



Deliverable 5.2

Harmonised method for assessing status and vulnerability

Authors and affiliation:
David Pulido Velázquez (IGME)
Leticia Baena Ruiz (IGME)
Antonio Juan Collados Lara (IGME)
AL. Hojberg (GEUS)

This report is part of a project that has received funding by the European Union's Horizon 2020 research and innovation programme under grant agreement number 731166.



Deliverable Data	
Deliverable number	D5.2
Dissemination level	Public
Deliverable name	Harmonised method for assessing status and vulnerability
Work package	WP5,
Lead WP/Deliverable beneficiary	IGME, Spain
Deliverable status	
Version	2.0
Date	15/04/2020

[This page has intentionally been left blank]

TABLE OF CONTENTS

1	INTRODUCTION	4
2	METODOLOGY	5
2.1	Historical Assessment of seawater intrusion (SWI) status (Baena-Ruiz et al., 2018).....	6
2.1.1	Maps of SWI affected volumes	7
2.1.2	2D conceptual cross-sections: mean penetration and thickness. Average Increment in concentration	8
2.1.3	Lumped index: Mass of affected area (Ma).....	8
2.1.4	Resilience and Trend (MART).....	9
2.2	Historical assessment of vulnerability to SWI	9
2.2.1	Maps of aquifer volumes where the vulnerability is above a certain threshold.....	9
2.2.2	2D cross-sections: Penetration and Thickness. Vulnerability classes	10
2.2.3	Lumped index: L_GALDIT	11
2.2.4	Resilience and Trend.....	11
2.3	Future assessment of SWI status at aquifer scale	11
3	APPLICATION TO CASE STUDIES	14
3.1	Case study: Plana de Oropesa-Torreblanca.....	14
3.1.1	Inputs required to perform the historical assessment	15
3.1.2	Inputs required to perform the future assessment.....	16
3.2	Maps of SWI status and vulnerability affected volumes	17
3.3	2D conceptual cross-sections: mean penetration and thickness.	18
3.4	Lumped indices: Ma and L-GALDIT values.....	20
4	REFERENCES:	22
	APPENDIX: GALDIT METHOD.....	23

1 INTRODUCTION

This TACTIC deliverable reports the outcome of tasks “5.2 developing a method to summarize in a harmonized way Sea Water Intrusion (SWI) status and vulnerability”. The objective of the deliverable has been to develop a method based on indices and variables to summarise SWI status and vulnerability at aquifer scale. Information on the aquifer volume affected by sea water intrusion at different spatial scales is generated, moving from areal maps to representative conceptual cross section and lumped indices. The maps can be generated by applying different tools, such as numerical groundwater flow and transport models, conceptual models and spatial interpolation techniques using observed chloride concentrations. The sensitivity of the affected volumes to the threshold employed to define them should be also tested. This threshold is defined from the natural background level in the aquifer. The proposed indices-based method has been implemented in a general GIS tool (Baena-Ruiz et al., 2019) to facilitate its application and comparison between SWI problems in different GW bodies and temporal periods. The resilience and trend of the system to SWI can be deduced from the time series of the proposed indices. Impacts of potential global change (GC) scenarios (climate change and Land Use and Land cover Change scenarios) can be also analysed. The method is published in a journal paper in Environmental Earth Science journal (Baena-Ruiz et al., 2020) that shows an application of this method to analyse potential climatic scenarios. The method has been also applied to perform historical assessment (Baena-Ruiz et al., 2018). This deliverable has been made by compiling the methodological descriptions included in the cited papers.

2 METODOLOGY

The inputs required and the steps to be followed to apply the method are represented in Figure 1. The **inputs** include variables (to characterise the historical evolution of hydraulic head and chloride concentration) and parameters (to define aquifer geometry and hydrodynamic behaviour) to determine the overall status of the aquifer. The data describing the historical evolution could come from direct observation (monitoring network) or other techniques (geophysical applications, etc.). For the vulnerability assessment, other intrinsic information (aquifer type, conductivity, distance from the shoreline, bicarbonate concentration) is also needed as inputs to apply the proposed method.

The information required (section 2.1) in order to summarize historical status and vulnerability to SWI through visual pictures and time series are: 1. Maps of SWI affected aquifer volumes; 2. 2D conceptual cross-sections (with mean penetration and thickness in specific dates or mean values in periods); 3. Lumped Index (Mass of affected area and lumped vulnerability index) to summarise the global dynamic of SWI within the aquifer, which will be described in the next subsections (2.1).

