

# Assessment of social vulnerability to groundwater pollution using K-means cluster analysis.

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## Research Article

**Keywords:** Social vulnerability, groundwater pollution, clustering analysis, K-means

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## Assessment of social vulnerability to groundwater pollution using K-means cluster analysis.

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### 17 Abstract

18 It is possible to assess the harm that society suffers from an anthropogenic event based on the impact  
19 of groundwater pollution on society. Indexing methodologies are commonly applied to assess the  
20 social vulnerability of aquifers. However, they assign weighting and rating values for the different  
21 factors involved, make them very subjective. This research proposes to assess the social vulnerability  
22 to groundwater pollution by considering three factors: the uses of groundwater resources, the exposed  
23 population, and the socio-economic losses. In order to eliminate the subjectivity of indexing  
24 methodologies, a K-means cluster analysis was used to assess the social vulnerability. Using this  
25 method, a social vulnerability map can be produced with greater objectivity. The proposed methodology  
26 was applied to an aquifer located in central Spain, an area with significant agricultural development.  
27 Low population density and unproductive zones result in low social vulnerability in most of the area.  
28 Nevertheless, high social vulnerability is observed in the southern regions due to agricultural  
29 development which leads to higher socio-economic variables and demand for groundwater resources  
30 for agricultural activities. Similarly, high social vulnerability is observed in the northeast, mainly  
31 influenced by groundwater use and exposed population. These results show that social vulnerability in  
32 most of the study area is not very significant for assessing the risk of groundwater contamination,  
33 because the damage to the social, environmental or economic sector is low. However, in the south and  
34 northeast in the study area, pesticides and fertilisers should be used with caution, as they significantly  
35 increase the risk of groundwater contamination and thus the impact on society. The K-means clustering

36 method proved to be an objective and effective option for assessing social vulnerability to groundwater  
37 pollution in aquifers.

38 **Key words:** Social vulnerability, groundwater pollution, clustering analysis, K-means.

39

## 40 **1. Introduction**

41

42 Aquifers represent the most important source of water supply for urban, industrial and agricultural uses  
43 in areas where surface water resources are scarce or the use of supply sources is limited by water  
44 quality. In general, groundwater is of better quality than surface water because it has a natural protection  
45 against anthropogenic pollutants. However, natural or geogenic contamination by dissolution or  
46 chemical reactions between water and solid matrix (rock, soil) is also important. In some cases, the use  
47 of contaminated groundwater negatively affects society, endangering human health, the environment  
48 or the economic development of a region (Cutter, 2010, 1996; Grondona et al., 2015; Perles et al.,  
49 2008)

50 Social vulnerability is a simply way of assessing the potential damage to society from a natural or  
51 anthropogenic event (Cutter 1996; Perles et al. 2008). In environmental studies, many authors (e.g.  
52 Ducci, 1999) consider that groundwater represent a valuable resource. Thus, the value of water supply  
53 resource has to be taken into account. The socio-economic value associated with groundwater supply  
54 uses incorporates variables such as population, number of employees and economic productivity linked  
55 to activities that depend on groundwater resource. (Ducci 1999; Vias 2005; Perles et al. 2008; French  
56 et al. 2017; Orellana-Macías and Perles Roselló 2022).

57 To assess the social vulnerability, some authors (Ducci 1999; Vias 2005; Perles et al. 2008; Grondona  
58 et al. 2015; Orellana-Macías and Perles Roselló 2022) have developed indexing methodologies that  
59 incorporate the factors noted above by assigning weighting and rating values that describe the degree  
60 of vulnerability of society to groundwater contamination. However, the subjectivity involved in the  
61 selection of relative weighting and rating values is a disadvantage in the application of these  
62 methodologies.

63 The main goal of this work is to develop a new methodology for the assessment of social vulnerability  
64 to anthropogenic groundwater pollution, through the application of K-means clustering techniques. The  
65 methodology will be applied to a case study related to a detrital aquifer located in the region of Madrid  
66 (central Spain).

