**Journal: Hydrol. Earth Syst. Sci.**
**Manuscript Number: hess-2017-262**
**Title: "Integrated assessment of future potential global change scenarios and their hydrological impacts in coastal aquifers. A new tool to analyse management alternatives in the Plana Oropesa-Torreblanca aquifer"**
**Special Issue: Assessing impacts and adaptation to global change in water resource systems depending on natural storage from groundwater and/or snowpacks**

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**Comments from the editors:**

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**Comments to the Author:**

**The manuscript requires major revision and additional review before publication. Please consider the comments of the reviewers carefully before submitting a new improved version of the manuscript. Especially reviewer#2 raise some serious issues that need to be carefully dealt with. The new version of the manuscript should be accompanied by detailed descriptions of how the new version considered the critical points raised by the reviewers**

**Response to Comments from the Editors:**

*We appreciate the Editor for giving us the opportunity to provide a new version of the manuscript. We have made an important effort to improve the manuscript in accordance with the editor and reviewer comments.*

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**Reviewer #1 Comments to Author:**

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1) **This paper defines a framework for assessing the effects of CC, LULC and SLR on a coastal aquifer where problems of saltwater intrusion are detected. Climate change models are integrated with LULC, SLR and double-density groundwater flow models in order to define future strategies for integrated water management in the study area. The approach is ambitious and valid scientifically. Many models, however, are introduced but not clearly explained. Some models are described with excessive jargon and others are barely defined and no reference is given (modified etr). As a result, the paper has a black box kind of content, which makes it very difficult to evaluate. I suggest that the authors upload some additional information that relates to the different models and steps they did in their work.**

*We thank the reviewer for the recognition of the interest of this research and for the comments formulated, which have helped us to realize that some aspects were not clearly stated in the original manuscript and could be improved in a new version of the manuscript. Following the reviewer suggestion we will upload some additional information that relates to the different models and steps we did in our work. More detail about it can be seen in the response to the specific comments.*

*For example, see the response to comment number 6, in which a more detailed description of the rainfall recharge model is proposed in order to understand and evaluate it.*

2) **Another confusing point is the use of the acronym GC, GCi, GC1, GC2, etc. which are never correctly explained.**

*Following the reviewer suggestion we have defined each of the employed acronyms within the new version of the manuscript.*

3) **The authors use also inconsistencies in defining concentration and relating it to density (density 1025 Kg/m3; salinity 1035 g/l), which can cause serious problems in the double-density models. It is not clear if in the models they use chloride concentration or salinity.**

*The salinity concentration of the seawater that we have used is 35 g/l in the SEAWAT simulations. We have used this value throughout all the revised version of the manuscript.*

4) **Also the porosity used seems very small compared to the permeability detected in the aquifer.**

*Sorry, there was a typo error in this paragraph. The specific yield takes values from 0.01 to 0.15 and effective porosity values from 0.01 to 0.13; We have already corrected it within the new version of the manuscript (line 15-19 page 10):*

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 0.15; effective porosity values from 0.01 to 0.13; and dispersion coefficients from 50 to 100 m.

*Nevertheless, in in order to explain more clearly the conceptual approach followed to define the model parameters we have added some sentences explaining it within the new version of the manuscript (line 18-22 page 10):*

We have replaced a highly heterogeneous porous media with an upscaled "equivalent" homogeneous porous media to represent the hydrogeological parameters since the cell size of the discretization is 250x250 m (e.g., Llopis-Albert and Capilla, 2010). Then, we have used a value of the effective porosity based on available data, which were subsequently calibrated and upscaled using expert judgment. The results of the calibration process prove the worth of this approach.

*-Llopis-Albert, C., Capilla, J.E. (2010). Stochastic inverse modelling of hydraulic conductivity fields taking into account independent stochastic structures: A 3D case study. Journal of Hydrology, 391(3–4), 277-288. DOI: 10.1016/j.jhydrol.2010.07.028.*

**5) Another point that the authors do not address is the connection between the carbonate basement and the detritic aquifer.**

*Thank to the reviewer comment we have realized that we did not explain it properly within the manuscript. In order to clarify it we have added the next sentences (Section 2.1; line 33-34 page 3):*

The carbonate basement receives the contributions coming from the bordering aquifer (Maestrazgo aquifer) and feeds the detrital aquifer. The direction of the groundwater flow is from the carbonate basement to the detrital aquifer.

*We have also added the next sentence in section 3.2.1 (rainfall-recharge models):*

The Maestrazgo aquifer recharge model is used to assess inflows to the carbonate basement, that produces lateral inflows (LI) to the Plana Oropesa-Torreblanca aquifer under various potential GC scenarios. The Maestrazgo aquifer has an important storage capacity which is almost in natural regime and does not present significant changes in hydraulic head. The Maestrazgo rainfall recharge model is employed to assess future recharge being the LI to the carbonate basement obtained by assuming a constant ratio between Maestrazgo rainfall recharge and these LI.

**6) Section 3.1.1 This section requires better explanation of the modeling (lines 20-30).**

*In the next paragraphs we include a more detailed description of the rainfall-recharge model:*

Based on the historical climate (rainfall and T) and recharge series for the period 1973-2010 described in sections 2.2, we define a simple empirical rainfall-recharge approach to generate yearly aquifer recharge series. The model assumes that P and T are the most important climatic variables determining potential aquifer recharge, and the variability of both of them will determine the impacts of future potential climatic scenarios.

It intend to define a correction function for the perturbation of the historical series defined as the difference in P and evapotranspiration (ETR) (hereafter referred to as PE series), modifying its mean and standard deviation to make them equal to the statistic of the historical aquifer recharge previously deduced from the lysimeter measurements (see section 2.2), as follows:

$$R_i = PEn_i.\sigma_R + \bar{R} \qquad (1)$$

where $R_i$ is the recharge series generated for the year i, $\sigma_R$ and $\overline{R}$ are the standard deviation and mean of the historical recharge series estimated using the infiltration rate coefficient obtained from previous lysimiter readings (Tuñon, 2000), and $Pn_i$ is the normalised historical PE series (P-E) obtained from:

$$Pn_i = \frac{PE_i - \overline{PE}}{\sigma_{PE}} \qquad (2)$$

where $PE_i$ is the historical PE series for the year i, and $\sigma_{PE}$ and $\overline{PE}$ are the standard deviation and mean historical values of the series. Taking the positive relationship of T and E into account (Arora, 2002; Gerrits et al., 2009), changes in T will determine the available non-evaporative fraction of P available for aquifer recharge. Different non-global empirical models could be applied to assess the historical E from T series (e.g., Turc, 1954, 1961; Coutagne, 1954; Budyko, 1974; amongst others) as described in Arora (2002), Gerrits et al. (2009), and España et al. (2013). In this study, we applied Turc's model (1954, 1961), in which the results depend on mean annual T and solar irradiation over the latitude.

In order to approach the impact of seasonal variability the annual rainfall recharge values obtained using the simplified model were distributed between the 12 months maintaining the pattern of the historical rainfall recharge series. 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.

NEW REFERENCES:

*Arora, V.K.: The use of the aridity index to assess climate change effect on annual runoff, Journal of Hydrology, 265, 164-177, 2002.*

*Budyko, M.I.: Climate and Life, Academic Press, New York, 508pp, 1974.*

*Coutagne, A.: 1954. Quelques considérations sur le pouvoir évaporant de l'atmosphere, le déficit d'écoulement effectif et le déficit d'écoulement maximum, La Houille Blanche, 360-369, 1954.*

*España, S., Alcalá, F.J., Vallejos, A., and Pulido-Bosch, A.: A GIS tool for modelling annual diffuse infiltration on a plot scale, Computers & Geosciences, 54, 318-325, 2013.*

*Gerrits, A.M.J., Savenije, H.H.G., Veling, E.J.M., Pfister, L.: Analytical derivation of the Budyko curve based on rainfall characteristics and a simple evaporation model. Water Resour. Res., 45, W04403, doi:10.1029/2008WR007308, 2009.*

*Kirn, L., Mudarra, M., Marín, A., Andreo, B., and Hartmann, A.: Improved Assessment of Groundwater Recharge in a Mediterranean Karst Region: Andalusia, Spain. In: Renard P., Bertrand C. (Eds.) EuroKarst 2016, Neuchâtel, Advances in Karst Science, 117-125, Springer, Cham, DOI: 10.1007/978-3-319-45465-8_13, 2017*

*Turc, L.: Water balance of soils: relationship between precipitation, evapotranspiration and runoff (in French), Ann Agron 5, 49-595 and 6, 5-131, 1954.*

*Turc, L.: Estimation of irrigation water requirements, potential evapotranspiration: A simple climatic formula evolved up to date, Annales Agronomiques, 12(1), 13-49, 1961.*

**7) I find the correlation between observed and modeled hydraulic head and salinity very poor. Can the authors explain on which basis the results of the models are acceptable as a predictive tool?**

*Thanks to the reviewer comment we have realized that we did not explain it properly within the manuscript. In order to highlight and clarify these issues within the new version of the manuscript we have added some paragraphs in a new* ***section*** *(Section 4.1 Hypotheses and limitations. Usefulness of the results). We agree with the reviewer, as he pointed in his first comments, from a methodological point of view the proposed approach is ambitious and valid scientifically, but we need to clarify assumptions and limitations in the application performed to the case study. We have added the next paragraphs (line 20 page 13 – 6 page 14)*

In this study we decided to employ a variable-density model instead of a sharp-interface solution, which have been extensively used to define management models because of its simplicity in terms of required parameters and computational burden (e.g., Mantoglou et al., 2004). This is because they better describe the dynamic of real complex coastal aquifers despite the limitations in the available data and the course discretization used for the Plana Oropesa-Torreblanca aquifer. Better adjustments between observed and modeled hydraulic head and salinity would provide greater confidence in the model predictions. Nevertheless, although due to there are some differences between observed and simulated data the uncertainty of the prediction coming from the model grows and we have to be cautious with the conclusions obtained, the fit is good enough to capture the general trend of the hydraulic head and salinity variables within a quite long calibration period (37 years, from 1973 to 2010), and therefore, to assess general impacts of climate and LULC changes. Note that it is difficult to improve the calibration of the proposed approach in this work for Plana de Oropesa-Torreblanca due to the following facts:

- The hydrogeological complexity of the aquifer makes it difficult to define a better approach taking into account its spatial heterogeneity, with fractured formations and preferential flow channels existing in the aquifer (Morell and Giménez, 1997). The spatial heterogeneity is handled by means of sequential indicator simulation using the computer code ISIM3D (Gómez-Hernández and Srivastava, 1990).

- The quality of some observation data is poor. This problem is accentuated when considering the long simulated time period with historical data, which spans from 1973 to 2010. In this way, for a certain observation borehole there are data close in time with measurements quite disparate, which cannot be explained by any physical phenomenon. A statistical processing of data with expert judgment would be advisable to dismiss the wrong data. We have opted for using all available data (as a transparency measurement and in order to ease the reproduction of this exercise by other researchers).
- The lack of reliable estimates of dispersion coefficients (Naji et al., 1999) may prevent a proper adjustment for the Plana Oropesa-Torreblanca aquifer.
- A better fit might be achieved using a more refined spatial discretization, which would allow modeling the preferential flow channels existing in the aquifer (Morell and Giménez, 1997). However, the high computational burden when solving the variable-density flow and transport equations with SEAWAT prevents the use of a fine grid (e.g. Sreekanth and Datta, 2010).
- As a further research, we are intended to couple the sea water intrusion model with a management simulation–optimization model for control and remediation that would further prevent the use of a fine grid.

REFERENCES:

**Mantoglou A, Papantoniou M, Giannoulopoulos P. 2004. Management of coastal aquifers based on nonlinear optimization and evolutionary algorithms. Journal of Hydrology 297(1-4): 209 228. DOI: 10.1016/j.jhydrol.2004.04.011*

**Morell, I. and Giménez, E.: Hydrogeochemical analysis of salinization processes in the coastal aquifer of Oropesa (Castellón, Spain), Environmental Geology, 29(1/2), 118-131, 1997.*

**Naji A, Cheng AD, Quazar D. 1999. BEM solution of stochastic seawater intrusion problems. Engineering Analysis with Boundary Elements 23: 529–37.*

**Sreekanth J, Datta B. 2010. Multi-objective management of saltwater intrusion in coastal aquifers using genetic programming and modular neural network based surrogate models. Journal of Hydrology 393: 245–256.*

**8) The discussion and conclusion sections are very short and poorly quantitative and fail to point out how this kind of modeling can be used in integrated coastal water management. The authors should elaborate on their results and say explicitly how this knowledge can be used in an integrated water management framework of a coastal zone. Give also explicit examples of how this can be done.**

*Following the reviewers' comment we have done our best to improve the **DISCUSSION SECTION** within the revised version of the manuscript.*

The proposed approach has similarities with the one described by Pulido-Velazquez et al. (2015), in which an integrated analysis of GC is performed including CC and LULC changes. The most important differences are related with the fact that a coastal aquifer is studied and we consider quality issues simulating with a variable density flow and transport model. The approach allows to propagate impacts of different CC and LULC change scenarios in terms of global flow balance, as well as a distributed approximation of the hydraulic head and salinity.

The GC scenarios show a higher variability in all the inflows and outflows in the aquifer (See Figure 12).

The mean components of the global balance for the simulated future scenarios show that, in general terms, the intrusion will not grow and will even be reduced slightly, as the outflows to the sea will not decrease, due in part to the reduction and redistribution of pumping in the mentioned scenarios (see Figure 13). The LULC scenario produces important reduction of pumping due to the transformation of irrigated areas in residential use, which are going to be supplied with water coming from desalination plants or recycled wastewater. It will also produce a decrease in the recharge due to the reduction of the returns coming from the irrigated areas. Nevertheless, in general, this LULC scenario would have an important role in avoiding an increasing degradation of the aquifer that would takes places in cases of maintaining the historical land uses, scenario that would be exacerbated in the future due to CC.

Figure 14 shows the evolution in terms of salinity at 4 specific observation points roughly equispaced. They were selected to cover the extension of the aquifer from north to south (starting with the more northerly and moving towards the south we have observation wells 33, 12, 39 and 21 respectively).

From the results in terms of salinity at specific observation points (Figure 14), we can observe the heterogeneity of the impacts of the LULC scenario and CC scenarios. The area around the observation point 33 is not affected by LULC changes and we only observe sensitivity to CC scenarios that produce a higher variability in the salinity evolution, but the mean trend of the concentration does not change. Around the observation point 12, in Torreblanca area, the LULC change scenario would produce a reduction in the recharge whose impacts can be observed as an increment in the salinity during the first decade of the future horizon. Nevertheless, in the last 10 years the reduction in pumping produced by the successive transformations of irrigated areas to residential land would reduce significantly the salinity. In this Torreblanca area CC scenarios would impact the salt concentration significantly during the first years due to the increment in pumping requirements produced by the higher water irrigation requirements obtained for these CC scenarios. Even considering the impacts of CC scenarios, during the last 10 year of the horizon it starts to recover due to the reduction in pumping produced by the new transformations of irrigated areas to residential land defined in the LULC scenario, being the concentration at the end of the horizon (2035) even under the values obtained for the BL scenario. In the observation point 39, located further away from the coast, the reduction in pumping due to LULC change would reduce the salinity during most of the year of the horizon. Nevertheless the reduction in recharge makes in some years the salinity to get close to the one obtained without LULC changes (BL scenario), being very similar at the end of the period. Again CC scenarios would increase the variability of the salinity in the simulated period.

We can also identify in the southern part areas where the situation will clearly improve throughout the future horizon contemplated with the proposed scenarios. For example, at observation point 21, in Oropesa area, the salinity would be reduced with the contemplated scenarios, which would be mainly related with the reduction of pumping in this area due to the transformation of irrigated areas to residential land defined in the LULC scenario.

**As commented above the expected results without considering GC impacts are likely to be too pessimistic or optimistic, depending on the location. These results can be useful for the authorities in charge of implementing management policies in the Plana de Oropesa Torrablanca. We can use this coupled modeling framework to assess potential effect of adaptation measures to GC by modifying the inputs of the models. Participatory processes including the relevant stakeholders might be essential in the definition of scenarios and successful adaptation measures (Pulido-Velazquez et al., 2015). This modeling framework could be useful in the search for consensus ("shared vision" models) between different stakeholders.**

Lastly, we analyzed the sensitivity of the GC scenarios to a SLR scenario (Figure 15). 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 3.1.3). A linear SLR was considered during the future horizon (2011-2035). Figure 15 shows the results obtained in terms of hydraulic head and salinity at a number of observation points. It shows that the sensitivity of hydraulic head is very low. The sensitivity of the salinity, although not very significant, is higher than that observed for hydraulic head. The low sensitivity of the results should be due to the maximum value of SLR considered, 0.19m in 2035, is quite low with respect to the level fluctuations experienced in most of the observation wells (see Figure 15). For this reason the sensitivity of the flow and transport solutions are low. We find in the literature other examples in which the sensitivity of seawater intrusion to the SLR would be low. Chan et al. (2011) obtained this conclusion in a synthetic confined coastal aquifer in which recharge in unchanged; Rasmussen et al. (2013) obtained the same conclusion for an inland coastal aquifer with minor SLRs. Nevertheless other authors, as Werner and Simmons (2009) showed that in unconfined aquifers the influence of the inland boundary condition can be significant to its sensitivity to SLR.

### 4. 1 Hypotheses and limitations. Usefulness of the results.

From the methodological point of view, the proposed approach is general, ambitious and valid scientifically. Nevertheless there are some assumptions and limitations in the application performed that we wanted to highlight and summarize in this section in order to clarify the accuracy and utility of the results obtained. We have grouped them in three categories:

(1) Generation of future potential climatic scenarios

- The research is focused on the analysis of future short-term-horizon (2011-2035). Other future horizons, such as mid-term and long-term scenarios, in which there should be even higher uncertainties about the impacts of CC for being further away in time, are not considered.
- Only the most severe IPCC scenario (RCP. 8.5) was analyzed to assess the most pessimistic impacts in the future short-term scenario.
- Potential plausible future climate scenarios are defined by combining information coming from different

Regional Climatic Models (RCMs) and General Circulation models (GCMs).

- Two downscaling approaches (correction of first and second order moments) under two different hypotheses (bias correction and delta change techniques) were applied to generate future climatic series in accordance with RCM simulations. Note that, depending on the problem and the target solution, several downscaling techniques of varying complexity and accuracy (correction of first- and second-order moments, regression approach, quantile mapping, etc.) can be applied by assuming different conceptual approaches, such as bias correction and delta change techniques (Räisänen and Räty, 2012).
- Two different hypotheses, equifeasible members or non-equifeasible members, were applied to define ensembles of the obtained future series for each RCM. They may help to achieve more representative future potential climate scenarios for assessing impacts on aquifer recharge.

(2) Hydrological propagation of the climatic impact to aquifer recharge

- A simple empirical precipitation-recharge model has been adopted; whose inputs are P and E. We have not tested other hydrological models, for example, based on a more physically based or detailed representation of the processes involved in the hydrological balance and the geological structures. We assume that P and T are the variables determining NAR, and their spatiotemporal variability determines the impacts of future potential climatic scenarios on renewable groundwater resources. We do not consider the change changes in other variables affecting recharge, such as soil properties, vegetation patterns and land-use. They are considered steady, despite there being expected to change according to global climate driving forces and new human actions on a local scale that will be induced by human adaptation to climate and water resource availability (Martínez-Valderrama et al., 2016).
- We assume that the climatic fields (P and T) taken from the Spain02 project (Herrera et al., 2016) are good enough to approximate the historical climate.
- The Turc's model (1954, 1961) was applied to estimate E. Its results depend on mean annual T and P. Different non-global empirical models could be applied to assess the historical E from T and P time series.