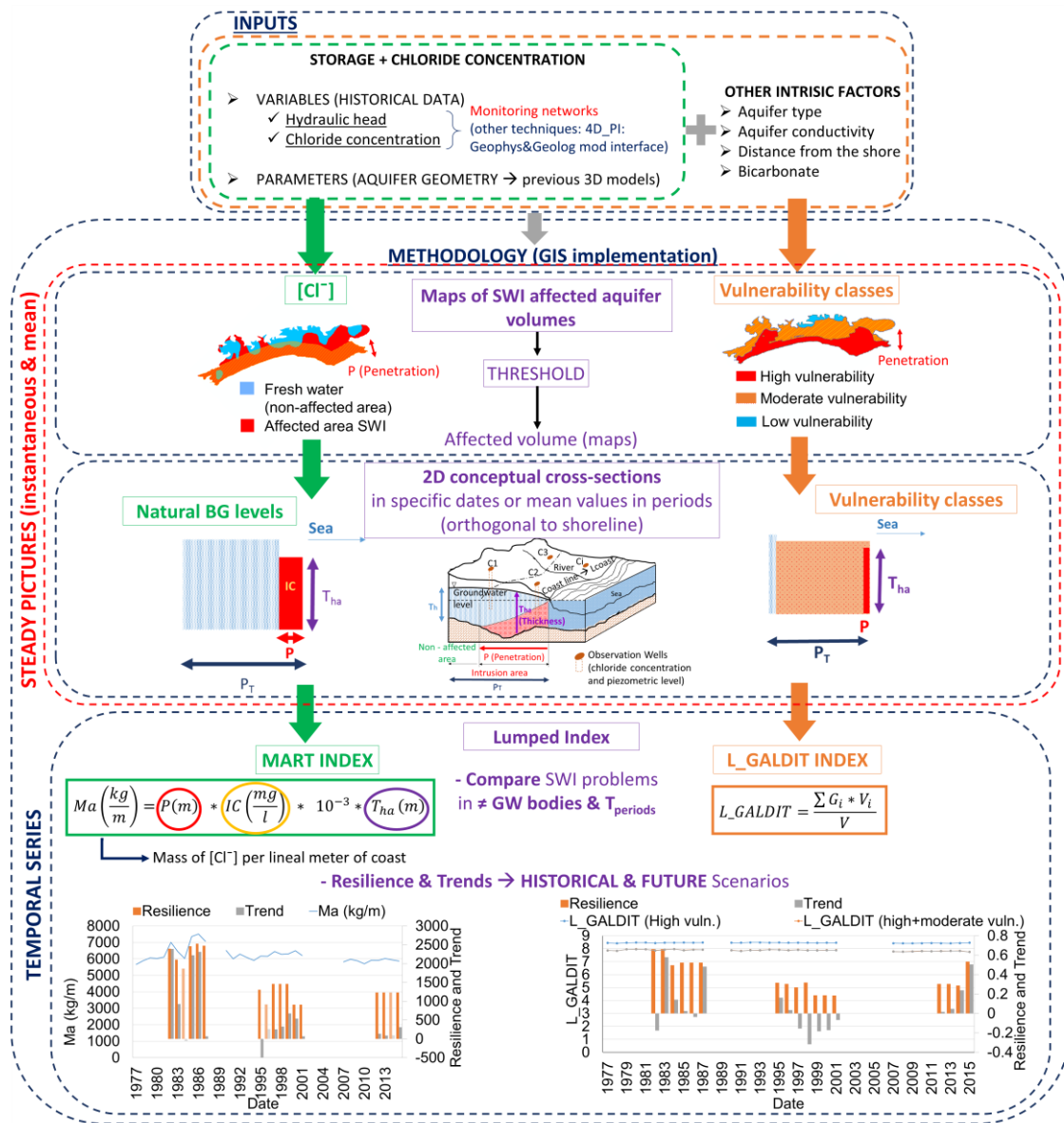


Fig 1 Flow chart of methodology (modified from Baena-Ruiz et al., 2018)

2.1 Historical Assessment of seawater intrusion (SWI) status (Baena-Ruiz et al., 2018)

The described inputs will be employed to assess and summarise SWI status for a specific date according to the following steps:



2.1.1 Maps of SWI affected volumes

In order to assess them we will need to estimate: A) Historical maps of chloride concentration and groundwater volumes B) Threshold of chloride concentration in the aquifer to identify when there is SWI C) Crossing this information we will identify maps of SWI affected volumes.

A. Maps of chloride concentration and groundwater volumes

Fields (maps) of chloride concentration and hydraulic head can be obtained by applying simple interpolation techniques or density dependent groundwater flow models. In case that interpolation techniques are applied, those maps will be obtained for each date with enough available information. Those fields will be defined over a mesh, whose spatial resolution should be appropriate to provide an appropriate distributed assessment in accordance with the available data and the adopted interpolation or modelling approach.

Maps of historical groundwater volumes can be obtained by combining hydraulic head maps with the geometry and the storage coefficient. Vertical aquifer geometry and storage coefficient can be obtained from previous 3D models and hydrogeological studies respectively.

If there is insufficient information to assess the vertical distribution of chloride concentration, an invariant concentration with depth is assumed at each point, thus obtaining 2D fields of chloride concentration.

B. Threshold of chloride concentration to identify SWI

A threshold value is used to determine the volume of the aquifer affected by SWI. Some European projects ("BRIDGE") (Dahlstrom and Müller 2006) have provided recommendations for its calculation, based on methodologies applied in some countries. This threshold can be derived from the natural background level (NBL), which depends on the geochemistry of the aquifer and is difficult to determine, or based on reference quality standards (ecosystems and human uses). Figure 2 shows a summary of the methodology proposed in BRIDGE project for threshold setting and NBL assessment.

Threshold (TV) for groundwater	NBL determination (groundwater "itself")	BRIDGE methodology	"Own approach" and experience	TV = NBL TV = (REF + NBL)/2; REF=drinking water standards or environmental quality standards
			Simplified (preselection) approach: 90-percentile of a preselected samples (97.7-percentile if no human influence exists) Statistical results for the same aquifer typology	
			Other methodologies (groundwater samples free from human impact; hydrochemical/hydrodynamical models; separation methods)	
			Resource: saline intrusion (TVs have to be set according to NBLs)	
	Quality standards	Resource: saline intrusion (TVs have to be set according to NBLs)	Escosystem	

Fig 2 Procedure for threshold and NBL determination in BRIDGE project

C. Maps of SWI affected volumes

From chloride concentration we can define the affected and non-affected volumes, taking into account the zones where the chloride concentration level is above the threshold value. For these zones we can calculate the affected volume by identifying the resources in those areas in accordance with the map of groundwater volumes.



2.1.2 2D conceptual cross-sections: mean penetration and thickness. Average Increment in concentration

2D conceptual cross-sections orthogonal to the shoreline can be deduced to summarise the mean geometry of the affected volume, i.e. the mean thickness and inland penetration, as well as the intensity of the intrusion ($IC \left(\frac{mg}{l}\right)$), defined as the increment in concentration above the threshold $TV \left(\frac{mg}{l}\right)$. The average affected thickness ($T_{ha}(m)$) and inland penetration ($P(m)$) of intrusion can be calculated as summation of values in each cell i of the aquifer mesh where the chloride concentration is above the threshold:

$$T_{ha}(m) = \frac{\sum V_{i(>TV)}}{\sum S_{i(>TV)}} \quad (1)$$

$$P(m) = \frac{\sum V_{i(>TV)}}{T_{ha} * L_{coast}} \quad (2)$$

$$V_{i(>TV)}(m^3) = S_i(m^2) * b_i(m) * \alpha_i \quad (3)$$

where:

- $V_{i(>TV)}(m^3)$ is the groundwater volume in the cell i with a concentration above TV ;
- $S_i(m^2)$ is the surface area in the cell i with Cl concentration $> TV$;
- $b_i(m)$ is the saturated thickness within the cell i with Cl concentration $> TV$;
- α_i (-) is the storage coefficient in the cell i ;
- $L_{coast}(m)$ is the length of coastline;

The mean chloride concentration (C) of the affected area is:

$$C \left(\frac{mg}{l}\right) = \frac{\sum (C_{i(>TV)} * V_{i(>TV)})}{V_{(>TV)}} \quad (4)$$

where:

- $C_{i(>TV)}$ is the chloride concentration (mg/l) above TV in cell i within the affected area ;
- $V_{i(>TV)}$ is the groundwater volumes (m^3) in cell i with a concentration above TV ;
- $V_{(>TV)}$ is the total groundwater volume (m^3) of the affected area;

The increment of concentration (IC) above the threshold (TV) in the affected volume is:

$$IC \left(\frac{mg}{l}\right) = C - TV \quad (5)$$

The conceptual cross sections give an overview of the magnitude and intensity of the intrusion process per linear metre of coast at a specific time. Mean conceptual cross sections can also be obtained to summarise the average values for a time period.

