniques in order to obtain a good approximation of the mean agricultural recharge by applying them to the irrigation series.

Instead of defining irrigation return coefficients that relate irrigation to agricultural recharge we have defined a transformation function (a modified irrigation return coefficient) that allows the agricultural recharge to be calculated from the difference between the irrigation and its ETR taking into account the climatic conditions. It will be based on the results obtained in this study (located in a neighbouring coastal area with very similar climatic and hydrological conditions to our case study) and the sequential simulations of the agronomic and climatic conditions with the Cropwat and the Turc model (as explained above).

The historical evolution of the agricultural recharge (AR) employed as inputs of the groundwater model is represented in Figure 9 (Section **3.1.3).** The future series of agricultural recharge (RRi) linked to the potential future climate conditions (Ei) are described in Section 4 (Results).

Future pumping scenarios (P1, P2, P3 and P4), which were estimated by using these predicted water demands and additional information about the origin of the water (see Section 2.3) are also described in Section 4.

3.1.3 Density dependent flow model (flow and transport)

Based on the hydrological description performed in Section 2.1 a conceptual model was defined to approach the aquifer as an unconfined heterogeneous detritic aquifer. The inflows to the aquifer include rainfall, Lateral Groundwater Inflows from the bordering aquifers (LGI) and irrigation returns. The outflows include natural springs that feed the wetland, pumping wells and outlets to the sea.

The 3D finite-difference numerical code SEAWAT (Guo and Langevin, 2002) was used to solve the coupled partial differential equations for variable-density flow and transport. It combines MODFLOW (McDonald and Harbough, 1988) and MT3DMS (Zheng and Wang, 1999) into a single code that conserves fluid mass, rather than fluid volume, and uses equivalent freshwater head as the primary dependent variable.

The domain has been divided into 32 columns and 90 rows in the horizontal plane, with a cell size of 250x250 m. Therefore, the groundwater flow and transport domain extends over a size of 8000x22500 m. The vertical discretization has 11 layers, defined as confined/unconfined layers where the transmissivity varies. The vertical discretization consist of 11 layers, since it requires a much greater level of detail to represent the complex flow patterns near areas of high concentration gradients (Guo and Langevin, 2002). On the one hand, for the flow boundary conditions a prescribed head of 0 m has been assigned to all cells belonging to the sea frontier of the model. For the transport boundary conditions a prescribed concentration of 35 mg/l has been assigned to all cells belonging to the sea frontier of the model.

We assumed a density of fresh water of 1000 kg/m3 and 1025 kg/m3 for the seawater of; with 0.7143 as the slope of the linear equation of state that relates fluid density to solute concentration.

The model was calibrated with the available historical data in the period (1981-2010), while the data in the period 1973-1981 was used to validate it. This was carried out by applying a trial and error procedure simultaneously considering quantity and quality, rather than using an inverse model; this is due to the complexity of the case study dealt with (Llopis-Albert et al., 2014, 2016). The calibrated model parameters encompass different zones of horizontal hydraulic conductivities ranging from 5 to 200 m/d, while the vertical hydraulic conductivities are between 0.5 to 20 m/d.. There are also different zones of specific storage values, which range from 10-5 to 5·10-4 1/m; specific yield, with values from 0.01 to 0.05; effective porosity values from 0.01 to 0.03; and dispersion coefficients from 50 to 100 m.

Good results in terms of goodness of fit to the historical hydraulic head and salinity concentrations were obtained, as shown in Figure 8 for various head and concentration observation wells.

The historical evolution of inflows and outflows in the aquifer model is represented in the Figure 9.

Finally, the calibrated model was used to assess the impacts of future LULC and CC scenarios.

3.2 Generation of potential future climate scenarios for the system

We propose a method to generate consistent picture of potential future climate scenarios for a short-term horizon (2011-2035) from the historical (1973-2010) data and the climate models simulations performed in the frame of the CORDEX EU project described in Sections 2.2. It requires an analysis of the results obtained by applying different downscaling techniques. A multi-criteria analysis of some statistic of these series was performed to identify the best simulations of the historical data. Different ensembles hypothesis has been adopted to define more representative potential future climate scenarios to be employed in the groundwater impacts study.

3.2.1 Application of different downscaling techniques (bias correction and delta change techniques)

In accordance with the hypotheses assumed to define future climate series in a water resource system (starting from the climate model simulations) we can consider two different kinds of downscaling techniques: bias correction techniques and delta change techniques (Räisänen and Räty, 2012). In the resent study we apply both conceptual approaches (bias correction and delta change techniques).

The bias correction techniques are based on analysing 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 scenarios 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., 2014, 2011; Räisänen and Räty, 2012).

When applying both correction techniques (bias and delta change) the spatial resolution of the data available for our systems is usually more detailed than those adopted by the climate model and, therefore, these transformations indirectly produce a downscaling approximation to the system. Therefore, they are commonly known as downscaling transformations. We have applied two downscaling techniques (correction of first and second order moments) for both conceptual approaches (bias correction and delta change techniques). As example, the first, second and third moments of the series obtained with both approaches for one of the RCM (RCA4 linked to CNRM-CM5) are represented in next Figure (Figure 10).

3.2.2 Multi-criteria analysis of the main statistic

Two multi-objective analyses are proposed: one related with the bias approaches and another with the delta ones.

In the delta change approaches the multi-criteria analysis that we propose intends to identify the models that provided the best approximations to the main historical statistics (mean, standard deviation and asymmetry coefficients) based on the analysis of their control simulation of the historical period. This analysis is similar to the one presented by Pulido-Velazquez et al., 2014 in a non-coastal aquifer extended to consider also the asymmetry coefficients in the analysis. The dominated

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solution or 'inferior' models approaching the historical statistic were identified and eliminated. A model is eliminated (see Table 2) if any other model's prediction provides better approximation to the cited two main statistics.

In this study we also propose a multiple-criteria analysis for the bias correction approaches. This allows us to identify the best combination of model and bias correction techniques (see Table 3) to approximate the main statistics of the historical series. Since most of the combinations of model and bias correction technique provide very good approximations to the first moment, a relative error threshold was defined to consider a corrected control to approach better an statistic when significant differences (higher than the threshold) are obtained.