(3) Hydrological impacts on aquifer status: Seawater intrusion simulation

In this study we decided to employ a variable-density model instead of a sharp-interface solution, which have been extensively used to define management models because of its simplicity in terms of required parameters and computational burden (e.g., Mantoglou et al., 2004). This is because they better describe the dynamic of real complex coastal aquifers despite the limitations in the available data and the course discretization used for the Plana Oropesa-Torreblanca aquifer. Better adjustments between observed and modeled hydraulic head and salinity would provide greater confidence in the model predictions. Nevertheless, although due to there are some differences between observed and simulated data the uncertainty of the prediction coming from the model grows and we have to be cautious with the conclusions obtained, the fit is good enough to capture the general trend of the hydraulic head and salinity variables within a quite long calibration period (37 years, from 1973 to 2010), and therefore, to assess general impacts of climate and LULC changes. Note that it is difficult to improve the calibration of the proposed approach in this work for Plana de Oropesa-Torreblanca due to the following facts:

- The hydrogeological complexity of the aquifer makes it difficult to define a better approach taking into account its spatial heterogeneity, with fractured formations and preferential flow channels existing in the aquifer (Morell and Giménez, 1997). The spatial heterogeneity is handled by means of sequential indicator simulation using the computer code ISIM3D (Gómez-Hernández and Srivastava, 1990).
- The quality of some observation data is poor. This problem is accentuated when considering the long simulated time period with historical data, which spans from 1973 to 2010. In this way, for a certain observation borehole there are data close in time with measurements quite disparate, which cannot be explained by any physical phenomenon. A statistical processing of data with expert judgment would be advisable to dismiss the wrong data. We have opted for using all available data (as a transparency measurement and in order to ease the reproduction of this exercise by other researchers).
- The lack of reliable estimates of dispersion coefficients (Naji et al., 1999) may prevent a proper adjustment for the Plana Oropesa-Torreblanca aquifer.
- A better fit might be achieved using a more refined spatial discretization, which would allow modeling the preferential flow channels existing in the aquifer (Morell and Giménez, 1997). However, the high computational burden when solving the variable-density flow and transport equations with SEAWAT prevents the use of a fine grid (e.g. Sreekanth and Datta, 2010).
- As a further research, we are intended to couple the sea water intrusion model with a management simulation–optimization model for control and remediation that would further prevent the use of a fine grid.

(4)Analysis of uncertainty in impacts

In this paper we do not intend to perform a detailed analysis of uncertainty in impacts, which could be deeply analyzed as a further research. In order to assess the uncertainty on hydrological impacts it would be more appropriate to assess results from each individual climate model. Note that it would require 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.

*As we show in the answer to the next reviewer comment (comment number 16), although the assessment of uncertainty out of the scope of the present paper, a proper analysis of it could be performed in **future research works**.*

*We have also rewritten the **CONCLUSION SECTION** in accordance with the discussion peformed:*

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. It has been applied in the Plana Oropesa-Torreblanca aquifer assuming some hypotheses or simplifications.. Representative future CC 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 a coupled 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 salinity. In global terms the intrusion will not grow in the considered potential future scenarios. The impacts on the aquifer salinity will be heterogeneous. We observed specific areas where the situation gets worse and other, where it will clearly improve in the contemplated future horizon due to transformation of irrigated areas to residential use foreseen in the future LULC scenario. They also show 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. We can use this coupled modeling framework to assess potential adaptation measures under different GC scenarios and horizons changing the inputs of the models. In the definition of scenarios and plausible adaptation measures to be analyzed participatory processes including the relevant stakeholders might be essential (Pulido-Velazquez et al., 2015). On the other hand, this modeling framework could be useful in the search for consensus ("shared vision" models) between different stakeholders.

## 9) SOME SPECIFIC POINTS ABOUT THE FIGURES:

**Figure 1: Vertical scale is missing in the figure. Not discussed in the text is the relationship between the carbonate rocks and the detritic aquifer. No explanation of the lithotype in the geologic time scale legend is given. There are too many eastings and northings in the map. Define them only at the corners of the figure. Confusing the color grey used for the aquifer and the Mediterrenean Sea.**

*Following the reviewer suggestion we have updated Figure 1.*

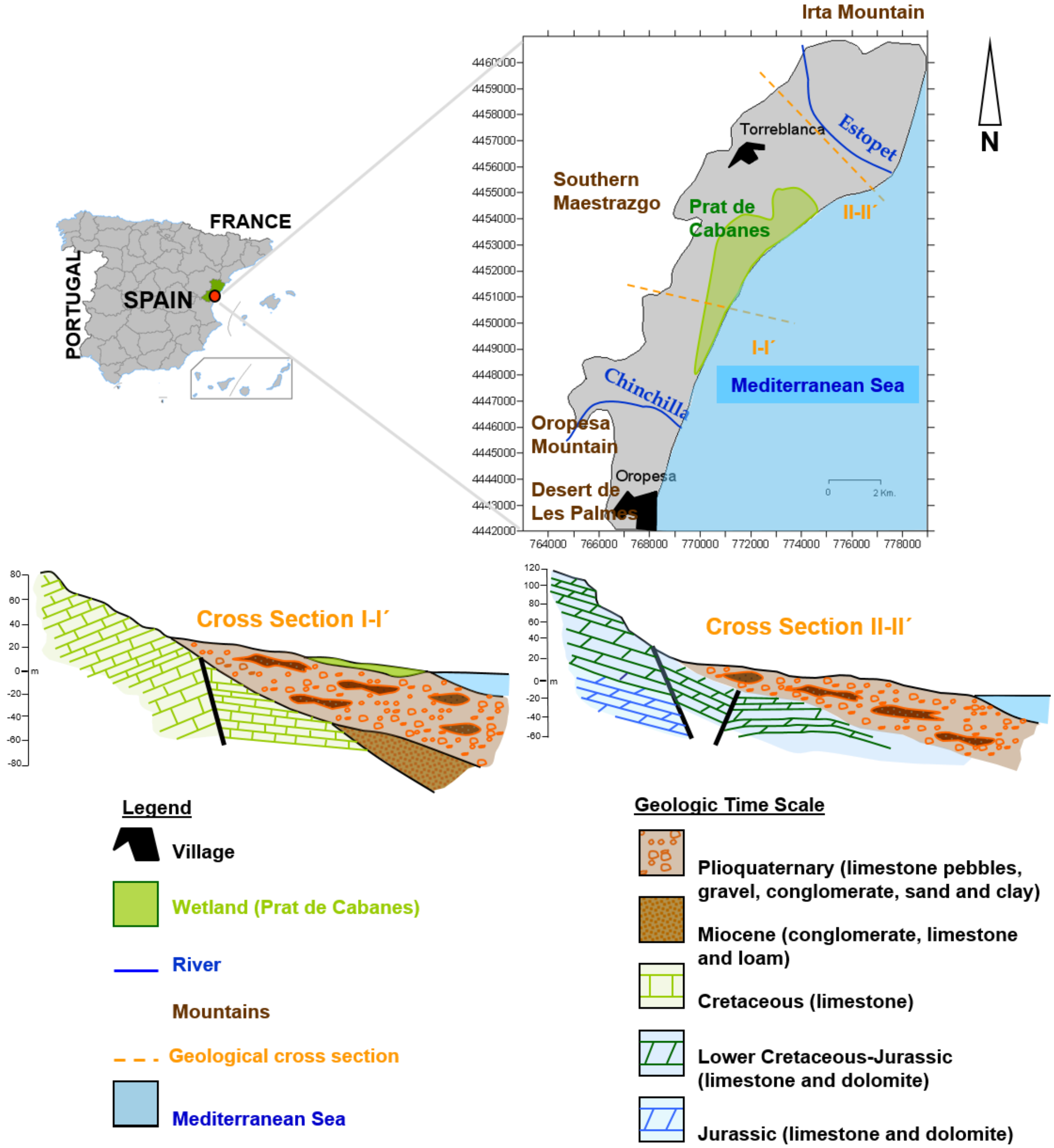



**Figure 2: The CORINE database is not mentioned in the text.**

*Following the reviewer suggestion we have mentioned it within the new version of the manuscript (line 8-10 page 4):*

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 3.2.2.

**Figure 3: The overlap does not allow to distinguish well the data from the two watersheds. Also the choice of color is poor. Maybe use the same color for the same watershed.**

*We have eliminated the overlap in the monthly data and we have changed other aspects to clarify the figure.*

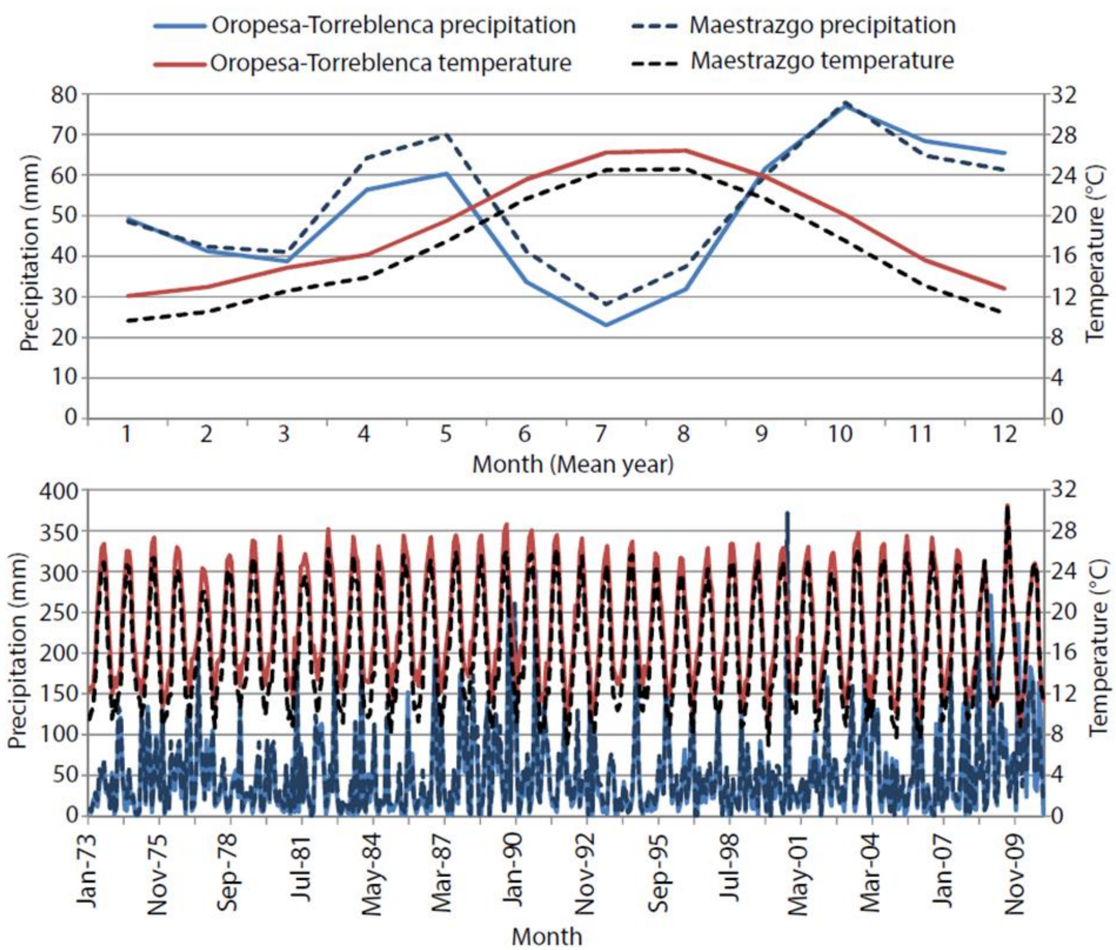



**Figure 5: Please give also some information about the fact that you are presenting climate models data. This caption is not sufficient to understand what kind of data are presented.**

*Done, we have modified the figure caption.*

Figure 6. Monthly mean and standard deviation of the historical and RCMs control series (rainfall and temperature) for the mean year in the period 1976-2000. RCMs data obtained from CORDEX project.

**Figure 6: See my note above. Also here some more information is needed. At least give the time frame for the climate change models.**

*Done, we have modified the figure caption.*

Figure 7. Relative monthly change in mean and standard deviation of the future series (2011-2035) with respect to the control series (1976-2000) for the considered RCMs under the RCP8.5 emission scenario.

**Figure 7: I would have presented this figure much earlier on in the paper.**

*Following the reviewer suggestion we will include it earlier in the new version of the manuscript (Figure 4 instead of Figure 7). This reviewer comment is also linked with the comment number 2 of the reviewer 2 about the organization of the manuscript (Chapter 2.3, 2.4 and 2.5 should be moved to Methods)*

**Figure 8: In wells 6, 23, 20, 8, and 21 there is a large difference between observed and modeled hydraulic head data. This, in a coastal context is not a good thing, because it makes the results of the double-density flow model unreliable. I think that the authors should address this large variability and explain how their flow model is still acceptable in view of this poor correlation.**

*See the answer to comment number 7*

**Figure 8: I find the correlation between observed and modeled salinity very poor also here. Can the authors explain on which basis the results of the models are acceptable as a predictive tool.**

*See the answer to comment number 7*

**Figure 9: It would be nice to separate the inflow from the outflow in this graph, so that it is clear the variation in the total yearly budget (you can do this by using the same color for inflows and different data point symbols; and a different color for outflows . with different data symbols).**

*Following the reviewers' comment we have separated the inflows (orange) and the outflows (blue) in Fig. 10 (Figure 9 in the previous version) and 12.*

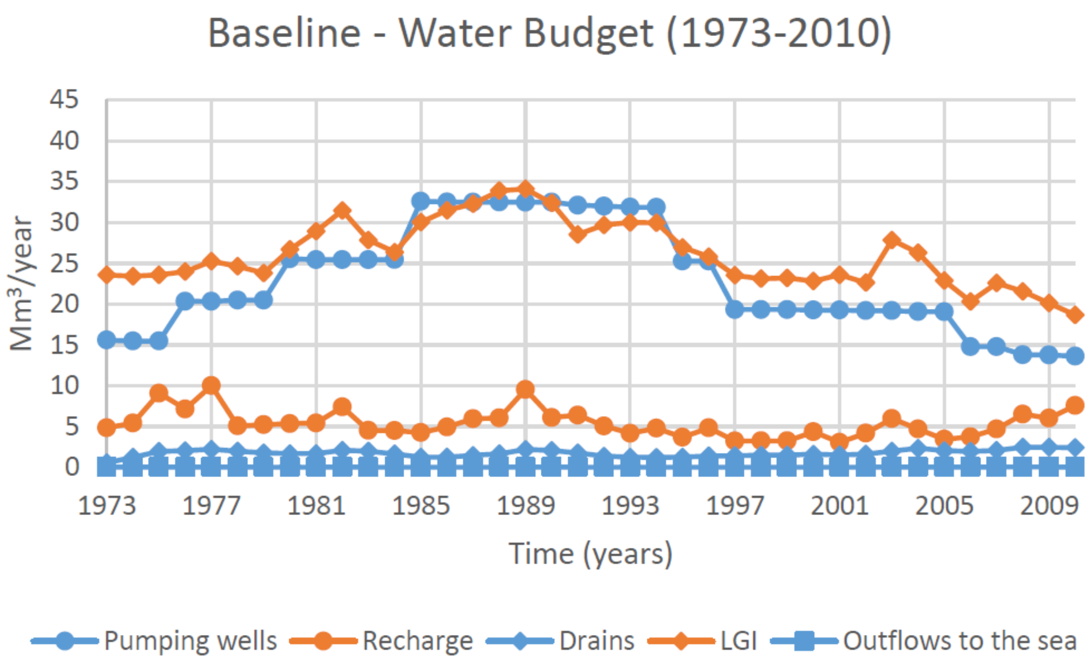



**Fig. 9**

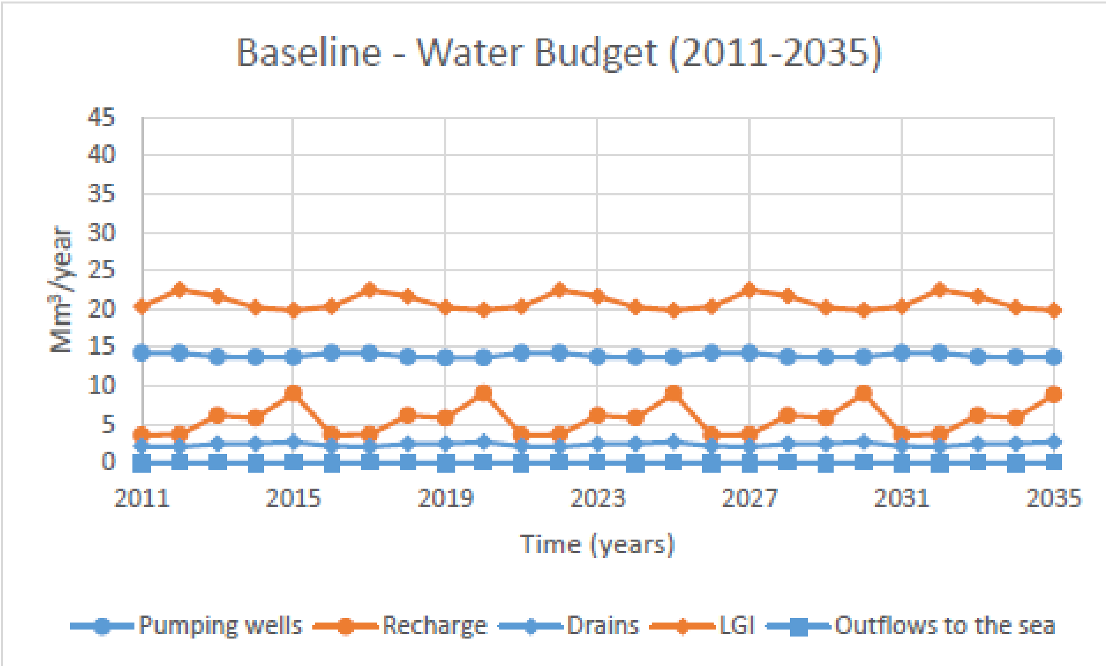
**Figure 11: Specify data are at monthly level.**

*Done, we have provided the information in the figure caption.*

Figure 9. Monthly mean and standard deviation of future precipitation and temperature series obtained by the four ensemble options.