2.1.3 Lumped index: Mass in affected volume (Ma)

The index Ma in a specific date is defined as the total additional mass of chloride that causes the concentration in some areas to exceed the natural threshold. It is obtained multiplying the increment of concentration (IC) by Penetration (P) and affected Thickness (T_{ha}) from equations 1,2 and 5.



$$Ma \left(\frac{kg}{m} \right) = P(m) * IC \left(\frac{mg}{l} \right) * 10^{-3} * T_{ha}(m) \quad (6)$$

The concept of Ma involves some simplifications, in accordance with the definition of the conceptual cross sections. While 2D maps and cross sections summarize the extent and magnitude of SWI in an aquifer at a specific time, Ma index show the intensity and temporal evolution of the problem.

2.1.4 Resilience and Trend (MART)

The evolution of the Ma index can give an overall assessment of the resilience (R) and trend (T) of the aquifer status according to the SWI problem. We propose calculating Resilience as the maximum relative change of the Ma index (relative difference between maximum and minimum value) over six-year periods, which is the horizon defined to update management plans in the Water Framework Directive (2000). Thus, Resilience shows the potential change for a short-term period, taking into account the measures occurred in this period.

Trend is also calculated for six-year periods. It is defined as the relative difference between the values of Ma at the beginning and end of the period. A positive trend indicates that the volume of water affected is increasing, while a negative trend indicates an improvement in aquifer status.

The combination of Mass in affected water body (Ma), Resilience (R) of the water body and Trend (T) of SWI defines the MART index, which summarize SWI evolution in the aquifer.

2.2 Historical assessment of vulnerability to SWI

While SWI status is calculated using only physical variables (chloride concentration and hydraulic head), vulnerability employs weighted qualitative characteristics. In this study, we summarise vulnerability status based on the application of the GALDIT method (Aquifer type; aquifer hydraulic conductivity; height of groundwater head above sea level; distance from the shore; impact of existing status of SWI; thickness of aquifer being mapped) (Chachadi and Lobo-Ferreira 2005). The proposed method to summarise the SWI vulnerability is analogous to the one proposed to summarise the SWI status. In this case, instead of chloride concentration values we will use GALDIT vulnerability values, and the thresholds have been replaced by vulnerability classes.

2.2.1 Maps of aquifer volumes where the vulnerability is above a certain threshold

The steps followed to perform this calculation for a specific date are:

A. Historical maps of aquifer vulnerability and groundwater resources

We need to estimate vulnerability maps instead of the chloride concentration maps required to summarise the status. Vulnerability maps are displayed from GALDIT method. This method considers that there are six indicators/factors influencing the vulnerability to SWI: aquifer type, hydraulic conductivity, height of GW level above sea level, distance from the shore, impact of existing status of SWI and thickness of aquifer. A rate of importance is assigned to the indicators

according to the value of each variable (Chachadi and Lobo-Ferreira 2005). The GALDIT Index is obtained by applying the expression:

$$GALDIT\ Index = \frac{\sum_{i=1}^6 W_i * R_i}{\sum_{i=1}^6 W_i} \quad (7)$$

where W_i is the weight of the i th indicator and R_i is the importance rating of the i th indicator. The weights and rates for each indicator are defined in Chachadi and Lobo-Ferreira (2005) and they are described in an Appendix of this report.

The GALDIT scores are then classified into three **vulnerability classes**: High (GALDIT Index range ≥ 7.5), Moderate (between 5 and 7.5) and Low (< 5).

The groundwater resources maps can be obtained taking into account the storage coefficient, the aquifer geometry and the hydraulic head.

B. Threshold of vulnerability

Different vulnerability thresholds could be adopted. We propose to use as threshold any of the vulnerability values adopted in GALDIT to define the moderate or high vulnerability classes (see previous section). Therefore, the “affected zones” will be those where vulnerability is higher than moderate or high, depending on the adopted threshold.

C. Maps of “affected volumes” with vulnerability values above the threshold

From the vulnerability maps we can define the “affected” and “non-affected” volumes, taking into account the zones where the vulnerability is above the adopted threshold. For these zones we can calculate the affected volume in accordance with the map of groundwater volumes.

2.2.2 2D cross-sections: Penetration and Thickness. Vulnerability classes

2D conceptual cross-sections orthogonal to the shoreline can be deduced to summarise the mean geometry of the “affected volume” (zones where the vulnerability is above the adopted threshold, noted as TV_{GALDIT} (m^2)) for a specific date. The mean Thickness ($(T_{haL_GALDIT}(m))$ and inland Penetration ($P_{L_GALDIT}(m)$) can be calculated as summation of values in each cell i of the aquifer mesh where the vulnerability is greater than the threshold. Therefore, the calculations are the same to those included in section 2.1.2, changing the target variable and its thresholds:

$$T_{haL_GALDIT}(m) = \frac{\sum V_{i(>TV_{GALDIT})}}{\sum S_{i(>TV_{GALDIT})}} \quad (8)$$

$$P_{L_GALDIT}(m) = \frac{\sum V_{i(>TV_{GALDIT})}}{T_{haL_GALDIT} * L_{coast}} \quad (9)$$

$$V_{i(>TV_{GALDIT})}(m^3) = S_i(m^2) * b_i(m) * \alpha_i \quad (10)$$

where:

- $V_{i(>TV_{GALDIT})}$ groundwater volume in each cell (m^3) with vulnerability greater than $V_{TV_{GALDIT}}$;
- S_i is the surface area in the cell i with vulnerability higher than $V_{TV_{GALDIT}}$;
- b_i is the saturated thickness within the cell i with vulnerability higher than $V_{TV_{GALDIT}}$;



- α_i is the storage coefficient in the cell i ;
- L_{coast} is the length of coastline (m);

The intensity of vulnerability is the GALDIT score in each zone for the thresholds established. These cross sections give an overview of the magnitude and intensity of the vulnerability per linear metre of coast at a specific time. Mean cross sections can also be obtained to summarise the average values for a time period.