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## **2. Materials and methods**

### **2.1. The study area**

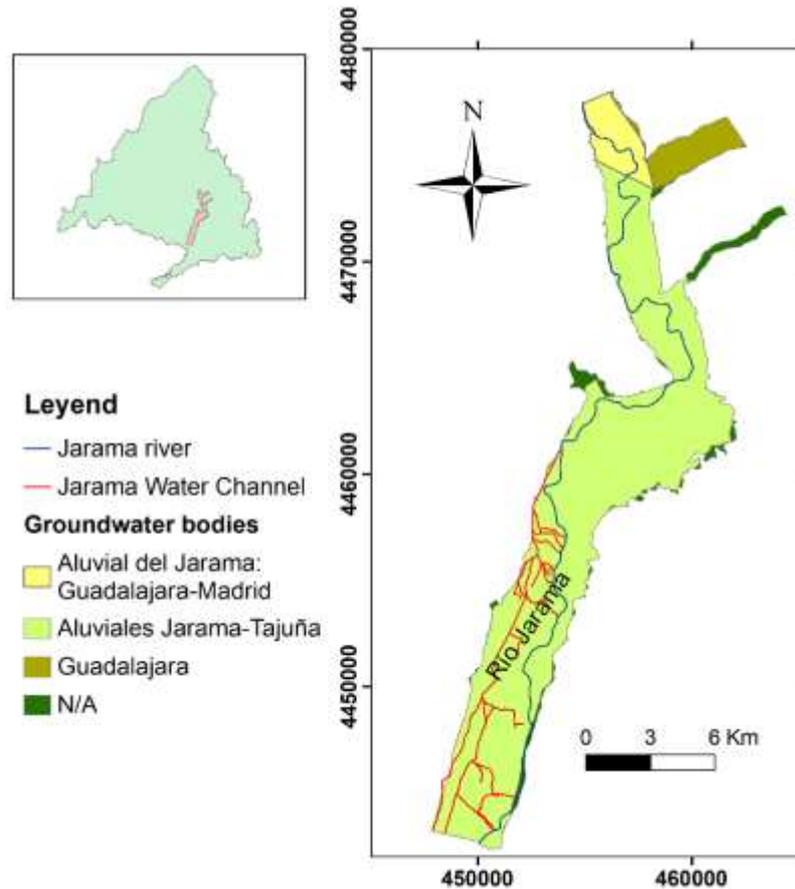
The study area is located in the southeast of Community of Madrid in central Spain and covers an approximate surface area of 133Km<sup>2</sup> (Fig. 1). The climate is temperate-continental Mediterranean with an average rainfall of 440 mm/year (Mostaza-Colado et al. 2018). The Jarama River is the main surface water resource, crossing the study area from north to south. In the south, a major water canal was constructed to canal the Jarama River and provide water for irrigation using the flooding technique (Mostaza 2019).

In the study area there is a detritic aquifer formed by three groundwater bodies, according to the definition of the Confederación Hidrográfica del Tajo (CHET): "Aluvial del Jarama: Guadalajara Madrid", "Guadalajara" and "Aluviales Jarama-Tajuña". The latter is the most important because it covers more than 80% of the area (Fig. 1). The aquifer is shallow and consists of gravels and sands, with intercalations of clays and silts. Its average thickness is about 10m (Carreño Conde et al., 2014).

The region has an important agricultural (mainly arable and tree crops) and livestock development (Fernández González 2013; MAPA 2021a). The population is scarce because most of the territory is used for agricultural activities (Comunidad de Madrid, 2020).

The aquifer provides water for some agricultural, urban and industrial activities in the study area (CHT 2015a). Although it is not the only source of water, it is an important and valuable water resource in the region.

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**Fig. 1** Study area showing the groundwater bodies defined by the Confederación Hidrográfica de El Tajo (CHET, 2010). ETRS 1989 UTM Zone30N

## 2.2. Data set collection

The data considered in this work included:

- Cartographical information: Municipal boundaries map (scale 1:25,000, (IGN 2021)); digital map of groundwater bodies (CHET, 2010); land use map (scale 1:100,000 Corine land cover map (IGN 2018)).
- Groundwater resource information: Groundwater uses (CHT 2015a)
- Population information: Population density (Comunidad de Madrid 2020). Employment by economic activity in the region of Madrid (Consejería de Economía, Hacienda y Empleo, 2021). Wages in agricultural activity in Spain (MAPA 2021b).
- Agricultural information: Agricultural regions (Fernández González 2013). Land prices (Subdirección General de Análisis, Coordinación y Estadística. 2020). Cereal yields and prices

127 in Spain (2020-2021) (MAPA 2021c, d). Yields and prices of woody crops in Spain (2020-2021)  
128 (MAPA 2020, 2021d; Subsecretaría de Agricultura, Pesca y Alimentación 2020). Livestock per  
129 groundwater bodies, yields and prices in Spain (CHT 2015a; MAPA 2021e, a). Agricultural  
130 demand units (UDA) from the Hydrological Plan of the Tajo basin for 2015-2021, (CHT 2015b).

131

132 The data were stored as a geographical database in ArcGIS v10.4.1. The whole study area (133 Km<sup>2</sup>)  
133 was divided into 5842 pixels with a cell size of 150m x 150m, in order to obtain a large data set to evaluate  
134 the different variables at each point.