**Figure 12: See my note for Figure 9.**

*As in Figure 10, we have separated the inflows and outflows in the graph.*



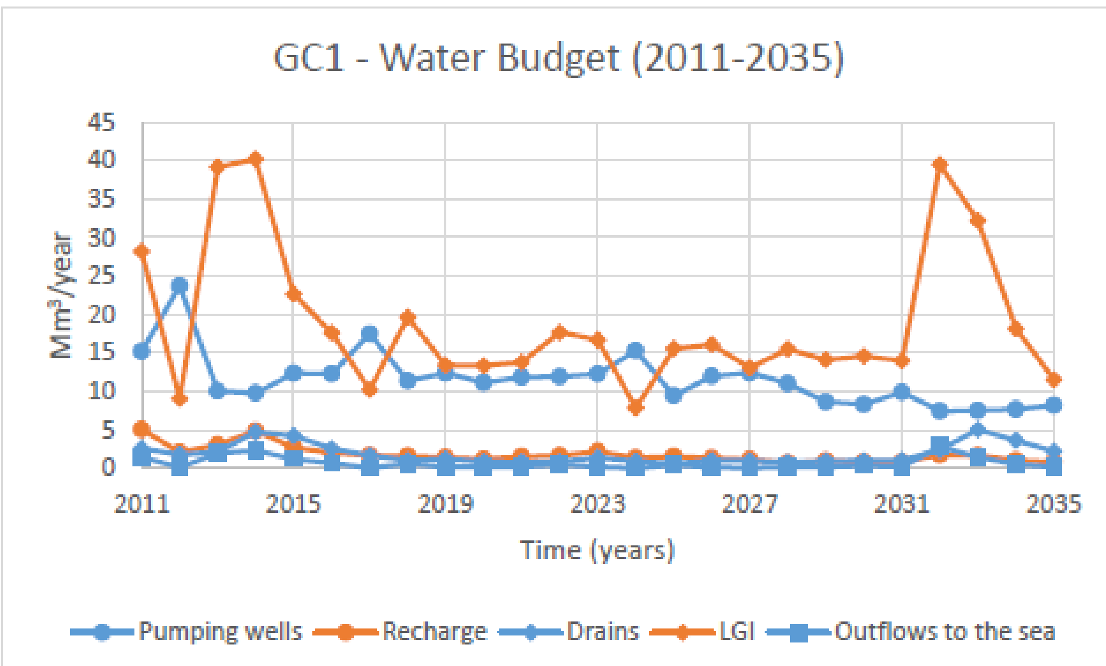




**Fig. 12**

**Figure 13: x axis should be "water budget components". Please specify a little bit better what the different CG's are. Hm3 / year is not a standard flow unit. Please specify.**

*Sorry for the mistake. It is a typo error. It should be GC scenarios (global change scenarios) instead of CG. We have corrected it. The units are Millions of cubic meters per year (Mm3/year), we will also correct it in the new version.*

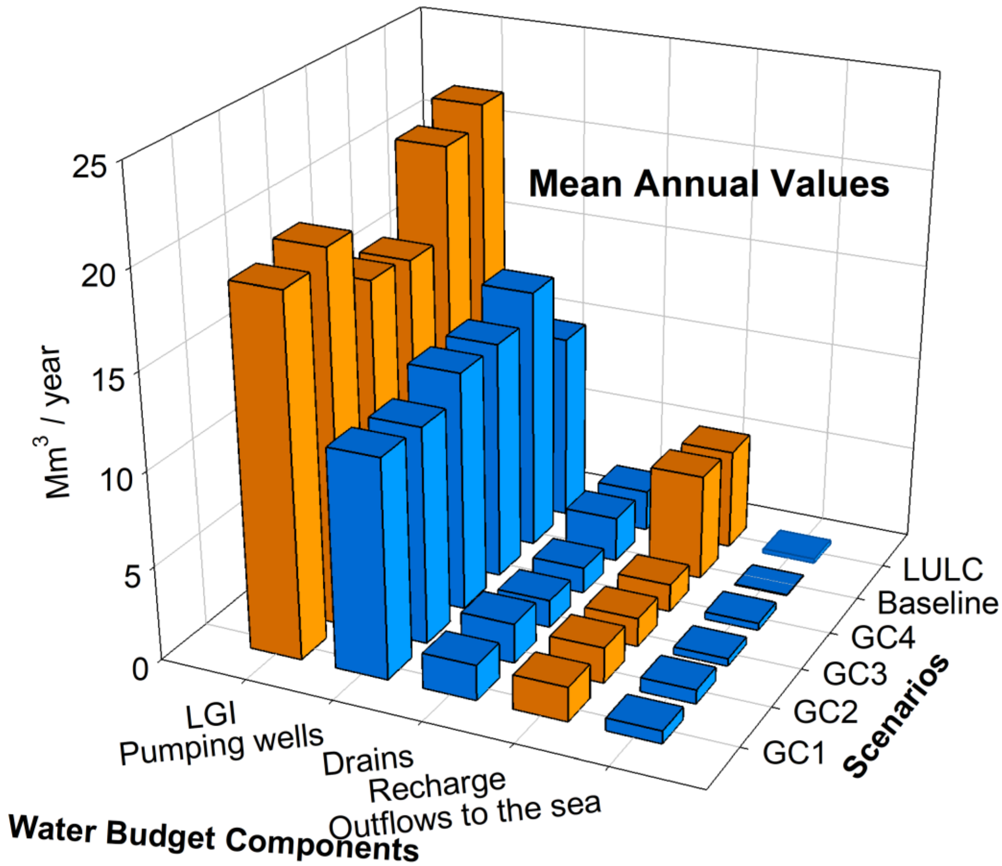



**Figure 13**

**Figure 14: A few words about well locations in the text would be helpful. Also, sometimes you talk about salinity and sometimes about chloride concentration. They are not the same thing. Could you please explain in the text what concentrations unit you are using and why?**

*Following the reviewer suggestion we will include some words describing the location of the wells represented in Figure 14.*

Figure 14 shows the evolution in terms of salinity at 4 specific observation points roughly equispaced. They were selected to cover the extension of the aquifer from north to south (starting with the more northerly and moving towards the south we have observation wells 33, 12, 39 and 21 respectively).

From the results in terms of salinity at specific observation points (Figure 14), we can observe the heterogeneity of the impacts of the LULC scenario and CC scenarios. The area around the observation point 33 is not affected by LULC changes and we only observe sensitivity to CC scenarios that produce a higher variability in the salinity evolution, but the mean trend of the concentration does not change. Around the observation point 12, in Torreblanca area, the LULC change scenario would produce a reduction in the recharge whose impacts can be observed as an increment in the salinity during the first decade of the future horizon. Nevertheless, in the last 10 years the reduction in pumping produced by the successive transformations of irrigated areas to residential land would reduce significantly the salinity. In this Torreblanca area CC scenarios would impact the salt concentration significantly during the first years due to the increment in pumping requirements produced by the higher water irrigation requirements obtained for these CC scenarios. Even considering the impacts of CC scenarios, during the last 10 year of the horizon it starts to recover due to the reduction in pumping produced by the new transformations of irrigated areas to residential land defined in the LULC scenario, being the concentration at the end of the horizon (2035) even under the values obtained for the BL scenario. In the observation point 39, located further away from the coast, the reduction in pumping due to LULC change would reduce the salinity during most of the year of the horizon. Nevertheless the reduction in recharge makes in some years the salinity to get close to the one obtained without LULC changes (BL scenario), being very similar at the end of the period. Again CC scenarios would increase the variability of the salinity in the simulated period.

We can also identify in the southern part areas where the situation will clearly improve throughout the future horizon contemplated with the proposed scenarios. For example, at observation point 21, in Oropesa area, the salinity would be reduced with the contemplated scenarios, which would be mainly related with the reduction of pumping in this area due to the transformation of irrigated areas to residential land defined in the LULC scenario.

*On the other hand, as the reviewer pointed out we have used both terms indistinctly in the text and we have made a mistake when using it within the Figure 14 caption. Instead of chloride concentration it should be salinity concentration. We have used both terms within the manuscript because data is provided as chloride concentration, while in SEAWAT simulations we use salinity (mg/l) as concentration unit. The conversion is performed according to the following equation (e.g., Williams and Sherwood, 1994):*

$$S\ ({}^{o}/_{oo}) = 1.80655 \times Cl^{-}\ ({}^{o}/_{oo})$$

*where S is salinity and Cl- is Chlorinity.*

*Williams, W.D., Sherwood, J.E.(1994). Definition and measurement of salinity in salt lakes. International Journal of Salt Lake Research 3(1), 53–63.*

**10) I have attached a file with detailed requests for explanation in the text, some English corrections and suggestions. I hope this is helpful.**

*We sincerely appreciate the annotations provided by the reviewer in the attached file as complementary material. It has helped us to identify the paragraphs and sentences that are not clear enough. Following the reviewer suggestions we have modified and improved them within the new version of the manuscript. They have been really helpful to improve the clarity of the exposition.*

*********************************************************************

**Reviewer #2 Comments to Author:**
*********************************************************************

**1) Unfortunately, the manuscript is not ready for publication yet. Below, a number of critical issues are raised, including methods, discussion and results.**

*We have made an important effort in order to improve the manuscript in accordance with the valuable comments provided by both reviewers.*

**2) Organization: Chapter 2.3, 2.4 and 2.5 should be moved to Methods**

*Following the reviewers' comment we have moved those chapters to the Method section.*

**3) Methods: The applied modeling system is described as "integrated". However, there are no feed-backs in the system so it is misleading to call it integrated. A term like "coupled" would be more appropriate.**

*Following the reviewers' comment we have changed "integrated modeling framework" by "coupled modeling framework" throughout all the manuscript.*

**4) It is not clear how the rainfall-recharge model was calibrated – which data and which period. Results on calibration missing.**

*Thank to the reviewer comment we have realized that the rainfall recharge model needed a more detailed and clear description within the manuscript. In order to explain it more properly we have modified section 3.1.1 (rainfall Recharge model): See line Line 10-28 page 8:*

Based on the historical climate (rainfall and T) and recharge series for the period 1973-2010 described in sections 2.2, we define a simple empirical rainfall-recharge approach to generate yearly aquifer recharge series. The model assumes that P and T are the most important climatic variables determining potential aquifer recharge, and the variability of both of them will determine the impacts of future potential climatic scenarios.

It intend to define a correction function for the perturbation of the historical series defined as the difference in P and evapotranspiration (ETR) (hereafter referred to as PE series), modifying its mean and standard deviation to make them equal to the statistic of the historical aquifer recharge previously deduced from the lysimeter measurements (see section 2.2), as follows:

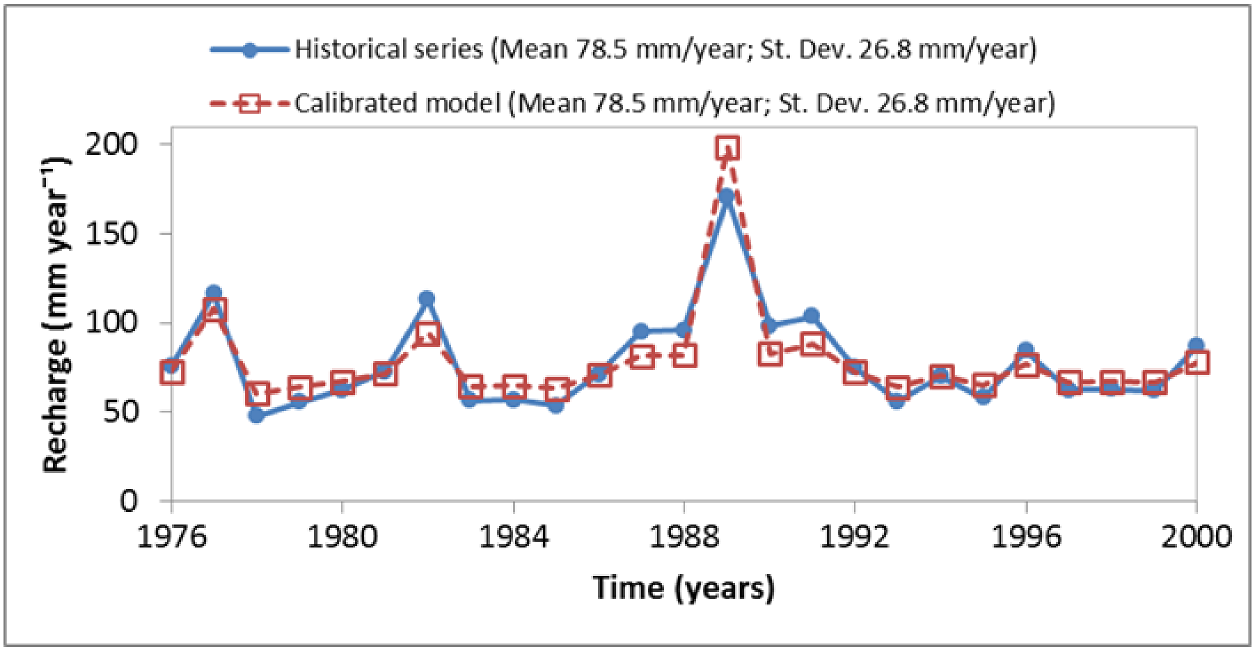
$$R_i = PEn_i.\sigma_R + \bar{R} \qquad (1)$$

where $R_i$ is the recharge series generated for the year i, $\sigma_R$ and $\bar{R}$ are the standard deviation and mean of the historical recharge series estimated using the infiltration rate coefficient obtained from previous lysimiter readings (Tuñon, 2000), and $Pn_i$ is the normalised historical PE series (P-E) obtained from:

$$\mathrm{Pn_i} = \frac{\mathrm{PE_i} - \overline{\mathrm{PE}}}{\sigma_{\mathrm{PE}}} \quad (2)$$

where $\mathrm{PE_i}$ is the historical PE series for the year i, and $\sigma_{\mathrm{PE}}$ and $\overline{\mathrm{PE}}$ are the standard deviation and mean historical values of the series. Taking the positive relationship of T and E into account (Arora, 2002; Gerrits et al., 2009), changes in T will determine the available non-evaporative fraction of P available for aquifer recharge. Different non-global empirical models could be applied to assess the historical E from T series (e.g., Turc, 1954, 1961; Coutagne, 1954; Budyko, 1974; amongst others) as described in Arora (2002), Gerrits et al. (2009), and España et al. (2013). In this study, we applied Turc's model (1954, 1961), in which the results depend on mean annual T and solar irradiation over the latitude.

*Next Figure shows the historical yearly evolution of the rainfall recharge in the aquifer obtained with the calibrated model and the historical series based on the lysimeter measurements:*





**REFERENCES:**

*Arora, V.K.: The use of the aridity index to assess climate change effect on annual runoff, Journal of Hydrology, 265, 164-177, 2002.*

*Budyko, M.I.: Climate and Life, Academic Press, New York, 508pp, 1974.*

*Coutagne, A.: 1954. Quelques considérations sur le pouvoir évaporant de l'atmosphere, le déficit d'écoulement effectif et le déficit d'écoulement maximum, La Houille Blanche, 360-369, 1954.*

*España, S., Alcalá, F.J., Vallejos, A., and Pulido-Bosch, A.: A GIS tool for modelling annual diffuse infiltration on a plot scale, Computers & Geosciences, 54, 318-325, 2013.*

*Gerrits, A.M.J., Savenije, H.H.G., Veling, E.J.M., Pfister, L.: Analytical derivation of the Budyko curve based on rainfall characteristics and a simple evaporation model. Water Resour. Res., 45, W04403, doi:10.1029/2008WR007308, 2009.*

*Kirn, L., Mudarra, M., Marín, A., Andreo, B., and Hartmann, A.: Improved Assessment of Groundwater Recharge in a Mediterranean Karst Region: Andalusia, Spain. In: Renard P., Bertrand C. (Eds.) EuroKarst 2016, Neuchâtel, Advances in Karst Science, 117-125, Springer, Cham, DOI: 10.1007/978-3-319-45465-8_13, 2017*

*Turc, L.: Water balance of soils: relationship between precipitation, evapotranspiration and runoff (in French), Ann Agron 5, 49-595 and 6, 5-131, 1954.*

*Turc, L.: Estimation of irrigation water requirements, potential evapotranspiration: A simple climatic formula evolved up to date, Annales Agronomiques, 12(1), 13-49, 1961.*

**5) It is not clear how spatial heterogeneity (it must be significant in this area) is handled. –**

*Following the reviewer's suggestion we have described it with more detail within the revised version of the manuscript (line 31 page 9 – 8 page 10 of the new version of the manuscript)*

The groundwater model covers the Pli-Quaternay and Pre-Quaternary formations. The spatial heterogeneity is tackled using the concept of multiple statistical populations (Llopis-Albert and Capilla, 2010), in which the rock matrix and each fracture is represented as independent statistical population. The random function for each structure (i.e., the aquifer matrix and fractures) is modeled based on a geostatistical analysis conditionated to its own statistical distribution (i.e., hydraulic conductivity data as well as geological information and expert judgment). The random function is supposed to be as MultiGaussian for the rock matrix, while the fractures are considered as non-MultiGaussian. In this way, the rock matrix is generated by sequential Gaussian simulation using the code GCOSIM3D (Gómez-Hernández and Srivastava, 1990), while the fractures are generated by sequential indicator simulation using the code ISIM3D (Gómez-Hernández and Journel, 1993). The latter code makes use of local conditional cumulative density functions (ccdfs) defined by conductivity measurements and the corresponding indicator variograms. Therefore, the spatial heterogeneity is modeled as an equivalent porous media (e.g., Llopis-Albert and Capilla, 2010). On the one hand, the hydraulic conductivity data for fractures presents high values, greater than 1000 m/d. This allows the reproduction of strings of extreme values of hydraulic conductivity that often take place in nature and can be crucial in order to obtain realistic and safe estimations of mass transport predictions. That is, it allows reproducing preferential flow channels in strongly heterogeneous aquifers or fractured formations. On the other hand, the hydraulic conductivity data for the aquifer matrix cover a wide range of values, i.e., from 5 to 200 m/d. In addition, for each cell we have defined a vertical hydraulic conductivity equal to a tenth of the horizontal hydraulic conductivity. The position of fractures is deterministically incorporated in the model based on geological information and expert judgment, thus allowing to classify the cell models. Those cells of the model intersected by a fracture are assigned conductivities according to the intersecting fracture, and those that are not are considered as cells belonging to the rock matrix.

*REFERENCES:*

*Llopis-Albert, C., Capilla, J.E. (2010). Stochastic inverse modelling of hydraulic conductivity fields taking into account independent stochastic structures: A 3D case study. Journal of Hydrology, 391(3–4), 277-288. DOI: 10.1016/j.jhydrol.2010.07.028.*

*-Gómez-Hernández, J. J., and Journel, A. G. (1993). "Joint simulation of MultiGaussian random variables." Geostatistics tróia′92, A. Soares, ed., Vol. 1, Kluwer, Dordrecht, The Netherlands, 85–94.*

*-Gómez-Hernández, J.J., Srivastava, R.M. (1990). ISIM3D: An ANSI-C three dimensional multiple indicator conditional simulation program. Computer and Geosciences 16 (4), 395–440.*

**6) Which area do the groundwater model cover? Do the groundwater model describe both the Plioquaternary and the prequaternary formations?**

*The groundwater flow model describes both formations. The K data cover both formations, so that the K field obtained using the ISIM3D code also takes them into account.*
*(see line 31 page 9 of the new version of the manuscript):*

The groundwater model covers the Pli-Quaternay and Pre-Quaternary formations.

