Hydrogeological processes and geological settings over Europe controlling dissolved geogenic and anthropogenic elements in groundwater of relevance to human health and the status of dependent ecosystem

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Deliverable D.7-4: Delivering of cross sections and maps of extend of selected aquifers in specific national pilot areas

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Version: 01-02-2021

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	D.7-4	
Dissemination level	Public	
Deliverable name	Report	
Work package	WP7, Harmonized vulnerability to pollution mapping of the upper aquifer	
Lead WP/Deliverable beneficiary	BGR	
Deliverable Status		
Submitted (Author(s))	01/02/2021	All WP7 partners. Lead author Pulido, D.
Verified (WP leader)	25/05/2021	Broda, S.
Approved (Coordinator)	25/05/2021	Gourcy, L.

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1 INTRODUCTION

This deliverable is part of work package (WP) 7 in the overall project HOVER - **H**ydrogeological processes and Geological settings **over** Europe controlling dissolved geogenic and anthropogenic elements in groundwater of relevance to human health and the status of dependent ecosystems. WP7 deals with the harmonized vulnerability to pollution mapping of the upper aquifer, with 16 member states partners.

This HOVER deliverable reports the outcome of tasks "7.4 Volumes and areas of special aquifer vulnerability to pollution". The objective of the deliverable has been to develop a method based on indices and variables to summarise vulnerability at aquifer scale. Information on the potentially "affected" volumes (where the vulnerability is over a certain threshold) is generated at different spatial scales, moving from areal maps to representative conceptual cross section and lumped indices. It needs information about the spatial distribution of the groundwater resources and the vulnerability values/classes obtained by applying different vulnerability methods (Eg. DRASTIC, COP, etc).

The sensitivity of the affected volumes to the threshold employed to define them should be also tested. The proposed indices-based method has been implemented in a general GIS tool (Baena-Ruiz et al., ur) to facilitate its application and comparison between different GW bodies and temporal periods. Impacts of potential global change (GC) scenarios (climate change and Land Use and Land Cover Change scenarios) can be also analysed. The method is a generalization of the methodology developed by some IGME researchers (Baena-Ruiz et al., 2018; 2020) to assess sea water intrusion status and vulnerability. This method has been adapted to analyse and summarise vulnerability to surface pollution.

2 METODOLOGY

The inputs required and the steps to be followed to apply the method are represented in Fig 1. The vulnerability assessment will require **information about** variables (to characterise the historical evolution of hydraulic head), parameters (to define aquifer geometry and hydrodynamic behaviour) that might come from direct observation (monitoring network) or other techniques (geophysical applications, etc.) and other intrinsic information depending on the vulnerability method (aquifer type, conductivity, distance from the shoreline, bicarbonate concentration).

The information generated (section 2.1) in order to summarize historical vulnerability to pollution through visual pictures and time series is, 1) maps of potentially “affected” groundwater volumes due to their vulnerability value, which is above a certain threshold, 2) 2D conceptual cross-sections (with mean area and thickness in specific dates or mean values in periods) and 3) lumped vulnerability Index to summarise the global dynamic of the vulnerability within the aquifer.