2.2.3 Lumped index: L_GALDIT

A lumped global value of GALDIT (L_GALDIT) is defined by weighting the GALDIT score for each point with the storage (Equation 11). This weighted value of GALDIT assesses the overall vulnerability of the aquifer. Similarly, a lumped affected value of GALDIT can be obtained for the different thresholds (Equations 12 and 13).

$$L_GALDIT = \frac{\sum(G_i * V_i)}{V} \quad (11)$$

$$L_GALDIT_{\text{high}} = \frac{\sum(G_{i(\geq 7,5)} * V_{i(\geq 7,5)})}{V_{(\geq 7,5)}} \quad (12)$$

$$L_GALDIT_{\text{high+moderate}} = \frac{\sum(G_{i(\geq 5)} * V_{i(\geq 5)})}{V_{(\geq 5)}} \quad (13)$$

where:

- G_i is the value of GALDIT in each cell i ;
- V_i is the groundwater volume in each cell i ;
- V is the total groundwater volume in the aquifer;
- $G_{i(\geq 7,5)}$ is the value of GALDIT of each cell greater or equal to 7,5;
- $G_{i(\geq 5)}$ is the value of GALDIT of each cell greater or equal to 5;
- $V_{i(\geq 7,5)}$ is the groundwater volume of each cell with a value of GALDIT $\geq 7,5$;
- $V_{i(\geq 5)}$ is the groundwater volume of each cell with a value of GALDIT ≥ 5 ;
- $V_{(\geq 7,5)}$ is the total groundwater volume with a value of GALDIT $\geq 7,5$;
- $V_{(\geq 5)}$ is the total groundwater volume with a value of GALDIT ≥ 5 ;

2.2.4 Resilience and Trend

An analogous procedure to the one described for the MART index is applied to determine the evolution over time of the L_GALDIT index, the Resilience and Trend of aquifer vulnerability.

This method employs the spatial distribution of groundwater volumes to obtain affected volume in the lumped indices (MART and L_GALDIT). Hydrogeological parameters as the transmissivity are implicitly considered in the spatial distribution of the hydraulic head. The method does not require complex modelling approaches and has been implemented in a **GIS tool** that encourages its application to other cases.

2.3 Future assessment of SWI status at aquifer scale

In order to assess and summarize future potential impacts of GC, we will need to generate potential future maps of chloride concentration and groundwater volumes. To obtain them, we



propose to define local climate series and Land Use and Land Cover scenarios representative of the future conditions. The series of cited potential maps can be obtained by propagating the future climate LULC scenarios with a modelling approach that includes a density dependent flow model.

The method described in Section 2.2 (for the historical assessment) to summarise SWI could be also applied to analyse the future SWI by replacing the historical maps by those future maps. The only difference is that, when a historical analysis is performed, at each date we will have a unique chloride concentration and groundwater volume map, and the analyses of the dynamic in a period allows to draw univocal conclusions about the resilience and trend in the aquifer (Baena-Ruiz et al., 2018). But in the assessment of future scenarios infinite potential future series could be feasible (although we finally considered a limited number of them), and, therefore, the conclusions about SWI dynamic should not be performed in the same way. Instead of studying the resilience and trend we propose to analyse the recovery or deterioration rate.

The recovery or deterioration rate, which can be obtained from the evolution of the global indices Ma and L_GALDIT , is defined as the mean change in the index value in a given period. Negative values are related with deterioration and positive with recovery. It may be represented in a box-whisker plot in order to provide a statistical assessment of the SWI dynamic in future horizons. The recovery rate for Ma index, which represents the mean recovery or deterioration velocity of the system, is defined as follow:

$$Recovery\ rate = \frac{Ma_t - Ma_{t-n}}{n} \quad (14)$$

Where:

- Ma_t is the global status (Ma index) in a specific date “t”;
- Ma_{t-n} is the global status (Ma index) in a specific date “t-n”;
- n is the difference between the date “t” and “t-n” (at monthly scale);

Assuming a linear behaviour, the impacts of CC could be also deduced from the impacts of some GC scenarios that includes both, CC and land use and LULC scenarios. They could be analysed through a sensitivity analysis in order to quantify the influence of the CC on the simulated GC scenarios. We should 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 are obtained with the next expressions:

$$Ma\% = \left(\frac{Ma(x) - Ma}{Ma} \right) * 100 \quad (15)$$

$$L_GALDIT\% = \left(\frac{L_GALDIT(x) - L_GALDIT}{L_GALDIT} \right) * 100 \quad (16)$$

Where:

- $Ma\%$ is the variation of the global status (Ma index) due to CC, expressed as a percentage;



- $Ma(x)$ is the average global status (Ma index) for each GC scenario;
- Ma is the average global status index (Ma index) for LULC scenario;
- $L_GALDIT\%$ is the variation of the vulnerability (L_GALDIT index) due to CC, expressed as a percentage;
- $L_GALDIT(x)$ is the average vulnerability (L_GALDIT index) for each GC scenario;
- L_GALDIT is the average vulnerability index (L_GALDIT) for LULC scenario;

3 APPLICATION TO CASE STUDIES

In this section we will include as an example the results obtained in each of the described steps of the method in the case study, Plana de Oropesa Torreblanca aquifer. The analyses and discussion of the obtained results for the historical and future SWI status and vulnerability at aquifer scale are included in the research papers Baena-Ruiz et al., (2018, 2020), respectively.

3.1 Case study: Plana de Oropesa-Torreblanca

The study case, the Plana de Oropesa-Torreblanca aquifer, is located in the Mediterranean coast of Spain, in Castellon province (Figure 3). The increasing population since 1970 and the continuing agricultural exploitation have produced SWI problems of different entity in this aquifer. The aquifer is unconfined, heterogeneous, detrital and multilayer composed of gravel and sand levels in a silty clay matrix (Ballesteros et al., 2016). The transmissivity in the Plio-Quaternary Plana de Oropesa-Torreblanca aquifer ranges from 300 to 1000 m²/day (García-Menéndez et al., 2016) and the storage coefficient varies between 2 and 12%.