3.2.3 Ensembles of predictions to define more representative future climate scenarios

We considered four options to define representative future scenarios by applying different ensembles of corrected projections. Two ensemble scenarios were generated by a liner combination of all the future series generated by delta change (E1) or bias correction (E2). Two other options were defined by combining only the non-eliminated models (E3, for the delta change approach) or combinations of models and correction techniques (E4, for the bias correction techniques), assuming that we do not trust on the eliminated ones.

All ensemble predictions show very similar increase in mean temperature. The standard deviation estimated with the delta change approaches are quite similar to the historical, but both ensembles defined by applying bias correction show significant reductions in this statistic.

A reduction in future mean rainfall is predicted by all the ensembles for every month except September, October, and December, when relative increases in rainfall are predicted. Since these are the months with highest historical rainfall, the overall effect is a higher total annual rainfall compared to the historical. Therefore, all these approaches predict an increase in the extreme events that in this area occur mainly in October and it would lead to a slightly higher mean future precipitation. As we also observed for the temperature, the standard deviation of the future precipitation predicted with the delta change approaches are quite similar to the historical, but both ensembles defined by applying bias correction show significant reductions.

3.3 Hydrological impacts: propagation of future climatic scenarios

Analysis of GC impacts will require a sequential simulation of the LULC change scenarios for the different climate scenarios (Ei) in the rainfall-recharge models and the crop irrigation requirement and irrigation returns models in order to define the inputs for the groundwater density-dependent model, which solves the flow and transport simultaneously (see Figure 7).

3.3.1 Assessment of the groundwater model inputs

The rainfall-recharge models, calibrated for the aquifer and its neighbour (see Section 3.1.1), are supplied with the potential future climate scenarios (E1, E2, E3 and E4; see Section 3.2.3) in order to define potential future scenarios of rainfall recharge (RR1, RR2, RR3 and RR4 which correspond, respectively, to E1, E2, E3 and E4).

The agronomic models are also employed to predict the water demand for the potential future LULC scenarios under the potential future climate conditions (see Section 3.2.3). From this potential future water demand, future agricultural recharge (AR1, AR2, AR3 and AR4) scenarios can be estimated as described in Section 3.1.1. Future pumping scenarios (P1, P2, P3 and P4) are also predicted based on these water requirements, taking into account additional information about the origin of the water (see Section 2.3). The potential recharge scenarios (rainfall and agricultural recharge) estimated for the Maestrazgo aquifer are employed to estimate potential lateral inflows in Plana Oropesa-Torreblanca aquifer (LI1, LI2, LI3 and L4 respectively) assuming an constant ratio between the recharge and this variable (see Section 3.1.1.).

3.3.2 Scenarios simulated with the groundwater model

In order to assess the potential impacts of GC (CC and LULC change scenarios) we have simulated the following scenarios using the density-dependent flow model:

1) Baseline (BL) scenario: No LULC change and no CC. We simulate a future scenario for the horizon 2011-2035 assuming that from 2011 we would have the same LULC that we observed in 2010. We also assume that the hydrological characteristic does not change and we have simulated assuming the rainfall recharge and the lateral inflows from the neighbour aquifer are equal to those estimated in the last 5 years of the historical periods (2006-2010). In this period of 5 years (2006-2010) there was no significant change in LULC and so this period could be adopted as being representative of the mean recent climatic-hydrological conditions. This scenario was defined in order to compare against the others to analyse the sensitivity to GC.
2) Global change (GC_i) scenarios assuming constant sea level: We simulate scenarios that simultaneously consider the potential impacts of the future LULC scenario (described in Section 2.3) under four different CC scenarios (Ei (described in Section 3.2.3). on agricultural recharge (AR_i), pumping volumes (Pi), rainfall recharge (RR_i) and lateral inflows (LI_i) from the neighbour aquifer. The comparison of these scenarios with the BL provides information about the GC impacts.
3) Sensitivity to SLR: We simulated four scenarios that differ from the GC scenarios (GC1, GC2, GC3, GC4) in terms of sea level, which is supposed to rise 0.19 cm in line with the pessimistic scenario outlined in Section 2.5.

4. Results and discussion

The hydrological inputs of the groundwater model under different GC scenarios (GCi) were obtained by sequential simulation of the climatic variables within the 'auxiliary models'. Figure 12 shows the yearly evolution of inflows and outflows under the BL scenario and the mean of the GC scenarios. The GC scenario shows a higher variability in all the flow components.

Figure 13 summarizes the mean values for each of these flow budget components for the various future scenarios. The GC scenarios would be related to a reduction in the pumping volume due to the abandonment of irrigated areas and the growth of urban areas. It will also produce a reduction in recharge, which is related to a reduction in mean rainfall in the area as one impact of CC. This reduction in mean rainfall would also produce a reduction in the mean lateral groundwater inflows (LGI). The reduction in pumping due to GC would be the main reason for increased outflows to the sea.

The inflows obtained for the four GC scenarios were simulated within the previously calibrated density-dependent flow model in order to analyse impacts in terms of the aquifer state. The evolution of future chloride concentrations at four of the observation points is represented for the BL scenario and the four GC scenarios in Figure 14. Again, the series of GC scenarios shows greater variability than the Baseline scenario. In many cases, the concentration in the GC scenarios is lower than in the BL scenario. This happens, for example, in areas where abandonment of irrigation has led to a reduction in pumping. Higher concentrations (e.g., Observation well 12) could be found, for example, in areas with reduced recharge or increased pumping due to GC. Therefore, the results depend on the location.

Lastly, we analyzed the sensitivity of the GC scenarios to a SLR scenario. A rise of 0.19 m at the end of the future horizon was used to define a very pessimistic scenario of maximum SLR (see Section 2.5). A linear sealevel rise was considered during the future horizon (2011-2035). Figure 15 show the results obtained in terms of hydraulic head and chloride concentration at a number of observation points. It shows that the sensitivity of hydraulic head is very low. The sensitivity of chloride concentration, although not very significant, is higher than that observed for hydraulic head.