**7) Do the model take into account that the formations are fractured?**

*Note that one of the main advantages of the ISIM3D code is that it does not require assuming the classical multiGaussian hypothesis, which allows the reproduction of strings of extreme values of K that often take place in nature and can be crucial in order to obtain realistic and safe estimations of mass transport predictions. That is, it allows reproducing preferential flow channels in strongly heterogeneous aquifers or fractured formations. Therefore the model takes into account the fractured formations. Following the reviewers' comment this considerations have been added to the manuscript (see new version of section 3.1.3 (section 3.2.3); see also answer to question 5).*

**8) 11 model layers are used – is that sufficient to avoid too much numerical dispersion?**

*Note that we need to balance the use of a more refined discretization (in order to reduce the numerical dispersion) and the computational burden when solving the variable-density flow and transport equations with SEAWAT. Hence, the computational cost prevents the use of a finer grid (e.g. Sreekanth and Datta, 2010).*
*Furthermore, according to Guo et al., (2002) experience suggests that 10 model layers per aquifer unit seem to be adequate, but users are encouraged to perform numerical experiments with different levels of grid resolution in order to determine the most appropriate number of*

*layers. Experience also has shown that models designed with spatially uniform cell volumes are less prone to numerical instabilities than models designed with variable cell volumes.*

*Then, following these recommendations we have used spatially uniform cell volumes and 11 model layers.*

*-Guo, Weixing, and Langevin, C.D., 2002, User's guide to SEAWAT: A computer program for simulation of three-dimensional variable-density ground-water flow: U.S. Geological Survey Techniques of Water-Resources Investigations, book 6, chap. A7, 77 p.*

*-Sreekanth J, Datta B. 2010. Multi-objective management of saltwater intrusion in coastal aquifers using genetic programming and modular neural network based surrogate models. Journal of Hydrology 393: 245–256.*

*In order to clarify it within the text of the new version of the manuscript we have added the next sentence (line 22-25 page 9 of the new version of the manuscript):*

We adopted a vertical discretization consist of 11 layers in order to avoid a high computational cost (e.g. Sreekanth and Datta, 2010) while maintaining reasonable levels of numerical dispersion and representing complex flow patterns near areas of high concentration gradients (Guo and Langevin, 2002) .

**9) It is stated that inverse modeling is not used "due to the complexity of the case study dealt with". Does that imply that auto-calibration cannot be used for complex systems? If that is what you mean, please argue why.**

*The reviewer is right. We apologize for not expressing ourselves sufficiently clearly. We have rewritten this phrase to avoid misunderstanding and possible interpretations of the reader regard that auto-calibration cannot be used for complex systems (see line 11-14 page 10):*

We have not used an inverse model (eg. Llopis-Albert et al., 2016) because its computational cost would be important in order to deal with such quantity of parameters (hydraulic conductivity, storativity, porosity, dispersion coefficients …) and variables (hydraulic head and salinity) within a seawat model over a long period of time (from 1973 to 2010), so that we have decided to apply a trial and error procedure.

**10) As a minimum the match to the observations should be quantified by a few statistics (e.g., Mean Error, Root Mean Squared value)**

*In accordance with this reviewer's comment we have included the root mean square value (RMS) within the manuscript (line 25-32 page 10).*

The root mean square value (RMS) of the departures between observed and simulated values for both, piezometric heads and salt concentrations, is presented for the whole domain and temporal discretization due to the large number of boreholes (21 boreholes for piezometric heads and 31 for salinity). These values are $\eta_h$ = 0.7 m; $\eta_c$ = 391.8 mg/l.

Note that this $\eta_h$=0.7 m could seems to be a little high but we should take into account that we have observation wells where the historical hydraulic head measurement fluctuates sometimes more than 6 m during the same month (see for example observation well 6). Note that the high value for $\eta_c$ =391.8 mg/l could be also explained by the scale of the salt concentration, which range from 0 to 35000 mg/l, and the measurement fluctuations, which in some wells is even higher than 4000 mg/l during some months.

*Some other comments regarding the calibration have been included in the new section 4.1 Hypotheses and limitations. Usefulness of the results.*

**11) Future climate signals are found by averaging the results from the available climate models and subsequently feed this averaged signal into the hydrological models. Alternatively, results from each individual climate model should have been used as input to the hydrological model system and averaged afterwards. Please document that the method used is appropriate.**

*The reviewer is right. In order to assess the uncertainty on hydrological impacts it would be more appropriate to obtain results from each individual climate model. Nevertheless, in this paper we do not intend to perform a detailed analysis of uncertainty, which could be deeply analyzed as a further research. Our main target is to provide an estimate of the most representative plausible future climate scenarios. For this reason we propose to simulate 4 plausible representative climate scenarios defined by ensemble of different climate models, which provide a better approach of future climate scenarios than taking directly a scenarios defined by a single model. The 'ensembles' coalesce and consolidate the results of individual climate projections, thus allowing for more robust climate projections that are more representative than those based on a single model (Spanish Meteorologial Agency, AEMET, 2009).*
*In order to clarify it within the new version of the manuscript we have added the next paragraph (line 37 page 5 – 5 page 6):*

Our main target is to provide an estimate of the most representative plausible future climate scenarios. For this reason we propose to generate and propagate 4 plausible representative climate scenarios defined by ensemble of different climate models, which provide a better approach of future climate scenarios than taking directly a scenarios defined by a single model. The 'ensembles' coalesce and consolidate the results of individual climate projections, thus allowing for more robust climate projections that are more representative than those based on a single model (Spanish Meteorological Agency, AEMET, 2009). In this paper we do not intend to perform a detailed analysis of hydrological uncertainty. In this case, in order to assess the uncertainty on hydrological impacts it would be more appropriate to obtain results from each individual climate model.

*On the other hand, we think that we made a mistake including the word uncertainty in the title. We have removed it in the new version of the manuscript; because it could produce misunderstand about the target of the paper.*

*REFERENCE:*

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

**12) Details on the downscaling methods completely missing. There are many versions of what you call "bias correction" – which one did you use?**

*We used a correction of the first and second moments analogous to those one applied by Pulido-Velazquez et al. (2014) for the delta change approach. The difference with those one is that, in the bias correction approach, the perturbation is defined or calibrated by modifying some statistics (first and second moments) of the control series in order to make them identical to the historical ones. It assumes that this perturbation will be maintained invariant during the future.*

*In order to clarify it within the new version of the manuscript we have added the next sentence in the new version of the manuscript (line 35-39 page 6):*

The correction of the first and second moments for the delta change approach was defined at monthly scale as described in Pulido-Velazquez et al. (2014). The bias correction case was also defined in an analogous way. The difference is that the perturbation is defined by modifying the statistics (first and second moments) of the control series to approximate the historical ones. It will be applied assuming to correct the future assuming that will be invariant.

*REFERENCE:*

*Pulido-Velazquez, D., García-Aróstegui, J.L., Molina, J.L., and Pulido-Velázquez, M.: Assessment of future groundwater recharge in semi-arid regions under climate change scenarios (Serral-Salinas aquifer, SE Spain). Could increased rainfall variability increase the recharge rate?, Hydrol. Process., 29(6), 828-844, doi:10.1002/hyp.10191, 2014.*

**13) How was the delta change method applied – monthly, yearly?**

*It was applied monthly in analogous way as presented in the previous work published by Pulido-Velazquez et al. (2014). We have specified it in the new version of the manuscript:*

The correction of the first and second moments for the delta change approach was defined at monthly scale as described in Pulido-Velazquez et al. (2014). The bias correction case was also defined in an analogous way. The difference is that the perturbation is defined by modifying the statistics (first and second moments) of the control series to approximate the historical ones. It will be applied assuming to correct the future assuming that will be invariant.

*REFERENCE:*

*Pulido-Velazquez, D., García-Aróstegui, J.L., Molina, J.L., and Pulido-Velázquez, M.: Assessment of future groundwater recharge in semi-arid regions under climate change scenarios (Serral-Salinas aquifer, SE Spain). Could increased rainfall variability increase the recharge rate?, Hydrol. Process., 29(6), 828-844, doi:10.1002/hyp.10191, 2014.*

**14) RESULTS: The result section is very short and does actually not explain why the presented results are obtained. For example, why is the impact of sea level rise to insignificant? What is most important – climate change or LULC changes?**

*We agree with the reviewer. Following his suggestion we have extended the results and discussion section (line 13 page 11 – 26 page 12) in order to explain the presented results.*

*For example, we have included a comment related with the questions asked by the reviewer about the sensitivity to SLR (line 19-22 page 12):*

The low sensitivity of the results should be due to the maximum value of SLR considered, 0.19m in 2035, is quite low with respect to the level fluctuations experienced in most of the observation wells (see Figure 15). For this reason the sensitivity of the flow and transport solutions are low.

*In order to ask the question about the significance of climate change and LULC changes we have defined an additional scenario and we have simulated it. It considers future LULC assuming that there is not climate change, which would help to analyses and discuss in a quantitative way the relative significance of the impacts of climate change and LULC future scenarios.*

*The scenario has been defined in section 3.3:*

In order to assess the potential impacts of the future LULC scenario (LULC scenario) and different 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 LI 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) LULC scenario: It considers the described future LULC scenario and assumes that there is not CC.

*The results obtained have been included in Figure 13 and 14.*

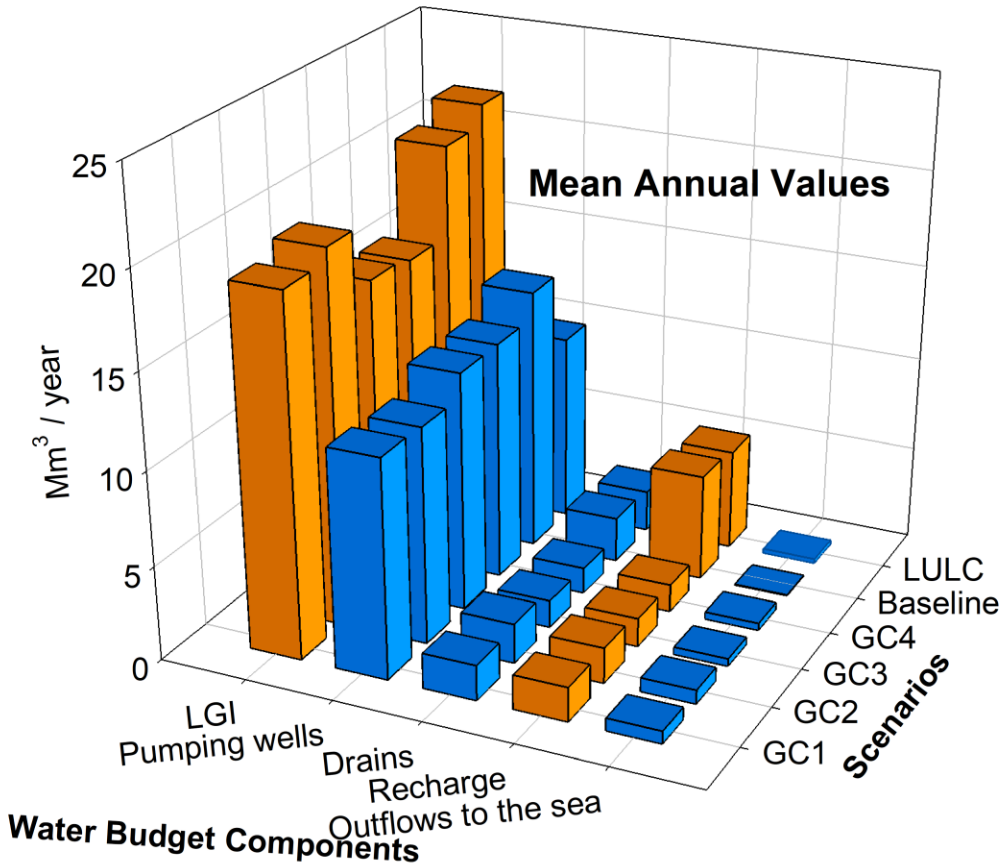
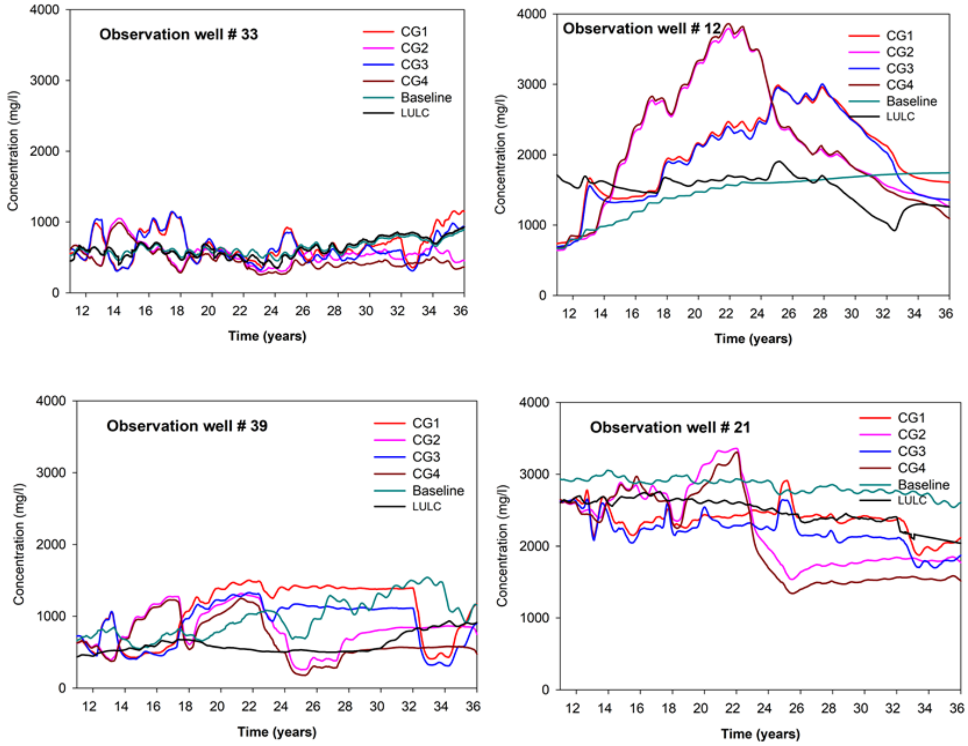



**Figure 13: Mean inflows and outflows for various global scenarios (GC1, GC2, GC3, GC4).**




**15) DISCUSSION: - There is no discussion of the results and this is critical. The manuscript cannot be published without a proper discussion of the results. This includes a comparison of methods and with results from other studies.**

*Following the reviewers' comment we have done our best to improve the results and discussion section (line 13 page 11 – 26 page 12) within the revised version of the manuscript. As commented in the answer to the previous reviewer question we have improved the result section, including and explaining new results. On the other hand we have also added some paragraph to discuss methods and results* ***comparing with other previous approaches*** *and studies.*

*For example, from a methodological point of view, we have added the next paragraph (line 14-16 page 11 of the new version of the manuscript) comparing with other previous studies:*

The proposed approach has similarities with the one described by Pulido-Velazquez et al. (2015), in which an integrated analysis of GC is performed including CC and LULC changes. The most important differences are related with the fact that a coastal aquifer is studied and we consider quality issues simulating with a variable density flow and transport model.

*In the discussion of results, the next comments have been added with respect to the significance of LULC with respect to CC in other previous studies:*

Figure 14 shows the evolution in terms of salinity at 4 specific observation points roughly equispaced. They were selected to cover the extension of the aquifer from north to south (starting with the more northerly and moving towards the south we have observation wells 33, 12, 39 and 21 respectively).

From the results in terms of salinity at specific observation points (Figure 14), we can observe the heterogeneity of the impacts of the LULC scenario and CC scenarios. The area around the observation point 33 is not affected by LULC changes and we only observe sensitivity to CC scenarios that produce a higher variability in the salinity evolution, but the mean trend of the concentration does not change. Around the observation point 12, in Torreblanca area, the LULC change scenario would produce a reduction in the recharge whose impacts can be observed as an increment in the salinity during the first decade of the future horizon. Nevertheless, in the last 10 years the reduction in pumping produced by the successive transformations of irrigated areas to residential land would reduce significantly the salinity. In this Torreblanca area CC scenarios would impact the salt concentration significantly during the first years due to the increment in pumping requirements produced by the higher water irrigation requirements obtained for these CC scenarios. Even considering the impacts of CC scenarios, during the last 10 year of the horizon it starts to recover due to the reduction in pumping produced by the new transformations of irrigated areas to residential land defined in the LULC scenario, being the concentration at the end of the horizon (2035) even under the values obtained for the BL scenario. In the observation point 39, located further away from the coast, the reduction in pumping due to LULC change would reduce the salinity during most of the year of the horizon. Nevertheless the reduction in recharge makes in some years the salinity to get close to the one obtained without LULC changes (BL scenario), being very similar at the end of the period. Again CC scenarios would increase the variability of the salinity in the simulated period.

We can also identify in the southern part areas where the situation will clearly improve throughout the future horizon contemplated with the proposed scenarios. For example, at observation point 21, in Oropesa area, the salinity would be reduced with the contemplated scenarios, which would be mainly related with the reduction of pumping in this area due to the transformation of irrigated areas to residential land defined in the LULC scenario.

As commented above the expected results without considering GC impacts are likely to be too pessimistic or optimistic, depending on the location. These results can be useful for the authorities in charge of implementing management policies in the Plana de Oropesa Torrablanca. We can use this coupled modeling framework to assess potential effect of adaptation measures to GC by modifying the inputs of the models. Participatory processes including the relevant stakeholders might be essential in the definition of scenarios and successful adaptation measures (Pulido-Velazquez et al., 2015). This modeling framework could be useful in the search for consensus ("shared vision" models) between different stakeholders.

*We have also added the next paragraph respect to the sensitivity of the results to SLR comparing with other previous studies:*

We find in the literature other examples in which the sensitivity of seawater intrusion to the SLR would be low. Chan et al. (2011) obtained this conclusion in a synthetic confined coastal aquifer in which recharge in unchanged;

Rasmussen et al. (2013) obtained the same conclusion for an inland coastal aquifer with minor SLRs. Nevertheless other authors, as Werner and Simmons (2009) showed that in unconfined aquifers the influence of the inland boundary condition can be significant to its sensitivity to SLR.

