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SUMMARISING IMPACTS OF FUTURE POTENTIAL GLOBAL CHANGE SCENARIOS ON SEAWATER INTRUSION AT GROUNDWATER BODY SCALE.

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Abstract

Climate change affects rainfall and temperature producing a breakdown in the water balance and a variation in the dynamic of the freshwater and seawater in coastal areas, exacerbating seawater intrusion (SWI) problems. The target of this paper is to propose a method to assess and analyze impacts of future global change (GC) scenarios on SWI in a coastal aquifer. Some adaptation measures have been integrated in the definition of future GC scenarios in which complementary resources will be incorporated within the system in accordance with the General Town Plans. The proposed methodology requires to generate potential GC scenarios and to propagate them with a chain of hydrological and agronomical models to define the inputs of a density dependent flow model. It provides results for hydraulic head, flows and chloride concentration, which are analyzed in terms of SWI status and vulnerability at groundwater (GW) body scale. The spatial distribution is summarized with steady pictures (maps and conceptual 2D cross sections) in which results for specific dates or statistics of a period are represented. Lumped indices series are proposed to assess the temporal evolution. The methodology allows to compare the significance of SWI problems in a GW body for different periods, but also to compare results between different GW bodies. It is applied to the Plana de Oropesa-Torreblanca aquifer. The results summarize the influence of GC scenarios in the global status and vulnerability to SWI under some management scenarios. These GC scenarios would produce higher variability of SWI status and its vulnerability.

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Keywords*:* global change impacts, adaptation measures, seawater intrusion; status and vulnerability, coastal aquifer; lumped index.

1 Introduction

It is a fact that climate change (CC) would imply a variation in the patterns of temperature and precipitation in the future. In general, in the Mediterranean area an increase in temperature and a decrease in precipitation expected. The available potential future scenarios show higher evapotranspiration, a lower GW recharge and an increase of the sea level. In coastal areas the problem is exacerbated due to overexploitation, intensifying SWI. Therefore, maintaining acceptable quantity and quality characteristics of GW reserves is important to ensure demand water supply (Sola et al. 2013; Renau et al. 2016).

Many investigations have focused on sea-level rise as an important effect of GC on SWI in coastal aquifers (Werner and Simmons 2009; Ferguson and Gleeson 2012; Loáiciga et al. 2012; Benini et al. 2016), but many aquifers are more vulnerable to CC and GW pumping than to sea-level rise (Ferguson and Gleeson 2012; Rasmussen et al. 2013).

An increase in temperature and a decrease in precipitation will force a greater use of available water resources, especially GW. Overexploitation is the main problem in most coastal aquifers since it produces the inland penetration of the saltwater. Therefore, in order to reduce the impacts of GC on SWI, different adaptation strategies could be applied. They include measures to reduce aquifer demands such as Land Use and Land Cover (LULC) changes, modernization and adaptation of irrigation areas and/or economic instruments (Escriba-Bou et al. 2016, Grundmann et al. 2012, Robins et al. 1999;). Different measures focused on the offer could be also applied to obtain complementary resources to supply demands, as for example water reuse, desalinations, water transfers and conjunctive use measures (Trinh et al. 2012; McEvoy and Wilder, 2012; Pulido-Velazquez et al. 2011).

Many authors have assessed hydrological impacts of CC and/or LULC changes in the SWI phenomenon using sharp interface or density-dependent flow models to simulate hydraulic head and salinity in the aquifer (Pulido-Velazquez et al. 2018, Romanazzi et al. 2015; Klove et al. 2014; Rajan et al. 2006). Potential climate scenarios are defined by simulating future emission scenarios within physically based climatic model (General Circulation Models (GCMs) and Regional Climatic Models (RCMs). Due to the significant bias that usually appears between the historical information and the control simulation of the model, in order to make this climate information relevant for case study, we need to translate them to the regional-local scale by applying some statistical corrections (Collados-Lara et al. 2018). Distributed hydrological models are useful tools to propagate scenarios to assess impacts on hydrological variables at specific time and location. Nevertheless, they do not allow to draw direct conclusions about the impacts on SWI (status and vulnerability) at GW body scale. For this purpose, an approach such as an index-based method, defined from the output of the model, is a useful tool to analyse this issue. It can also help to summarize SWI problems at GW body scale in different periods and different GW bodies.

The vulnerability to contamination in coastal aquifers under future climate scenarios has been previously studied by several authors by employing different vulnerability indices. Li and Merchant (2013) employed a modified DRASTIC index to model GW vulnerability under future climate and LULC scenarios. Benini et al. (2016) used the GALDIT method to assess vulnerability in the Quinto Basin by employing some CC and LULC change scenarios in a long-term period. They did not use a flow model to simulate salinity and hydraulic head variables. Luoma et al. (2017) assess the potential impacts of CC on the vulnerability to pollution of an aquifer comparing AVI, SINTACS and GALDIT methods. Although the assessment of vulnerability under future scenarios using an index-based method has been applied by different authors (Huang et al. 2017; Koutroulis et al. 2018), none of them intend to summarise and analyse this issue at GW body scale.

In Baena-Ruiz et al. (2018) a novel index-based method was proposed to perform an integrated assessment of the global status and vulnerability to SWI in coastal aquifers. The methodology was applied in the Plana de Oropesa-Torreblanca and Plana de Vinaroz aquifers. It was obtained from hydraulic head and chloride concentration data available in observation wells for the historical period (1977 – 2015). In that approach, the distributed fields of variables required to define the indices were obtained by applying a simple interpolation method.

In this paper an integrated methodology is proposed to assess/summarise the impacts of GC scenarios on the global status and vulnerability to SWI in GW bodies using different spatio-temporal resolutions. Some adaptation measures have been integrated in the definition of more feasible future GC scenarios in which complementary resources will be incorporated within the system in accordance with the General Town Plans. The proposed methodology requires to generate potential GC scenarios and to propagate them in accordance with a modelling framework. It provides results for hydraulic head, flows and chloride concentration. These results will be summarized in terms of SWI status and vulnerability at GW body scale.