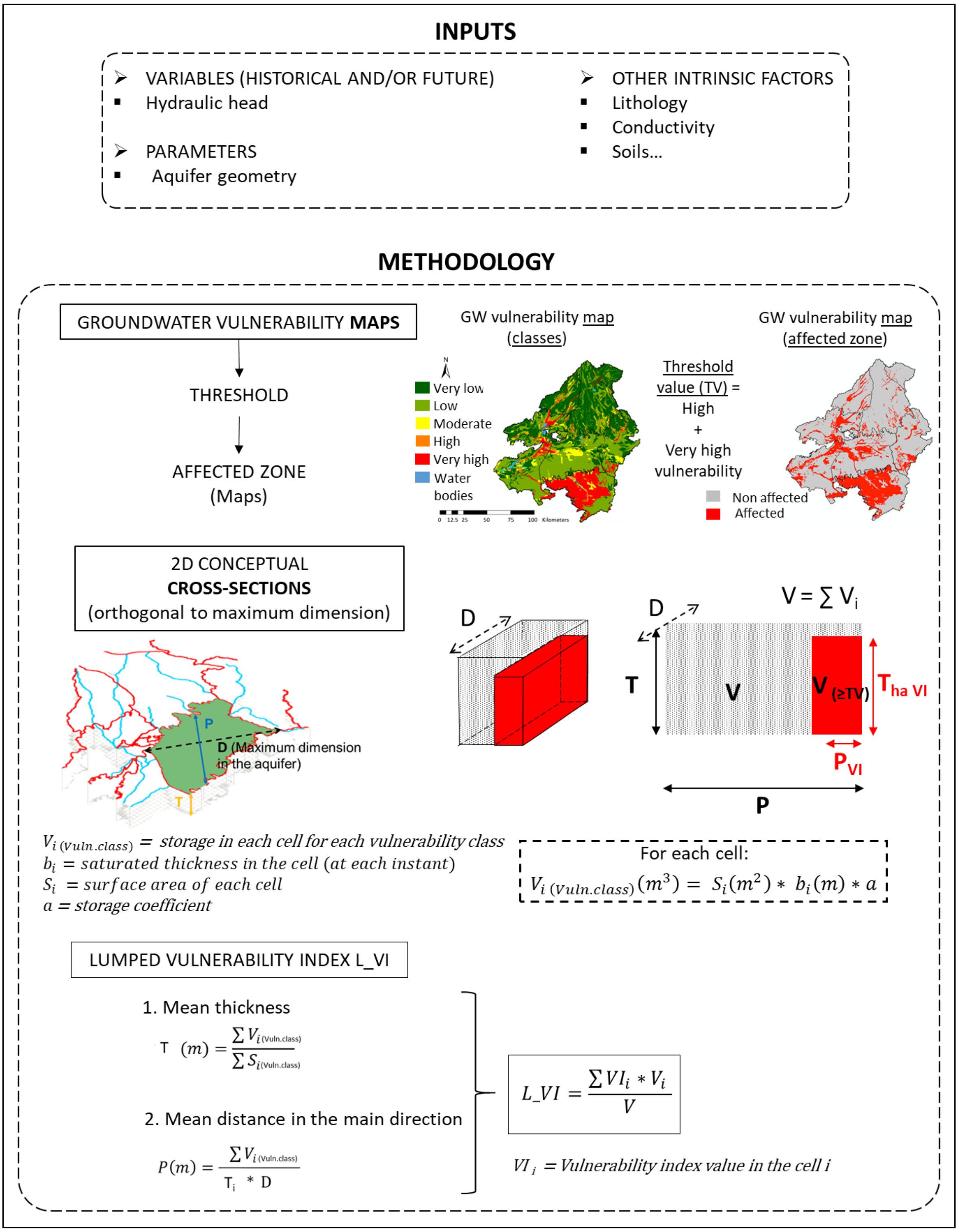

Fig 1 Flow chart of methodology (modified from Baena-Ruiz et al., 2018)

2.1 Historical Assessment of vulnerability

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

2.1.1 *Maps of potentially "affected" volumes due to their high vulnerability*

In order to asses them we will need to estimate: A) Historical maps of vulnerability and groundwater volumes B) Selected threshold of vulnerability values in the aquifer C) Crossing this information we will identify maps of potentially affected volumes due to their vulnerability.

A. Maps of groundwater volumes and vulnerability

Fields (maps) of 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 a satisfactory distributed assessment in accordance with the available data and the adopted interpolation or modelling approached. Maps of historical groundwater volumes can be obtained by combining hydraulic head maps with the aquifer geometry and the storage coefficient. Vertical aquifer geometry and storage coefficient can be obtained from previous 3D models and hydrogeological studies respectively.

Maps of vulnerability to surface pollution can be also obtained by applying different methods (DRASTIC, COP, etc).

B. Threshold of vulnerability

Different vulnerability values or classes can be used as thresholds to determine the volume of the aquifer potentially "affected" due to their vulnerability. For example, if we use as threshold the moderate or high vulnerability classes, the "affected zones" will be those where vulnerability is higher than moderate or high, depending on the adopted threshold.

C. Maps of potentially "affected" volumes due to their vulnerability

From vulnerability maps we can define the affected and non-affected volumes, taking into account the zones where the vulnerability level is above the adopted threshold. For these zones we can calculate the potentially "affected" volume from the map of groundwater volumes.

2.1.2 *2D conceptual cross-sections: mean area and thickness. Average Increment in vulnerability*

2D conceptual cross-sections orthogonal to the larger dimension within the aquifer can be deduced to summarise the mean geometry of the potentially "affected" volume (m^2), which can be defined as the zones where the vulnerability is above the adopted threshold (noted as TV) for a specific date.