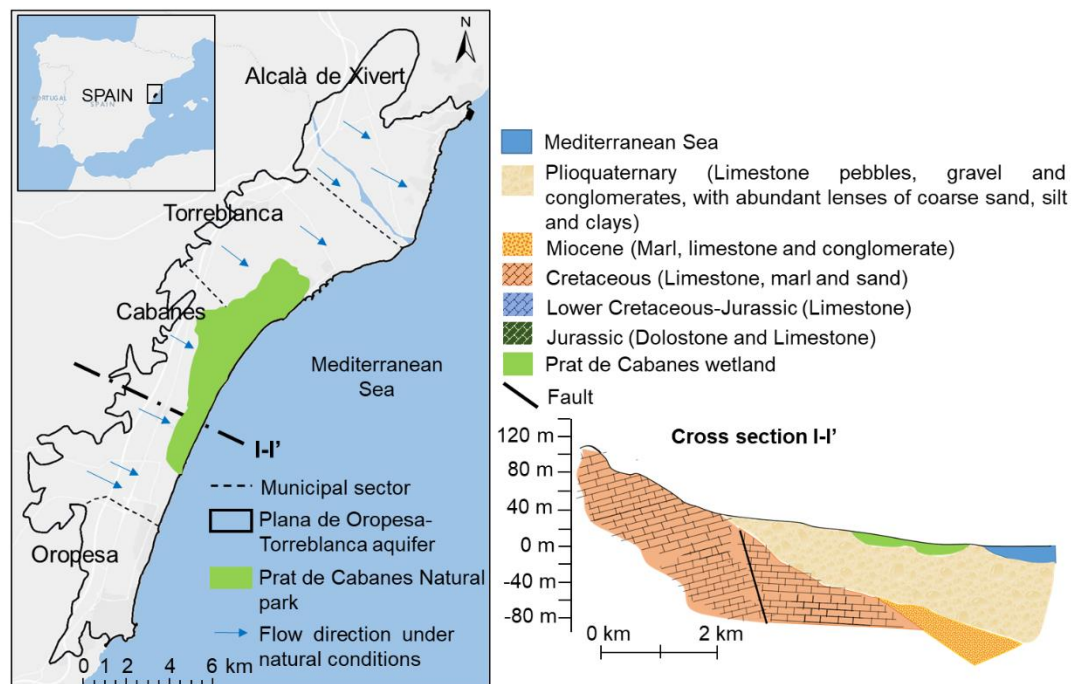


Fig 3 Situation of the study area and hydrogeology (modified from Baena-Ruiz et al., 2020)

There are no chloride concentration data for this study area from 1988 to 1989 neither from 2001 to 2005. The number of monitoring points of chloride concentration varies over time between 12 and 34, while the monitoring points of hydraulic head ranges between 9 and 1.



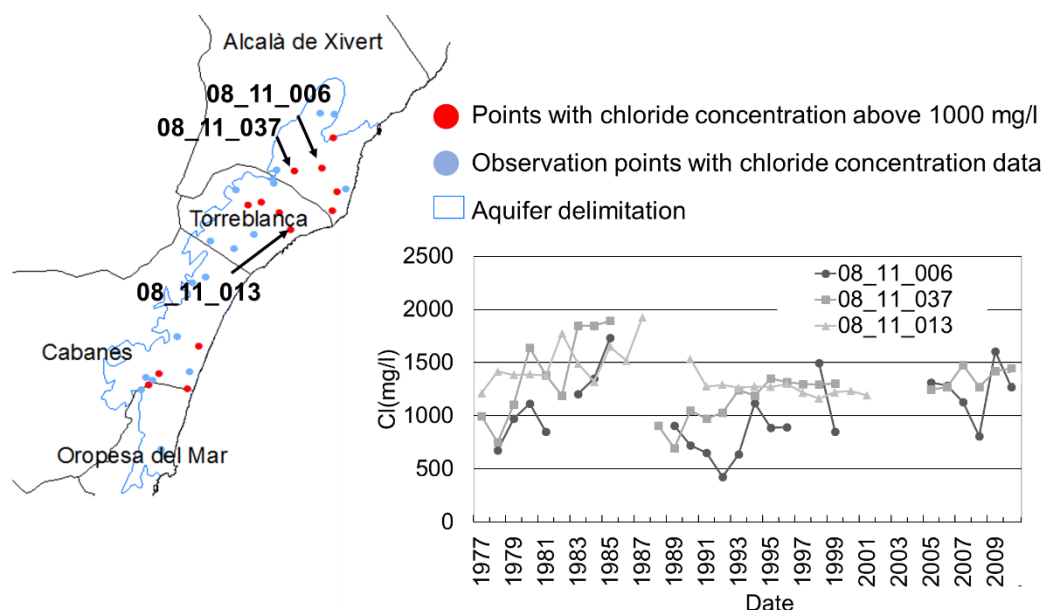


Fig 4 Location of the observation points in Plana de Oropesa-Torreblanca and evolution of the chloride concentrations in monitoring points (modified from Baena-Ruiz et al., 2018)

The chloride concentration exceeds 1000 mg/l in zones close to the coast. Points inland exhibit lower concentrations that are more stable through time. Concentrations increased over the 1980s as a consequence of the expansion in irrigated croplands, associated with a period of scarce rainfall. Subsequently, there was a drop in mean chloride concentrations due to the reduction in pumping, together with improved hydrological planning (Figure 4).

Groundwater flow approximately follows a NW-SE direction before discharging to the sea. The range of piezometric levels varies in the Plana de Oropesa-Torreblanca reaching maximum about 3 m a.s.l. at points furthest from the coast. The piezometric level is depressed in zones close to the coast. Aquifer geometry is derived from previous 3D models (Renau Pruñonosa 2013). The Plana de Oropesa-Torreblanca aquifer is wedge-shaped being the maximum thickest located near to the coastline, where it can reach 90 m thick.

3.1.1 Inputs required to perform the historical assessment

In this section of the technical notes we are going to show some examples of the historical maps of chloride concentration and groundwater volumes/resources required to apply the method to assess and summarize SWI status. In the presented maps we have represented the mean chloride concentration in the aquifer depth. We will also show examples of the historical vulnerability maps required to assess SWI vulnerability.



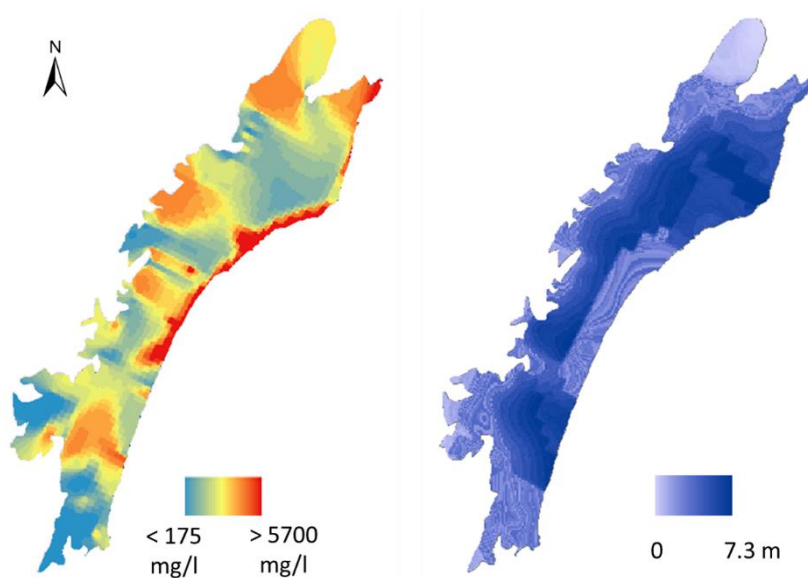


Fig 5 Historical maps of chloride concentration (left) and groundwater resources (right) (October 1985)