The novelty of this paper consists on the combined use of an integrated method to evaluate/propagate impacts of GC scenarios (including adaptation strategies) and a method to summarize results in terms of SWI status and vulnerability at GW body scale. It intends to contribute in the definition of methods to harmonize the assessment of GC impacts on SWI problems (status and vulnerability) at GW body scale. It allows to compare the significance of the SWI problems in different historical and future periods for a GW body, but also to compare results between different GW bodies. The method proposed by Baena-Ruiz et al. (2018) is adapted to analyze future potential scenarios since, instead of having a single well known series (as in the historical period), an infinite number of potential future series are feasible. The method has been applied to the Plana de Oropesa-Torreblanca case study, where the impacts of different future GC scenarios are compared. Moreover a sensitivity analysis is conducted to assess the influence of CC on the simulated scenarios. The method has been implemented in a GIS tool that helps to apply it to other case studies.

The paper is organized as follows. Section 2 presents the proposed methodology, section 3 describes the study area and data, section 4 show the results and discussion and section 5 summarizes the main conclusions.

2 Methodology

Figure 1 shows the flowchart of the proposed methodology. A modelling framework is proposed to generate and propagate potential future scenarios (section 2.1). It intends to provide a distributed assessment of potential future chloride concentration and hydraulic head fields. From these distributed results a method is proposed to summarize future potential SWI status and vulnerability at GW body scale. The methodology will allow to assess impacts comparing the significance of the SWI problems in different periods for a GW body, but it will also allow to compare results between different GW bodies.

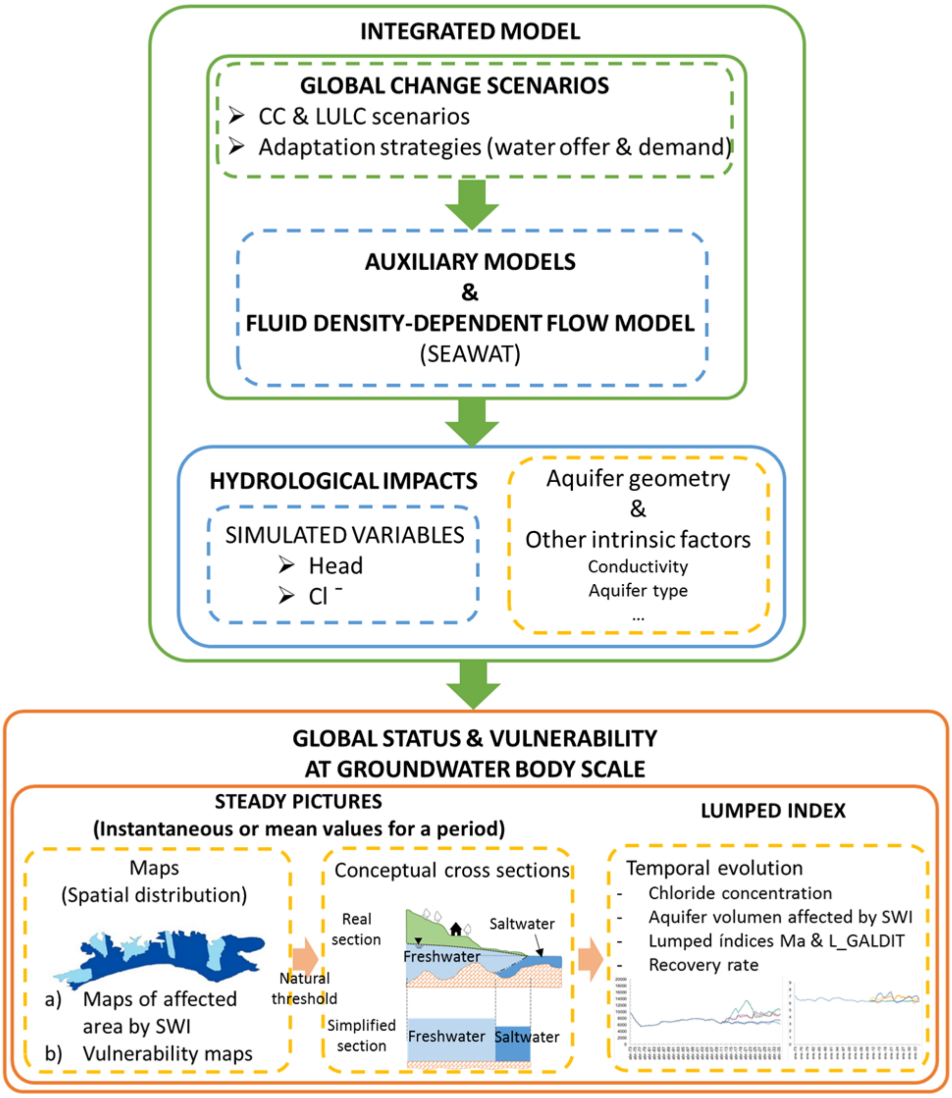

Fig. 1 Flowchart of the proposed methodology

2.1 Generation of future global change scenarios and propagation of their impacts

We propose to apply the downscaling method presented by Collados-Lara et al. (2018) to generate future short-term CC scenarios from historical information and climate model simulations data, which could be obtained from EU CORDEX project (2013). Due to the significant bias between the historical data and the control simulation data, two different correction techniques (bias correction and delta change) can be applied to generate future scenarios (Räisänen and Räty, 2012). A multi-criteria analysis is proposed to identify the best models and correction techniques (in the bias correction approach). In order to define more representative projections, different ensemble of corrected projections are proposed: equi- feasible and non- feasible ones.

Future GC scenarios will be generated by combining the CC and the future LULC scenarios. In order to define more realistic future scenarios we propose to integrate plausible adaptation measures in accordance with the physical, social and legal context of the case study.

The impacts of these plausible future GC scenarios are assessed by propagating them through a modelling framework defined with a chain of auxiliary models a (rainfall-recharge models, crop irrigation requirements, and irrigation returns models) and a density dependent flow model (SEAWAT). It provides a spatio-temporal distribution of the chloride concentration and hydraulic head evolution for the different scenarios.