**16) Uncertainty: The uncertainty of the results are not touched at all. Considering the chain of model component that are used the total uncertainty of the obtained results must be significant. A discussion of this element is mandatory. Quantification would be even better.**

*We think that we made a mistake including the word uncertainty in the title and we propose to remove it, because it could produce misunderstand about the target of the paper. We agree with the reviewer that a deeper and broader treatment of the uncertainty would be advisable. However, we consider this is out of the scope of the present paper. Note that it would require to deal with different sources of uncertainty. 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.*

*There are numerous classification schemes for sources of uncertainty in the literature. In this sense, the uncertainties covered in this work could be summarized as (Matott et al., 2009):*
*-Parameter, model, and modeller uncertainty.*
*-Initial system state, parameter, input, and output uncertainty.*
*-Context, input, parameter, structural, and technical uncertainty.*
*-Statistical variation, subjective judgment, linguistic imprecision, variability, inherent randomness, disagreement, approximation.*

*There are also a lot of quantitative methods and tools for uncertainty assessment in integrated models (Matott et al., 2009), which would be worth a paper by itself when applied to the Plana Oropesa-Torreblanca aquifer.*
*Data analysis (DA): to evaluate or summarize input, response, or model output data.*
*Identifiability analysis (IA): to expose inadequacies in the data or suggest improvements in the model structure.*
*Parameter estimation (PE): to quantify uncertain model parameters using model simulations and available response data.*
*Uncertainty analysis (UA): to quantify output uncertainty by propagating sources of uncertainty through the model.*
*Sensitivity analysis (SA): to determine which inputs are most significant screening, local, global.*
*Multimodel analysis (MMA): to evaluate model uncertainty or generate ensemble predictions.*
*Bayesian networks (BN): to combine prior distributions of uncertainty with general knowledge and site-specific data to yield an updated (posterior) set of distributions.*

*As a further research we could apply some of these models and techniques to deal with the uncertainty.*

*Following the reviewers' comment this consideration has been added to the manuscript within the limitation section.*

- *Matott, L. S., J. E. Babendreier, and S. T. Purucker (2009), Evaluating uncertainty in integrated environmental models: A review of concepts and tools, Water Resour. Res., 45, W06421, doi:10.1029/2008WR007301.*

# 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 (GC) 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~~behavior. They are also fed with series representatives of potential global change ~~GC~~ scenarios in order to perform a sensitivity analysis regarding future scenarios of rainfall recharge, lateral flows coming from~~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~~GC 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~~salinity. 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 (P) 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 ~~global change (~~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 studies~~also studied~~ considers quality impacts, though groundwater quality can be affected by GC in many different ways (~~-~~Pulido-Velazquez et al., 2014; Dragoni and Sukhija, 2008). Only some of them are focused ~~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 use them as inputs~~feed~~ of 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 is steady~~n~~ ~~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~~GC 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 seawater~~altwater~~ 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~~GC 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~~GC scenarios involving different sources of uncertainty (Section 3.1). A~~n 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 along~~, with a length~~ of 21 Km~~,~~ being its inland dimension in a range ~~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~~meters 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 1% to 13% with the highest porosity nearest to the coastline. Inflows to the system consist of lateral groundwater transfers coming from adjacent aquifers, infiltration from ~~precipitation~~ P 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 carbonate basement receives the contributions coming from the bordering aquifer (Maestrazgo aquifer) and feeds the detrital aquifer. The direction of the groundwater flow is from the carbonate basement to the detrital aquifer.

The Prat de Cabanes is a wetland located in the ~~centre~~center 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~~meters 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 coupled~~integrated~~ modelling framework described in Section 3:

2) 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 3.2~~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%.

3) Historical rainfall and temperature (T) 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 3.2~~1~~.2~~1~~.)

4) 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 these series is included in ~~Figure 9 in~~ Section 3.~~1~~2.3 (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 with similar characteristic (Plana de Castellón; Tuñon, 2000). It has been used to generate historical series of rainfall recharge by applying an infiltration coefficient directly to P data, which is a simple approximation commonly applied (Kirn et al., 2016). 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).

~~1)~~2) Irrigation return coefficients for the crops in the area where taken from a previous study performed by Tuñon (2000). They have been used to assess return from irrigation demands.

~~2)~~3) Hydraulic heads and salinity~~concentrations~~ in different observation wells.

The available observation network (21 points of hydraulic head and 31 points for salinity~~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~~is described in Section 3.~~1~~2.3 (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 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. Method. Application to the case studys

The flowchart of the method has been represented in Figure ~~1~~4. It summaries the steps that we propose to follow in order to perform an integrated assessment of potential GC scenarios~~ of climate and land use change in the aquifer~~. First of all, we propose and approach to generate future potential GC scenarios (section 3.1) considering, LULC, CC and SLR. Then, a~~A~~ modelling framework (Section 3.~~1~~2) 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. Finally, i~~I~~t ~~was~~ is used to propagate~~simulate~~ the generated potential future ~~global change~~GC 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 Generation of future ~~Global change~~GC scenarios

They have been defined by combining the future LULC scenario approved in the General Town Plans in the area and the generated CC and SLR scenarios.

#### 3.1.1 Future LULC change scenarios

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. 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.

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 industrial. Even along the coast, to the north of Prat de Cabanes, is the projected ~~urbanisation~~urbanization – included in the so-called 'Integrated Activity Plan' (PAI) – of Doña Blanca Golf (Figure 5).

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 5). 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.

### 3.1.2 Generation of potential future climate scenarios for the system

We propose a method to generate consistent potential future climate scenarios for a short-term horizon (2011-2035) from the historical (1973-2010) data (see section 2.2) and the climate models simulations performed in the frame of the CORDEX EU project (2013). 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 have been adopted to define more representative potential future climate scenarios to be employed in the groundwater impacts study. Our main target is to provide an estimate of the most representative plausible future climate scenarios. For this reason we propose to generate and propagate 4 plausible representative climate scenarios defined by ensemble of different climate models, which provide a better approach of future climate scenarios than taking directly a scenarios defined by a single model. The 'ensembles' coalesce and consolidate the results of individual climate projections, thus allowing for more robust climate projections that are more representative than those based on a single model (Spanish ~~Meteorologial~~Meteorological Agency, AEMET, 2009). In this paper we do not intend to perform a detailed analysis of hydrological uncertainty. In this case, in order to assess the uncertainty on hydrological impacts it would be more appropriate to obtain results from each individual climate model.

- **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. Figure 6 shows a significant bias between the historical data and the control simulation that will force us to apply a correction technique to generate future scenarios ~~(see Section 3.2)~~.
We also observe important differences between the statistic of future (2011-2035) and control (1976-2000) series (rainfall and ~~temperature~~T) for each RCM (Figure 7).

- **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 present study we apply both conceptual approaches (bias correction and delta change techniques).

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 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 historical data available for our systems is usually more detailed than those adopted by the climate model and, therefore, these transformations indirectly produce solutions with higher spatial resolution than the RCM one. 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). The correction of the first and second moments for the delta change approach was defined at monthly scale as described in Pulido-Velazquez et al. (2014). The bias correction case was also defined in an analogous way. The difference is that the perturbation is defined by modifying the statistics (first and second moments) of the control series to approximate the historical ones. It will be applied assuming to correct the future assuming that will be invariant. 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 Figure 8.

- **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 we applied the multi-criteria analysis proposed by Pulido-Velazquez et al.. (2014). It ~~itends~~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. The dominated 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 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.

- **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 ($E_i$) were generated by a linear combination of all the future series generated by delta change ($E_1$) or bias correction ($E_2$). 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). They do not consider the eliminated options because they provide inferior approximations to the historical series that make us mistrust their predictions.

All ensemble predictions show very similar increase in mean ~~temperature~~T (see Figure 9). The standard deviation estimated with the delta change approaches are quite similar to the historical, but both ensembles defined by applying bias correction show smaller standard deviations.

A reduction in future mean rainfall is predicted by all the ensembles for every month except September and October, 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. During September and October in this Mediterranean area we have important storms related with the phenomenon known as the "cold drop" (Roth, 2003). It is related with the higher total ~~precipitation~~P observed in these months. In accordance with the obtained potential scenarios, in the future we would have an increment of these extreme ~~precipitation~~P events.

As we also observed for the ~~temperature~~T, the standard deviation of the future ~~precipitation~~P predicted with the delta change approaches are quite similar to the historical one, but both ensembles defined by applying bias correction show significant reductions.

#### 3.1.3 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).

### 3.2~~1~~ Definition of a~~n~~ coupled ~~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 outputs of the auxiliary models ~~is~~ are used as inputs ~~to~~ of the groundwater model (see Figure ~~7~~4).

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~~2.1 Rainfall-recharge models

Based on the historical climate (rainfall and ~~temperature~~T) and recharge series for the period 1973-2010 described in sections 2.2, we define a simple empirical rainfall-recharge approach to generate yearly aquifer recharge series. The model assumes that ~~precipitation (P)~~ and ~~temperature (T)~~ are the most important climatic variables determining potential aquifer recharge, and the variability of both of them will determine the impacts of future potential climatic scenarios.

It intend to define a correction function for the perturbation of the historical series defined as the difference in P and ~~E~~evapotranspiration (ETR) (hereafter referred to as PE series), modifying its mean and standard deviation to make them equal to the statistic of the historical aquifer recharge previously deduced from the lysimeter measurements (see section 2.2), as follows:

$$R_i = PEn_i . \sigma_R + \bar{R} \qquad (1)$$

where $R_i$ is the recharge series generated for the year i, $\sigma_R$ and $\bar{R}$ are the standard deviation and mean of the historical recharge series estimated using the infiltration rate coefficient obtained from previous lysimiter readings (Tuñon, 2000), and $Pn_i$ is the normalised historical PE series (P-E) obtained from:

$$Pn_i = \frac{PE_i - \overline{PE}}{\sigma_{PE}} \qquad (2)$$

where $PE_i$ is the historical PE series for the year i, and $\sigma_{PE}$ and $\overline{PE}$ are the standard deviation and mean historical values of the series. Taking the positive relationship of ~~temperature (T)~~ and E into account (Arora, 2002; Gerrits et al., 2009), changes in T will determine the available non-evaporative fraction of ~~precipitation~~P available for aquifer recharge. Different non-global empirical models could be applied to assess the historical E from T series (e.g., Turc, 1954, 1961; Coutagne, 1954; Budyko, 1974; amongst others) as described in Arora (2002), Gerrits et al. (2009), and España et al. (2013). In this study, we applied Turc's model (1954, 1961), in which the results depend on mean annual T and solar irradiation over the latitude.

~~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.~~

~~In order to~~ approach the impact of seasonal variability t~~T~~he annual rainfall recharge values obtained using the simplified model were ~~divided~~ distributed between the 12 months~~,~~ maintaining the ~~historical~~ pattern of the historical rainfall recharge series~~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,~~T ~~t~~he Maestrazgo aquifer recharge model is~~, was~~ used to assess inflows to the carbonate basement, that produces lateral inflows (LI) ~~from the Maestrazgo~~ to the Plana Oropesa-Torreblanca aquifer under various potential GC scenarios. The Maestrazgo aquifer has an important storage capacity which is almost in natural regime and does not present significant changes in hydraulic head. The Maestrazgo rainfall recharge model is employed to assess future recharge being the ~~lateral inflows~~LI to the carbonate basement obtained by assuming a constant ratio between Maestrazgo rainfall recharge and these ~~lateral inflows~~LI.

~~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~~2.2 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 ETR for the rainfall allows us to determine the ETR related to irrigation, taking into account the climate conditions (rainfall and ~~temperature~~T). The estimated irrigation demands have been also 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.

~~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~~2.3 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 recharge, Lateral Groundwater Inflows from the bordering aquifers (LGI) and irrigation returns. The outflows include natural springs that feed the wetland, pumping wells and outflows~~lets~~ to the sea. The historical evolution of the inflows and outflows has been represented in Figure 10.

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.~~ We adopted a vertical discretization consist of 11 ~~layers~~~~The vertical discretization has 11 layers, defined as confined/unconfined layers where the transmissivity varies.~~ ~~in~~layers in order to avoid a high computational cost (e.g. Sreekanth and Datta, 2010) while maintaining reasonable levels of numerical dispersion and representing complex flow patterns near areas of high concentration gradients (Guo and Langevin, 2002) ~~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)~~. These 11 layers, were defined as confined/unconfined layers where the transmissivity varies. 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 ~~m~~g/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 groundwater model covers the Pli-Quaternay and Pre-Quaternary formations. The spatial heterogeneity is tackled using the concept of multiple statistical populations (Llopis-Albert and Capilla, 2010), in which the rock matrix and each fracture is represented as independent statistical population. The random function for each structure (i.e., the aquifer matrix and fractures) is modeled based on a geostatistical analysis conditionated to its own statistical distribution (i.e., hydraulic conductivity data as well as geological information and expert judgment). The random function is supposed to be as MultiGaussian for the rock matrix, while the fractures are considered as non-MultiGaussian. In this way, the rock matrix is generated by sequential Gaussian simulation using the code GCOSIM3D (Gómez-Hernández and Srivastava, 1990), while the fractures are generated by sequential indicator simulation using the code ISIM3D (Gómez-Hernández and Journel, 1993). The latter code makes use of local conditional cumulative density functions (ccdfs) defined by conductivity measurements and the corresponding indicator variograms. Therefore, the spatial heterogeneity is modeled as an equivalent porous media (e.g., Llopis-Albert and Capilla, 2010). On the one hand, the hydraulic conductivity data for fractures presents high values, greater than 1000 m/d. This allows the reproduction of strings of extreme values of hydraulic conductivity that often take place in nature and can be crucial in order to obtain realistic and safe estimations of mass transport predictions. That is, it allows reproducing preferential flow channels in strongly heterogeneous aquifers or fractured formations. On the other hand, the hydraulic conductivity data for the aquifer matrix cover a wide range of values, i.e., from 5 to 200 m/d. In addition, for each cell we have defined a vertical hydraulic conductivity equal to a tenth of the horizontal hydraulic conductivity. The position of fractures is deterministically incorporated in the model based on geological information and expert judgment, thus allowing ~~toclassify~~to classify the cell models. Those cells of the model intersected by a fracture are assigned conductivities according to the intersecting fracture, and those that are not are considered as cells belonging to the rock matrix.

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~~.~~;~~ We have not used an inverse model (eg. Llopis-Albert et al., 2016) because its computational cost would be important in order to deal with such quantity of parameters (hydraulic conductivity, storativity, porosity, dispersion coefficients …) and variables (hydraulic head and salinity) within a seawat model over a long period of time (from 1973 to 2010), so that we have decided to apply a trial and error procedure.~~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~~15; effective porosity values from 0.01 to 0.~~03~~13; and dispersion coefficients from 50 to 100 m. We have replaced a highly heterogeneous porous media with an upscaled “equivalent” homogeneous porous media to represent the hydrogeological parameters since the cell size of the discretization is 250x250 m (e.g., Llopis-Albert and Capilla, 2010). Then, we have used a value of the effective porosity based on available data, which were subsequently calibrated and upscaled using expert judgment. The results of the calibration process prove the worth of this approach.

Reasonably gGood results in terms of goodness of fit to the historical hydraulic head and ~~salinity concentration~~salinity~~s~~ were obtained, as shown in Figure ~~8~~ 11 for various head and salinity~~concentration~~ observation wells.

The root mean square value (RMS) of the departures between observed and simulated values for both, piezometric heads and salt concentrations, is presented for the whole domain and temporal discretization due to the large number of boreholes (21 boreholes for piezometric heads and 31 for salinity). These values are $\eta_h = 0.7$ m; $\eta_c = 391.8$ mg/l. Note that this $\eta_h$=0.7 m could seems to be a little high but we should take into account that we have observation wells where the historical hydraulic head measurement fluctuates sometimes more than 6 m during the same month (see for example observation well 6). Note that the high value for $\eta_c$ =391.8 mg/l could be also explained by the scale of the salt concentration, which range from 0 to 35000 mg/l, and the measurement fluctuations, which in some wells is even higher than 4000 mg/l during some months.

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

Finally, the calibrated model is~~was~~ used to propagate~~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 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 ($E_1$) or bias correction ($E_2$). 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~~ 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 ($E_i$) in the auxiliary models (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 ($E_1$, $E_2$, $E_3$ and $E_4$; see Section 3.2.3) in order to define potential future scenarios of rainfall recharge ($RR_1$, $RR_2$, $RR_3$ and $RR_4$ which correspond, respectively, to $E_1$, $E_2$, $E_3$ and $E_4$).~~

~~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 ($AR_1$, $AR_2$, $AR_3$ and $AR_4$) scenarios can be estimated as described in Section 3.1.1. Future pumping scenarios ($P_1$, $P_2$, $P_3$ and $P_4$) 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 ($LI_1$, $LI_2$, $LI_3$ and $L_4$ 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 the future LULC scenario (LULC scenario) and different GC (CC and LULC change scenarios) we have simulated the following scenarios using the density-dependent flow 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~~:

3) 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~~LI 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.

~~3)~~4) LULC scenario: It considers the described future LULC scenario and assumes that there is not CC.

~~4)~~5) ~~Global~~ change ~~($GC_i$)~~ scenarios ($GC_i$) assuming constant sea level: We consider four GC scenarios~~simulate scenarios~~ that simultaneously consider the potential impacts of the described future LULC scenario ~~(described in Section 2.3)~~ under the four generated~~different~~ CC scenarios (Ei~~ (described ~~see~~in~~ Section 3.1.2.~~3~~4). ~~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.

~~5)~~6) ~~Sensitivity to~~ SLR scenarios: We have also simulated the four ~~global change~~GC scenarios assuming ~~scenarios that differ from the GC scenarios ($GC_1$, $GC_2$, $GC_3$, $GC_4$) in terms of sea level, which is supposed to rise 0.19 cm in line with the pessimistic scenario outlined in Section 2.5~~ that the sea level grows in a linear way 0.19 m during the future horizon (2011-235).

The results obtained are summarized and discussed in next section.

## 4. Results and discussion

The proposed approach has similarities with the one described by Pulido-Velazquez et al. (2015), in which an integrated analysis of ~~global change~~GC is performed including CC and LULC changes. The most important differences are related with the fact that a coastal aquifer is studied and we consider quality issues simulating with a variable density flow and transport model. The approach allows to propagate impacts of different CC and LULC change scenarios in terms of global flow balance, as well as a distributed approximation of the hydraulic head and salinity.

The GC scenarios show a higher variability in all the inflows and outflows in the aquifer (See Figure 12).

The mean components of the global balance for the simulated future scenarios show that, in general terms, the intrusion will not grow and will even be reduced slightly, as the outflows to the sea will not decrease, due in part to the reduction and redistribution of pumping in the mentioned scenarios (see Figure 13). The LULC scenario produces important reduction of pumping due to the transformation of irrigated areas in residential use, which are going to be supplied with water coming from desalination plants or recycled wastewater. It will also produce a decrease in the recharge due to the reduction of the returns coming from the irrigated areas. Nevertheless, in general, this LULC scenario would have an important role in avoiding an increasing degradation of the aquifer that would takes places in cases of maintaining the historical land uses, scenario that would be exacerbated in the future due to CC~~climate change~~.

Figure 14 shows the evolution in terms of salinity at 4 specific observation points roughly equispaced. They were selected to cover the extension of the aquifer from north to south (starting with the more northerly and moving towards the south we have observation wells 33, 12, 39 and 21 respectively).

From the results in terms of salinity at specific observation points (Figure 14), we can observe the heterogeneity of the impacts of the LULC scenario and CC scenarios. The area around the observation point 33 is not affected by LULC changes and we only observe sensitivity to CC scenarios that produce a higher variability in the salinity evolution, but the mean trend of the concentration does not change. Around the observation point 12, in Torreblanca area, the LULC change scenario would produce a reduction in the recharge whose impacts can be observed as an increment in the salinity during the first decade of the future horizon. Nevertheless, in the last 10 years the reduction in pumping produced by the successive transformations of irrigated areas to residential land would reduce significantly the salinity. In this Torreblanca area CC scenarios would impact the salt concentration significantly during the first years due to the increment in pumping requirements produced by the higher water irrigation requirements obtained for these ~~climate change~~CC scenarios. Even considering the impacts of CC scenarios, during the last 10 year of the horizon it starts to recover due to the reduction in pumping produced by the new transformations of irrigated areas to residential land defined in the LULC scenario, being the concentration at the end of the horizon (2035) even under the values obtained for the ~~baseline~~BL scenario. In the observation point 39, located further away from the coast, the reduction in pumping due to LULC change would reduce the salinity during most of the year of the horizon. Nevertheless the reduction in recharge makes in some years the salinity to get close to the one obtained without LULC changes (~~Baseline~~BL scenario), being very similar at the end of the period. Again CC scenarios would increase the variability of the salinity in the simulated period.