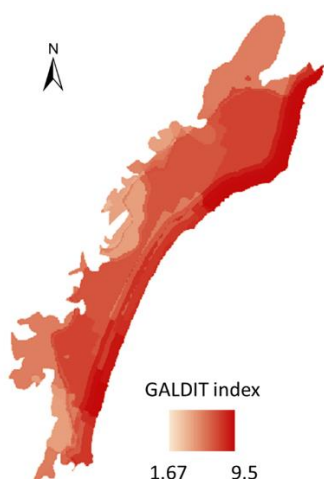


Fig 6 Historical maps of vulnerability (October 1985)

3.1.2 *Inputs required to perform the future assessment*

The generation of the future local GC scenarios (including CC and LULC scenarios), and the description of the modeling framework employed to propagate their impacts is detailed in detail in the paper Baena-Ruiz et al., (2020). In this section of the technical note we are going to show examples of the future maps of chloride concentration and groundwater resources required to apply the method to assess and summarize impacts on SWI status. We will also show examples of the future vulnerability maps required to assess future SWI vulnerability. We show the results only for one GC scenario.

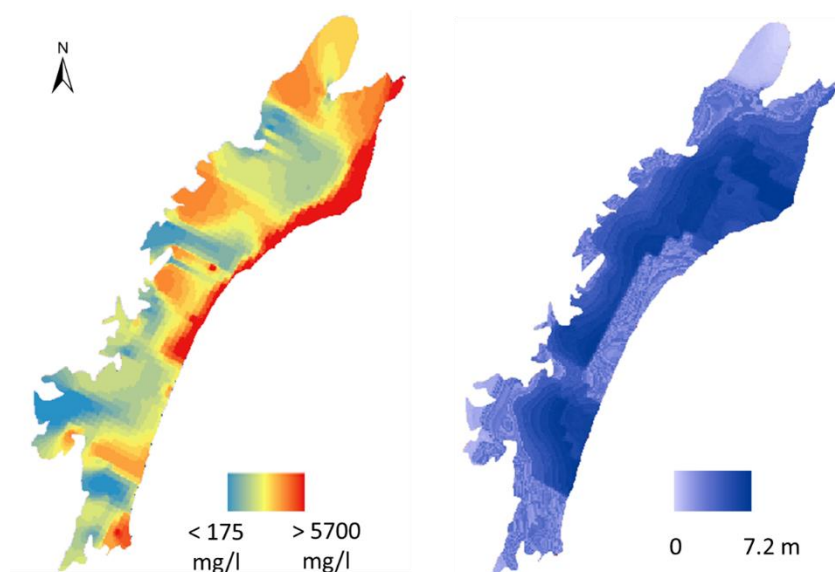


Fig 7 Maps of potential future chloride concentration and groundwater resources for the simulated scenario (September 2027)

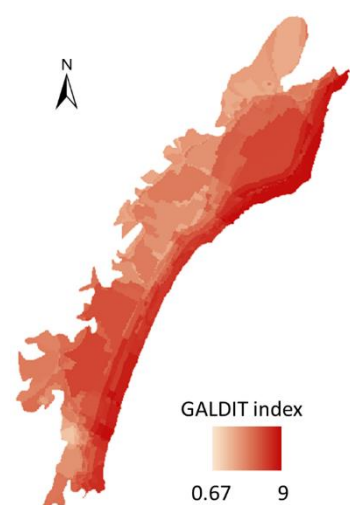


Fig 8 Maps of potential future vulnerability for the simulated scenario (September 2027)

3.2 Maps of SWI status and vulnerability affected volumes

Following the steps described in section 2.1.1 and 2.2.1 of the methodology we obtain the maps of affected volumes in terms of SWI status and vulnerability respectively. In the historical analysis we assumed two different threshold values to SWI status (250 mg/l and 1100 mg/l) and SWI vulnerability (moderate + high vulnerability and high vulnerability). It allows us to show the sensitivity of the results to this parameter.

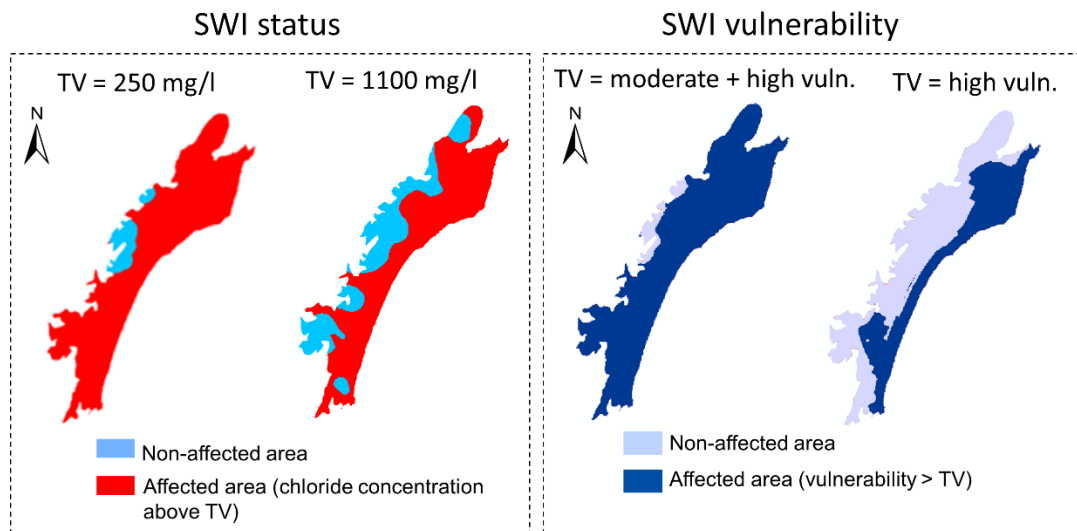


Fig 9 Maps of historical SWI status and vulnerability “affected volumes” (October 1985)

