GLOBAL ASSESSMENT OF SEAWATER INTRUSION PROBLEMS (STATUS AND VULNERABILITY)

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Abstract

In this research paper we propose a novel method to perform an integrated analysis of the status and vulnerability of coastal aquifers to seawater intrusion (SWI). The method is based on a conceptual approach of intrusion that allows to summarised results in a visual way at different spatial scales, moving from steady pictures (corresponding to instantaneous or mean values in a period) including maps and 2D conceptual cross-sections and temporal series of lumped indices. Our aim is to help in the identification of coastal groundwater bodies at risk of not achieving good chemical status according to the Water Framework Directive. The indices are obtained from available information about aquifer geometry and historical monitoring data (chloride concentration and

hydraulic head data). This method may be applied even in cases where a reduced number of data are available. It does not require complex modelling and has been implemented in a GIS tool that encourages its use in other cases. Analysis of the evolution of historical time series of these indices can be used to assess resilience and trends with respect to SWI problems. This method can be also useful to compare intrusion problems in different aquifers and temporal periods.

1. INTRODUCTION

Seawater intrusion affects a great number of coastal aquifers all over the world, and this is a problem often due to the intense economic activity in these zones and the consequent exploitation of their groundwater resources. Several authors have highlighted this problem in Africa (Steyl and Dennis 2010; Bouderbala 2015), America (Barlow and Reichard 2010, Boschetti et al. 2015), Asia (Parck et al. 2012; Pratheepa et al. 2015), Oceania (Werner and Gallagher 2006; Werner 2010) and Europe (Custodio 2010; García-Menéndez et al. 2016). In Mediterranean Europe, seawater intrusion (SWI) is a common problem in Spain (Guhl et al. 2006; García-Menéndez et al. 2016), Italy (Barrocu 2003; Benini et al. 2016), Greece (Petalas and Lambrakis 2006; Kazakis et al. 2016), and Turkey (Günay 1997; Arslan et al. 2012). It is due to several factors such as a high summer population density and the intensification of irrigated croplands, which increment the risk of SWI. These factors have led to an increasing water demand since the 1970s. Since 2000, after Water Framework Directive (2000) came into effect, there has been an increase in the number of groundwater quality assessment studies, and consequently in the development of methodologies to quantify groundwater pollution in an aquifer.

Many different distributed approaches have been applied to assess spatio-temporal distribution of GW quality issues in coastal regions, depending on the aim of the investigation. They can be classified into two main groups: physical quantitative assessment of aquifer status and mixed quantitative-qualitative assessment of vulnerability to seawater intrusion.

The spatio-temporal distribution of the aquifer status can be estimated from available information by applying different modelling approaches (simple interpolation methods or sharp interface solutions and density dependent approaches). The flow models have been extensively applied to study SWI problems (Smith 2004; Eeman et al. 2011). They attempt to determine the position of the seawater-freshwater interface and to simulate SWI processes using analytical or numerical procedures. Several authors have discussed the advantages and limitations of different quantitative flow approaches (Llopis and Pulido 2014). Numerical approaches can simulate complex intrusion processes under transient conditions, but they require numerical approaches and excessive data to obtain a parsimonious approach with enough data to calculate representative parameters on a large scale (with significantly greater requirements in density-dependent flow approaches) (Wriedt and Bouraoui 2009).

On the other hand, qualitative methods can be applied to assess vulnerability and/or risk mapping in coastal regions. They aim to identify the parts of a groundwater body that could be contaminated as a result of human activities, taking into account physiographic characteristics such as geology or piezometric level. A numerical index or score is assigned to the different attributes, which are then weighted. The numerical scores cluster similar areas into classes of vulnerability (e.g., low, moderate and high), which are then displayed on a map. They can be used to define hydrogeological subregions with different levels of severity (Kumar et al. 2015). Due to their easy implementation, many index-based techniques have been applied to assess vulnerability. Several authors have criticised the roughness of these index-based methods, however they also reveal the easy implementation and interpretation of these techniques to get a preliminary assessment of vulnerability of groundwater bodies (Werner et al. 2012).

The groundwater vulnerability assessment technique was started in 1987 by Aller et al. (1987) through the development of DRASTIC, though this system has undergone several modifications over time (Kumar et al. 2015). Several indices have been developed to assess vulnerability to pollution (SINTAC (Civita 1994), EPIK (Doerfliger et al. 1999) and AVI (Stempvoort et al. 1993)) but they are not usually employed to evaluate vulnerability to SWI. The GALDIT method was developed by Chachadi and Lobo-Ferreira (2001) with the aim of assessing the spatial vulnerability of hydrogeological settings to SWI. GALDIT has been mostly used to perform large-scale assessments of SWI (Benini et al. 2016). The major drawback of this method is that the effect of pumping on the SWI process is not considered (Trabelsi et al. 2016). Despite this limitation, this model shows many advantages, such as its low computational cost. Moreover, it requires few, easy to collect historical variables and parameters, and it can be applied over large areas. However, vulnerability methods only highlight specific areas in the aquifer that are at risk or prone to pollution due to their intrinsic characteristics, whereas it might be interesting to adopt measures in order to improve them. In the literature, there are examples of works developed to provide a global assessment of aquifer status (e.g., Ballesteros et al. 2016), but none that address aquifer vulnerability.

In this paper we propose a new systematic method to analyse status and vulnerability to SWI at different spatial scales. The method is based on a conceptual approach that allows to define steady pictures (representing instantaneous or mean values in a period) to move from maps to 2D schematic cross sections, and temporal series of lumped indices. The analysis of these temporal series of the indices, which summarize global status and vulnerability, allows to study the SWI dynamic, resilience and trend. The proposed method can be useful to identify aquifers in risk of not achieve the objective defined in the Water Framework Directive (2000). The paper is structured as follows. Section 2 describes the method, defining the proposed indices and specifying the steps to obtain them. Section 3 describes the case studies and the available data, while section 4 outlines the results and discussion. Section 5 gives our main conclusions.

2. METHODOLOGY

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 is also needed as inputs to apply the proposed method.

The steps proposed in order to summarize status and vulnerability to SWI through visual pictures and time series are described in the next subsections.

Fig 1 Flow chart of methodology

2.1. Assessment of seawater intrusion (SWI) status

The described inputs will be employed to assess SWI status according to the following steps:

2.1.1. Maps of chloride concentration

Fields (maps) of chloride concentration and hydraulic head can be obtained by applying simple interpolation techniques in each date with enough available information. 3D maps of the saturated thickness (with a finite number of cells) 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.