Finally, a sensitivity analysis is proposed in which a future LULC scenario without CC is also simulated in order to quantify the influence of CC on the GC scenarios.

2.2 Summarising potential future SWI problems (status and vulnerability) at GW body scale

We intend to study impacts of GC on SWI status at GW scale from the distributed results (hydraulic head and chloride fields) obtained with the proposed modelling framework for the future GC scenarios, taking into account the aquifer geometry and hydrodynamic parameters. The vulnerability has been also assessed taking into account other intrinsic aquifer parameters (aquifer type, etc). In order to analyse the results steady pictures (maps and 2D conceptual cross sections) and lumped indices will be employed.

The spatial distribution of SWI status will be summarized with two types of steady pictures: maps of affected volume and conceptual 2D cross sections. The affected volume in the aquifer is defined as the volume where the chloride concentration level is above the natural background level (Dahlstrom and Müller 2006; Baena-Ruiz et al. 2018)). Therefore, knowing the aquifer natural background, the affected volume and the chloride concentration of the affected area (C) can be assessed from the field maps of chloride concentration and hydraulic head (obtained from the output of the physical model).

Furthermore, a conceptual cross-section orthogonal to the coastline is proposed to summarize the SWI status at GW body scale (see Figure 1). It can be calculated for a specific time and/or for the statistics (eg. mean, minimum, and maximum values) of a period. It represents average affected geometry, including the Penetration (P) and the Affected Thickness (Th_a).

$$P(m) = \frac{\sum V_{i(>V_r)}}{T_{ha} * L_{coast}} \tag{1}$$

$$T_{ha}(m) = \frac{\sum V_{i(>V_r)}}{\sum S_{i(>V_r)}} \tag{2}$$

Where:

- $V_{i(>Vr)}$ is the storage in each cell (m^3) with a concentration greater than V_r $V_{i(>V_r)}(m^3) = S_i(m^2) * b_i(m) * \alpha$;
- V_r = Reference threshold (natural background of the aquifer or vulnerability class);
- L_{coast} is the length of coastline (m);
- S_i is the surface area of each cell in the model (m^2);
- b_i is the saturated thickness at each instant considered (m);
- α is the storage coefficient;

The affected zone has an increment of concentration (IC) above the natural threshold.

$$IC\left(\frac{mg}{l}\right) = C - V_r \tag{3}$$

Where:

- C=Concentration in the affected volume

$$C\left(\frac{mg}{l}\right) = \frac{\Sigma(C_{i(>V_r)} * V_{i(>V_r)})}{V_{(>V_r)}} \tag{4}$$

On the other hand, vulnerability maps can be also obtained by applying the GALDIT method (Chachadi and Lobo-Ferreira 2005). From them, the affected volume is defined as the areas in which the vulnerability is higher than a specific vulnerability class or value (eg. High vulnerability). A conceptual cross section to summarize vulnerability results at GW body scale could be defined following an analogous reasoning to those applied to assess the status.

In order to assess the temporal evolution of global status and vulnerability at GW body scale, two lumped indices, "Ma" and "L_GALDIT" respectively, are proposed. The "Ma" index is "the total additional mass of chloride that causes the concentration in some areas to exceed the natural threshold" (Baena-Ruiz et al. (2018)).

$$Ma\left(\frac{kg}{m}\right) = P(m) * IC\left(\frac{mg}{l}\right) * 10^{-3} * T_{ha}(m) \tag{5}$$

In an analogous way, the "L_GALDIT" is defined as the weighted GALDIT index by the aquifer storage:

$$L\_GALDIT = \frac{\Sigma(G_i * V_i)}{V} \tag{6}$$

where:

- G_i is the value of GALDIT in each cell;
- V_i is the storage in each cell;
- V is the total storage in the aquifer;

The temporal evolution of the lumped indices is analyzed taking into account the particularities of the future scenarios. In an historical assessment we have a single real climatic series that allows to draw conclusion about the resilience and trend in the aquifer (Baena-Ruiz et al. 2018). But in the assessment of future scenarios an infinite number of potential future series could be feasible, and therefore the summary of the temporal analyses cannot be performed in the same way. In this work we propose to apply an index, the recovery rate that can be obtained from the evolution of the global indices Ma and L_GALDIT. It is defined as the reduction in Ma index in a given period. It may be represented in a whisker plot in order to provide a statistical assessment of the SWI aquifer's temporal variability during the potential future scenarios.

2.2.1 Sensitivity analysis

A sensitivity analysis is conducted in order to quantify the influence of the CC on the simulated GC scenarios. We compare results obtained for the GC scenarios, which include both, future LULC and potential future CC scenarios, and a future LULC scenario defined assuming that there is not CC. The relative differences in the global status (Ma%) and GW vulnerability (L_GALDIT%) for those scenarios is obtained with the next expressions:

$$Ma\% = \left(\frac{Ma(x) - Ma}{Ma}\right) * 100 \tag{7}$$

$$L\_GALDIT\% = \left(\frac{L\_GALDIT(x) - L\_GALDIT}{L\_GALDIT}\right) * 100 \tag{8}$$

Where:

- Ma% is the variation of the global status (Ma index) expressed as a percentage;
- Ma(x) is the global status affected by CC (average Ma index for each GC scenario);
- Ma is the average global status index (Baena-Ruiz et al.2018) for LULC scenario;
- L_GALDIT% is the variation of the vulnerability (L_GALDIT index) expressed as a percentage;
- L_GALDIT(x) is the vulnerability affected by CC (average L_GALDIT index for each GC scenario);
- L_GALDIT is the average vulnerability index (Baena-Ruiz et al.2018) for LULC scenario;

3 Description of the study area and data

The Plana de Oropesa-Torreblanca is a detrital Mediterranean aquifer which extends over 75 km^2 in the province of Castellon in Spain. It has a length of 21 km and a width of between 2.5 and 6 km. This Plio-Quaternary aquifer is unconfined and heterogeneous and consist on a silty clay matrix with gravel and sand levels. The aquifer is wedge-shaped and it can reach 90 m thick near to the coast. The transmissivity varies between 300-1000 m^2/day (García-Menéndez et al. 2016) and the storage coefficient ranges from 2-12%. Figure 2 show the location and hydrogeology of the aquifer.