135

### 136 **2.3. Estimation of factors to determine the social vulnerability**

137 The social vulnerability assessment was carried out in the following two stages:

138 • *Estimation of factors affecting the social vulnerability.* Three different factors were considered  
139 to assess the social vulnerability to a groundwater contamination event. These factors, which  
140 include social, economic and environmental aspects, were evaluated by considering the  
141 following settings:

- 142 ✓ Vulnerability of groundwater resources ( $V_{GR}$ )
- 143 ✓ Vulnerability of exposed population ( $V_P$ ).
- 144 ✓ Socio-economic vulnerability ( $V_{S-E}$ )

145 • *Mapping of social vulnerability using cluster analysis (K-means algorithm)*

146 A normalization of the obtained factor values was performed to standardize the ranges of the values in  
147 order to avoid the bias of higher values over lower values (0-1) (Eq. 1, (Salazar and Del Castillo 2018)).

$$148 \quad \text{Normalized Factor value} = \frac{(F_x - F_{min})}{(F_{max} - F_{min})} \quad (1)$$

149 Where  $F_x$  is the value of the factor in the  $x$  point, and  $F_{min}$ ,  $F_{max}$  are the minimum and maximum  
150 values of the range, respectively.

151

#### 152 **2.3.1. Vulnerability of groundwater resources ( $V_{GR}$ )**

153 This factor represents the amount of the groundwater resources that can be affected from a  
154 contamination, as it reduces the groundwater available for different uses. Groundwater contamination  
155 also has a negative impact because the contaminated water can reach other water bodies, affecting  
156 associated ecosystems. In the study area, the Jarama river and the aquifer have a hydraulic connection

157 that incorporates water from the aquifer to the river (Mostaza 2019). To obtain the vulnerability of  
158 groundwater resources according to groundwater uses, three variables were used: urban uses ( $U_u$ ),  
159 agricultural uses ( $A_u$ ) and industrial uses ( $I_u$ ). The amount of water abstracted for the different uses is  
160 estimated by Confederación Hidrográfica del Tajo (CHET) to each groundwater body (CHT 2015a).

161 The vulnerability of groundwater resources was calculated using the following equation (Eq. 2):

162

$$163 \quad V_{GR} = U_u + A_u + I_u \quad (2)$$

164

165 Where  $V_{GR}$  is the vulnerability of groundwater resources,  $U_u$  is the urban uses map of groundwater,  $A_u$   
166 is the agricultural uses map of groundwater and  $I_u$  is the industrial uses map of groundwater.

167 The ArcGIS v10.4.1 Raster calculator tool was used to sum maps.

168

### 169 **2.3.2. Vulnerability of exposed population ( $V_p$ )**

170 The exposed population was calculated from the population density located in the study area  
171 (Comunidad de Madrid 2020) and the percentage of urban groundwater use (CHT 2015a). The  
172 population affected by the consumption of polluted groundwater was calculated as the number of  
173 inhabitants per square kilometre multiplied by the percentage of urban groundwater use (Eq. 3).

174

$$175 \quad V_p = \text{Population density} * \% \text{ of groundwater urban use} \quad (3)$$

176

177 Urban groundwater use was calculated as the percentage of total groundwater use in each groundwater  
178 body (Table 1).

179 The population density map was obtained using the number of inhabitants per square kilometre within  
180 each municipality in the study area (Comunidad de Madrid 2020)

181 The ArcGIS v10.4.1 Raster calculator tool was used to multiply maps.

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190 Table 1 Percentage of urban groundwater use from different groundwater bodies in the study area

Groundwater body	Code (CHET)	Urban use (hm <sup>3</sup> /year)	All uses. Total groundwater (hm <sup>3</sup> /year)	Percentage of urban groundwater use from total uses (%)
Guadalajara	030.006	6.311	23.018	16.1
Aluviales Jarama-Tajuña	030.007	0.895	14.199	2.3
Aluvial del Jarama: Guadalajara-Madrid	030.024	0.138	2.016	0.3
Total groundwater		7.344	<b>39.233</b>	18.7
% of groundwater use		18.7	100	

191

192

193 **2.3.3. Socio-economic vulnerability ( $V_{S-E}$ )**

194 To assess this factor, social and economic activities that depend on the groundwater resources were  
 195 considered. The study area has an important agricultural development which predominates over other  
 196 economic activities (Mostaza-Colado et al. 2018; Mostaza 2019). For this reason, four variables  
 197 associated with this productive sector were chosen to evaluate this factor:

- 198 • Land prices, according to the type of crops and irrigation uses.
- 199 • Agricultural production (crops)
- 200 • Livestock production
- 201 • Employment related to the agricultural activities

202 Socio-economic vulnerability ( $V_{S-E}$ ) was calculated using the following equation (Eq. 4)

203

$$204 \quad V_{S-E} \left( \frac{\text{€}}{\text{year}} \right) = \text{Land prices} + \text{crops production} + \text{livestock production} + \text{agricultural employment} \quad (4)$$

205

206  
 207 However, irrigation facilities using surface water (a water canal from the Jarama river canal) reduce  
 208 the use of groundwater for irrigation, which in turn contributes to reduce the socio-economic vulnerability  
 209 due to groundwater contamination. Thus, a reduction factor ( $Rf$ ) can be considered according to the  
 210 percentage of surface water irrigated areas, as shown in Table 2.

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Table 2 Reduction factor values (*Rf*)

Percentage of surface water irrigated areas	Rf
0	1
10	0.9
20	0.8
30	0.7
40	0.6
50	0.5
60	0.4
70	0.3
80	0.2
90	0.1
100	0

214

215 Some municipalities into the study area use the Jarama river water canal to irrigate part of the cultivated  
 216 areas, due to the facility offered by this canal. The percentage of surface area irrigated with water from  
 217 the Jarama River canal is shown in Table 3.

218

219 Table 3 Surface (%) in the study area irrigated with water from the Jarama Canal

Municipality	Surface irrigated with water from the Jarama Canal (%)
Arganda del Rey, Coslada, Chichón, Loeches, Madrid, Mejorada del Campo, San Fernando de Henares, Titulcia, Torrejón de Ardoz, Valdemoro, Velilla de San Antonio	0
Rivas-Vaciamadrid	0.08
Aranjuez	2.79
San Martín de la Vega	14.7
Ciempozuelos	22.9

220

(Comunidad de Regantes de la Real Acequia del Jarama 2021)

221

222 According to the percentage of surface area irrigated with water from the Jarama Canal in each  
 223 municipality in the study area, a reduction factor (*Rf*) was assigned according to Table 2.

224 The spatial distribution of the reduction factor in the study area is shown in Fig. 2.

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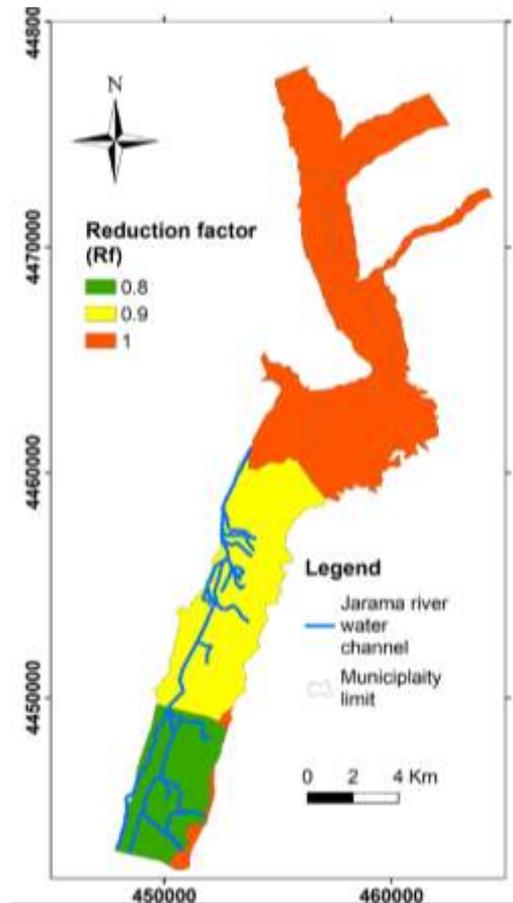
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245 **Fig.2** Spatial distribution of the reduction factor (Rf) in the study area.

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247 Finally, the socio-economic vulnerability was calculated by applying the reduction factor to Eq. 4 (Eq.  
248 5).

$$249 \quad V_{S-E} \left( \frac{\text{€}}{\text{year}} \right) = R_f * (\text{Land prices} + \text{crops production} + \text{livestock production} +$$

$$250 \quad \text{agricultural employment}) \tag{5}$$

251

252 The ArcGIS v10.4.1 Raster calculator tool was used to sum and multiply the maps.

253

254 ✓ **Land prices**

255 The price of land is directly associated to the type of activity developed. As mentioned before, the  
256 agricultural activity is the most important economic activity in the study area. For this reason, it was  
257 considered to obtain land prices according to the types of crops and irrigation uses. It is important to

258 note that the soil contamination by irrigation with polluted water degrades the soil conditions for future  
259 crops, thus devaluing the land. Land prices for 2019 in the study area are shown in Table 4.