The mean Thickness (($T_{L\_VI}(m)$) and mean longitude perpendicular to the longer aquifer dimension ($P_{L\_VI}(m)$) can be calculated as summation of values in each cell i of the aquifer mesh where the vulnerability is greater than the threshold:

$$T_{ha\,VI}(m) = \frac{\sum V_{i(>TV\,_{VI})}}{\sum S_{i(>TV_{VI}\,)}} \tag{1}$$

$$P_{VI}(m) = \frac{\sum V_{i(>TV\,_{VI})}}{T_{ha\,VI} * \mathrm{D}} \tag{2}$$

$$V_{i(>\mathrm{TV}_{VI})}(m^3) = S_i(m^2) * b_i(m) * \alpha_i \tag{3}$$

where:

- $V_{i(>TV\ VI)}$ groundwater volume in each cell (m^3) with vulnerability greater than $V_{TV\ VI}$;
- S_i is the surface area in the cell i with vulnerability higher than $V_{TV\ VI}$;
- b_i is the saturated thickness within the cell i with vulnerability higher than $V_{TV\ VI}$;
- α_i is the storage coefficient in the cell I;
- D is the mean longitude orthogonal to the largest dimension (m);

These cross sections and lumped index give an overview of the magnitude (per linear meter of the longer aquifer dimension) of the vulnerability at a specific time. Mean cross-sections can also be obtained to summarise the average values for a time period.

2.1.3 Lumped index (L_VI): Volume in the affected area

A lumped global value of vulnerability (L_VI) is defined by weighting the vulnerability score in each cell by the storage (Equation 4). This weighted value of vulnerability assesses the overall vulnerability of the aquifer. A lumped affected value of vulnerability can be obtained for the different thresholds (Equations 5 and 6).

$$L\_VI = \frac{\sum(VI_i * V_i)}{V} \tag{4}$$

$$L\_VI_{High} = \frac{\sum(VI_{i(\geq\mathrm{High})} * V_{i(\geq\mathrm{High})})}{V_{(\geq\mathrm{High})}} \tag{5}$$

$$L\_VI_{Moderate} = \frac{\sum(VI_{i(\geq\mathrm{Moderate})} * V_{i(\geq\mathrm{Moderate})})}{V_{(\geq\mathrm{Moderate})}} \tag{6}$$

where:

- VI_i is the value of vulnerability in each cell i;
- V_i is the groundwater volume in each cell i;
- V is the total groundwater volume in the aquifer;
- $G_{i(\geq High)}$ is the value of vulnerability of each cell greater or equal to High;
- $G_{i(\geq Moderate)}$ is the value of vulnerability of each cell greater or equal to Moderate;
- $V_{i(\geq High)}$ is the groundwater volume of each cell with a value of vulnerability ≥ High;
- $V_{i(\geq Moderate)}$ is the groundwater volume of each cell with a value of vulnerability ≥ Moderate;
- $V_{(\geq High)}$ is the total groundwater volume with a value of vulnerability ≥ High;
- $V_{(\geq Moderate)}$ is the total groundwater volume with a value of vulnerability ≥ Moderate;

The intensity of vulnerability is the lumped vulnerability value in each zone for the thresholds established.

3 APPLICATION TO CASE STUDIES.

In this section, we include examples of results obtained in each of the described steps of the method in aquifers of the Upper Guadiana Basin aquifer.

3.1 Pilot description: Input data for DRASTIC vulnerability maps

The IGME case study is the Upper Guadiana Basin, which is located in the central part of Spain, in the Mediterranean region of EU (Fig 2). It is composed of eight unconfined groundwater bodies where the DRASTIC method has been applied.