We can also identify in the southern part areas where the situation will clearly improve throughout the future horizon contemplated with the proposed scenarios. For example, at observation point 21, in Oropesa area, the salinity would be reduced with the contemplated scenarios, which would be mainly related with the reduction of pumping in this area due to the transformation of irrigated areas to residential land defined in the LULC scenario.

As commented above the expected results without considering ~~global change~~GC impacts are likely to be too pessimistic or optimistic, depending on the location. These results can be useful for the authorities in charge of implementing management policies in the Plana de Oropesa Torrablanca. We can use this coupled modeling framework to assess potential effect of adaptation measures to ~~global change~~GC by modifying the inputs of the models. Participatory processes including the relevant stakeholders might be essential in the definition of scenarios and successful adaptation measures (Pulido-Velazquez et al., 2015). This modeling framework could be useful in the search for consensus ("shared vision" models) between different stakeholders.

~~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 (Figure 15). 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 3.1.3~~2.5~~). A linear ~~sea level rise~~SLR was considered during the future horizon (2011-2035). Figure 15 shows the results obtained in terms of hydraulic head and ~~chloride concentration~~salinity at a number of observation points. It shows that the sensitivity of hydraulic head is very low. The sensitivity of the salinity~~chloride concentration~~, although not very significant, is higher than that observed for hydraulic head. The low sensitivity of the results should be due to the maximum value of SLR considered, 0.19m in 2035, is quite low with respect to the level fluctuations experienced in most of the observation wells (see Figure 15). For this reason the sensitivity of the flow and transport solutions are low. We find in the literature other examples in which the sensitivity of seawater intrusion to the SLR would be low. Chan et al. (2011) obtained this conclusion in a synthetic confined coastal aquifer in which recharge in unchanged; Rasmussen et al. (2013) obtained the same conclusion for an inland coastal aquifer with minor SLRs. Nevertheless other authors, as Werner and Simmons (2009) showed that in unconfined aquifers the influence of the inland boundary condition can be significant to its sensitivity to SLR.

## 4. 1 Hypotheses and limitations. Usefulness of the results.

From the methodological point of view, the proposed approach is general, ambitious and valid scientifically. Nevertheless there are some assumptions and limitations in the application performed that we wanted to highlight and summarize in this section in order to clarify the accuracy and utility of the results obtained. We have grouped them in three categories:

(1) Generation of future potential climatic scenarios

- The research is focused on the analysis of future short-term-horizon (2011-2035). Other future horizons, such as mid-term and long-term scenarios, in which there should be even higher uncertainties about the impacts of ~~climate change~~CC for being further away in time, are not considered.
- Only the most severe IPCC scenario (RCP. 8.5) was analyzed to assess the most pessimistic impacts in the future short-term scenario.

- Potential plausible future climate scenarios are defined by combining information coming from different Regional Climatic Models (RCMs) and General Circulation models (GCMs).
- Two downscaling approaches (correction of first and second order moments) under two different hypotheses (bias correction and delta change techniques) were applied to generate future climatic series in accordance with RCM simulations. Note that, depending on the problem and the target solution, several downscaling techniques of varying complexity and accuracy (correction of first- and second-order moments, regression approach, quantile mapping, etc.) can be applied by assuming different conceptual approaches, such as bias correction and delta change techniques (Räisänen and Räty, 2012).
- Two different hypotheses, equifeasible members or non-equifeasible members, were applied to define ensembles of the obtained future series for each RCM. They may help to achieve more representative future potential climate scenarios for assessing impacts on aquifer recharge.

(2) Hydrological propagation of the climatic impact to aquifer recharge

- A simple empirical precipitation-recharge model has been adopted; whose inputs are P and E. We have not tested other hydrological models, for example, based on a more physically based or detailed representation of the processes involved in the hydrological balance and the geological structures. We assume that ~~precipitation (P)~~ and ~~temperature (T)~~ are the variables determining NAR, and their spatiotemporal variability determines the impacts of future potential climatic scenarios on renewable groundwater resources. We do not consider the change changes in other variables affecting recharge, such as soil properties, vegetation patterns and land-use. They are considered steady, despite there being expected to change according to global climate driving forces and new human actions on a local scale that will be induced by human adaptation to climate and water resource availability (Martínez-Valderrama et al., 2016).
- We assume that the climatic fields (P and T) taken from the Spain02 project (Herrera et al., 2016) are good enough to approximate the historical climate.
- The Turc's model (1954, 1961) was applied to estimate E. Its results depend on mean annual T and P. Different non-global empirical models could be applied to assess the historical E from T and P time series.

(3) Hydrological impacts on aquifer status: Seawater ~~intrusión~~intrusion simulation

In this study we decided to employ a variable-density model instead of a sharp-interface solution, which have been extensively used to define management models because of its simplicity in terms of required parameters and computational burden (e.g., Mantoglou et al., 2004). This is because they better describe the dynamic of real complex coastal aquifers despite the limitations in the available data and the course discretization used for the Plana Oropesa-Torreblanca aquifer. Better adjustments between observed and modeled hydraulic head and salinity would provide greater confidence in the model predictions. Nevertheless, although due to there are some differences between observed and simulated data the uncertainty of the prediction coming from the model grows and we have to be cautious with the conclusions obtained, the fit is good enough to capture the general trend of the hydraulic head and salinity variables within a quite long calibration period (37 years, from 1973 to 2010), and therefore, to assess general impacts of climate and LULC changes. Note that it is difficult to improve the calibration of the proposed approach in this work for Plana de Oropesa-Torreblanca due to the following facts:

- The hydrogeological complexity of the aquifer makes it difficult to define a better approach taking into account its spatial heterogeneity, with fractured formations and preferential flow channels existing in the aquifer (Morell and Giménez, 1997). The spatial heterogeneity is handled by means of sequential indicator simulation using the computer code ISIM3D (Gómez-Hernández and Srivastava, 1990).
- The quality of some observation data is poor. This problem is accentuated when considering the long simulated time period with historical data, which spans from 1973 to 2010. In this way, for a certain observation borehole there are data close in time with measurements quite disparate, which cannot be explained by any physical phenomenon. A statistical processing of data with expert judgment would be advisable to dismiss the wrong data. We have opted for using all available data (as a transparency measurement and in order to ease the reproduction of this exercise by other researchers).
- The lack of reliable estimates of dispersion coefficients (Naji et al., 1999) may prevent a proper adjustment for the Plana Oropesa-Torreblanca aquifer.
- A better fit might be achieved using a more refined spatial discretization, which would allow modeling the preferential flow channels existing in the aquifer (Morell and Giménez, 1997). However, the high computational burden when solving the variable-density flow and transport equations with SEAWAT prevents the use of a fine grid (e.g. Sreekanth and Datta, 2010).
- As a further research, we are intended to couple the sea water intrusion model with a management simulation–optimization model for control and remediation that would further prevent the use of a fine grid.

(4)Analysis of uncertainty in impacts

In this paper we do not intend to perform a detailed analysis of uncertainty in impacts, which could be deeply analyzed as a further research. In order to assess the uncertainty on hydrological impacts it would be more appropriate to assess results from each individual climate model. Note that it would require 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. 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. It has been applied in~~,~~ the Plana Oropesa-Torreblanca aquifer assuming some hypotheses or simplifications.. Representative future ~~climate change~~CC 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 a~~n~~ coupled ~~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~~salinity. In global terms the intrusion will not grow in the considered potential future scenarios. The impacts on the aquifer salinity will be heterogeneous. We observed specific areas where the situation gets worse and other, where it will clearly improve in the contemplated future horizon due to transformation of irrigated areas to residential use foreseen in the future LULC scenario. They~~It~~ also show~~s~~ 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~~. We can use this coupled modeling framework to assess potential adaptation measures under different ~~global change~~GC scenarios and horizons changing the inputs of the models. In the definition of scenarios and plausible adaptation measures to be analyzed participatory processes including the relevant stakeholders might be essential (Pulido-Velazquez et al., 2015). On the other hand, this modeling framework could be useful in the search for consensus ("shared vision" models) between different stakeholders.

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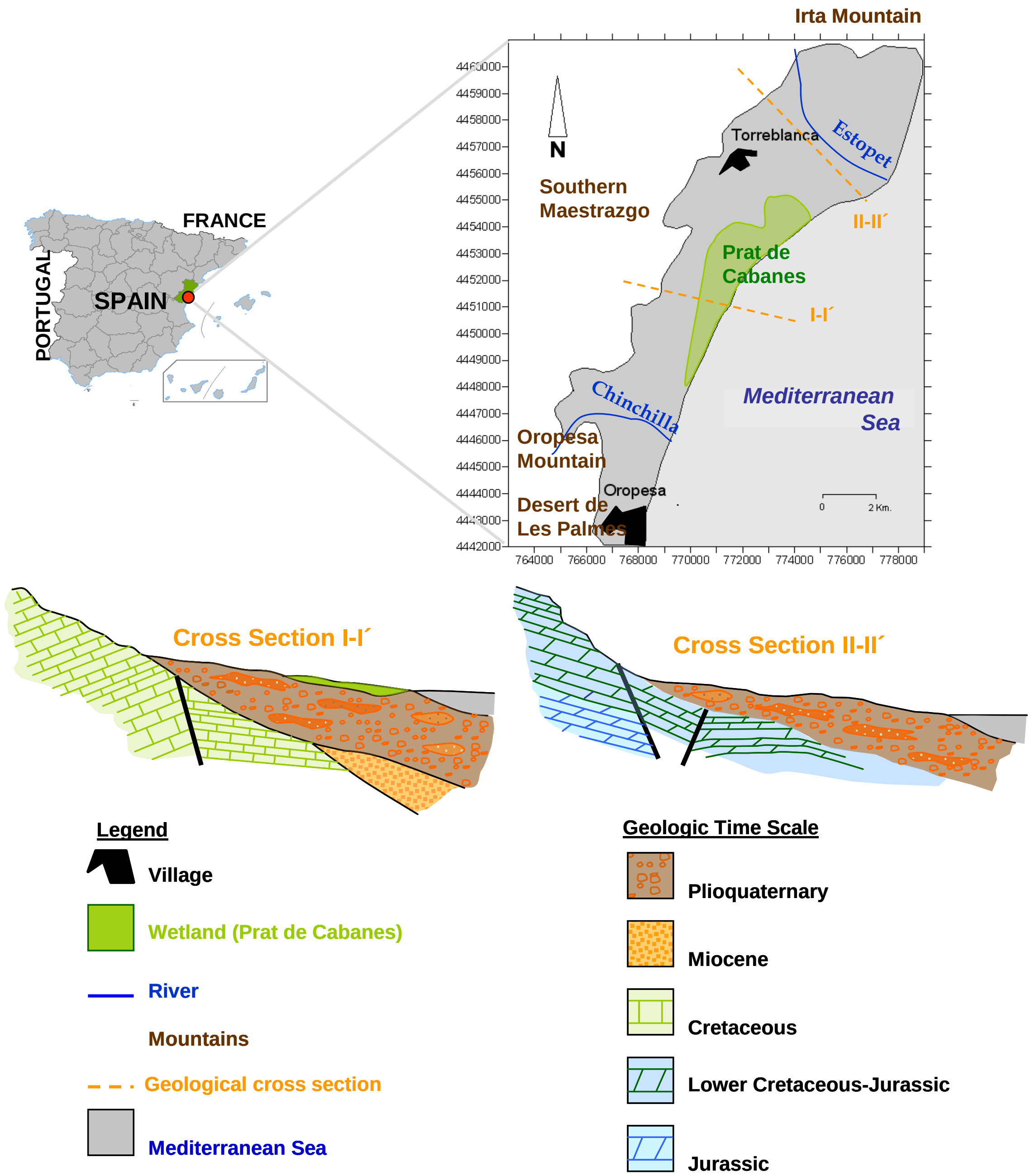

Irta Mountain
FRANCE
PORTUGAL
SPAIN
N
Southern Maestrazgo
Torreblanca
Estopet
II-II´
Prat de Cabanes
I-I´
Chinchilla
Mediterranean Sea
Oropesa Mountain
Oropesa
Desert de Les Palmes
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2 Km.
4460000
4459000
4458000
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4455000
4454000
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774000
776000
778000
Cross Section I-I´
Cross Section II-II´
Legend
Village
Wetland (Prat de Cabanes)
River
Mountains
Geological cross section
Mediterranean Sea
Geologic Time Scale
Plioquaternary
Miocene
Cretaceous
Lower Cretaceous-Jurassic
Jurassic

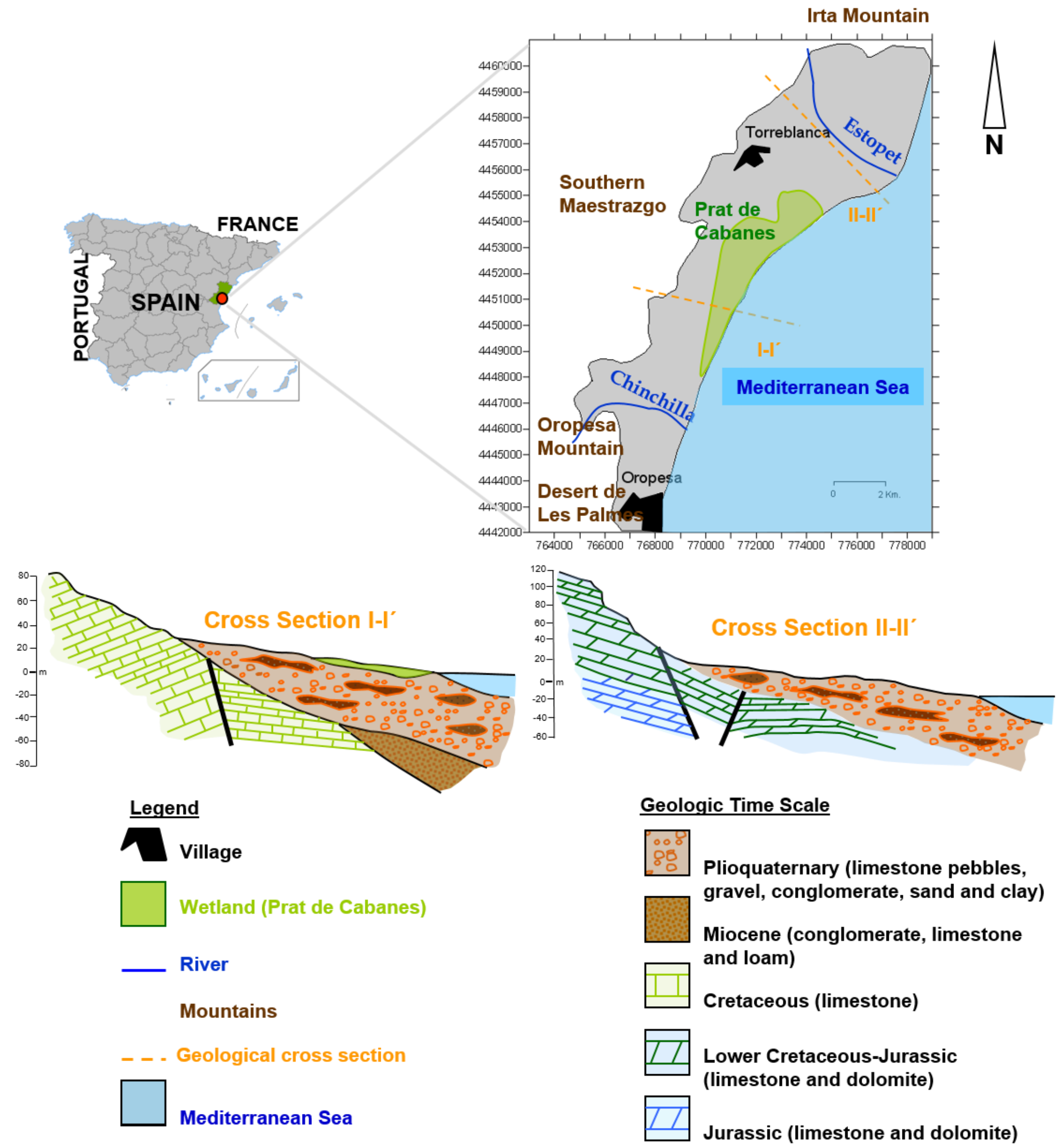



**Figure 1: Location map area and cross sections of the study.**

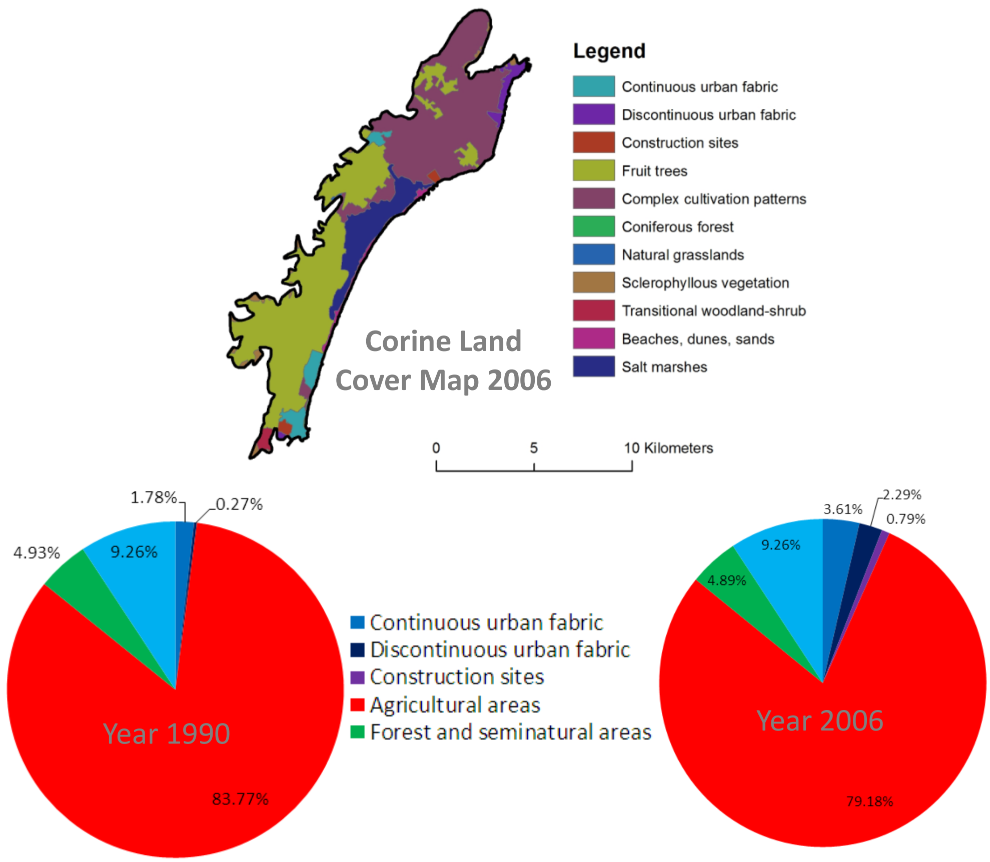



**Figure 2: Land use change (comparing the CORINE Land Cover databases for 1990 and 2006) over the Plana de Oropesa-Torreblanca and Maestrazgo aquifers.**