260

261 Table 4 Land prices according to crop type and irrigation use for 2018-2019

Land type	Crop type	€/ha
Non-irrigated land	Arable/Herbaceous	7079
	Fruit trees	8979
	Vineyard	14474
	Olive groves	20586
Irrigated land	Arable/Herbaceous	17552
	Vegetables	35534
	Rice	31048
	Cítricos	40186
	Fruit trees	37770
	Vineyard	23105
	Olive groves	38506
	Pasture	6298
Natural meadow	8247	

(Brezmes 2018; Subdirección General de Análisis, Coordinación y Estadística. 2020)

262

263

264 The land use map (IGN 2018) was used to delimit the type of crop type and land classes in the study  
265 area (Fig. 3).

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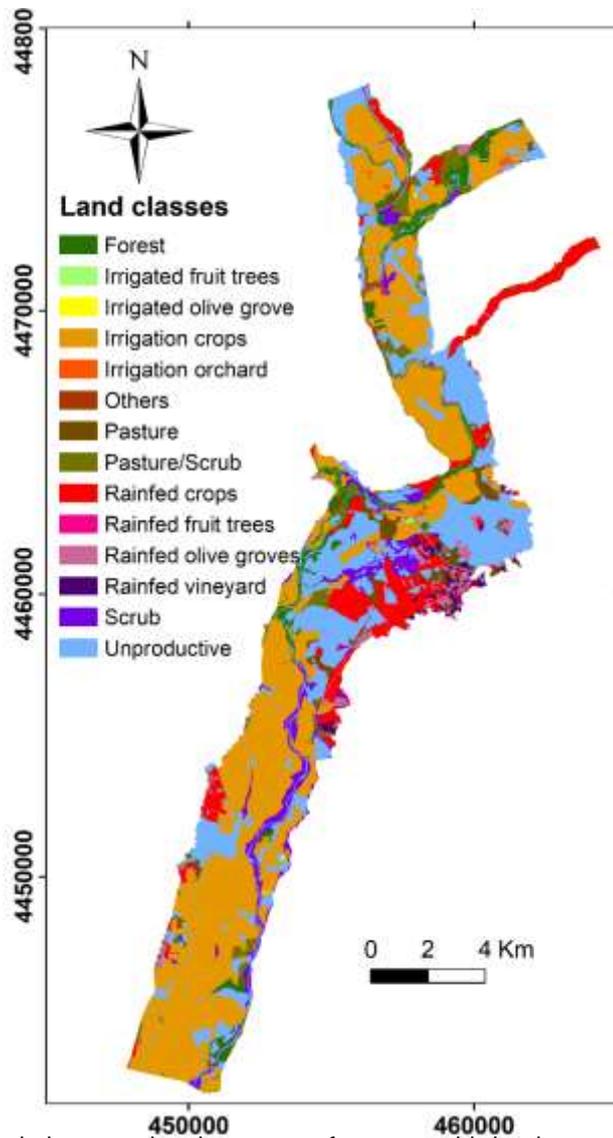


Fig.3 Land classes, showing types of crops and irrigation uses.

✓ **Agricultural production (crops)**

There are two types of crops in the study area: arable crops and woody crops. Both are delimited in the agricultural regions established by the government authority (Ministerio de Agricultura, Alimentación y Medioambiente de España) (Fernández González 2013). Thus, the agricultural regions provided the information about surface of the cultivated areas of different crops.

The main arable crops in the study area are: wheat, barley, corn, chickpea and oat (Fernández González 2013). Each type of crop has its own yield and market price (MAPA 2020, 2021c, d) (Table 5).

312

Table 5 Production of arable crops (2020-2021)

Arable crop	Yield (Tn/ha)	Price €/Tn	Production €/ha
Wheat	3.8	247.0	938.6
Barley	4.0	184.0	736.0
Corn	11.9	221.0	2629.9
Chickpea	2.5	138.0	345.0
Oatmeal	1.3	650.0	845.0

313

(MAPA 2020, 2021c, d)

314 The main woody crops in study area are: Vineyard, olive groves and fruit trees (not citrus) (Fernández  
315 González 2013). As with arable crops, each type of crop has a particular yield and a market price (MAPA  
316 2020; Subsecretaría de Agricultura, Pesca y Alimentación 2020) .

317 The value of the production obtained by woody crops varies according to the specific product obtained.  
318 For this reason, the prices of the different product were averaged to obtain a single value per product  
319 (Table 6). The production of each type of woody crop is shown in Table 7.