5. Conclusions

We have proposed a method to perform an integrated analysis of the potential impacts of future CC, LULC change and SLR in a coastal aquifer, the Plana Oropesa-Torreblanca aquifer. Representative future climate change scenarios are generated by using different equifeasible and non-equifeasible (deduced form a multicriteria analysis) ensemble of series generated with several RCMs applying different downscaling approaches (bias or delta change corrections). A future LULC scenario was defined in accordance with the plan approved by the local government (PGOU, 2009). Four GC scenarios were defined by combining the LULC scenario and the CC scenarios. These GC scenarios have been propagated to assess hydrological impact by simulating them within an integrated modelling framework based on density-dependent model whose inputs are defined by a sequential coupling of different models (rainfall-recharge models, crop irrigations requirements and irrigation return models). These global scenarios' simulations show a significant increase (respect to a BL scenario with no GC) in the variability of the flow budget components and in the chloride salinity concentration. It also shows a low sensitivity to an extreme SLR scenario, especially in terms of hydraulic head. The proposed analysis is valuable to improve our knowledge about the aquifer and so comprise a tool to support decisions about sustainable adaptation management strategies taking into account the uncertainty in future global change conditions and their impacts.

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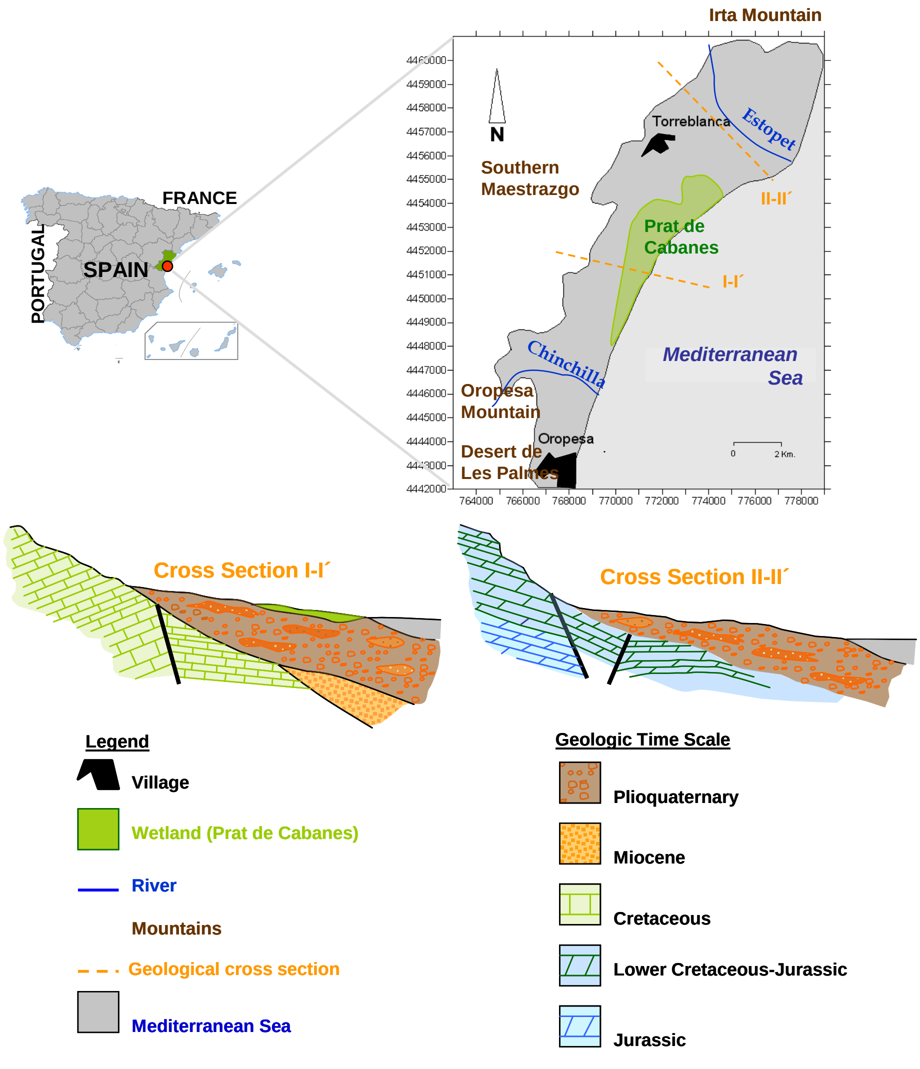

Figure 1: Location map area and cross sections of the study.

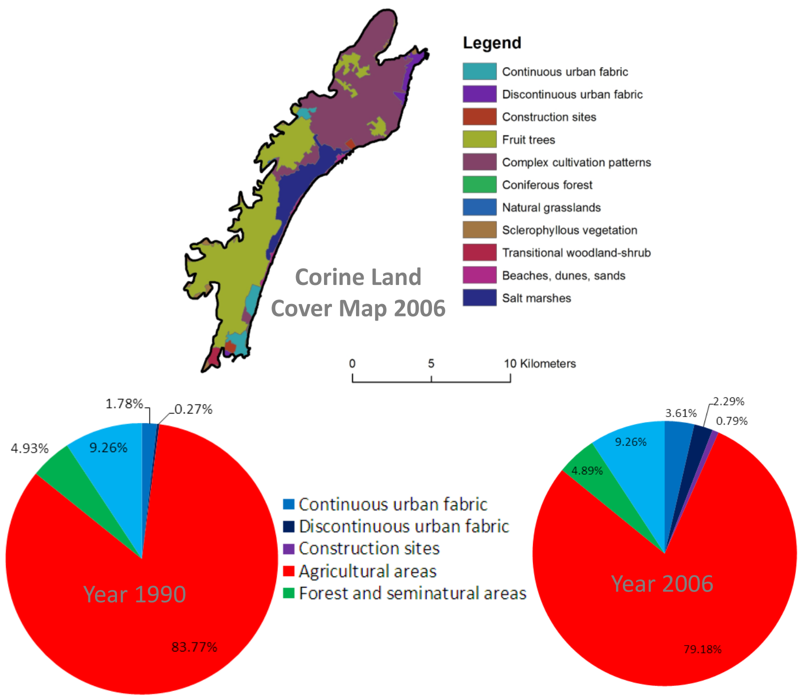

Figure 2: Land use change (comparing the CORINE Land Cover databases for 1990 and 2006) over the Plana de Oropesa-Torreblanca and Maestrazgo aquifers.