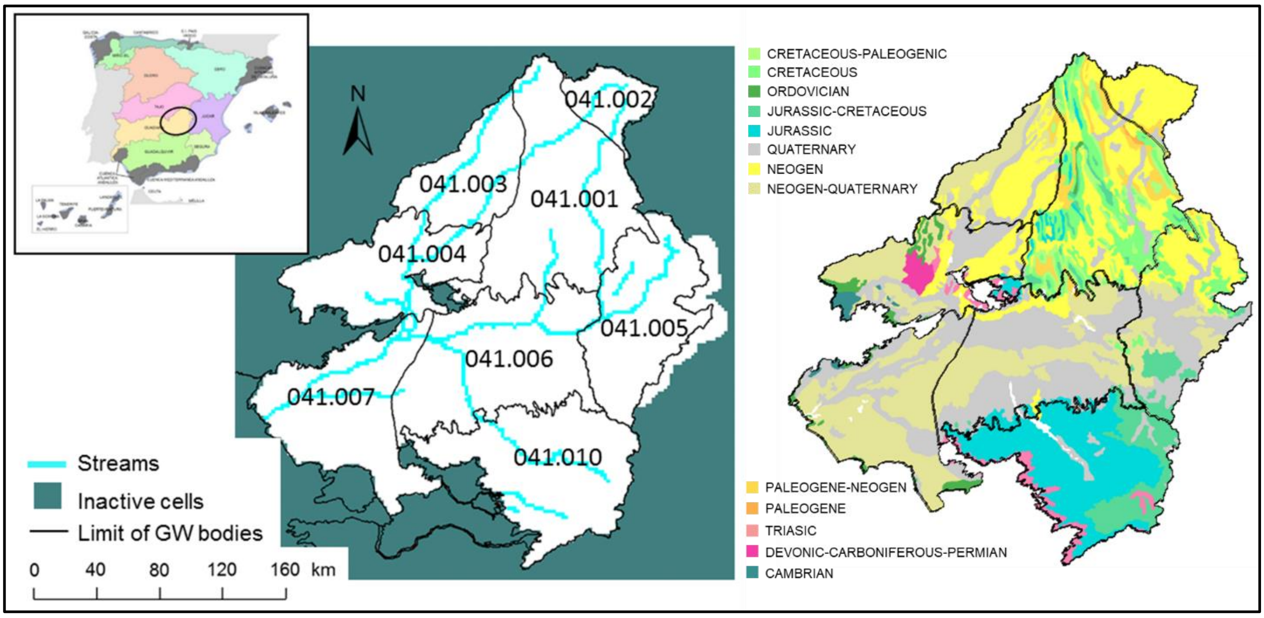

Fig 2 Location of the Upper Guadiana Basin (Spain) (left) and geology of the basin (right).

The basin shows strong natural interaction between groundwater and surface water and gives rise to over one hundred wetlands that make up UNESCO's "Mancha Húmeda Biosphere Reserve". The most part of them are groundwater-dependent wetlands. Intensive groundwater withdrawal depleted the water table by more than 20 m between the mid-1970s and the first decade of the new century, although an important and unexpected recovery of the Mancha Occidental aquifer has occurred recently. In general, depth to water table is higher than 15 meters in most of the area, so the most area of the Upper Guadiana Basin has lower values of 'D'-parameter.

Rainfall is the main source of aquifers recharge. The mean annual recharge estimated varies between 45 and 70 mm/a, although there is not an agreement in these values.

The geology is complex, including detrital and carbonated aquifers and the groundwater connectivity between the Upper Guadiana's aquifer is also structurally complex. In the southern half of the Upper Guadiana Basin the aquifers are predominantly composed by limestones, with many karstified zones. Many areas in the central aquifer are formed by tertiary detrital materials. The northern aquifers are more heterogeneous. There are no large karstified areas and other formations of metamorphic materials can be found in these aquifers. The unsaturated zone is formed by poorly permeable lithologies in the northern area and higher permeability values can be found in the southern part.

The soils in the basin mainly belong to the cambisol group according to the FAO classification. It can also be found regosol and others such as luvisol and podzol in the southeast area. The soil texture in the northern area is predominantly silty-loam, whereas the soil in the southern area is composed by peat.

The area is predominantly flat, sloping gently over 150 km, from the northeast (elevation 730 m a.s.l.) to the southwest (600 m a.s.l.).

The hydraulic conductivity in the Upper Guadiana Basin takes values in all the ranges proposed for the classification of this parameter in DRASTIC. The northern area has low conductivity (below $1.5x10^{-4}$ m/s although there exists a small area with conductivity higher than 10^{-3}. The central area takes values between $1.5x10^{-4}$ and 10^{-3} m/s and the conductivity in the southern area is mainly in the range of $3.5x10^{-4}$ - $5x10^{-4}$ m/s.

3.1.1 Inputs required to applied the proposed method

In this section, we show some examples of the historical maps of groundwater volumes/resources (Fig 3) and vulnerability (Fig 4) required to apply the method.