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

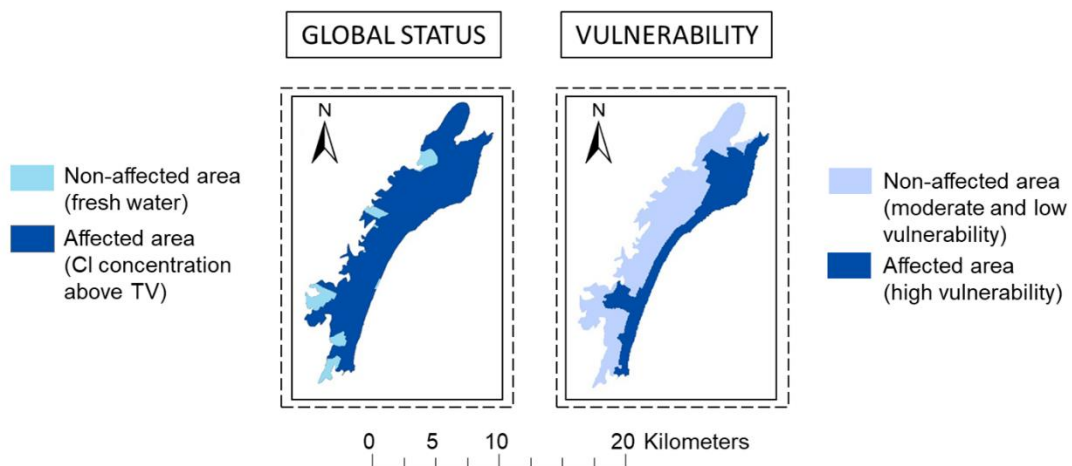


Fig 10 Maps of potential future SWI status and vulnerability “affected volumes” for the simulated scenario (September 2027)

3.3 2D conceptual cross-sections: mean penetration and thickness.

Following the steps described in section 2.1.2 and 2.2.2 of the methodology we obtain the conceptual cross section to summarise results in terms of SWI status and vulnerability respectively. They are also obtained for two different values of the thresholds values in the historical period to SWI status (250 mg/l and 1100 mg/l) and vulnerability (moderate + high



vulnerability and high vulnerability) to show the sensitivity of the results to this parameter (Figure 11).

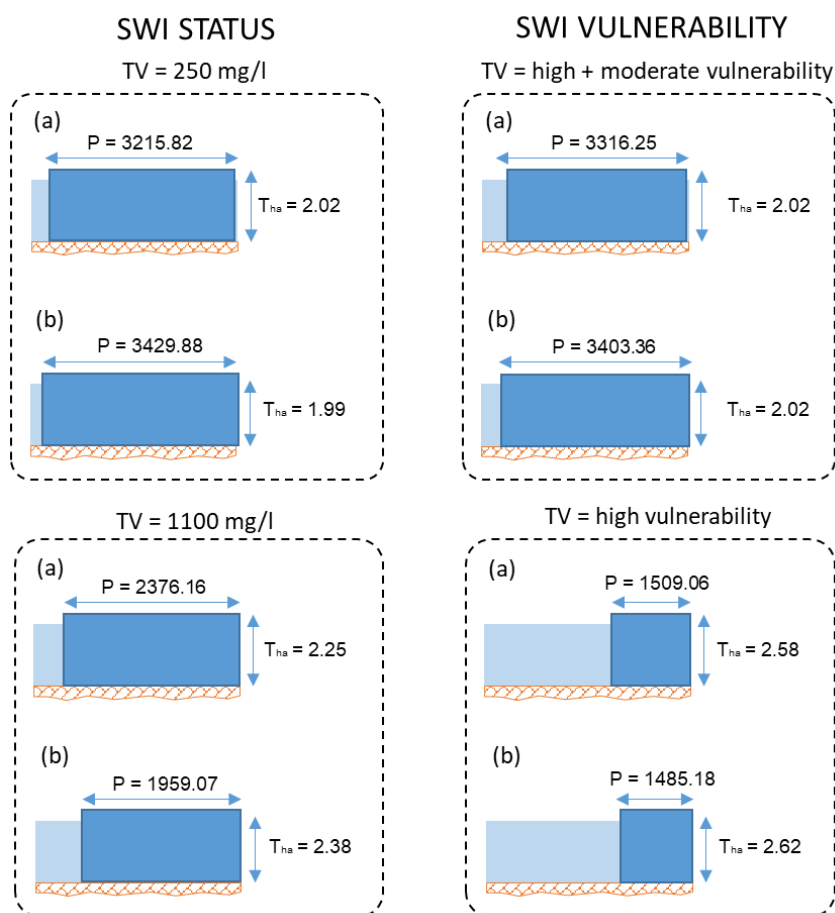


Fig 11 2D conceptual cross-sections. Historical results in October 1985 (a) and mean values for the period 1973-2010 (b) (units in km)

In the future assessment we considered only one threshold value (1100 mg/l for SWI status and the high vulnerability values of the GALDIT index to assess vulnerability to SWI) (Figure 12).

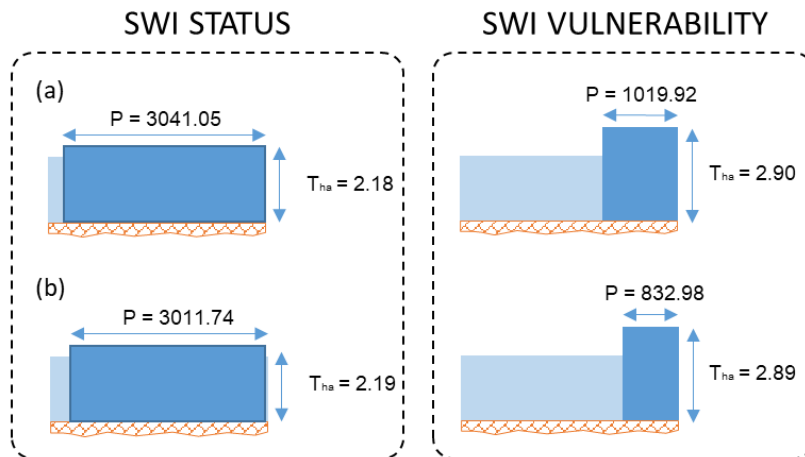


Fig 12 2D conceptual cross-sections. Potential Future Results for the simulated scenario in September 2027 (a) and mean values for the period 2011-2035 (b) (units in km)

3.4 Lumped indices: Ma and L-GALDIT values.

Following the steps described in section 2.1.3 and 2.2.3 of the methodology we obtain the lumped indices Ma and L-GALDIT, to summarise the global dynamic of affected volumes in terms of SWI status and vulnerability respectively (Figure 13).