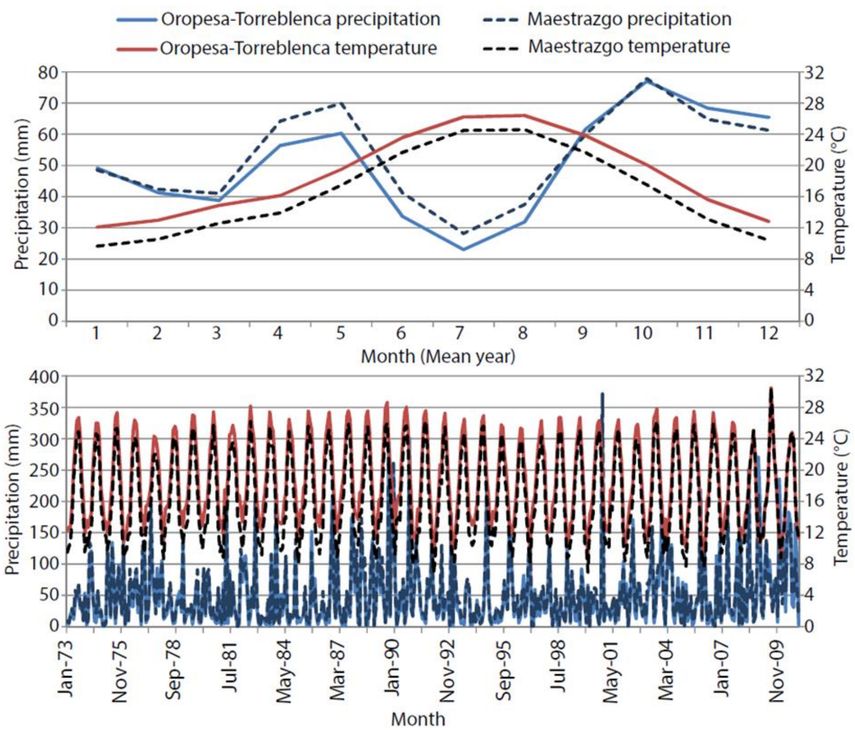



**Figure 3: Historical rainfall and temperature in the Plana de Oropesa-Torreblanca and ~~Maestrago~~Maestrazgo aquifers.**

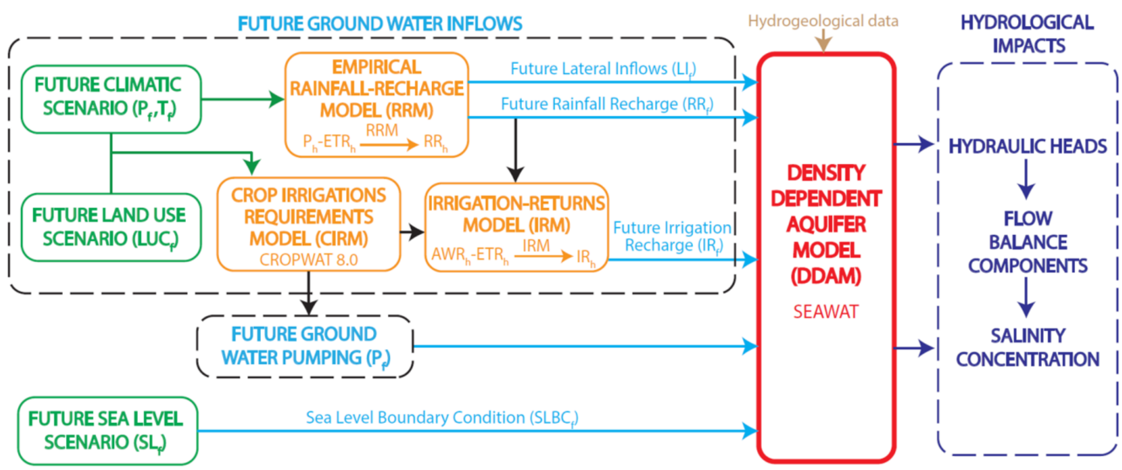
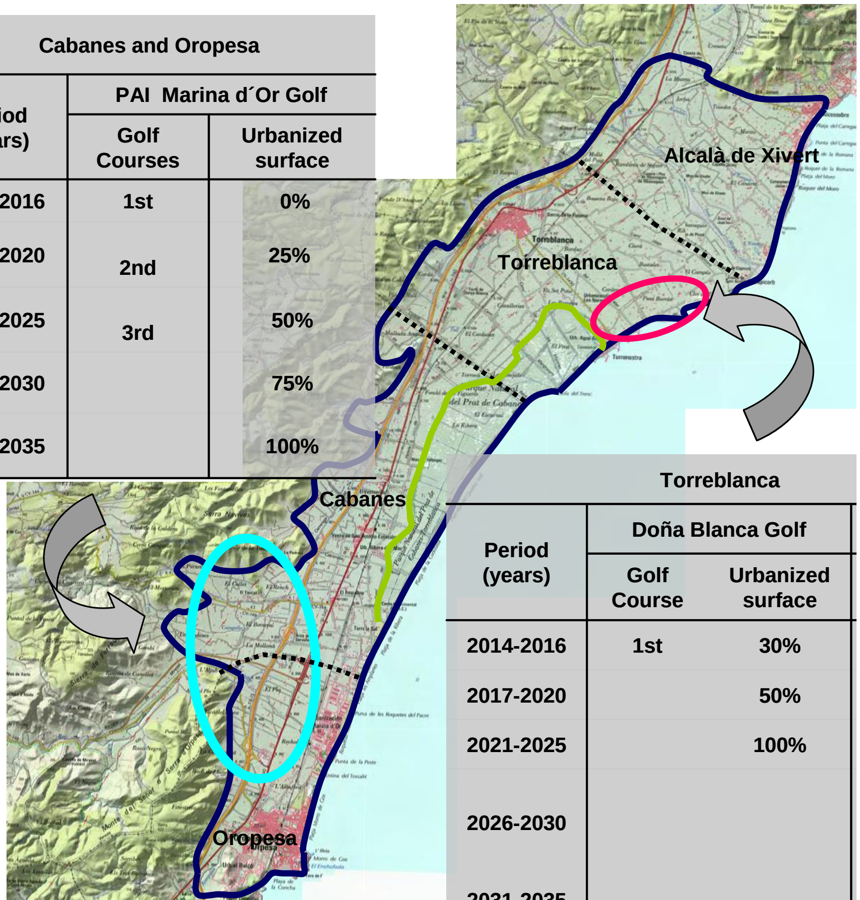



**Figure 4: Flowchart of the modelling framework.**

| Cabanes and Oropesa | | |
|---|---|---|
| Period (years) | PAI Marina d´Or Golf | |
| | Golf Courses | Urbanized surface |
| 2014-2016 | 1st | 0% |
| 2017-2020 | 2nd | 25% |
| 2021-2025 | 3rd | 50% |
| 2026-2030 | | 75% |
| 2031-2035 | | 100% |




| Torreblanca | | |
|---|---|---|
| Period (years) | Doña Blanca Golf | |
| | Golf Course | Urbanized surface |
| 2014-2016 | 1st | 30% |
| 2017-2020 | | 50% |
| 2021-2025 | | 100% |
| 2026-2030 | | |
| 2031-2035 | | |

**Leyend**

- Plana Oropesa-Torreblanca Aquifer
- Municipal Sector
- Doña Blanca Golf Course
- Prat de Cabanes
- Marina d´Or Golf Cours

**~~Figure 4~~5: Future land use scenarios in 2035.**

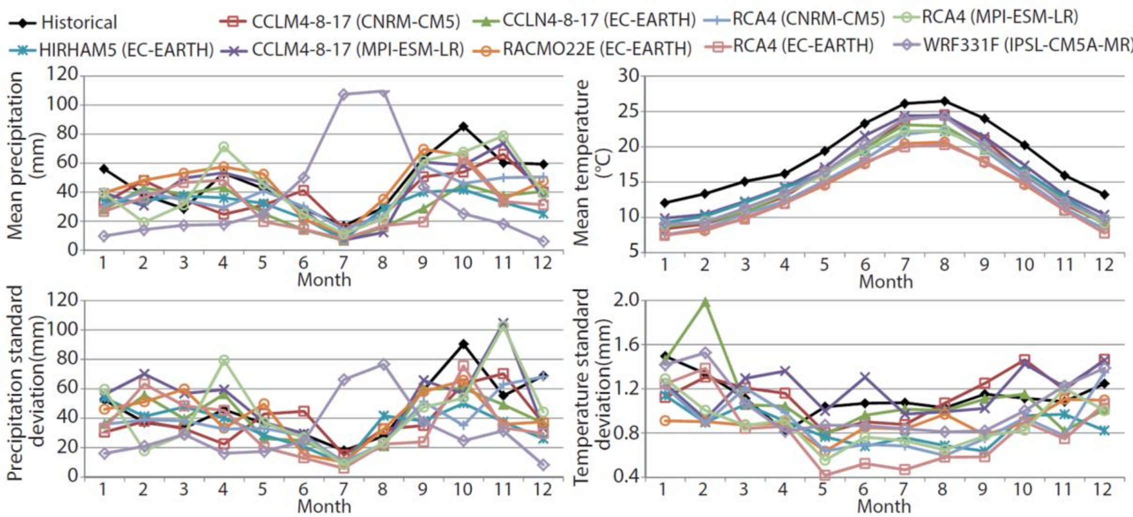



**Figure 6. Monthly mean and standard deviation of the historical and RCMs control series (rainfall and temperature) for the mean year in the period 1976-2000. RCMs data obtained from CORDEX project.**

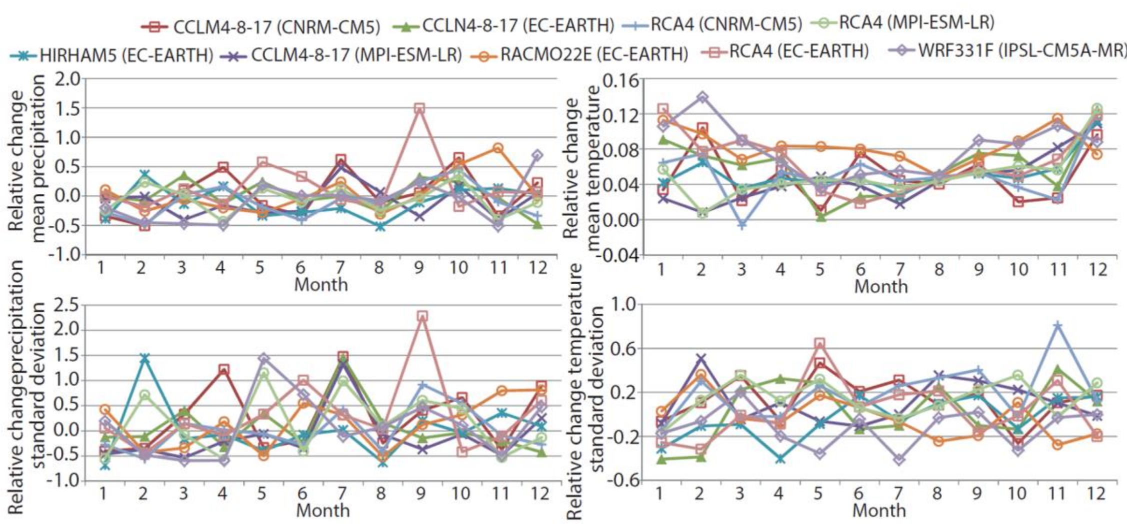



**Figure 7. Relative monthly change in mean and standard deviation of the future series (2011-2035) with respect to the control series (1976-2000) for the considered RCMs under the RCP8.5 emission scenario.**

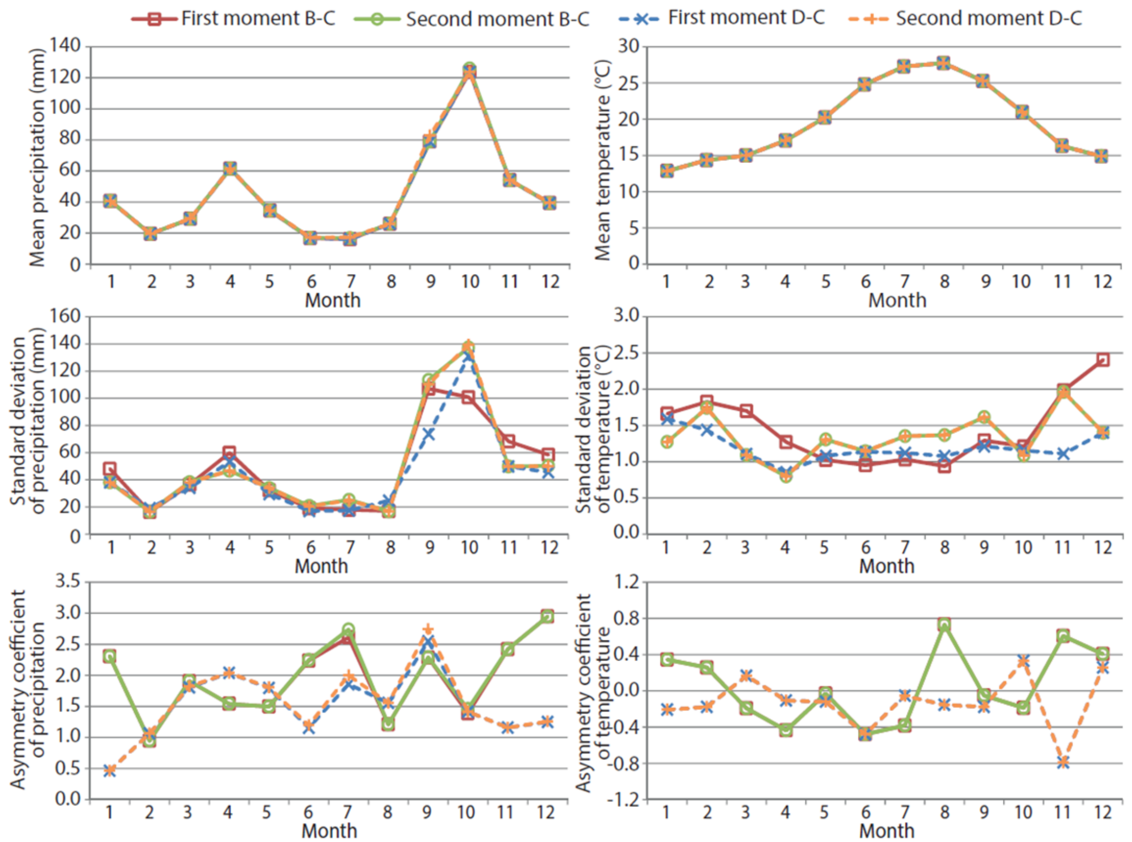



**Figure 8: Mean, standard deviation and asymmetry coefficients of future precipitation series (A) and future temperature series (B) for the average year for the RCM RCA4 model linked to the GCM CNRM-CM5.**

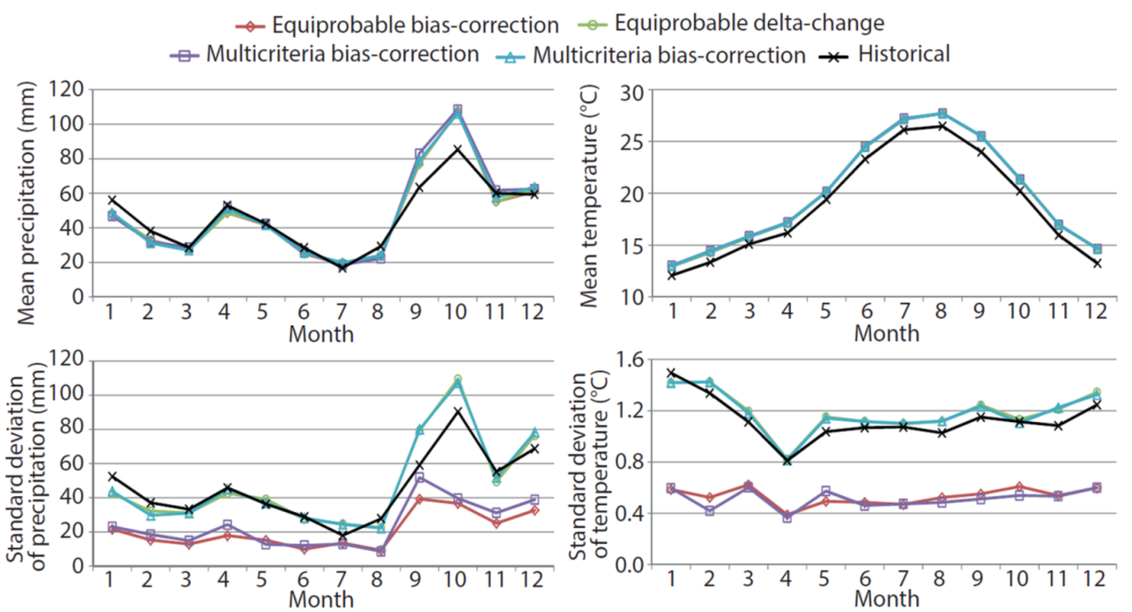



**Figure 9. Monthly mean and standard deviation of future precipitation and temperature series obtained by the four ensemble options.**