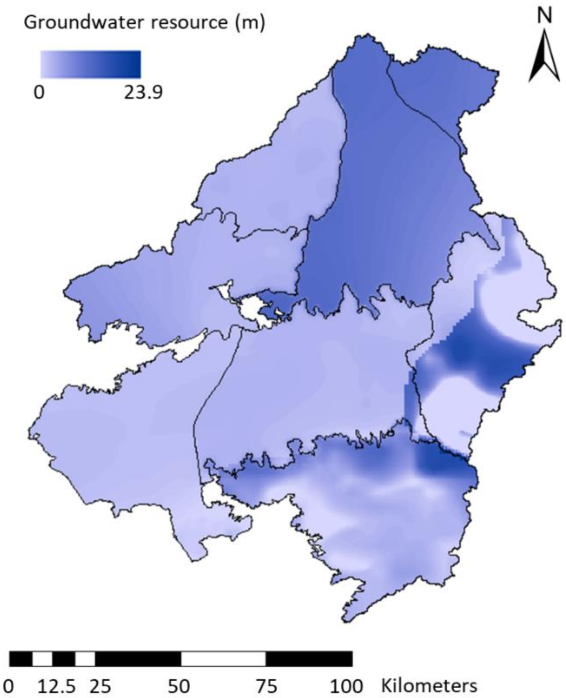

Fig 3 Historical maps of groundwater resources (mean values of the period 1974-2015)

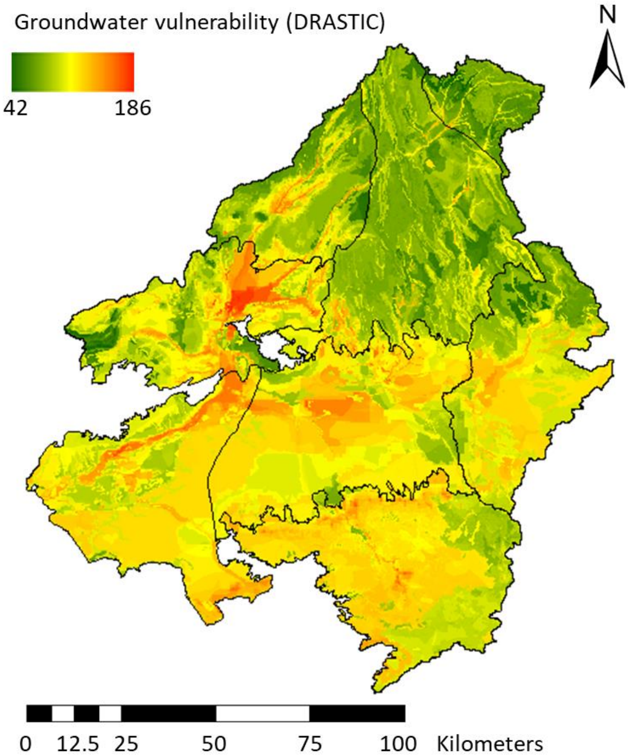

Fig 4 Historical maps of vulnerability (mean values of the period 1974-2015)

3.2 Maps of potential affected volumes due to their vulnerability values

Following the steps described in Section 2.1.1 of the methodology, we obtain the maps of potential affected volume where the vulnerability is above a certain threshold (Fig 5). In the historical analysis, we assumed two different thresholds, Moderate and High vulnerability. It allows us to show the sensitivity of the results to this parameter.