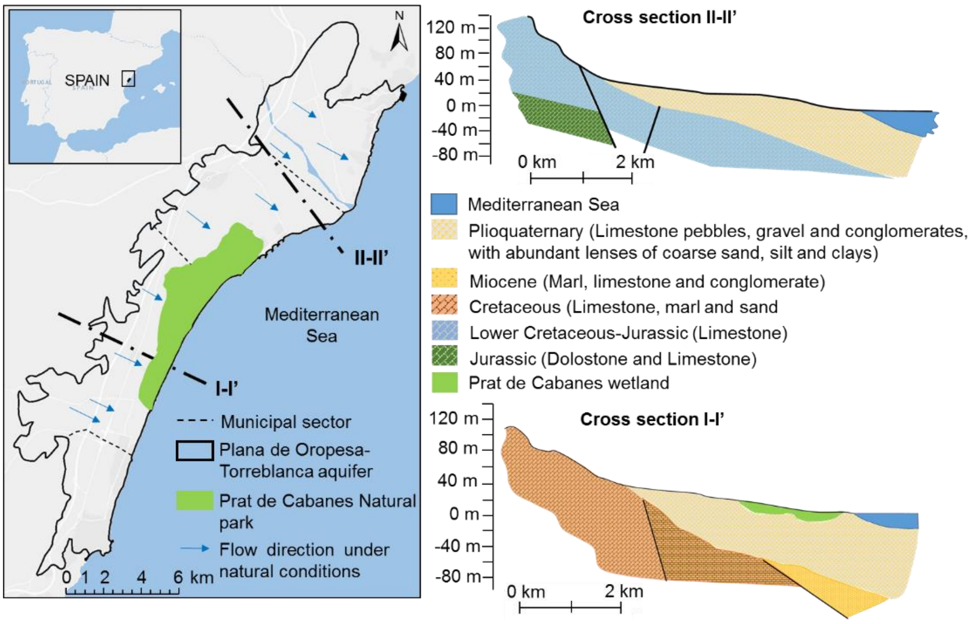

Fig. 2 Situation of the study area and hydrogeological sections

In the central zone of the Plana, parallel to coastline, is situated the wetland Prat de Cabanes which extends approximately 9 km^2. Its formation is due to the clogging of an old lagoon that reaches several meters thick. This wetland is separated from the sea by a coastal bar of sorted pebbles.

The aquifer is laterally connected with adjacent aquifers which provide inflows to the system. Moreover the aquifer recharges from infiltration of precipitation and irrigation returns. Pumped abstractions, the seep in the Prat de Cabanes wetland and GW discharges to sea compound the outflows (Pulido-Velazquez et al. 2018). Groundwater follows a NW-SE direction under natural conditions (Morell and Giménez 1997; Renau-Pruñonosa et al. 2016).

3.1 Data: hydro-climatic conditions, LULC, and pumping data

Historical temperature and precipitation data come from the Spain02 project dataset (Herrera et al. 2012; Herrera et al. 2016). The monthly average precipitation in the period 1973-2010 varied between 20-30 mm in summer and it reached almost 80 mm in the rainiest month. The monthly average temperature went from 12ºC to 28ºC throughout the year. Yearly scale does not show a clear trend in precipitation and temperature.

We have also used control and future climatic series data simulated with RCMs in the framework of the CORDEX project (2013) for the most pessimistic emission scenario RCP8.5. They have been employed to generate the potential future climate scenarios for our GW body.

In the study area there have been important land use changes from 70's. Until 1995 there was a transformation in the crop irrigation, turning it into irrigation lands. From this date to 2010 the main change was an increase of artificial surfaces (mainly residential LULC along the coast) (Feranec et al. 2010) and an improvement in the efficiency of irrigation techniques (CHJ 2015).

Pumping was deduced from historical data. The land use changes are reflected in the evolution of total pumping in the Plana de Oropesa-Torreblanca aquifer. First, the transformation into irrigated croplands from 1975 to 1995 produce an increase in pumping and a drop in GW level. In this period the SWI problem became greater. Later the transformation of irrigation techniques and land uses led to a reduction in pumping (Pulido-Velazquez et al. 2018).

The estimated historical pumping and recharge (deduced from the climate and Land use data) in the aquifer, and the hydraulic head and chloride concentration data available in the observation points during the period 1981-2010 were employed to calibrate the physical model (Pulido-Velazquez et al. 2018). Data from 1973 to 1981 were used to validate it.

3.2 Future LULC scenarios. Implementation of adaptation measures

The future LULC change scenarios are defined taking into account the General Town Plans. It has projected land uses changes that are mainly the construction of golf courses and the transformation of the land use from agricultural to residential. The main changes in each municipality are the following:

- In Alcalà de Xivert there are not expected significant changes.
- The General Town Plan (PGOU) for Torreblanca contemplate the land use change from agricultural to residential (70% of the total area of municipality will be classified as buildable residential or industrial). In the coastal area, north of Prat de Cabanes, Doña Blanca Golf Course has been projected.
- In Cabanes and Oropesa municipalities has been approved the integrated development plan Marina d'Or Golf which will include three golf courses, private urbanization, hotels and landscapes areas.

In order to mitigate the impacts of CC on the GC scenarios, we have also considered the next adaptation measures to increase the complementary resources, which were also requirements included in the General Town Plans: the irrigation in the golf courses must be supplied by reclaimed water from residential use and water from desalinization plant will be used for human consumption.

In order to make the model more realistic, it is supposed that these land use changes would be executed gradually from 2015 to 2035. Figure 3 shows the evolution of changes in time.