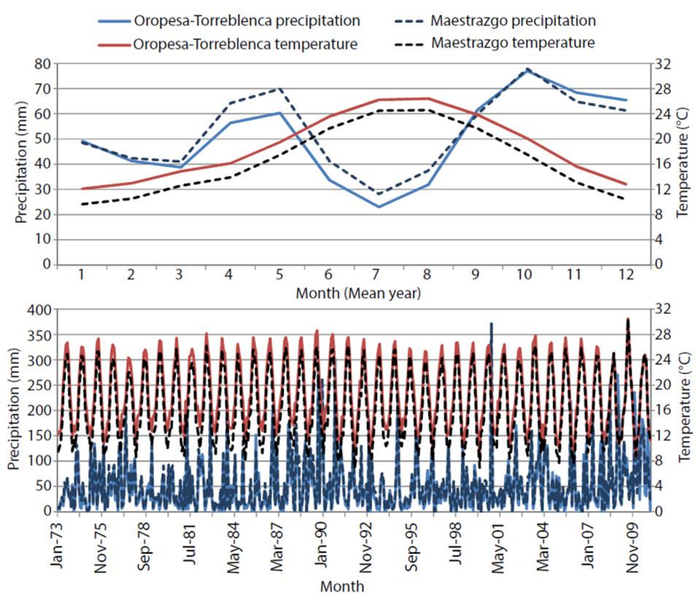

Figure 3: Historical rainfall and temperature in the Plana de Oropesa-Torreblanca and Maestrago aquifers.

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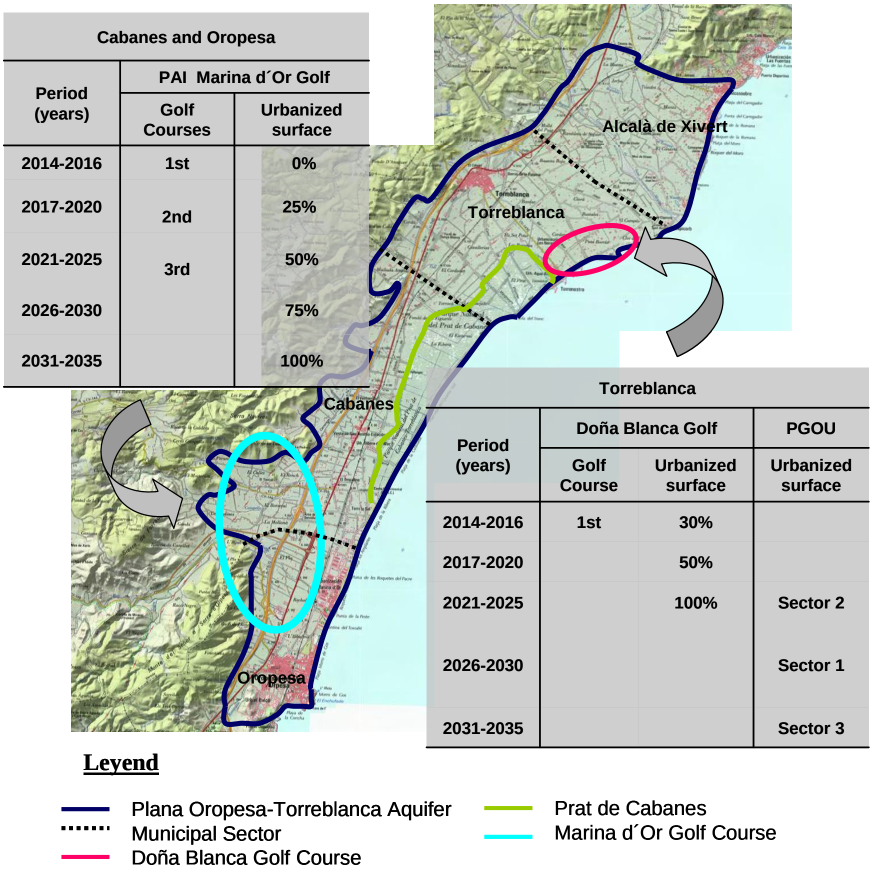

Figure 4: Future land use scenarios in 2035.

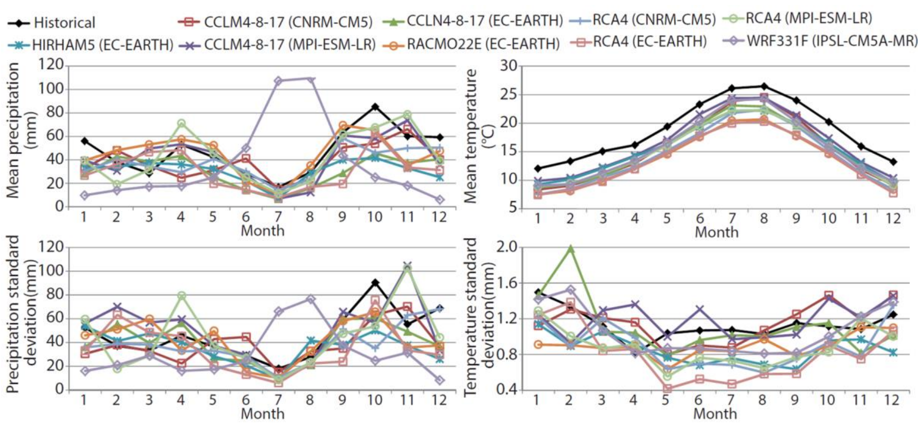

Figure 5: Monthly mean and standard deviation of the historical and control series (rainfall and temperature) for the mean year in the period 1976-2000.