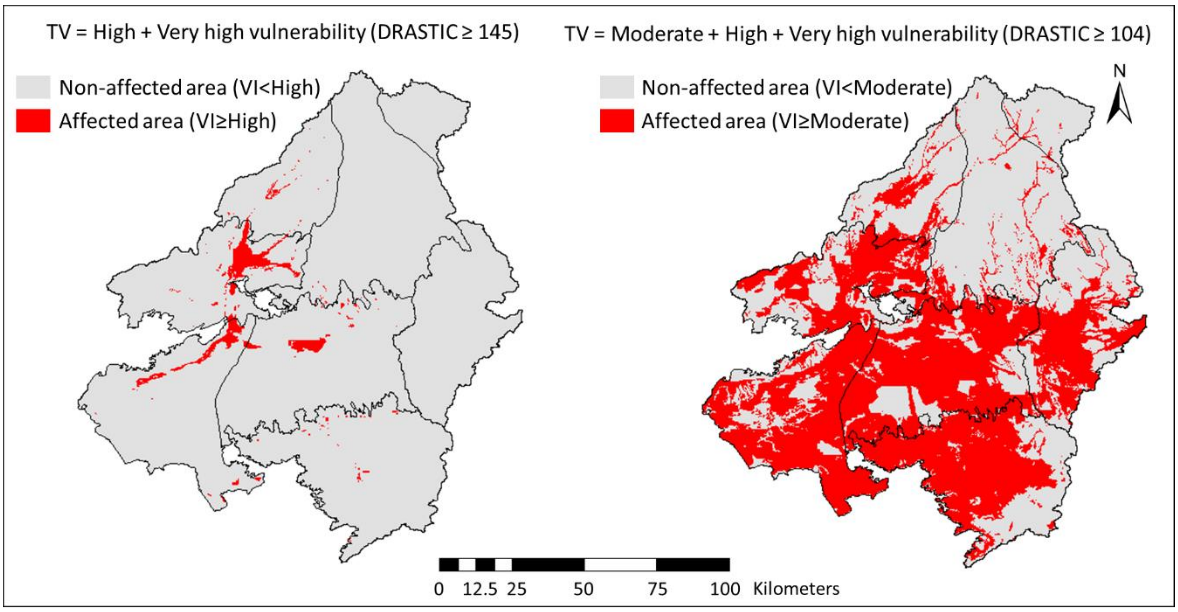

Fig 5 Maps of potential "affected volume" due to the vulnerability values (mean values of the period 1974-2015)

3.3 2D conceptual cross-sections: mean longitude orthogonal to the largest dimension and mean thickness.

Following the steps described in section 2.1.2 of the methodology, we obtain the conceptual cross section to summarise results in terms of vulnerability. They are also obtained for two different thresholds, Moderate and High vulnerability, to show the sensitivity of the results to this parameter (Fig 6).