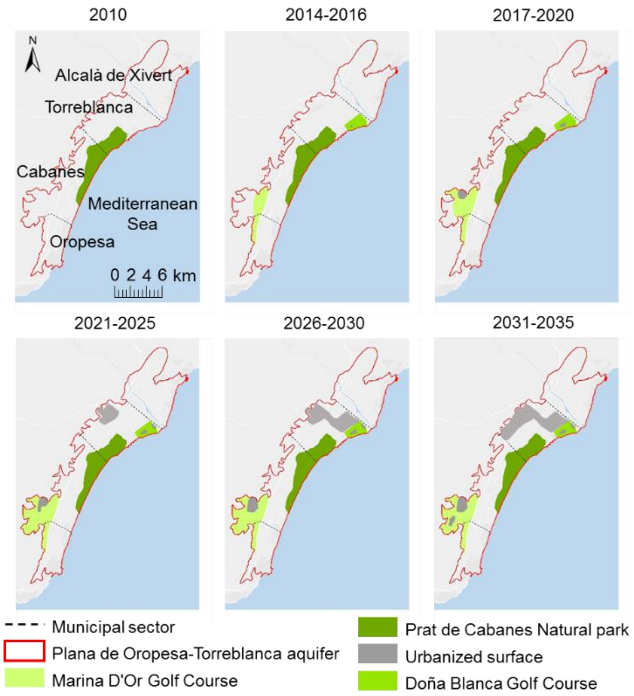

Fig. 3 Expected land use changes in the Plana de Oropesa-Torreblanca aquifer (2010-2035)

4 Results and discussion

The proposed methodology is applied to Plana de Oropesa-Torreblanca aquifer in order to assess impacts of GC scenarios on SWI problems at GW body scale.

4.1 Generation of future global change scenarios and propagation of their impacts

The future GC scenarios have been defined combining a future LULC and different CC scenarios in which some adaptation measures have been assumed to make them more realistic (see section 3.2).

Four future climate scenarios are generated by applying different ensembles of corrected projections (Pulido-Velazquez et al. 2018): E1: Ensemble scenario generated by a linear combination of all the future series generated by delta change; E2: Ensemble scenario generated by a linear combination of all the future series generated by bias correction; E3: Ensemble scenario generated by a combination of models from the multi-criteria analysis for the delta change approach; E4: Ensemble scenario generated by a combination of models and correction techniques from the multi-criteria analysis for the bias correction approach. Figure 4 shows the average characteristics for the ensemble options of the future climate scenarios generated for the period 2011-2035 under the emission scenario RCP 8.5 (the most pessimistic one). These scenarios are generated by combining different models corrected by correction techniques.

All of them show an increase in mean temperature and a reduction in future mean rainfall almost every month. Standard deviation of corrected series estimated by delta change are very similar to the historical one, while the bias correction shows significant reductions in this statistic for both precipitation and temperature.

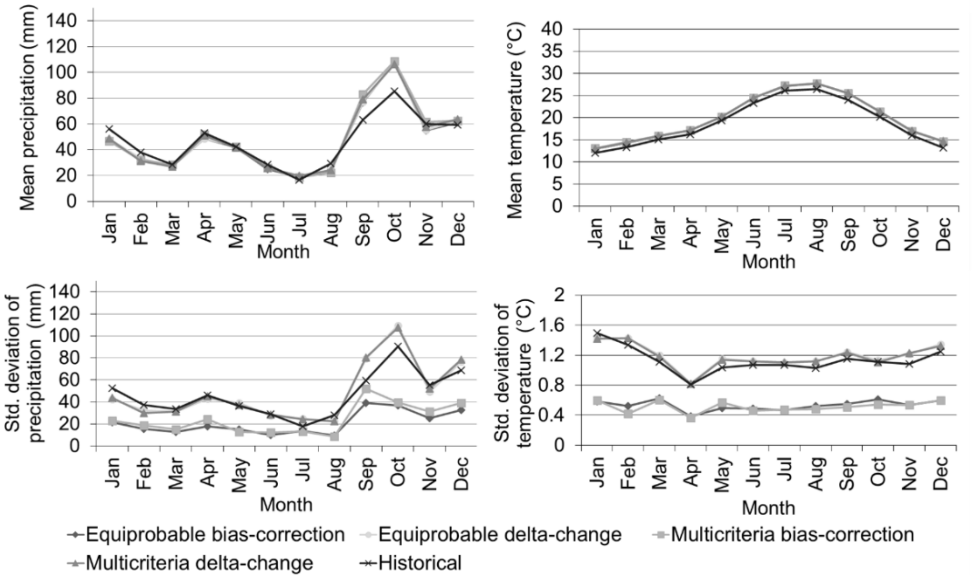

Fig. 4 Statistics of future precipitation and temperature series

These CC scenarios are combined with a land use change scenario (see section 3.2), including some adaptation measures oriented to define more feasible/realistic future scenarios in accordance with the General Town Plan, in which complementary resources will be incorporated within the system (water reuse and water from desalination plants for human consumption in the new urban areas).

The next scenarios are finally analyzed:

- Four GC scenarios (GC_i) defined by combining the four cited CC scenarios (Ei) (see section 2.1) with the future LULC scenario;
- LULC scenario defined assuming that there is not CC;
- Baseline scenario assuming that the LULC will be maintained as in 2010 and the historical hydro-climatic characteristics will be analogous to those of the period 2006-2010.

These last two scenarios will provide us information about the sensitivity of the results to GC and CC respectively.

Figure 5 shows the mean annual values of the budget for the six scenarios.