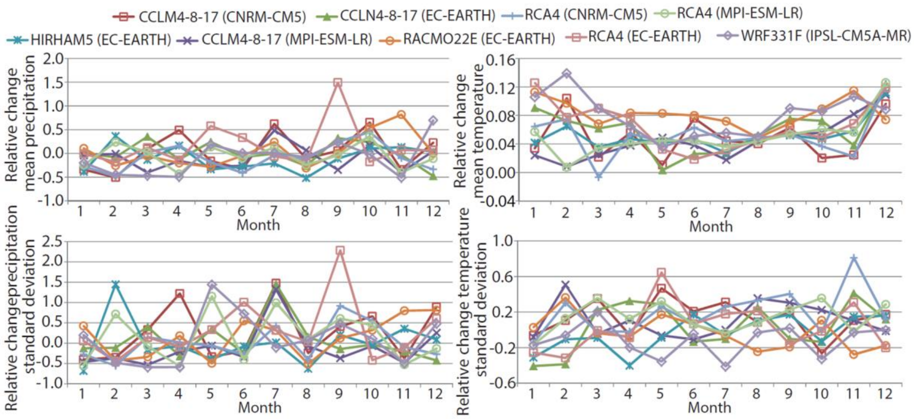

Figure 6: Relative monthly change in mean and standard deviation of the future series with respect to the control series (rainfall and temperature).

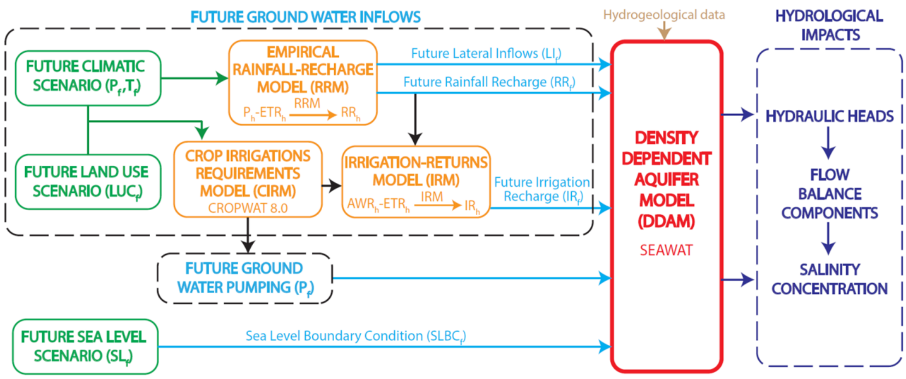

Figure 7: Flowchart of the modelling framework.

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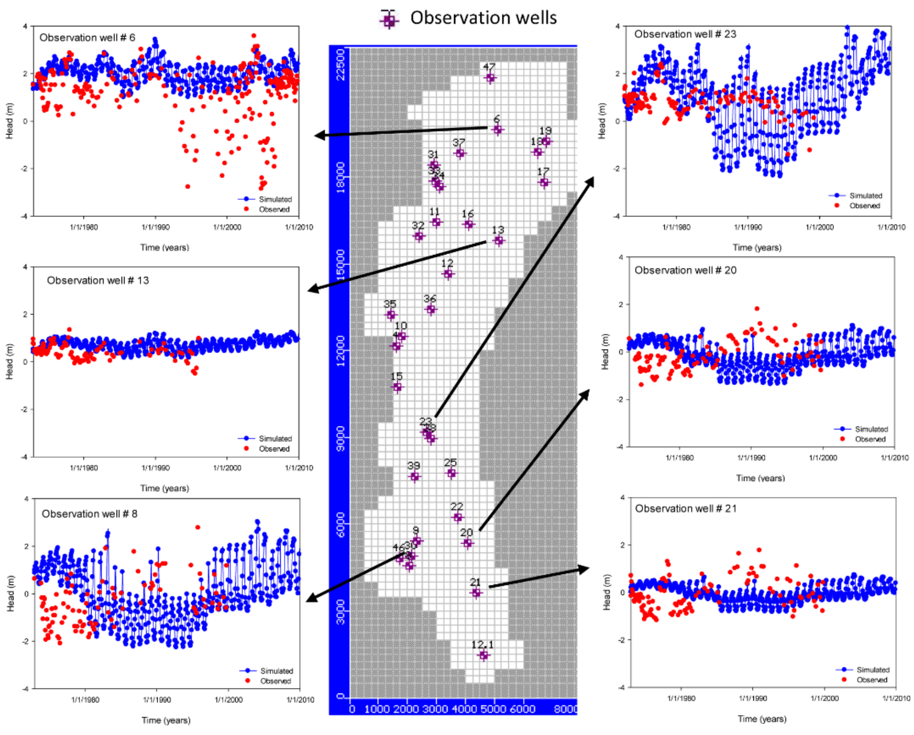

Figure 8.a: Hydraulic head obtained with the models vs. data at some observation points.