From chloride concentration and saturated thickness maps, we can define the affected and non-affected zone (areas where the chloride concentration level is above the natural background level). This threshold, which depends on the geochemistry of the aquifer, is difficult to determine. Some European projects ("BRIDGE") (Dahlstrom and Müller 2006) have provided recommendations for its calculation, based on methodologies applied in some countries. Some of them determine the background level as the concentration in non-contaminated areas. Other define the threshold as 90 percentile of the concentration measured in the groundwater monitoring network, while sometimes they only use data from monitoring networks to define a background concentration. In other cases the threshold is based on the typical background level, the origin of the chloride (natural or anthropogenic) and the possible impacts on ecosystems or human health. For this area we can calculate the affected volume taking into account the storage coefficient and the aquifer geometry.

2.1.2. 2D cross-sections: Penetration and Thickness. Increment in concentration

2D representative cross-sections can be deduced to summarise the mean geometry (thickness and penetration) and intensity of the intrusion (increment in concentration). The average affected thickness (T_{ha}) and inland penetration (P) of intrusion can be calculated as follow:

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

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

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

where:

- $V_{i(>Vr)}$ is the storage in each cell (m^3) with a concentration greater than V_r;
- S_i is the surface area of each cell (m^2);
- b_i is the saturated thickness at each instant considered (m);
- α is the storage coefficient;
- L_{coast} is the length of coastline (m);

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

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

$$V_r\left(\frac{mg}{l}\right) = Reference\ threshold \quad (5)$$

where:

- C_i is the concentration (mg/l) in each cell;
- $V_{(>Vr)}$ is the total storage (m^3) with a concentration greater than V_r;

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

$$IC\left(\frac{mg}{l}\right) = C - V_r \quad (6)$$

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

2.1.3. Global index: Mass of affected area (Ma)

The index Ma 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 and 2.

$$Ma\left(\frac{kg}{m}\right) = P(m) * IC\left(\frac{mg}{l}\right) * 10^{-3} * T_{ha}(m) \quad (7)$$

The concept of Ma involves some simplifications, which are schematised in Figure 1.

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 the mass of water affected is increasing, while a negative trend indicates an improvement in aquifer status.

The combination of Mass of 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. 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).

2.2.1. Maps of vulnerability

Vulnerability maps are displayed from GALDIT method. The GALDIT Index is obtained by applying the expression:

$$GALDIT\ Index = \frac{\sum_{i=1}^{6} W_i * R_i}{\sum_{i=}^{6} W_i} \quad (8)$$

where W_i is the weight of the i^{th} indicator and R_i is the importance rating of the i^{th} indicator. 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). These vulnerability classes are the threshold to define the “affected zone” (area where vulnerability is higher than the adopted reference threshold (moderate or high vulnerability)).

For this area we can calculate the affected volume taking into account the storage coefficient and the aquifer geometry.

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

2D cross sections can be deduced to summarise the mean geometry and intensity of the GALDIT vulnerability score. Penetration (P_{L_GALDIT}) and Thickness ($T_{ha\ L\_GALDIT}$) can be calculated from formulas 9 and 10:

$$T_{ha\ L\_GALDIT}(m) = \frac{\sum V_{i(>V_r\ GALDIT)}}{\sum S_{i(>V_r\ GALDIT)}} \quad (9)$$

$$P_{L\_GALDIT}(m) = \frac{\sum V_{i(>V_r\ GALDIT)}}{T_{ha\ L\_GALDIT} * L_{coast}} \quad (10)$$

$$V_{i(>V_r\ GALDIT)}(m^3) = S_i(m^2) * b_i(m) * \alpha \quad (11)$$

$$V_{r\ GALDIT} = GALDIT\ threshold\ (G \geq 7{,}5;\ G \geq 5) \quad (12)$$

where:

- $V_{i(>Vr\ GALDIT)}$ the storage in each cell (m^3) with a concentration greater than $V_{r\ GALDIT}$;
- S_i is the surface area of each cell (m^2);
- b_i is the saturated thickness at each instant considered (m);
- α is the storage coefficient;
- L_{coast} is the length of coastline (m).

The intensity of vulnerability is the GALDIT score in each zone for the thresholds established.

2.2.3. Global 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 13). This weighted value of GALDIT assesses the overall vulnerability of the aquifer. On the other hand, a lumped affected value of GALDIT can be obtained for the different thresholds (Equations 14 and 15).

$$L\_GALDIT = \frac{\sum(G_i * V_i)}{V} \quad (13)$$

$$L\_GALDIT_{high} = \frac{\sum(G_{i(\geq 7,5)} * V_{i(\geq 7,5)})}{V_{(\geq 7,5)}} \quad (14)$$

$$L\_GALDIT_{high+moderate} = \frac{\sum(G_{i(\geq 5)} * V_{i(\geq 5)})}{V_{(\geq 5)}} \quad (15)$$

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;
- $G_{i(\geq 7,5)}$ 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 volume of each cell with a value of GALDIT ≥ 7,5;
- $V_{i(\geq 5)}$ is the volume of each cell with a value of GALDIT ≥ 5;
- $V_{(\geq 7,5)}$ is the total volume with a value of GALDIT ≥ 7,5;
- $V_{(\geq 5)}$ is the total 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.

The method employs the spatial distribution of the storage coefficient to obtain affected volume in the lumped indices (MART and L_GALDIT) and hydrogeological parameters as the transmissivity are implicitly considered in the spatial distribution of the hydraulic head, which considers effects of the aquifer system. Even so it does not require complex modelling approaches and has been implemented in a **GIS tool** that encourages its application to other cases.

3. STUDY AREA

3.1. Geological and hydrogeological characterisation

The study area is situated on the Mediterranean coast of Spain, in Castellon province. Two different aquifers were studied: the Plana de Oropesa-Torreblanca and Plana de Vinaroz (Figure 2). The increasing population since 1970 and the continuing agricultural exploitation have produced SWI problems of different entity in these aquifers.

Fig 2 Situation of the study area and hydrogeology

Both aquifers are unconfined, heterogeneous, detrital and multilayer aquifers composed of gravel and sand levels in a silty clay matrix (Ballesteros et al. 2016). Figure 2 also shows the hydrogeology of these aquifers. The transmissivity in the Plio-Quaternary Plana de Oropesa Torreblanca aquifer ranges from 300-1000 m^2/day (García-Menéndez et al. 2016) and the storage coefficient varies between 2-12%, while in Plana de Vinaroz these parameters take the value of 250-1200 m^2/day and 5-15% respectively.