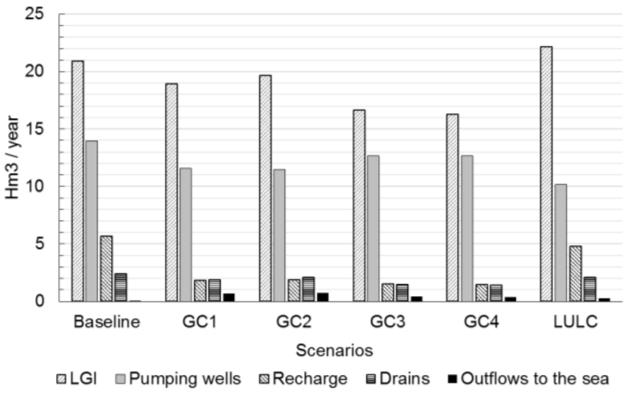

Fig. 5 Mean annual values of the budget four GC, LULC and Baseline scenarios

It shows that, in the future LULC scenario and the four GC scenarios, the pumping is reduced due to changes in land use and due to the proposed adaptation measures (water reuse for irrigation and water from desalinization plant for human consumption in the new urban areas) defined in accordance with the General Town Plans. It shows that the recharge (direct and lateral) decreases due largely to CC and waterproofing of the land in the Torreblanca area and urbanizations. The decrease in recharge is larger in the GC scenarios than in LULC scenario.

4.2 Summarising potential future SWI problems (status and vulnerability) at GW body scale

The area affected by SWI in the aquifer have been identified taking into account the natural background in the aquifer, which is 1100 mg/l of chloride concentration (CHJ 2015, Baena-Ruiz et al. 2018). Figure 6 shows the affected areas in the years with the largest affected volume, in the historical period and in the future period for different scenarios (future baseline, LULC and GC4). The future baseline and LULC scenarios (defined including the cited adaptation measures) do not show a clear deterioration of the aquifer. The worst hypothetical scenario is the GC4, in which practically the whole aquifer would have a chloride concentration above 1100 mg/l.

The affected areas in terms of high vulnerability is pretty similar for the future LULC and baseline scenarios. The GC4 scenario shows a zone of high vulnerability at the north of the aquifer that corresponds with an area with high conductivity.

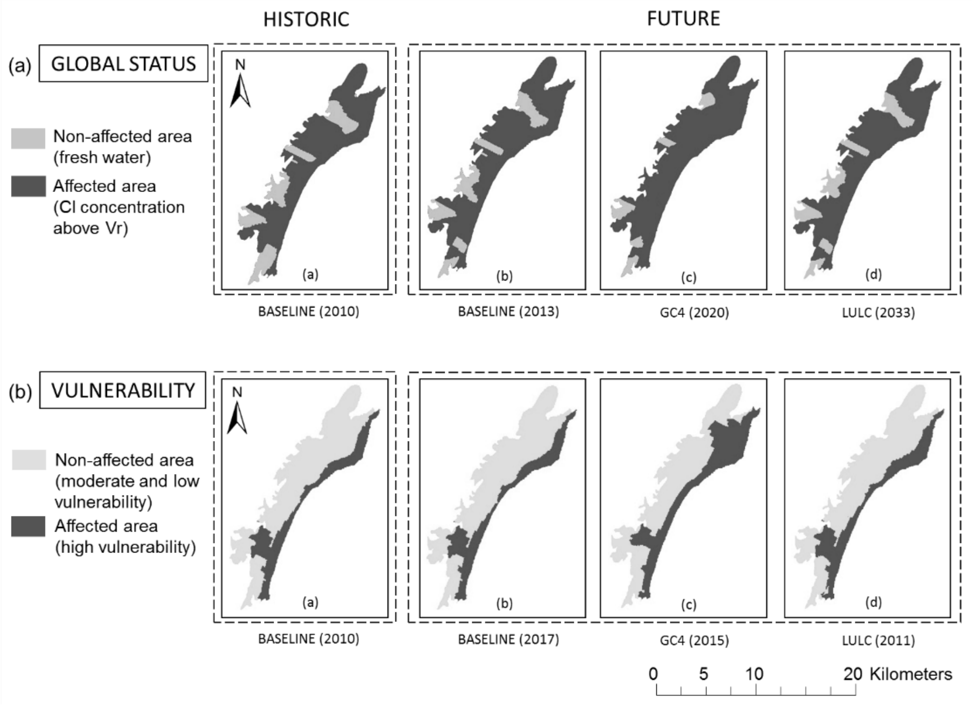

Fig. 6 Maps of affected areas in the years with the largest affected volume (a) chloride concentration and (b) vulnerability

Due to the applied adaptation strategies, the considered changes in land use (LULC scenario) would not produce a high increase in the maximum values of affected volume. The reduction of pumping in this LULC scenario would reduce the amplitude of the fluctuations of the affected volumes within the aquifer (Figure 7(a) and 7(b)). Those non-distributed stresses cause that faster fluctuations on the aquifer status.

Note that the LULC scenarios are defined assuming that the adaptation measures contemplated within the General Town Plan (reduction of pumping due to water reuse and water desalination) will be applied, which would help to reduce the potential impacts of these LULC scenario on SWI. On the other hand, the waterproofing due to the increase in the residential use contributes to a lower recharge (increasing slightly the mean sea water intrusion volume) in the future (Figure 5) and the urbanized area in Torreblanca would continue being supplied with GW.

The GC scenarios (GC1-GC4) show an increase in the affected volume and an increase in their variability. Taking into account that this increase is not observed in the LULC scenarios, it is mainly due to the impact of CC (Figure 7 (a) and (b)). The decrease in pumping is less significant than the reduction of the inflows in the aquifer (LGI + recharge) producing an increase in the affected volume.