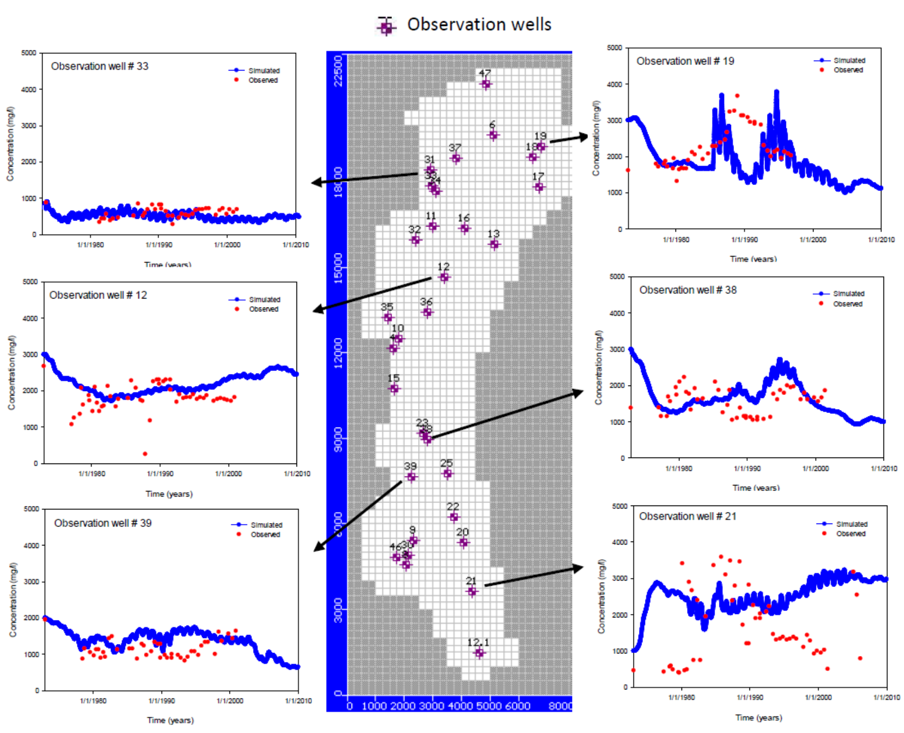

Figure 8.b: Salinity concentration obtained with the models vs. data at some observation points.

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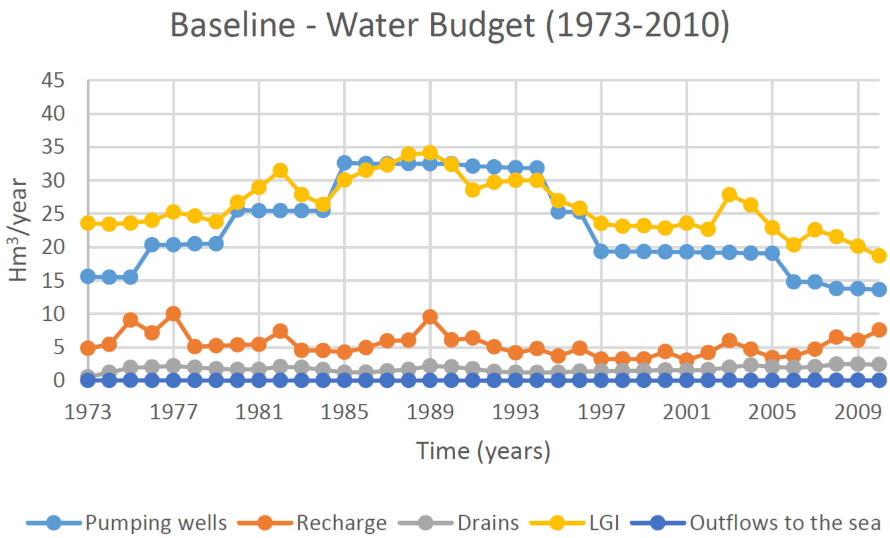

Figure 9: Historical evolution of inflows and outflows in the aquifer.

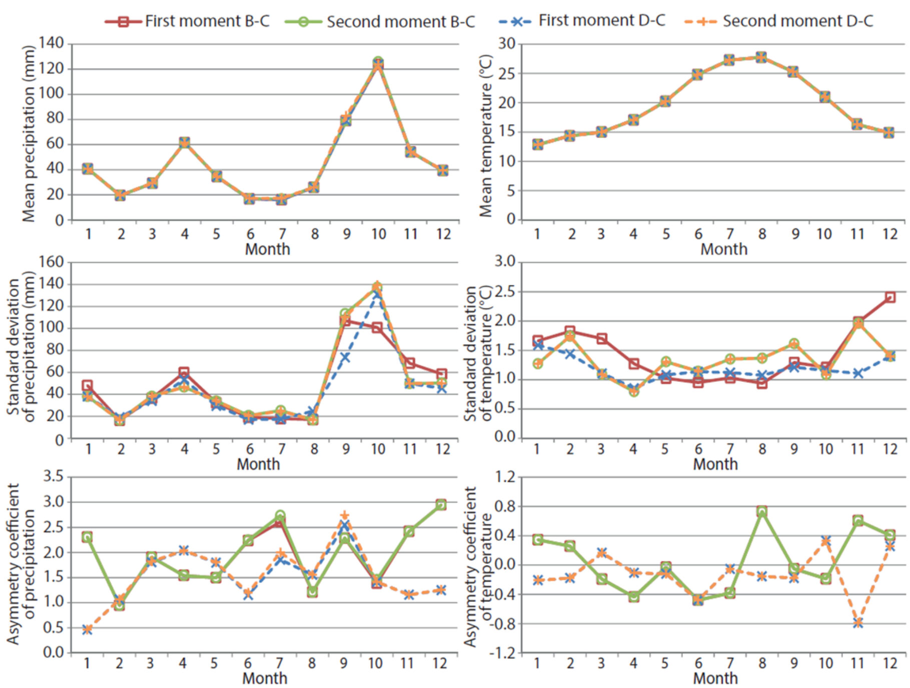

Figure 10: Mean, standard deviation and asymmetry coefficients of future precipitation series (A) and future temperature series (B) for the average year for the RCM RCA4 model linked to the GCM CNRM-CM5.