320

321

Table 6 Market prices of woody crops products (2021)

Woody crop	Product	Marker price (€/Kg)	Price average (€/Kg)
Vineyard	Grapes	0.35	0.35
Olive groves	Olive oil	3.10	1.9
	Olives	0.73	
Fruit trees (not citrus)	Stone fruits (Cherry, plum, kiwi, peach, nectarine and medlar)	0.15	0.12
	Pome fruits (apple and pear)	0.08	

322

(MAPA 2021c, d)

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324

Table 7 Woody crops production by 2021 in Spain

Woody crop	Yield (Kg/ha)	Price €/Kg	Production €/ha
Vineyard	4685	0.35	1640
Olive grove	1014	1.9	1927
Fruit trees	300	0.12	36

325

(MAPA 2021c, d)

326 The agricultural production of each type of crop was obtained by multiplying the cultivated area of the  
327 different crops by the economic production. The ArcGIS v10.4.1 Raster calculator tool was used to  
328 multiply maps.

329 Finally, the total production of agricultural crops was obtained from the sum of agricultural production  
 330 maps (arable and woody) obtained for different crops. To obtain that value, the maps were summed  
 331 using the Raster calculator tool of ArcGIS v10.4.1.

332

333 ✓ **Livestock production**

334 Livestock production in the study area is based on bovine, ovine, goats, porcine and poultry livestock,  
 335 depending on the water resources available from different groundwater bodies (Table 8).

336

337 Table 8 Livestock yield related to from different groundwater bodies

Groundwater body	Code (CHET)	Area (ha)	Heads/ha				
			Bovine	Ovine	Goats	Porcine	Poultry
Guadalajara	030.006	731.6	0.05	0.34	0.05	0.10	0.63
Aluviales Jarama-Tajuña	030.007	11209.1	0.06	0.46	0.04	0.02	0.10
Aluvial del Jarama: Guadalajara-Madrid	030.024	771.3	0.01	1.71	0.10	0.21	0.09

(CHT 2015a)

338

339

340 Each livestock production generates different products, which have an associated yield and market  
 341 price. The number of livestock per hectare multiplied by the surface area of each groundwater body  
 342 resulted in the total number of heads for each type of livestock. The total production for the different  
 343 types of livestock was obtained by multiplying the number of heads related to each groundwater body  
 344 by the annual production in €/year of each associated by-products (meat, milk, wool and eggs) (Tables  
 345 9,10 and 11).

346 The total livestock production was obtained using the following equation applied to the groundwater  
 347 bodies in the study area (Eq. 6):

$$348 \text{ Livestock production} \left( \frac{\text{€}}{\text{year}} \right) = \text{Bovine production} + \text{Ovine production} + \text{Goat production} +$$

$$349 \text{ porcine production} + \text{poultry production} \quad (6)$$

350

351 The sum of each of the by-products and the total livestock production was done with the map algebra  
 352 tool in ArcGIS v10.4.1.

353

354

Table 9 Meat production from different types of livestock

Livestock	Carcase weight (Kg/unit)	Price€/Kg	Annual production €/head
Bovine	287.45	2.50	718.63
Ovine	13.19	5.0	65.95
Goats	6.27	6.9	43.26
Porcine	123.11	1.36	167.43
Poultry	2.41	1.30	3.13

(MAPA 2021a, e).

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Table 10 Milk production from different types of livestock

Livestock	Milk production (Kg)	Price €/Kg	Annual production €/head
Bovine	5835.25	0.3243	1892.37
Ovine	166.23	0.95	157.92
Goats	457.92	0.80	366.34

(MAPA 2021a, e).

359

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Table 11 Other products from different livestock types

Livestock	Product	Annual production (Kg/unit)	Price€/Kg	Annual production €/head
Ovine	Wool	2.54	2.00	5.08
Poultry	Eggs	10.00	0.88	8.80

(MAPA 2021a, e).

361

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✓ **Employment related to agricultural activities**

365 In this research, employment was considered the main social variable to evaluate the vulnerability.

366 Although there are four productive sectors in the study area (agriculture, industry, building and

367 services), the agricultural sector is the main and most important sector that depends on groundwater

368 resources. For this reason, the agricultural employment was chosen to assess the impact of the

369 groundwater contamination. The employment was calculated considering the permanent employment

370 between June 2020 and July 2021, and the employment density per square kilometre (Table 12).