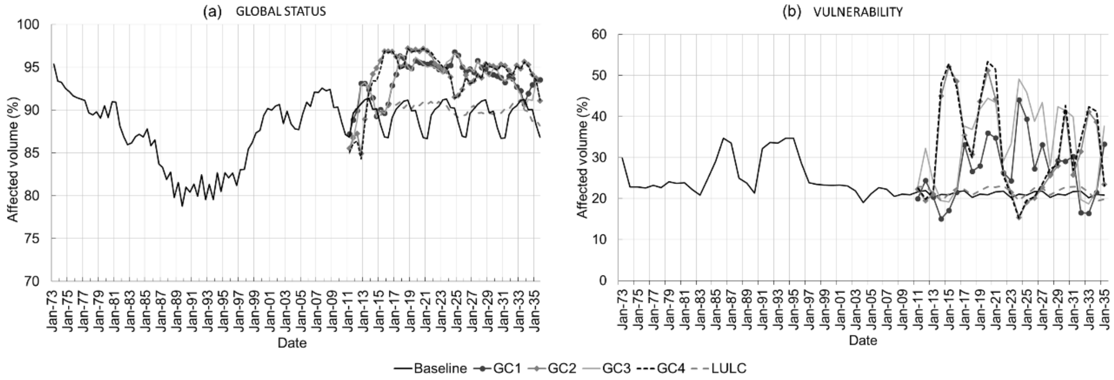

Fig. 7 Evolution of (a) affected volume by a chloride concentration above 1100 mg/l and (b) affected volume by high vulnerability

All potential future GC scenarios would undergo an increase in average and maximum affected cross section, although the aquifer was largely affected in the historical period (Pulido-Velazquez et al. 2018). LULC scenario (including adaptation measures) would not show substantial changes in the affected areas with respect the baseline scenario, while GC3 and GC4 scenarios would involve the largest affected area in the aquifer (Figure 8). The expected future climatic conditions would have a negative impact in the salinization of the aquifer resources and in its vulnerability to SWI.

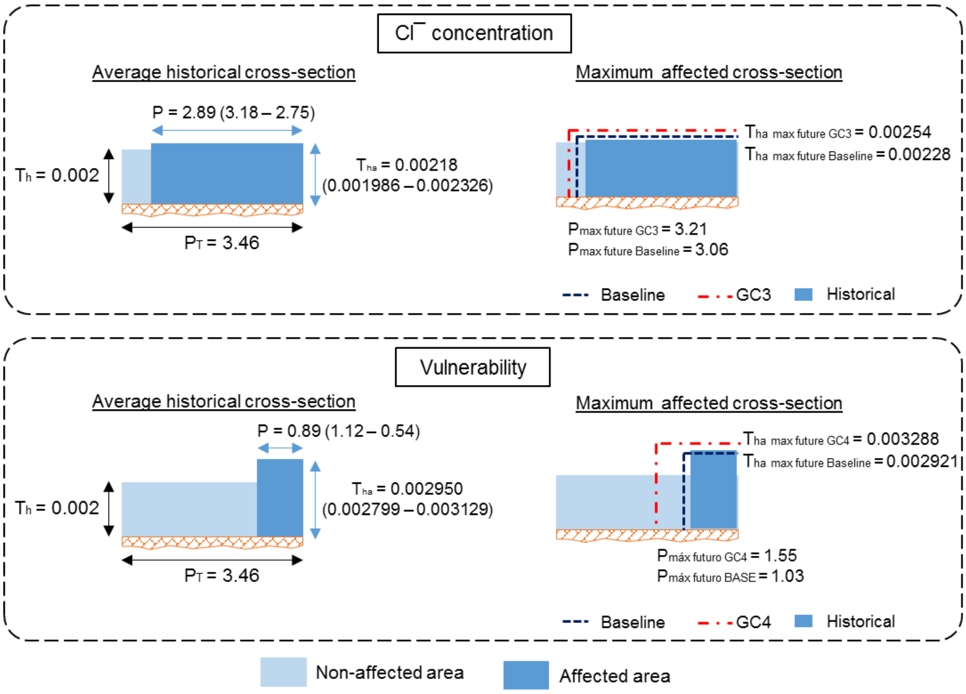

Fig. 8 Average historical and maximum future affected cross-sections (linear dimensions in kilometers. Vertical exaggeration scale: 500)

The global indices (Ma and L_GALDIT) calculated for the baseline, LULC and the GC scenarios (Figure 9) shows that LULC changes would not produce a clear deterioration of the global status and vulnerability of the aquifer. The continuous trend of increment (in the LULC and GC scenarios) in the Ma index observed from 2025 (Figure 9 (b)) are related with the impacts of the planned urbanization of a large area in Torreblanca, which produces an increase of chloride concentrations. GC scenarios forecast a large affected mass in the future, which is mainly due to the potential climatic conditions. The maximum values of the lumped indices (Ma and L_GALDIT) during the GC scenarios are induced by periods with high temperature and low precipitation.

The LULC scenario does not produce significant changes in the vulnerability. The vulnerability is more sensitive to the GC scenarios. All of them show a significant increment in its variability. All of them show a mean increment in the vulnerability within the period, but there are some periods in which the vulnerability even decrease. (Figure 9 (b)).