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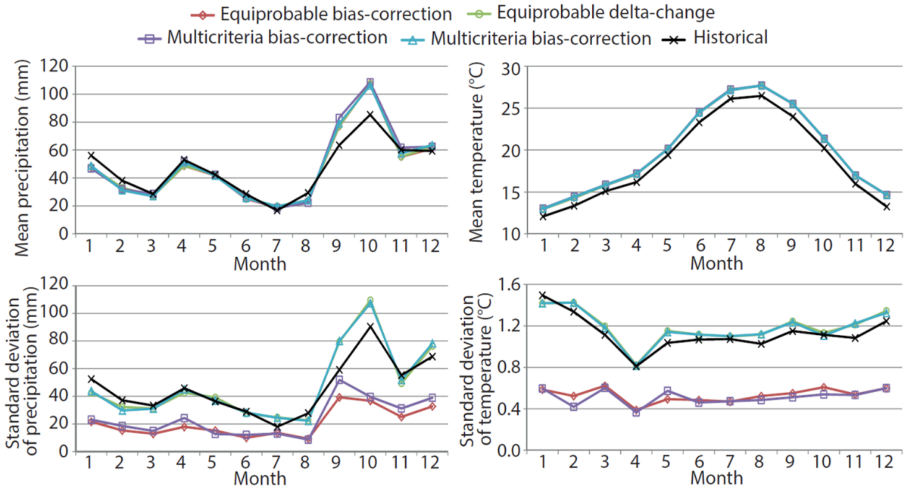

Figure 11: Mean and standard deviation of future precipitation and temperature series obtained by the four ensemble options.

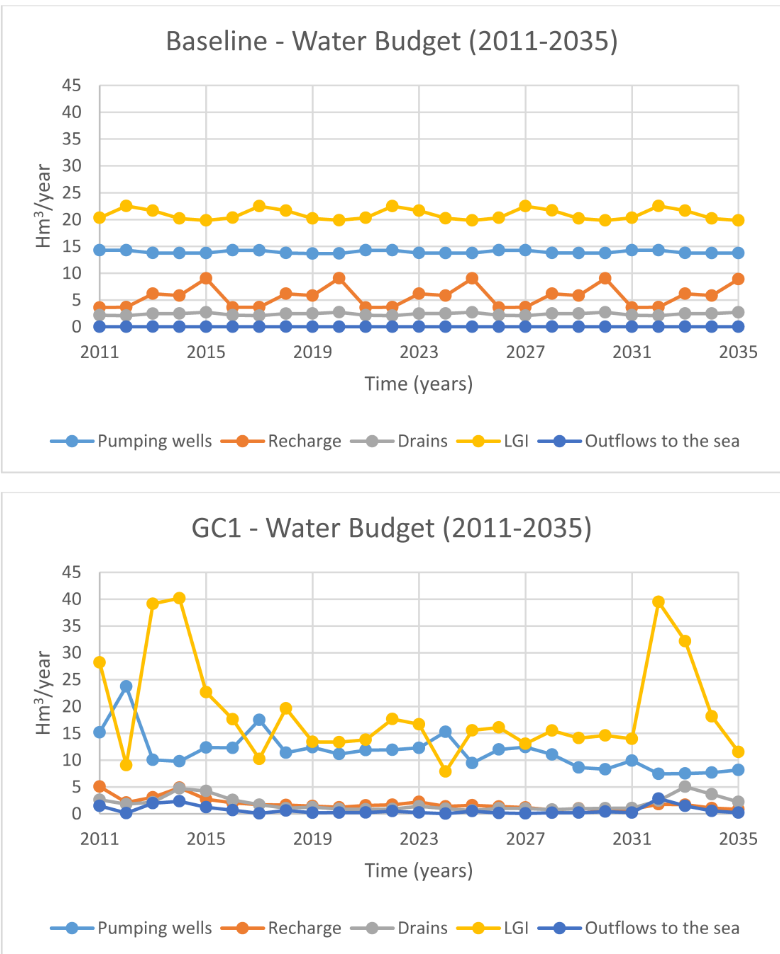

Figure 12: Components of the flow budget evolution for the BL scenario and the mean of the potential future scenarios (horizon 2011-2035).

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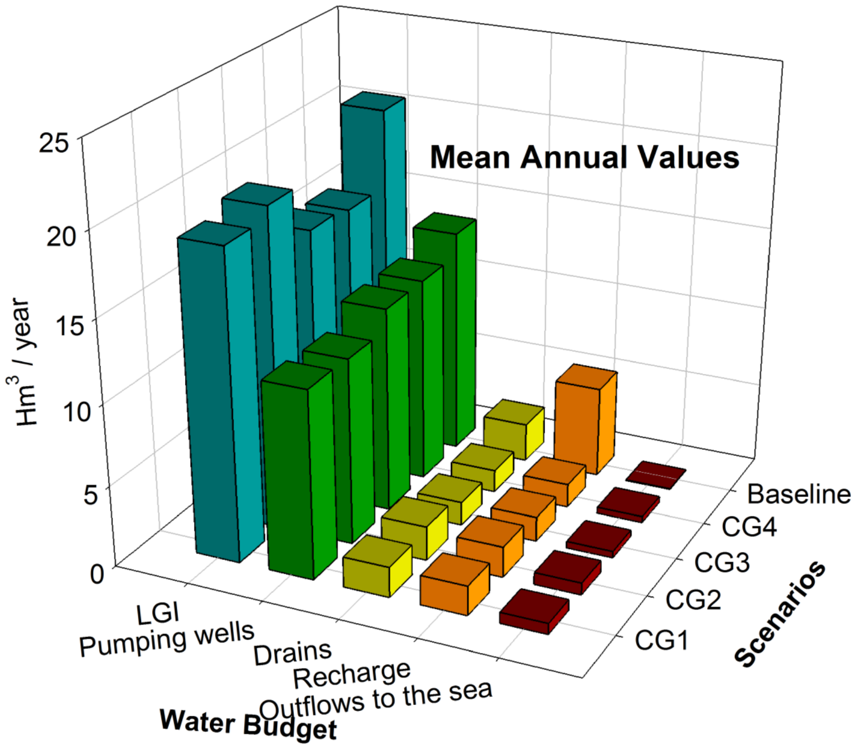

Figure 13: Mean inflows and outflows for various global scenarios (GC1, GC2, GC3, GC4).