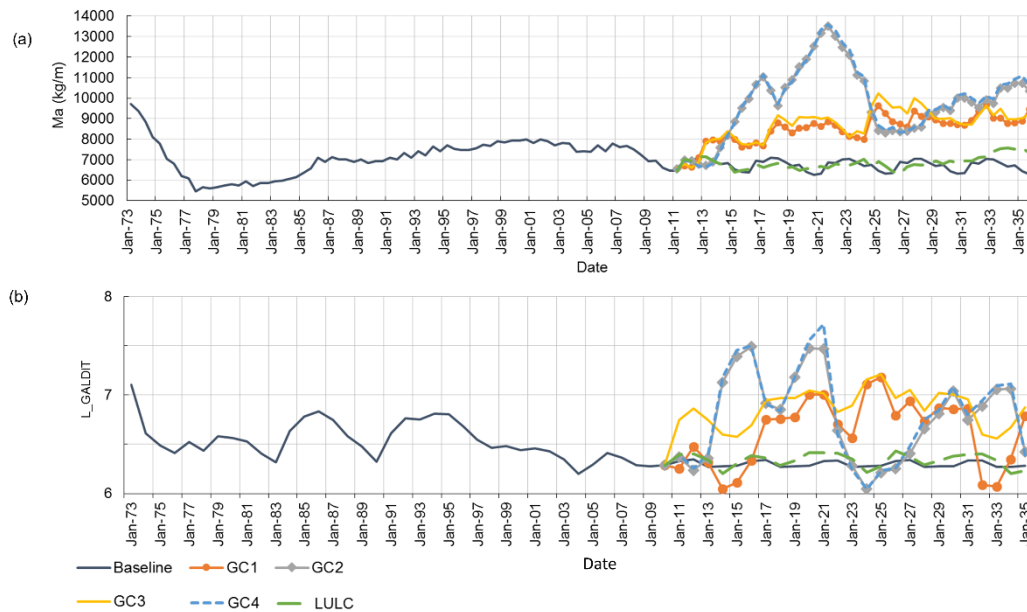


Fig 13 Time series of the indices Ma and L-GALDIT in the historical (1973-2010) and potential future results for the simulated scenario in the horizon 2011-2035 (modified from Baena-Ruiz et al., 2020).

From this future series we can assess the recovery/degradation rate of the lumped index Ma (Figure 14).



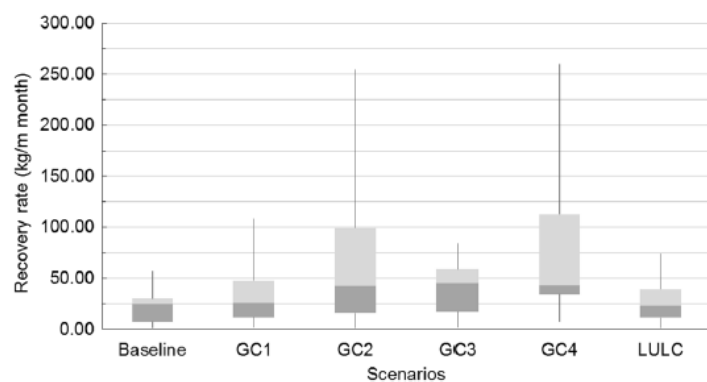


Fig 14 Statistics of recovery rate for all scenarios analyzed in the simulated scenario in the horizon 2011-2035.

4 REFERENCES:

Baena-Ruiz L, Pulido-Velazquez D, Collados-Lara AJ, Renau-Pruñonosa A, Morell I., J. Senenet-Aparicio, C. Llopis-Albert, 2018. Summarising impacts of future potential global change scenarios on seawater intrusion at aquifer scale. *Environmental Earth Sciences*. <https://doi.org/10.1007/s12665-020-8847-2>

Baena-Ruiz L, Pulido-Velazquez D, Collados-Lara AJ, Renau-Pruñonosa A, Morell I. 2018. Global assessment of seawater intrusion problems (status and vulnerability). *Water Resources Management*, 32(8): 2681-2700. doi: 10.1007/s11269-018-1952-2

Baena-Ruiz L, Pulido-Velazquez D, ur. GIS-SWIAS: tool to summarize seawater intrusion status and vulnerability at aquifer scale. *Scientific Programming*. Under Review.

Ballesteros BJ, Morell I, García-Menéndez O, Renau-Pruñonosa A (2016) A standardized index for assessing seawater intrusion in coastal aquifers: the SITE index. *Water Resour Manag* 30(13):4513–4527. <https://doi.org/10.1007/s11269-016-1433-4>

García-Menéndez O, Morell I, Ballesteros BJ, Renau-Pruñonosa A, Esteller MV (2016) Spatial characterization of the seawater upconing process in a coastal Mediterranean aquifer (Plana de Castellón, Spain): evolution and controls. *Environ Earth Sci* 75:728. <https://doi.org/10.1007/s12665-016-5531-7>

Renau Pruñonosa A (2013) Nueva herramienta para la gestión de las aguas subterráneas en acuíferos costeros. Volumen ecológico de remediación (VER). Metodología y aplicación a la Plana de Oropesa-Torreblanca (MASub 080.110), Universitat Jaume I

APPENDIX: GALDIT METHOD

GALDIT was proposed by Chachadi and Lobo-Ferreira (2005) to assess the vulnerability to SWI. This method considers that there are six parameters/variables influencing the vulnerability to SWI: aquifer type, hydraulic conductivity, height of GW level above sea level, distance from the shore, impact of existing status of SWI and thickness of aquifer. A rate of importance is assigned to the parameters according to the characteristics of each parameter. The values of the parameters are weighted by a factor to obtain the GALDIT index.

$$GALDIT\ index = \frac{\sum_{i=1}^6 (W_i * R_i)}{\sum_{i=1}^6 W_i} \quad (A1)$$

Where W_i is the weight of the i^{th} indicator and R_i is the importance rating of the i^{th} indicator. The rates and weights are showed in Table A1:

Indicator	Weight	Indicator Variables	Range	Importance Rating
Groundwater occurrence/Aquifer type	1	Confined Aquifer	-	10
		Unconfined Aquifer		7.5
		Leaky confined Aquifer		5
		Bounded Aquifer (recharge and/or impervious boundary aligned parallel to the coast)		2.5
Aquifer Hydraulic Conductivity (m/day)	3	High	>40	10
		Medium	10-40	7.5
		Low	5-10	5
		Very low	<5	2.5
Height of ground water Level above msl (m)	4	High	<1.0	10
		Medium	1.0-1.5	7.5
		Low	1.5-2.0	5
		Very low	>2.0	2.5
Distance from shore / High Tide (m)	4	Very small	<500	10
		Small	500-750	7.5
		Medium	750-1000	5
		Far	>1000	2.5
Impact status of existing seawater intrusion	1	High	>2	10
		Medium	1.5-2.0	7.5
		Low	1-1.5	5
		Very low	<1	2.5
Aquifer thickness (saturated) in metres	2	Large	>10	10
		Medium	7.5-10	7.5
		Small	5-7.5	5
		Very small	<5	2.5

Table A1 Rates and weights of GALDIT parameters



The GALDIT index is classified into three vulnerability levels:

- $GALDIT \geq 7,5 \rightarrow$ High vulnerability
- $7,5 > GALDIT \geq 5 \rightarrow$ Moderate vulnerability
- $GALDIT < 5 \rightarrow$ Low vulnerability