3.2. Data

Historic data for the variables of chloride concentration and hydraulic head were provided by the Confederación Hidrográfica del Júcar. There are no data for this study area from 1988 to 1989 or from 2001 to 2005. The number of observation wells varies over time and also from one aquifer to another. The number of monitoring points of chloride concentration in Plana de Oropesa-Torreblanca and Plana de Vinaroz aquifers varies between 12-34 and 9-58 respectively, while the monitoring points of hydraulic head ranges between 9-19 and 6-28 in both aquifers.

The number of data available was also variable for each observation point over the period. Observation points were considered if they had data for at least 20% of the study period.

The chloride concentration exceed 1000 mg/l in zones close to the coast in both aquifers. 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 3).

Fig 3 Observation points for chloride concentration and evolution of the chloride concentrations in monitoring points in Plana de Oropesa-Torreblanca (top) and Plana de Vinaroz (down) aquifers

Groundwater flow in both aquifers approximately follows a NW-SE direction before discharging to the sea. The range of piezometric levels varies significantly depending on the aquifer: in the Plana de Oropesa-Torreblanca the piezometric level at points furthest from the coast is about 3 m a.s.l., while in the Plana de Vinaroz it reaches 50 m a.s.l. The piezometric level is depressed in both aquifers at certain times in zones close to the coast.

Aquifer geometry is derived from previous 3D models (Renau Pruñonosa 2013). The Plana de Oropesa-Torreblanca aquifer is wedge-shaped being the maximum thickest located near to the coastline, where it can reach 90 m thick. The Plana de Vinaroz has a lenticular geometry and its thickness varies between 30 m and 160 m in the inland zones.

4. RESULTS

Here we present the results obtained when the proposed methodology was applied to the two case studies.

4.1. MART Index

4.1.1. 2D – 3D maps. Evolution of chloride concentration and affected volume (Graphics)

In terms of the natural background, two different chloride thresholds were used for the calculations. First, a chloride concentration level is established according to the natural background for each aquifer. In CHJ (2016) a reference value of 1100 mg/l is established for both Plana de Oropesa-Torreblanca and Plana de Vinaroz aquifers. In order to analyse the sensitivity to the threshold value, we also tested a threshold of 250 mg/l, which is the default value for all aquifers set in other previous studies (Ballesteros et al. 2016).

Figure 4 shows an example of the chloride concentration map obtained, with the affected and unaffected zones for both thresholds.

Fig 4 Chloride concentration maps in Plana de Oropesa-Torreblanca for October 1985

The 2D maps of chloride concentration show that the zone of SWI in Plana de Oropesa-Torreblanca aquifer grew. However Plana de Vinaroz aquifer has undergone a slight improvement in the study period. Moreover the affected zone in the Plana de Oropesa is significantly greater than for Plana de Vinaroz (Figure 5a).

The mean concentration in the zone affected for each aquifer, based on the natural background threshold concentration, lies between 2000-2500 mg/l in both aquifers over almost the entire period (Figure 5b). Although a fall in mean chloride concentration of the affected zone is observed in Plana de Oropesa-Torreblanca aquifer from 1977 to 1983, it does not indicate an improvement in the water quality in this period since the affected volume increased in this period (Figure 5a). Chloride concentration is spread over a wider area although the mean concentration in the impacted zone diminished.

Fig 5 Evolution of (a) affected volume (rg (%)) and (b) average chloride concentration in total aquifer and in the affected volume for the two aquifers

The mean chloride concentration in the entire aquifer shows an increasing trend until 1987 (Figure 5b), which may be explained by the increased abstractions made during this period; after this date, chloride concentrations fell again. The greater the distance between the mean aquifer concentration and the mean concentration in the affected zone, the better the overall status of the aquifer. This does not mean that the aquifer does not suffer grave SWI problems in certain zones. In the Plana de Oropesa-Torreblanca these curves are very close, and so there are significant SWI problems over almost all of the aquifer, the difference being much greater than in the Plana de Vinaroz.

Lastly, we analysed the sensitivity of the results to variations in the reference value used. The volume affected using a threshold of 250 mg/l for the two aquifers is much greater than when using a threshold corresponding to the natural background of each aquifer (Figure 5a). In contrast, of course, the mean concentration of the zone affected using the natural background threshold (Figure 5b) is much larger. This phenomenon highlights the need to determine the natural background of each aquifer precisely, since the assessment of whether there are SWI problems is quite sensitive to this threshold value.

4.1.2. 2D cross-sections: Penetration and Thickness. Increase in concentration

Fig 6 Average cross-sections for two thresholds (natural background and 250 mg/l) (MART index) over the period 1977-2015 (vertical exaggeration scale: 500)

The volume of the Plana de Vinaroz aquifer is significantly larger than the Plana de Oropesa-Torreblanca (Figure 6). In both aquifers, the thickness affected is greater than the mean thickness of the aquifer. These results are consistent with the aquifer geometry and the location of affected areas.

Again, the sensitivity of the results to the reference value used can be seen. The lower the value of the threshold, the further the affected zone extends inland. For example, using the 250 mg/l threshold, the entire Plana de Oropesa-Torreblanca aquifer is affected during certain years.

Both penetration and thickness reveal the proportion of the aquifer affected.

4.1.3. Global index: Mass of affected area (Ma)

Fig 7 Evolution of the global index, Ma, in the two aquifers studied

The trend of the index Ma in the two aquifers is similar for both thresholds tested (Figure 7). In general, there was a period when the water quality in the aquifers fell continuously (1977-1986), with Ma rising until 1986. In subsequent years, there was a generalised improvement in both aquifers, particularly after 2007. This improvement could be the result of the wet period from 2002 to 2004 (García-Menéndez et al. 2016) and the effect of newly implemented policies to comply with the Water Framework Directive (2000).

The value of Ma (Figure 7) in the Plana de Oropesa-Torreblanca for the natural background is greater than in the Plana de Vinaroz, indicating that the Plana de Oropesa-Torreblanca is in a more critical state than the Plana de Vinaroz. This index, Ma, provides information about the overall importance of SWI in each aquifer and its evolution over time. For a more detailed description of the problem, this index can be combined with the mean concentration of the affected zone (to give an idea of the intensity of the problem) and the 2D section (which informs about the size of the zone affected). For example, comparing the mean concentration of the affected zone when considering the natural background level as the threshold for identifying the presence of SWI in each of the two aquifers (Figure 5b), it can be seen that they take similar values (2000–2500 mg/l); however, the section affected in the Plana de Oropesa-Torreblanca (Figure 6) and the proportion of its volume affected (Figure 5a) are much greater than in the Plana de Vinaroz. These results indicate that the Plana de Oropesa-Torreblanca aquifer suffers grave problems due to SWI over almost all its entirety.