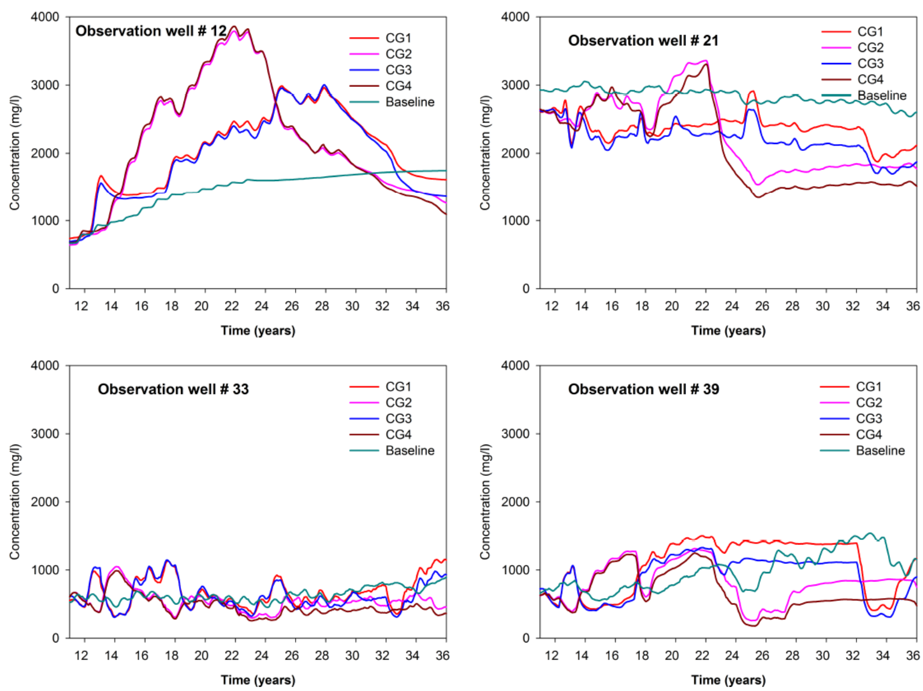

Figure 14: Evolution of future chloride concentration at four observation points for the Baseline (BL) scenario and the four Global Change scenarios.

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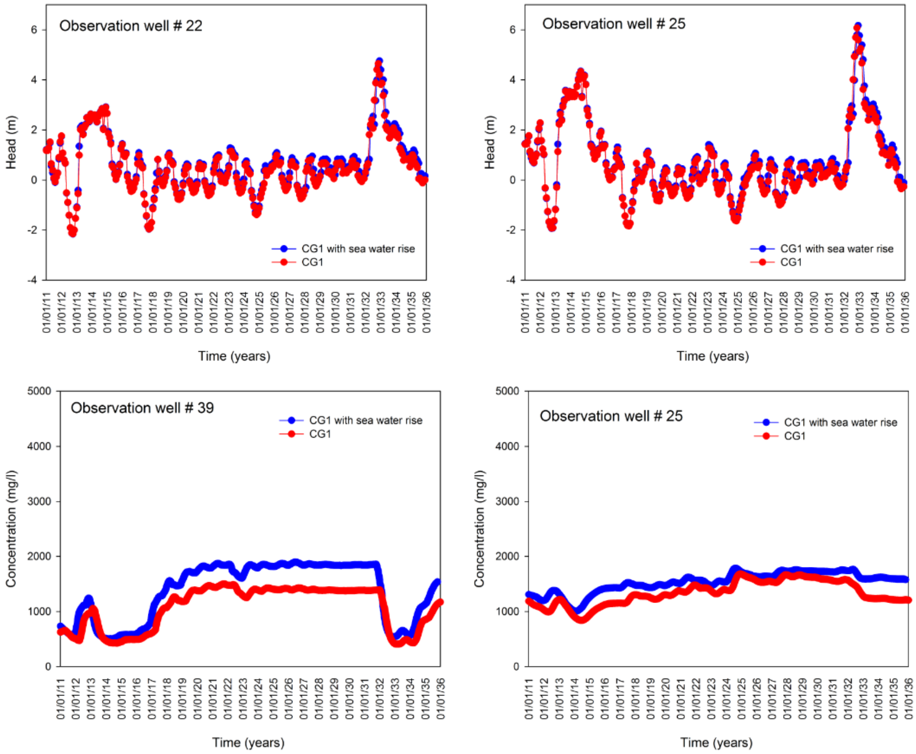

Figure 15: Sensitivity of head and salinity concentration obtained for GC1 to a SLR (0.19 m) scenario.

GCM / RCM	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

Table 1: RCMs and GCMs considered.

ELIMINATED?	RCM	GCM
NO	CCLM4-8-17	CNRM-CM5
NO	CCLM4-8-17	EC-EARTH
NO	CCLM4-8-17	MPI-ESM-LR
NO	HIRHAM5	EC-EARTH
NO	RACMO22E	EC-EARTH
NO	RCA4	CNRM-CM5
NO	RCA4	EC-EARTH
YES	RCA4	MPI-ESM-LR
NO	WRF331F	IPSL-CM5A-MR

Table 2: Eliminated and non-eliminated models in the multiple-criteria analysis

THRESHOLD 1% ELIMINATED?	RCM	GCM	TECHNIQUE

NO	CCLM4-8-17	CNRM-CM5	First moment
NO	CCLM4-8-17	CNRM-CM5	Second moment
YES	CCLM4-8-17	EC-EARTH	First moment
NO	CCLM4-8-17	EC-EARTH	Second moment
YES	CCLM4-8-17	MPI-ESM-LR	First moment
YES	CCLM4-8-17	MPI-ESM-LR	Second moment
NO	HIRHAM5	EC-EARTH	First moment
NO	HIRHAM5	EC-EARTH	Second moment
NO	RACMO22E	EC-EARTH	First moment
NO	RACMO22E	EC-EARTH	Second moment
YES	RCA4	CNRM-CM5	First moment
NO	RCA4	CNRM-CM5	Second moment
NO	RCA4	EC-EARTH	First moment
NO	RCA4	EC-EARTH	Second moment
YES	RCA4	MPI-ESM-LR	First moment
NO	RCA4	MPI-ESM-LR	Second moment
YES	WRF331F	IPSL-CM5A-MR	First moment
NO	WRF331F	IPSL-CM5A-MR	Second moment

Table 3: Eliminated and non-eliminated combinations of model and bias-correction technique.