371

372

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Table 12 Agricultural employment in the study area (June 2020-july 2021)

Municipality in study area	Agricultural employment (2020-2021)	Municipal extension (Km2)	Agricultural employment density (Employment/Km2)
Arganda del Rey	55	80	0.69
Aranjuez	242	189.2	1.28
Chinchón	129	115.84	1.11
Ciempozuelos	16	49.31	0.32
Coslada	0	12.02	0.00
Loechos	2	44.09	0.05
Madrid	4798	605.14	7.93
Mejorada del Campo	0	17.09	0.00
San Fernando de Henares	8	39.79	0.20
San Martín de la Vega	36	105.84	0.34
Tilucia	0	9.88	0.00
Torrejón de Ardoz	77	32.65	2.36
Rivas Vaciamadrid	17	67.16	0.25
Valdemoro	21	64.53	0.33
Velilla de San Antonio	6	14.42	0.42

(Consejería de economía, hacienda y empleo 2021)

375

376

377 To assess the social impact of employment in the sector, the economic value generated through wages  
 378 was considered. Taking into account that the average salary in agricultural sector from 2019-2020  
 379 period in Spain was 16470€/year (MAPA 2021b), the value of employment was calculated using the  
 380 following equation (Eq. 7).

381

$$382 \text{ Agricultural employment } \left( \frac{\text{€}}{\text{year}} \right) = \text{Number of contracts} * \text{Annual salary} \quad (7)$$

383

384 The raster calculator tool in ArcGIS v10.4.1 was used to obtain the agricultural employment map.

385

#### 386 **2.4.Social vulnerability mapping by cluster analysis (K-means method)**

387 K-means cluster analysis was applied to the entire data set for the three factors obtained above. There  
 388 were 5842 points (records) and three factors (vulnerability of groundwater resources - $V_{GR}$ -, vulnerability  
 389 of exposed population - $V_P$ -, and Social and economic vulnerability - $V_{S-E}$ -).

390 Data processing was carried out using RStudio v.4.0.5 software. Each factor was normalized with the  
 391 max-min scaling method, in order to reduce the bias caused by predominance of very high ranges over

392 lower ranges. The tool of extract values to point in ArcGIS v10.4.1 was used to obtain the value of each  
393 variable for the 5842 points.

394 The goal of K-means is to cluster data points with intrinsic similarities in the data set. This iterative  
395 process started with the selection of the optimal number of clusters, which was determined by the R  
396 package NbClust using the majority rule (Charrad et al. 2014). Euclidean distance was used to find the  
397 distance from each point in the data set to a temporal cluster. The minimum distance of the sum of  
398 squared errors of the distance  $A$  (Eq. 8) between each point to the centroid of each cluster is considered  
399 to locate points in them.

$$400 \quad A = \min \sum_{i=1}^k \sum_{x \in k_i} \|x_k - m_i\|^2 \quad (8)$$

401 (Dabbura 2020)

402 Where  $x_k = (x_1, x_2, x_3, \dots, x_n)$  are the data belonging to the  $k_i$  cluster; and  $m_i$  is the centroid of the  
403 cluster  $k_i$  (Eq. 9):

$$404 \quad m_i = \frac{\sum_{k=1}^{N_i} x_k}{N_i} * x_k \in k_i \quad (9)$$

405 (Dabbura 2020)

406 Where  $N_i$  is the number of data objects in the cluster  $i$ .

407 The procedure finishes when no points are reallocated from one cluster to another or when a pre-defined  
408 number of iterations is reached (Dabbura 2020).

409

### 410 **3. Results and discussion**

#### 411 **3.1. Factors affecting the social vulnerability**

##### 412 **3.1.1. Vulnerability of groundwater resources ( $V_{GR}$ )**

413 Table 13 shows the amount of groundwater for different uses in each groundwater body. It is clear that  
414 agricultural uses account for the largest groundwater consumption in at least two of the three  
415 groundwater bodies (more than 50% of groundwater uses). For this reason, the activities associated  
416 with this sector are more severely impacted than the others. On the other hand, groundwater body  
417 “Guadalajara” has the highest consume, although it represents a small area in the study (Fig. 1).