4.1.4. Resilience and Trend (MART)

Higher values of Resilience were obtained for the period up to 1987 (Figure 8), which indicates that changes in the intrusion were more significant. The value of Trend in the Plana de Oropesa-Torreblanca is positive and also elevated, showing that the change has been a deterioration in the state of the aquifer; while in the Plana de Vinaroz there are periods of improvement (negative trend) though the changes are not significant (low resilience values).

Although changes have decreased in the last period, the values of Resilience in Plana de Oropesa-Torreblanca aquifer are higher than in Plana de Vinaroz aquifer.

The results are represented only for the threshold established by the natural background (1100 mg/l).

Due to the geometry and hydrodynamics of each aquifer, it is more complicated in some aquifers to recover good water quality than in others. In this way, the geometry is more of an obstructing factor in the case of Plana de Oropesa-Torreblanca, which is thickest close to the coastline.

Fig 8 Ma, Resilience and Trend in Plana de Oropesa-Torreblanca and Plana de Vinaroz aquifers (scale exaggeration Resilience and Trend: 10000)

4.2. GALDIT Index

4.2.1. Maps. Vulnerability and identification of affected volume (Graphics)

Figure 9 shows examples of vulnerability maps from GALDIT for a specific date in both aquifers studied. The red circles indicate zones where changes occurred during the study period (1977-2015).

Fig 9 L_GALDIT maps in Plana de Oropesa-Torreblanca for April 2015

This leads to several conclusions. In the Plana de Vinaroz aquifer the zone of mean vulnerability occupies almost the whole aquifer while the zone of low vulnerability is very small since conductivity is greatly elevated in almost the entire aquifer.

The Plana de Oropesa-Torreblanca aquifer is highly vulnerable due to the characteristics of its formation (it is an aquifer lying parallel to the coast with a wedge shaped geometry, very shallow inland, thicker close to the coastline, and with high conductivity) and to the elevated chloride concentration along the coastline.

Furthermore, the concentration of bicarbonates is low, which is an indicator of the presence of seawater (Chachadi and Lobo-Ferreira 2005).

The volume affected when considering each vulnerability threshold shows little temporal variability over the period of study (1977-2015).

4.2.2. 2D cross sections: Penetration and Thickness. Vulnerability classes

There are certain similarities in the cross-sections of L_GALDIT (Figure 10) and MART. In the Plana de Oropesa-Torrebanca aquifer, the sections obtained for MART for both threshold are similar as those obtained for GALDIT though less so for the Plana de Vinaroz.

Fig 10 Average cross-sections in two aquifers (L_GALDIT index) for the period 1977-2015 (vertical exaggeration scale: 500)

It should be borne in mind that the vulnerability and the overall state of the aquifer do not have to concur. Poor quality is not necessarily found in a vulnerable zone. The zone affected by intrusion can be small, even if a large part of the aquifer is classed as vulnerable due to its intrinsic characteristics.

4.2.3. Lumped Index: L_GALDIT. Resilience and Trend

The aggregated index, L_GALDIT (Figure 11), exhibits little variability compared to the Ma Index (Figure 8). This is due to the various factors that are used in calculating vulnerability (Benini et al. 2016), especially those factors that have greater weight and less spatial variability (conductivity and distance from the coast), which help to smooth out the results.

Almost the entire extension of both aquifers has moderate+high vulnerability. Nevertheless, in the Plana de Oropesa-Torreblanca, the mean vulnerability is higher.

These results indicate that the Plana de Oropesa-Torreblanca aquifer is much more vulnerable quantitatively, and second, that the vulnerable zone occupies a much larger extension.

Fig 11 L_GALDIT, Resilience and Trend in Plana de Oropesa-Torreblanca and Plana de Vinaroz aquifers (scale exaggeration Resilience and Trend: 100)

Resilience and Trend are represented only for the threshold delimiting high vulnerability (GALDIT=7.5). The Resilience values are low and very similar in both the Plana de Vinaroz and Plana de Oropesa-Torreblanca (values less than 0.01). Such low values are due to the fact that the values of the index L_GALDIT vary within a narrow range, as well as to the fact that the index has low variability due to the reasons commented above.

5. CONCLUSIONS

This paper presents a novel methodology for assessing the overall status of seawater intrusion and vulnerability in coastal aquifers using a mixed lumped-distributed analysis. The problem of chloride contamination is represented in coastal aquifers on different spatial scales, obtaining 2D maps, mean cross-sections and an aggregated index of overall state. In addition, we propose an aggregated index for assessing vulnerability, L_GALDIT, based on the GALDIT method that is already known. The method allows the significance of intrusion and vulnerability to be compared across different aquifers and time periods. Moreover, it can be used to assess resilience and trend respect to SWI.

In terms of the overall status of the two aquifers studied, we deduce that the Plana de Oropesa-Torreblanca aquifer has a worse state and it needs more important changes in groundwater use. Resilience indicates that this aquifer has more potential to recover a good status, although it would require great changes in the current pumping management. In addition, due to its intrinsic characteristics it has a high vulnerability and is susceptible to contamination.

With respect to vulnerability, again the Plana de Oropesa-Torreblanca is the more vulnerable of the two aquifers, both in terms of its extent and magnitude. Though the Plana de Vinaroz is also vulnerable over almost all of it extent, the value for vulnerability is moderate.

Bearing in mind the overall status and vulnerability conjointly, we can say that the aquifer affected in the Plana de Oropesa-Torreblanca (47.6 – 86.7%) is similar to the aquifer classified as vulnerable (56.6 – 99.8%) for both thresholds. However, in the Plana de Vinaroz, though the majority of the aquifer is vulnerable (94.1% with an index of moderate vulnerability), no all of it exhibits SWI problems (the aquifer affected by high chloride concentration is less than 66% of the total aquifer).