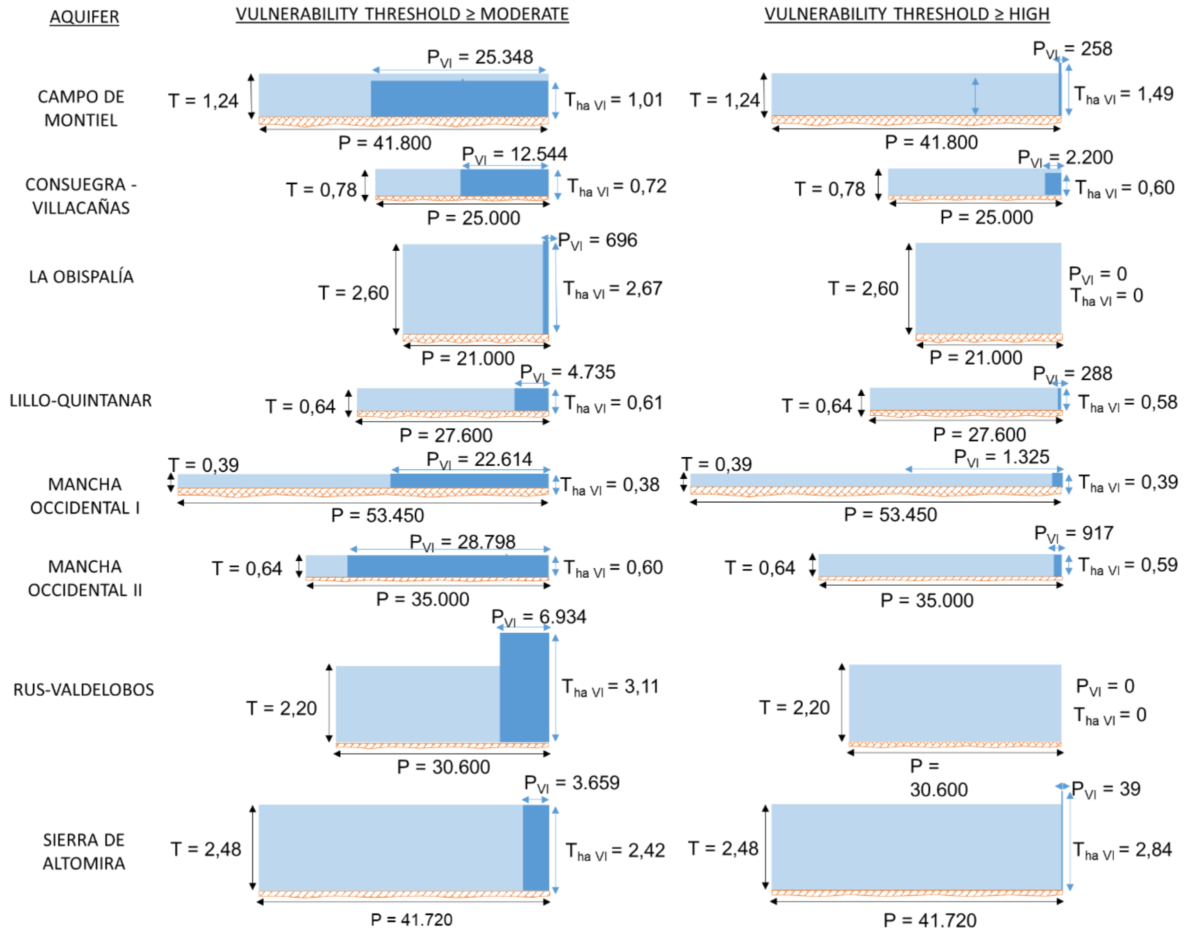

Fig 6 2D conceptual cross-sections. Mean values in the period 1974-2015 (units in m)

3.4 Lumped index: L-VI value.

Following the steps described in section 2.1.3 of the methodology we obtain the lumped index L_VI for each aquifer considering different TV values (Fig 7). We also represent the temporal evolution of the mean L_VI index for each aquifer to summarise the global dynamic of the vulnerability (Fig 8).

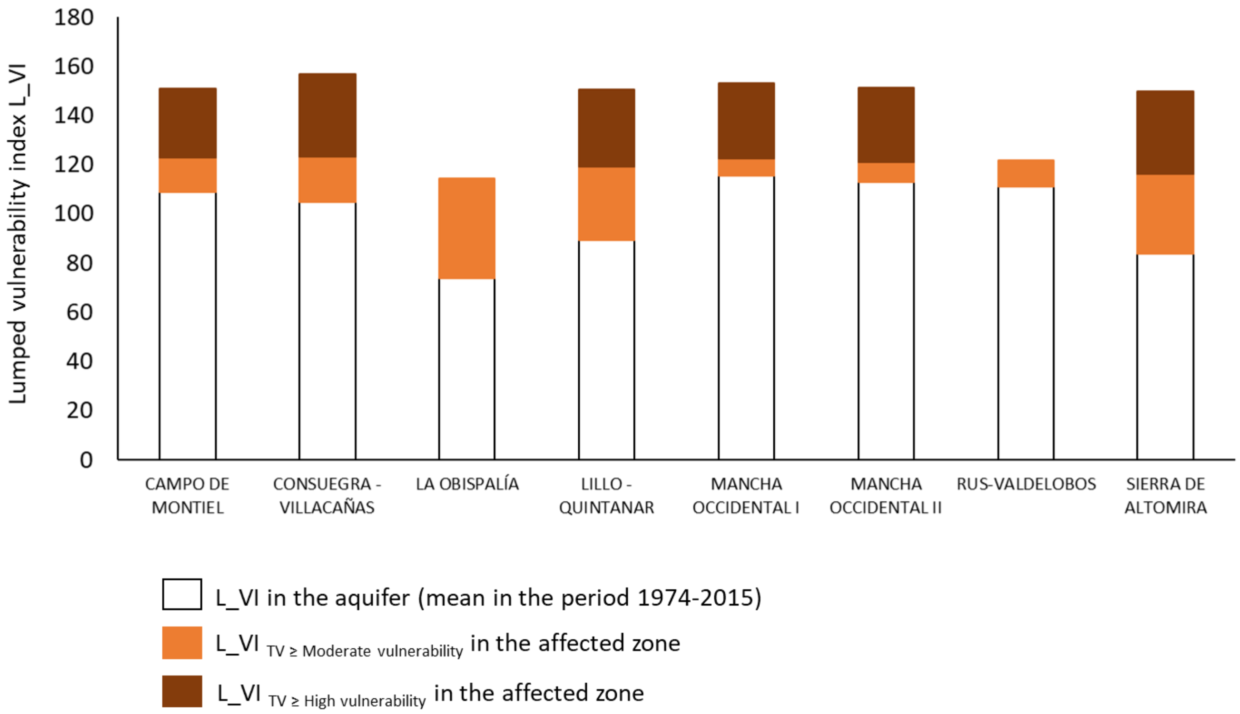

Fig 7 L_VI in the period 1974-2015 for different TV.