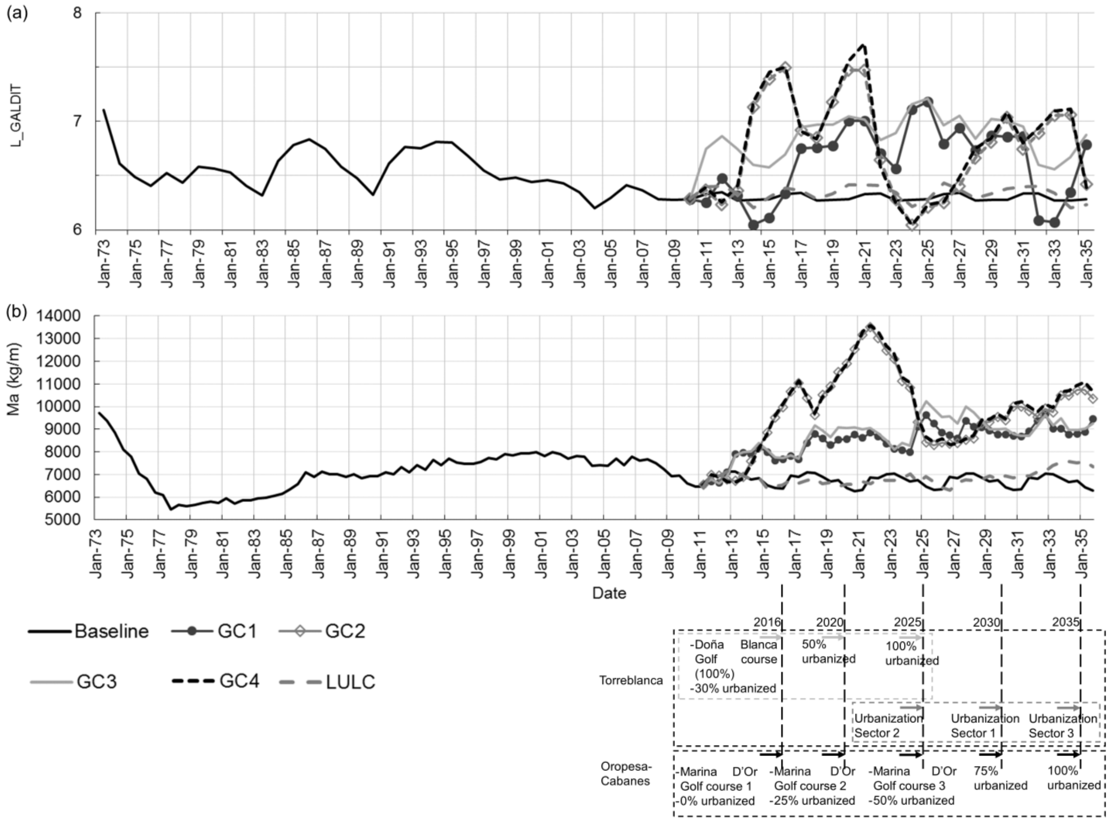

Fig. 9 Lumped indices for vulnerability and global status: (a) L_GALDIT index; (b) Ma index

In Baena-Ruiz et al. (2018) the resilience and trend of the lumped indices were analysed for the historical period. In CC studies we cannot analyze the trend of the indices due to the uncertainty of the chronological sequence. Instead the recovery rate is assessed. Figure 10 shows that the aquifer is able to respond to the severe climatic conditions estimated in GC scenarios. Based on the calibrated model, GC2 and GC4 scenarios present more extreme values but also they show higher recovery rates.

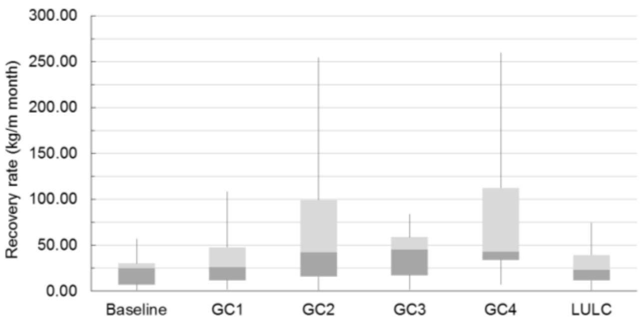

Fig. 10 Statistics of recovery rate for baseline, LULC and GC scenarios

4.2.1 Sensitivity analysis

A sensitivity analysis is carried out to evaluate the impact of CC on global status and vulnerability to SWI at GW scale. Figure 11 shows that CC would have a great impact in Ma index (related to global status of the aquifer). Vulnerability is less sensitive to CC due to other factors that are used in the index (conductivity and distance from the coast) which have greater weight and less temporal variability.

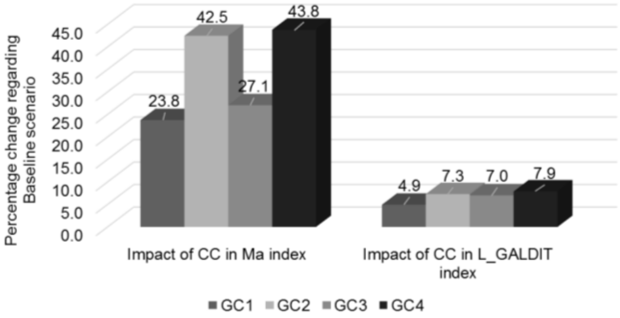

Fig. 11 Sensitivity analysis of CC in lumped indices

Figure 11 explains that CC would produce a deterioration in global status of up to 43,8% regarding the LULC scenario. The GC scenarios with a more extreme climatic conditions involve a great impact in lumped indices.

5 Conclusions

In this paper an integrated methodology is applied in order to assess the hydrological impacts of GC scenarios on the global status and vulnerability to SWI at GW body scale. The novelty of this paper consists on the combined use of an integrated method to evaluate/propagate impacts of GC scenarios (including adaptation strategies) and a method to summarize results in terms of SWI status and vulnerability at GW body scale. It intends to contribute in the definition of methods to harmonize the assessment of GC impacts on SWI problems (status and vulnerability) at GW body scale. It allows to compare the significance of the SWI problems in different historical and future periods for a GW body, but also to compare results between different GW bodies. The method has been implemented in a GIS tool that helps to apply it to any case study.

Some adaptation measures have been integrated in the definition of more feasible future GC scenarios in which complementary resources will be incorporated within the system in accordance with the General Town Plans. The proposed methodology requires to generate potential GC scenarios and to propagate them in accordance with a modelling framework. It provides results for hydraulic head, flows and chloride concentration. These results will be summarized in terms of SWI status and vulnerability at GW body scale. The spatial distribution of SWI status will be summarized with two types of steady pictures: maps of affected volume and conceptual 2D cross sections that are obtained for specific times and the statistics of period. In order to assess the temporal evolution of global status and vulnerability at GW body scale, two lumped indices, “Ma” and “L_GALDIT” respectively, are proposed.

It has been applied to the Plana de Oropesa Torreblanca aquifer. Results show that GC scenarios would imply a greater deterioration in the aquifer than LULC scenario. The adaptation strategies will produce a reduction of pumping in some areas of the aquifer, which would reduce the impacts of the potential future LULC and GC scenarios. The lumped indices reveal that GC would involve more variability in SWI problems (global status and vulnerability) and CC would increase the degradation of the aquifer (43,8% regarding the LULC scenario). On average it is expected a greater area affected by intrusion and an extreme weather conditions might produce an increase of the aquifer more vulnerable. GC would produce a greater impact in global status than in vulnerability of the aquifer. Nevertheless the resilience capacity of the aquifer would allow to recover from the impacts of the extreme weather conditions.

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