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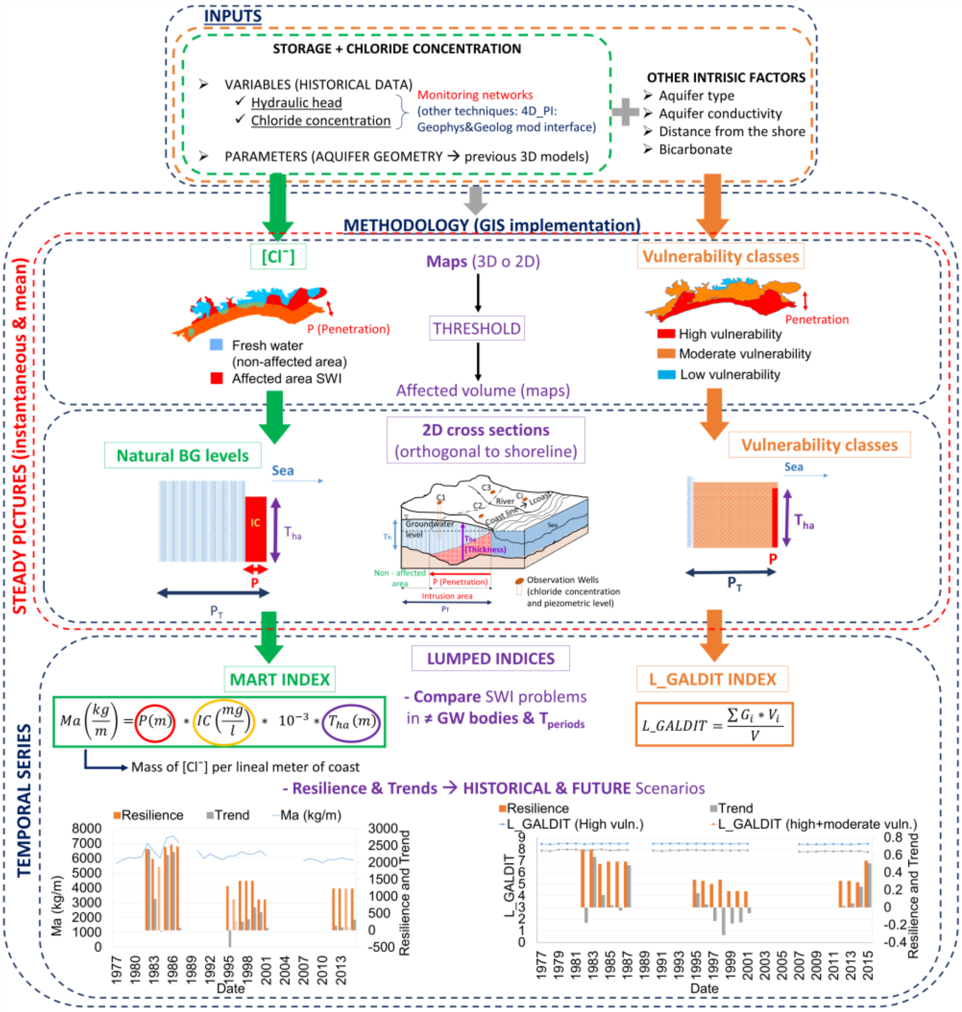