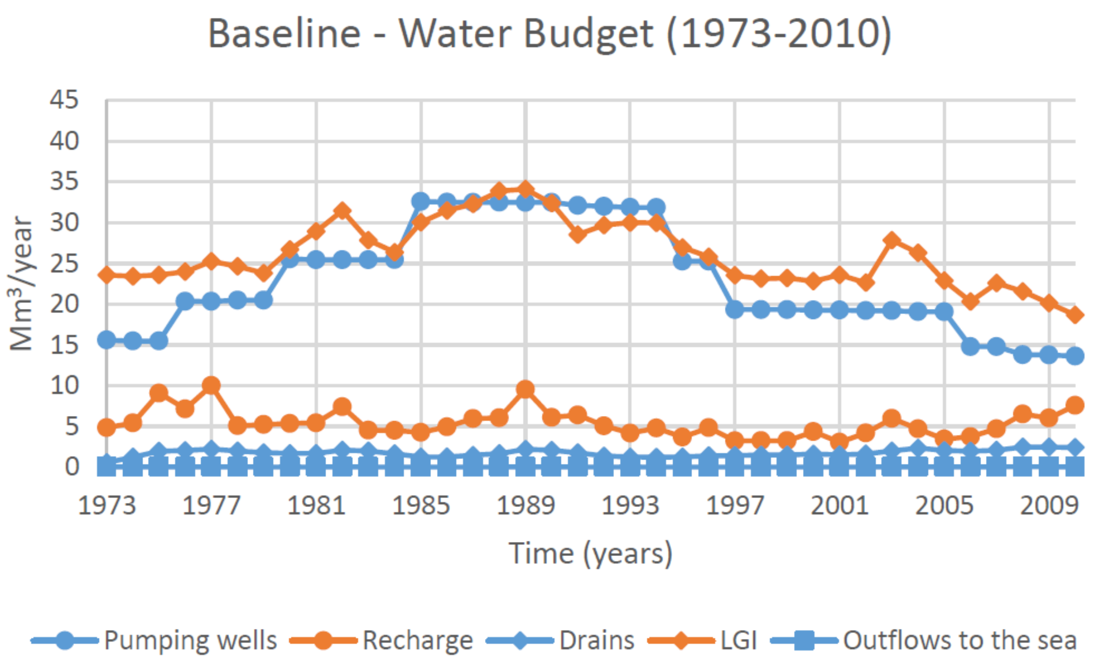



**Figure 10: Historical evolution of inflows and outflows in the aquifer.**

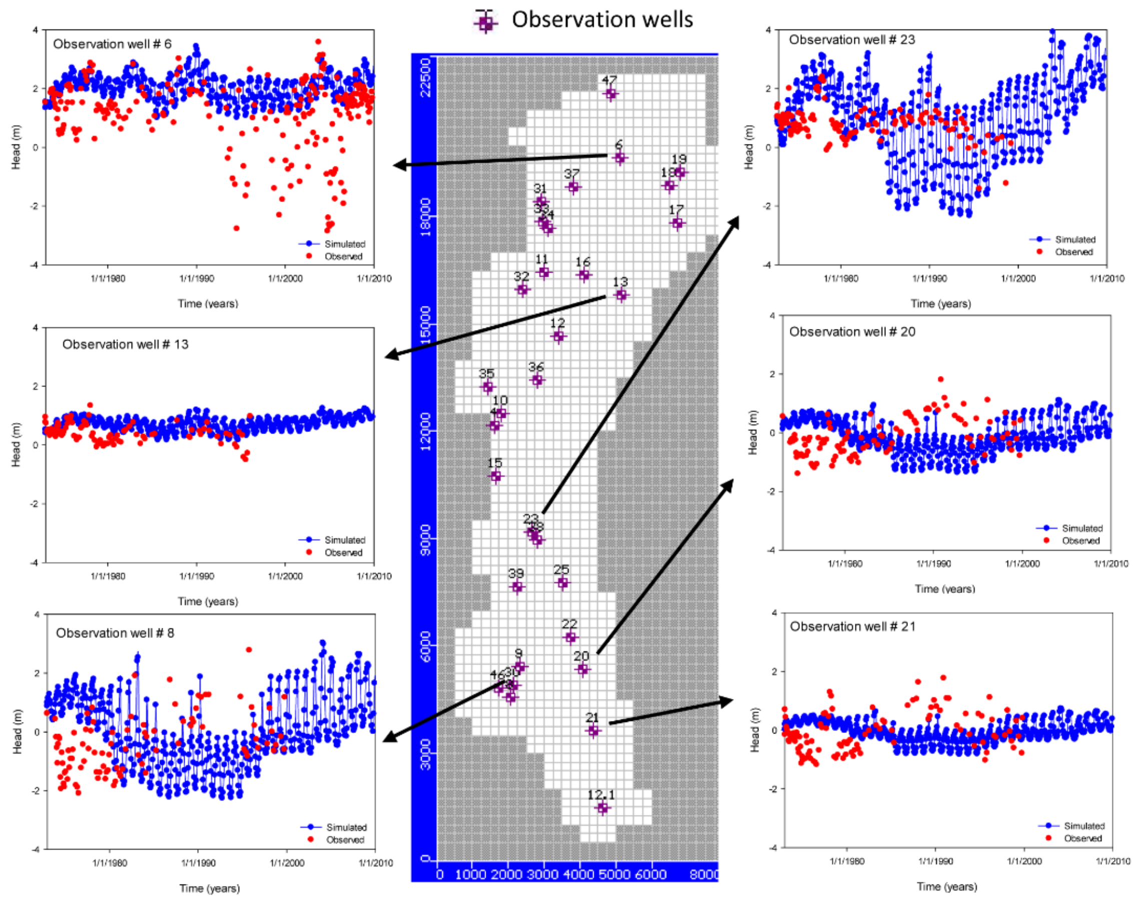



**Figure ~~8~~11.a: Hydraulic head obtained with the models vs. data at some observation points.**

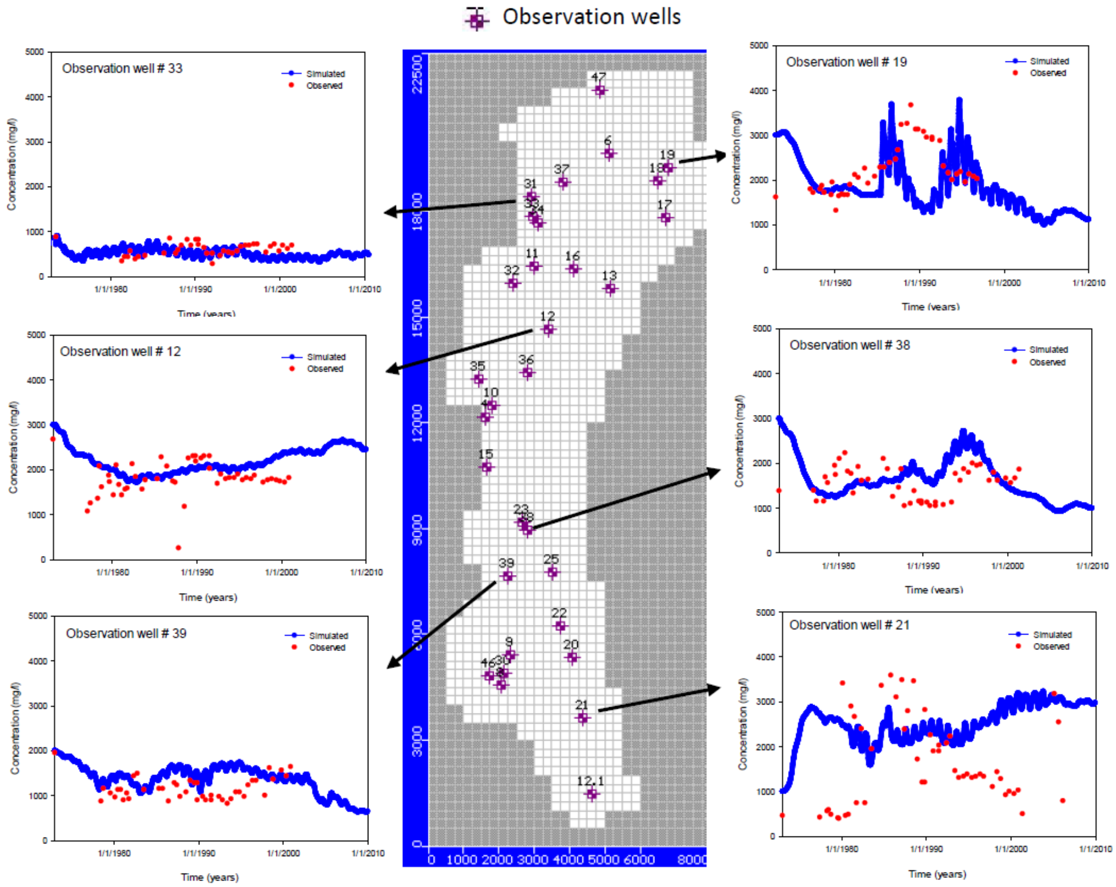



**Figure ~~8~~11.b: ~~Salinity concentration~~Salinity obtained with the models vs. data at some observation points.**

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

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

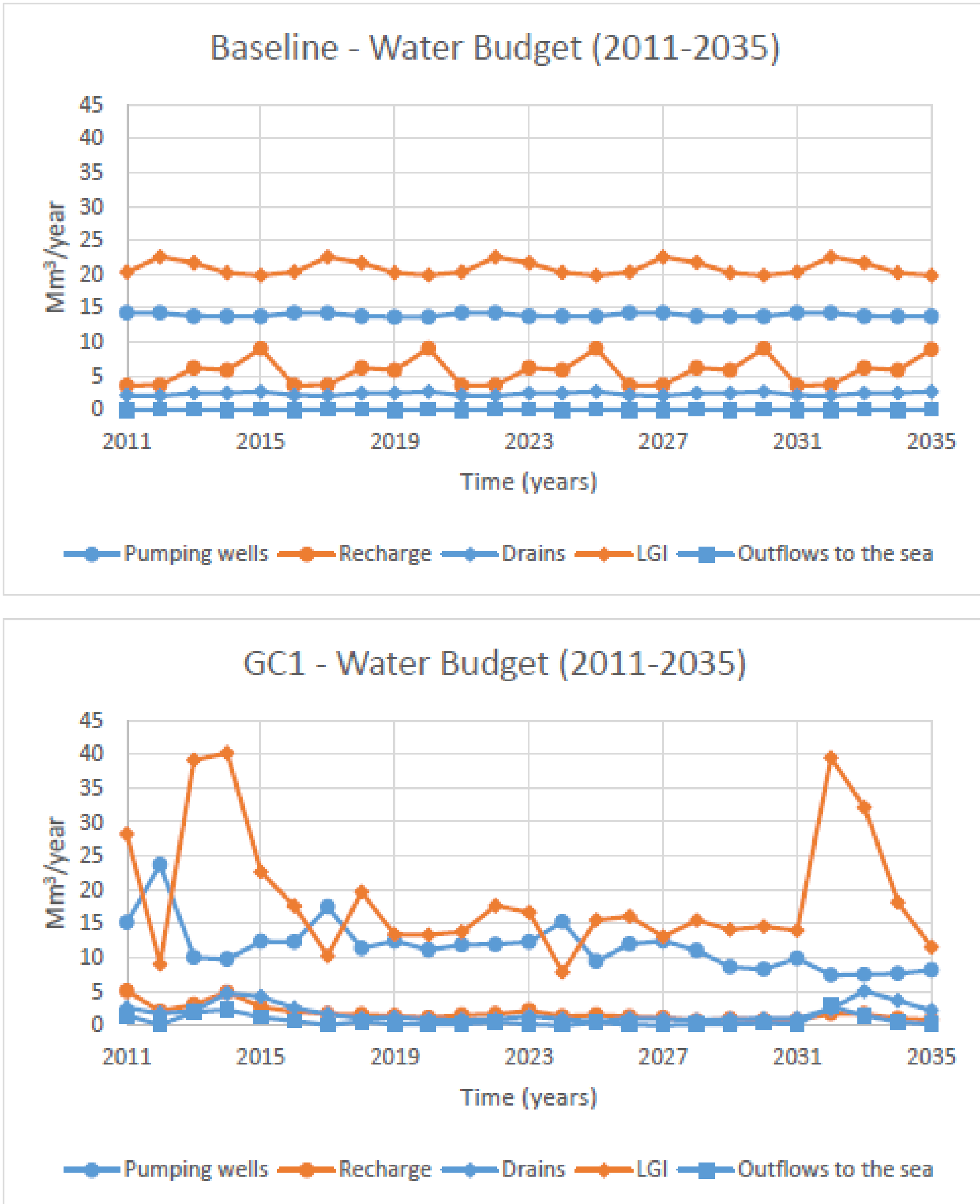



**Figure 12: Components of the flow budget evolution for the BL scenario and the mean of the potential future scenarios (horizon 2011-2035).**

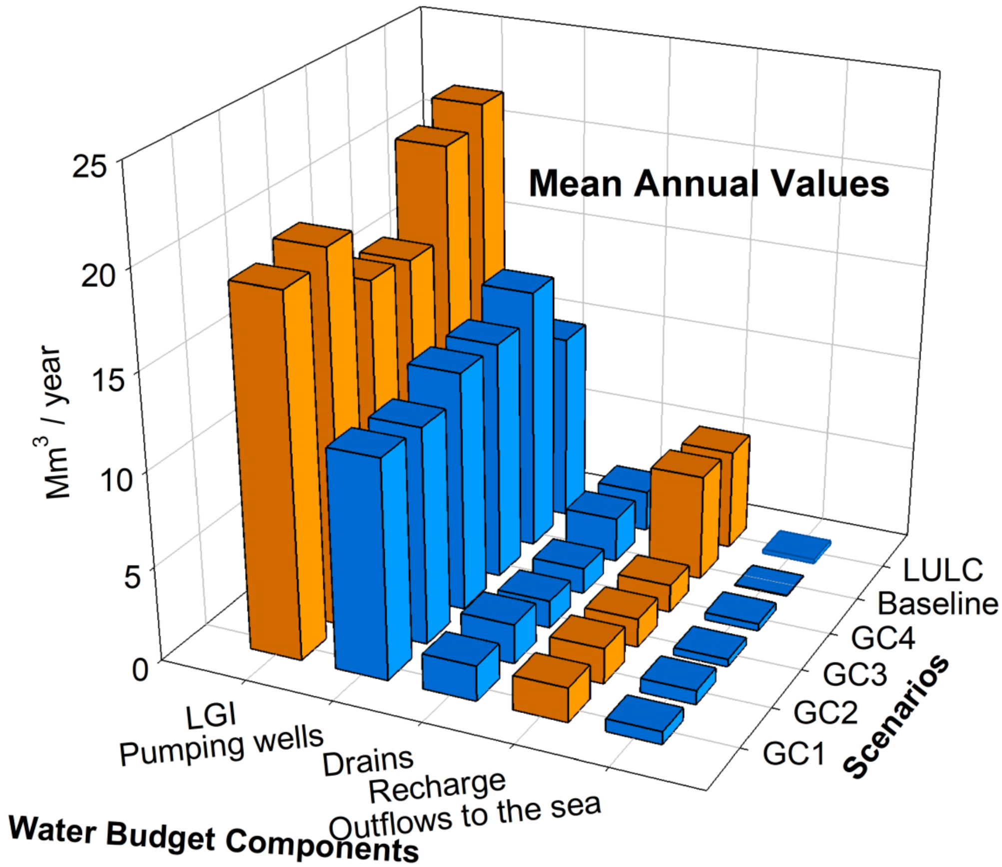



**Figure 13: Mean inflows and outflows for various global scenarios (GC1, GC2, GC3, GC4).**

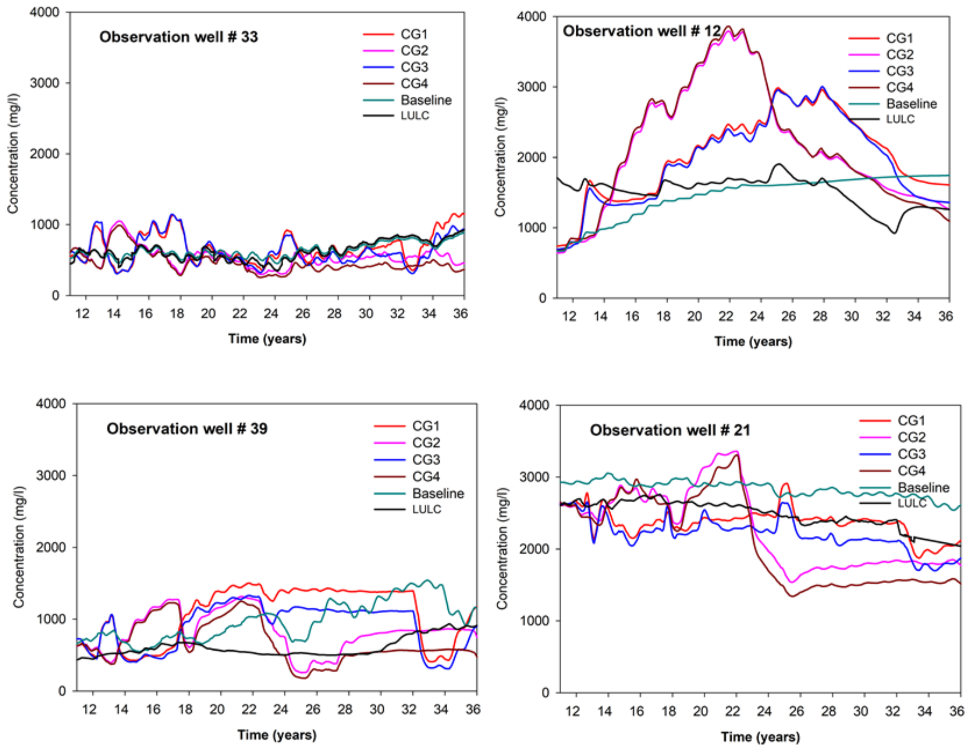



**Figure 14: Evolution of future salinity~~chloride~~ concentration at four observation points for the Baseline (BL) scenario and the four Global Change scenarios.**

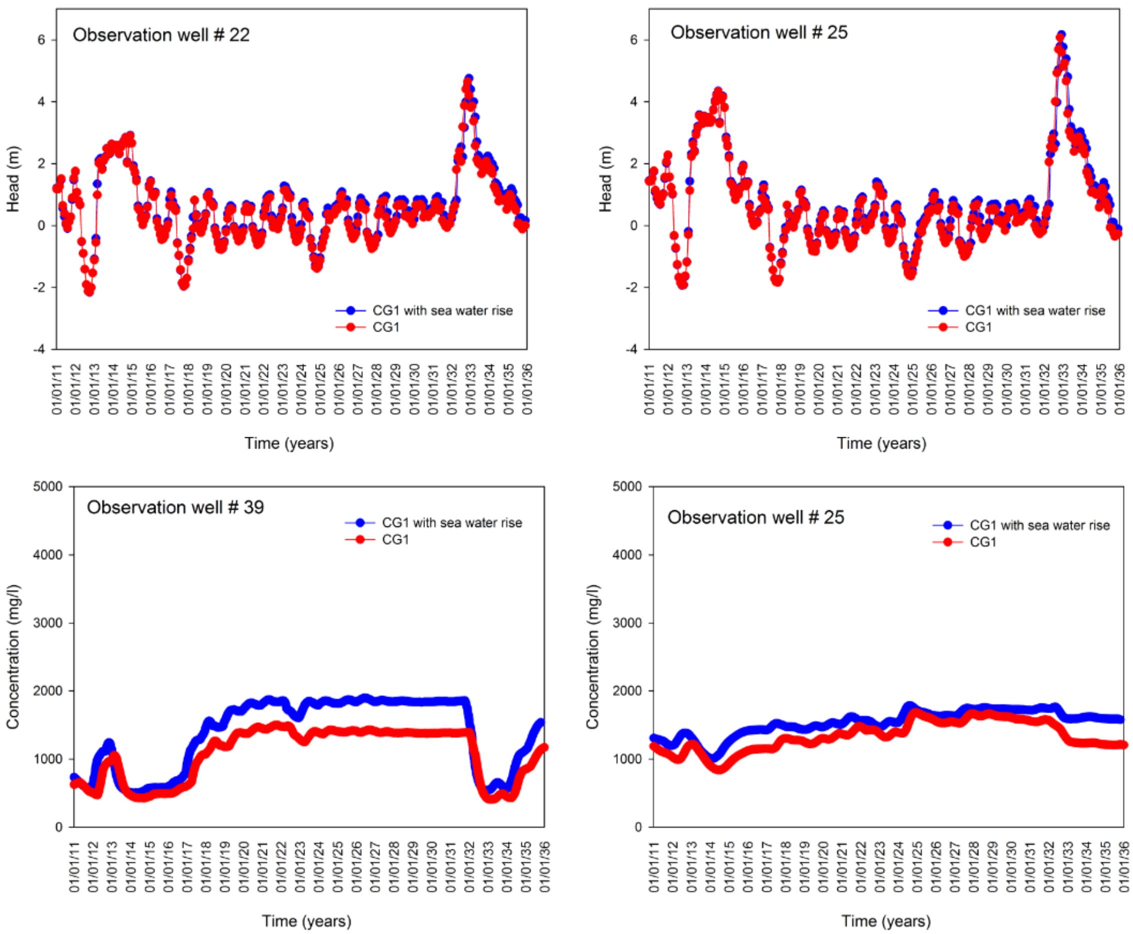



**Figure 15: Sensitivity of head and ~~salinity concentration~~salinity obtained for GC1 to a SLR (0.19 m) scenario.**

| 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.**