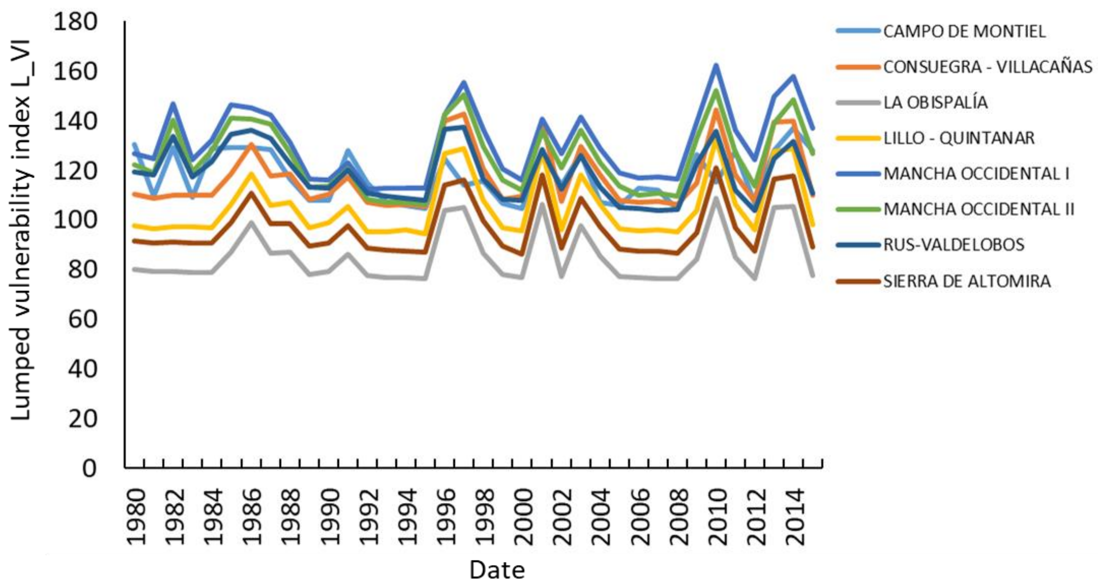

Fig 8 Temporal evolution of mean L_VI in the period (1974-2015).

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APPENDIX 1: DRASTIC SUMMARY

Pilot area Upper Guadiana Basin (Spain) – IGME (Cell size: 100 m, Total area: 14,093 km^2)

DRASTIC input data specification

Factor	Title of dataset	Name of the input dataset file	Status / version (june 2020)	Data source	Methodology	Remark (optional)
D	Depth to water table	D_IGME.tiff	Final version	Data from simulation flow model (CHG) (mean of the simulated data for each grid point from 1974 to 2015)	Spatial interpolation using IDW of groundwater level data and reclassification into D index values.	-
R	Net recharge	R_ IGME.tiff	Final version	Recharge time series calculated from SACRAMENTO model. Mean recharge value in the period 1974-2015.	Estimation of the mean net recharge taking into account the different hydrology cycle variables in the period 1974-2015.	-
A	Aquifer media	A_ IGME.tiff	Final version	Hydrogeological map of Spain 1:200,000 (IGME)	Direct assignment of A index values for each hydrogeological unit delimitated	-
S	Soil media	S_ IGME.tiff	Final version	Soil Map of Spain at 1:1,000,000 (IGN)	Direct assignment of S index values for each soil type	-
T	Topography/slope	T_ IGME.tiff	Final version	Digital Terrain Model at 100 x 100 m cell size (IGN)	Calculation of the slope rasterfile and reclassification of values into T index values	-
I	Impact of vadose zone media	I_ IGME.tiff	Final version	Lithostratigraphic map of Spain at 1:200,000 (IGME)	Direct assignment of I index values for each lithostratigraphic unit	-
C	Hydraulic conductivity	C_ IGME.tiff	Final version	Flow model at 1000 x 1000 m cell size (CHG)	Spatial interpolation using IDW of conductivity data and reclassification into C index values.	-

Pilot area Upper Guadiana Basin (Spain) – IGME (Cell size: 100 m, Total area: 14,093 km^2)
Spatial distribution of DRASTIC input data ratings