Fig 1 Flow chart of methodology

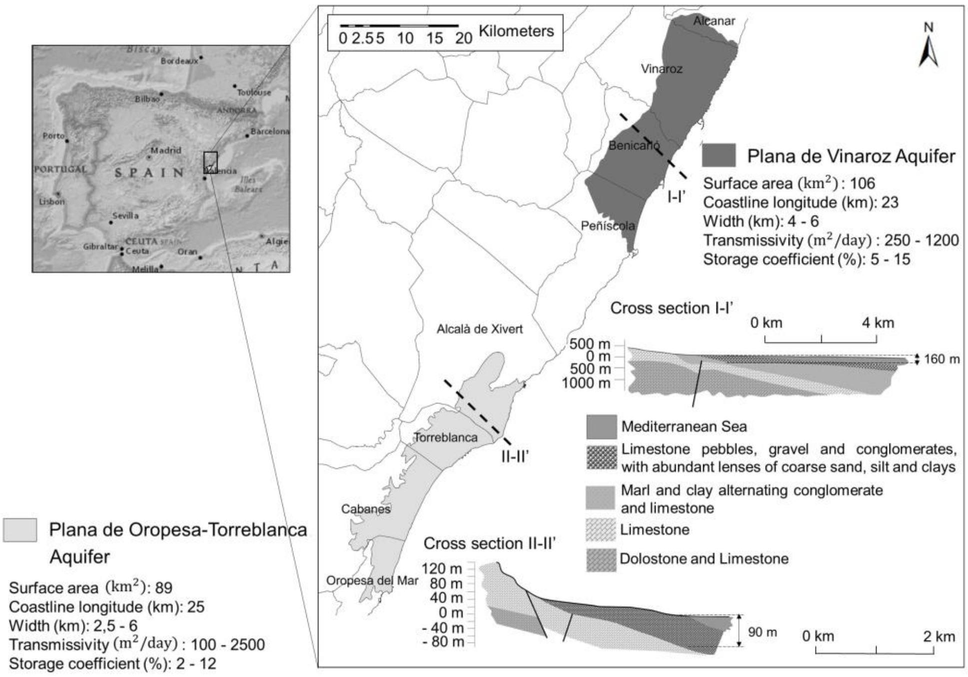

Fig 2 Situation of the study area and hydrogeology

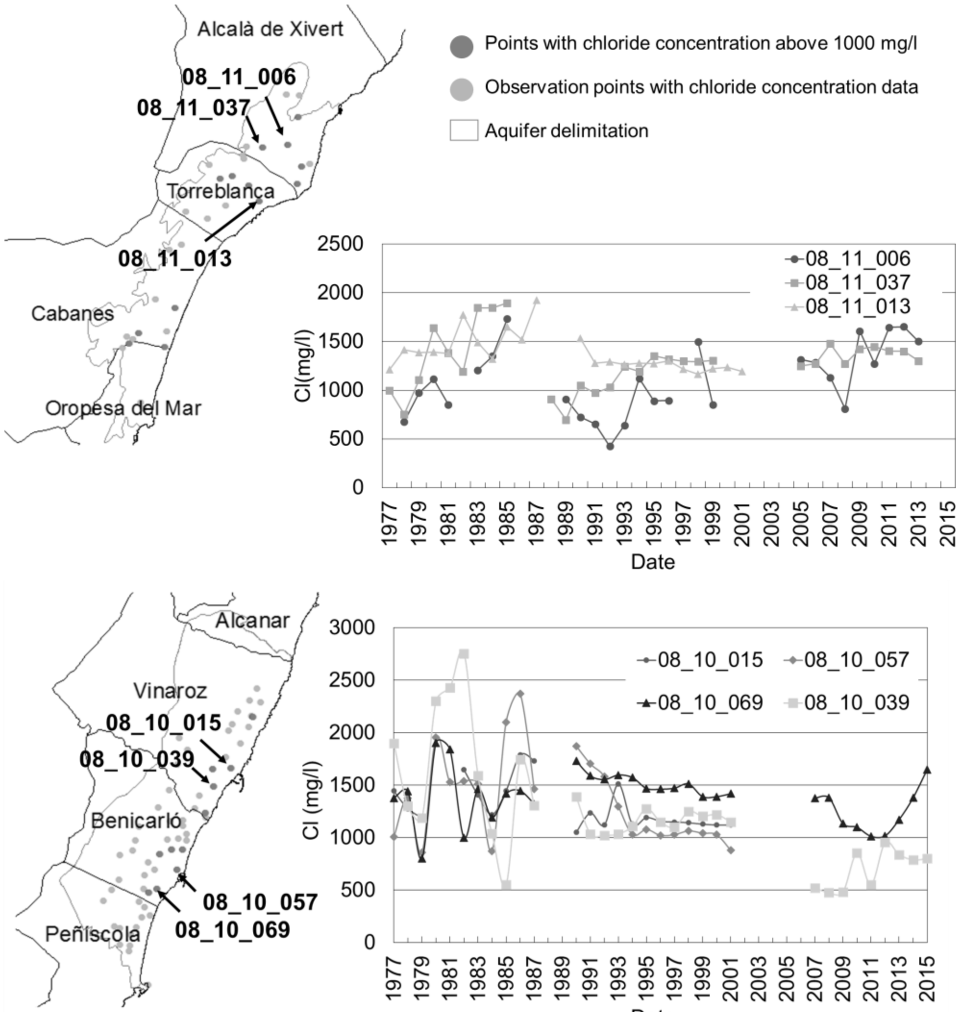

Fig 3 Observation points for chloride concentration and evolution of the chloride concentrations in monitoring points in Plana de Oropesa-Torreblanca (top) and Plana de Vinaroz (down) aquifers

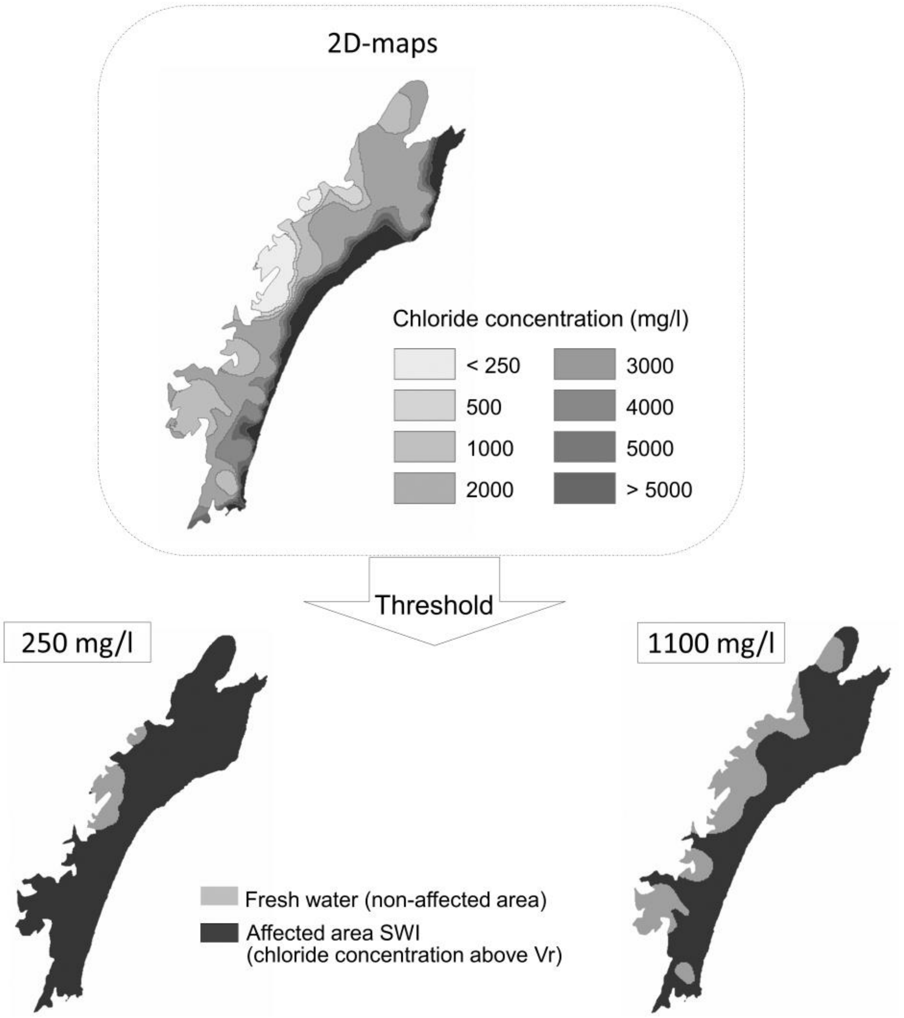

Fig 4 Chloride concentration maps in Plana de Oropesa-Torreblanca for October 1985

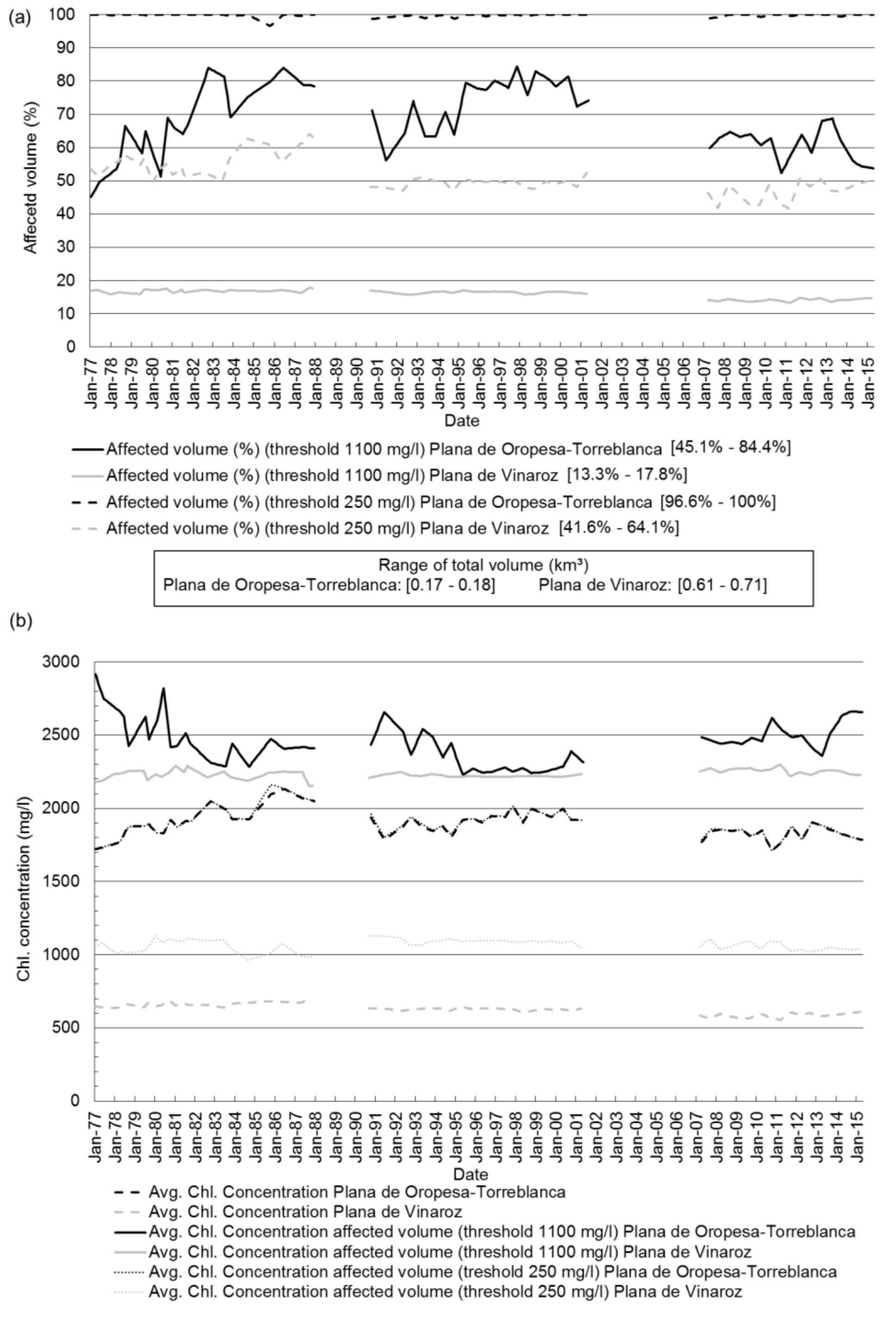

Fig 5 Evolution of (a) affected volume (rg (%)) and (b) average chloride concentration in total aquifer and in the affected volume for the two aquifers

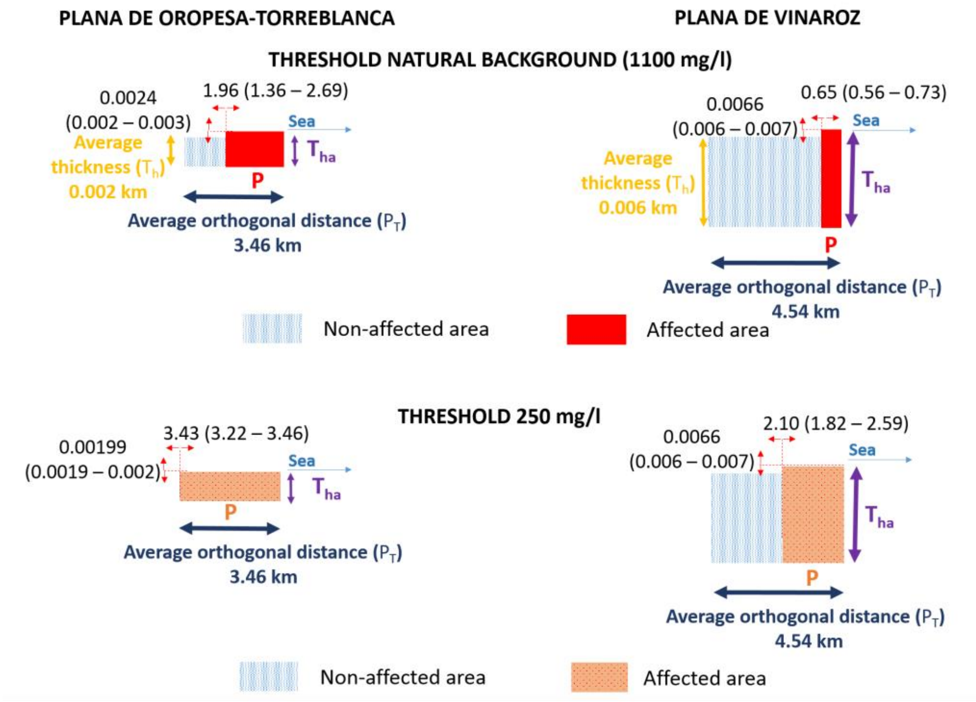

Fig 6 Average cross-sections for two thresholds (natural background and 250 mg/l) (MART index) over the period 1977-2015 (vertical exaggeration scale: 500)

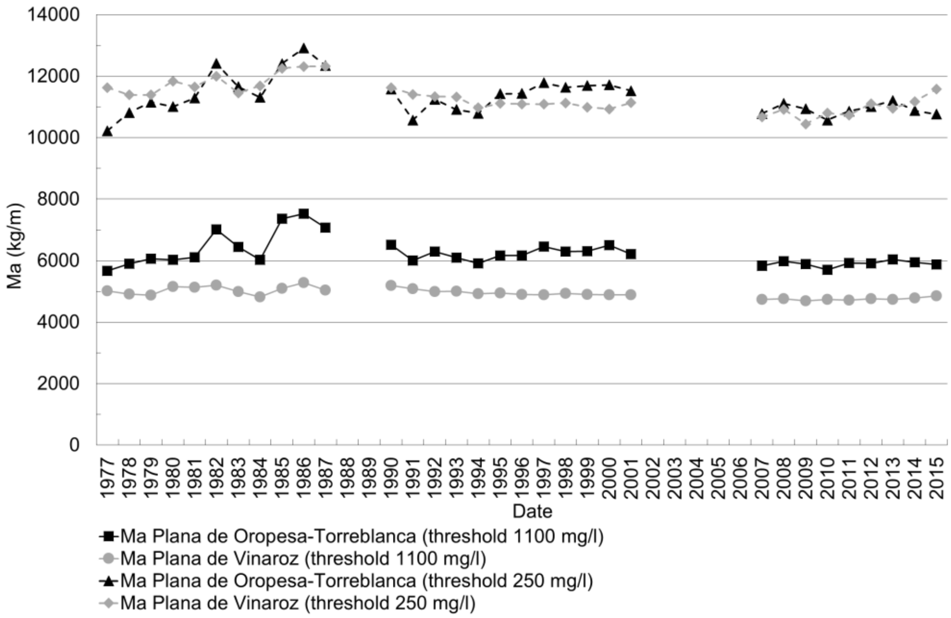

Fig 7 Evolution of the global index, Ma, in the two aquifers studied

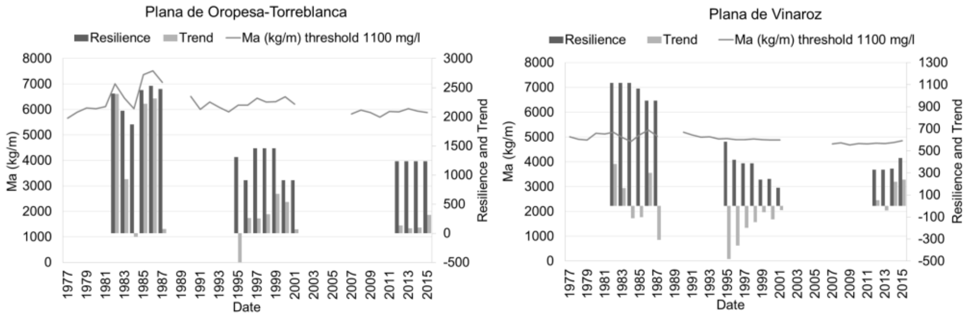

Fig 8 Ma, Resilience and Trend in Plana de Oropesa-Torreblanca and Plana de Vinaroz aquifers (scale exaggeration Resilience and Trend: 10000)

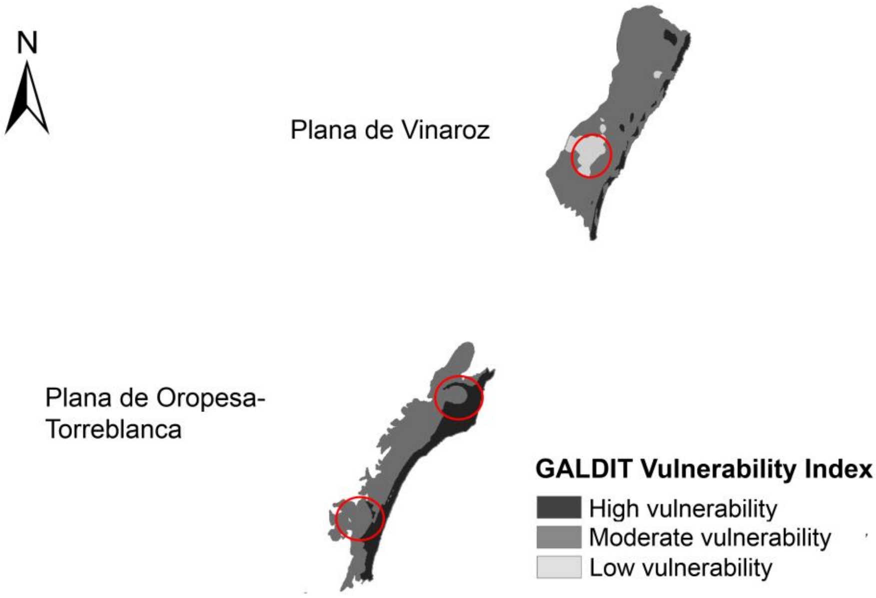

Fig 9 L_GALDIT maps in Plana de Oropesa-Torreblanca for April 2015

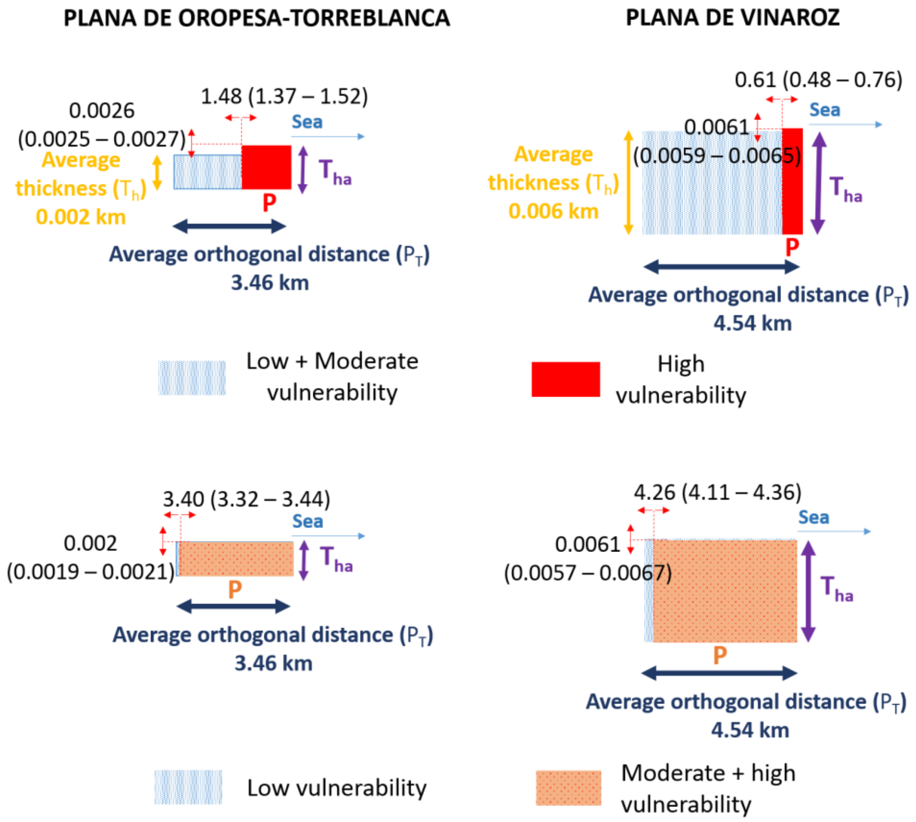

Fig 10 Average cross-sections in two aquifers (L_GALDIT index) for the period 1977-2015 (vertical exaggeration scale: 500)

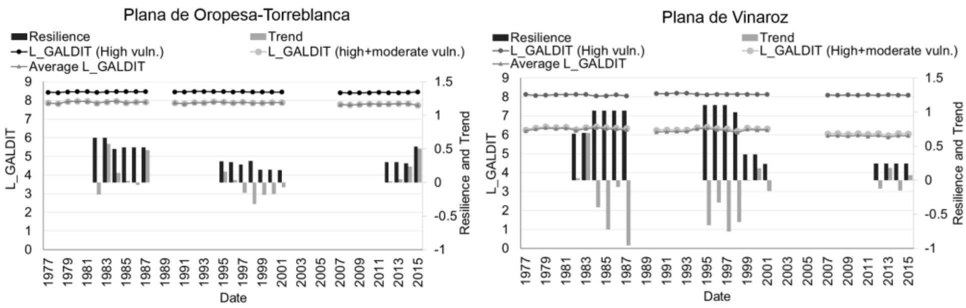

Fig 11 L_GALDIT, Resilience and Trend in Plana de Oropesa-Torreblanca and Plana de Vinaroz aquifers (scale exaggeration Resilience and Trend: 100)