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Table 13 Water uses in groundwater bodies in the study area

Groundwater body	code (CHET)	Groundwater use (hm <sup>3</sup> /year)			Total of groundwater uses (hm <sup>3</sup> /year)	% Groundwater use
		Urban use	Agricultural use	Industrial use		
Guadalajara	030.006	6.311	11.772	4.935	23.018	58.7
Aluviales Jarama-Tajuña	030.007	0.895	10.138	3.166	14.199	36.2
Aluvial del Jarama: Guadalajara-Madrid	030.024	0.138	0.674	1.204	2.016	5.1
Total Groundwater use		7.344	22.584	9.305	39.233	100
% Groundwater use		18.7	57.6	23.7	100	

(CHT 2015a)

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425 Fig. 4 shows the spatial representation of total groundwater consumption. Most of groundwater uses  
 426 (more than 80% of the study area) are located from north to south. They consume 14.20 hm<sup>3</sup>/year (Fig.  
 427 4a), about 40 % of the available groundwater in the region (Fig. 4b), which represents a significant  
 428 amount of the groundwater resources. This means that an eventual contamination of the aquifer could  
 429 generate a major impact on the environment and agricultural activities, negatively affecting the  
 430 economic and social development of the region. In fact, the hydraulic connection between the aquifer  
 431 and the Jarama river favours an eventual contamination of the river water from the aquifer.

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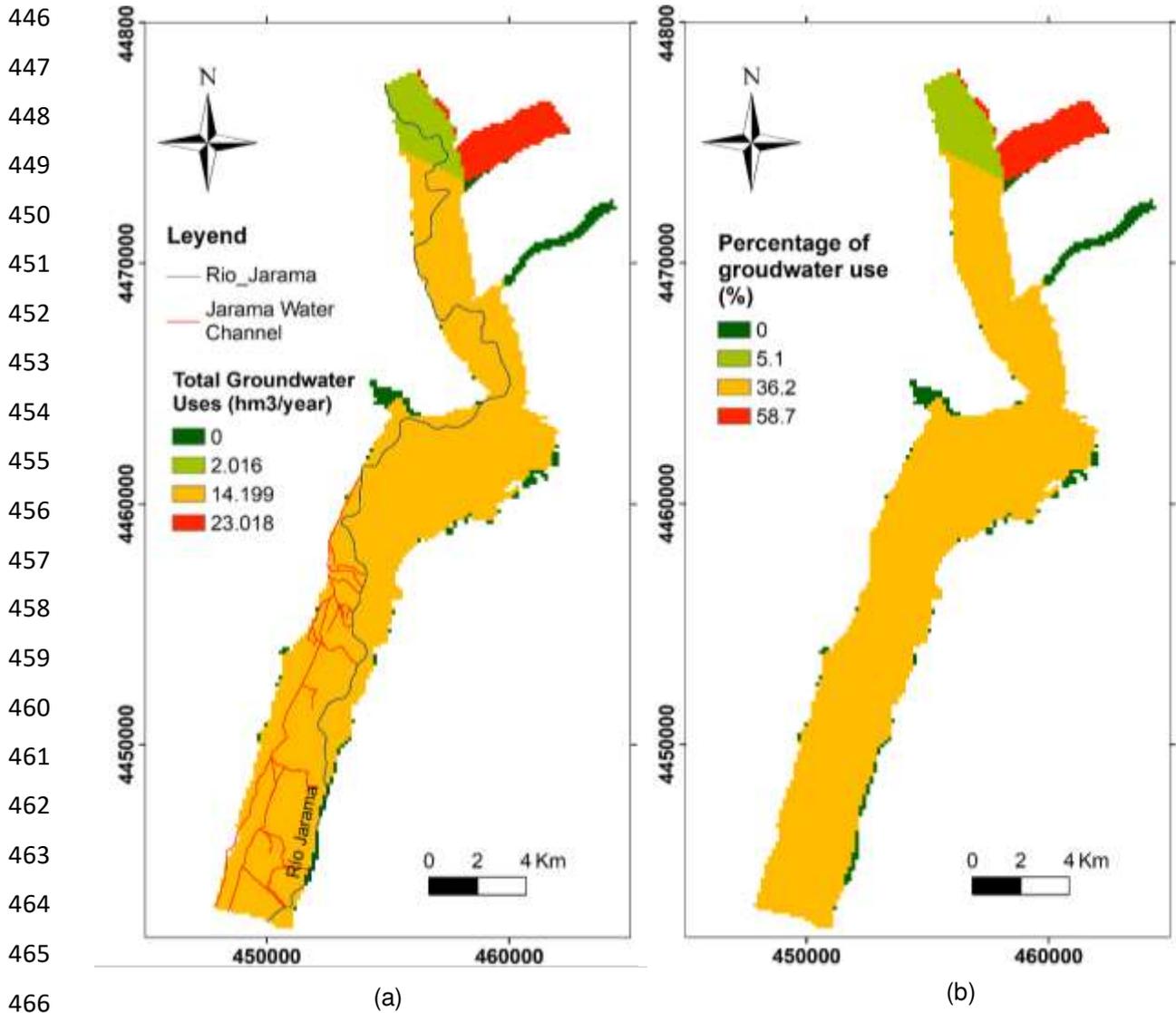
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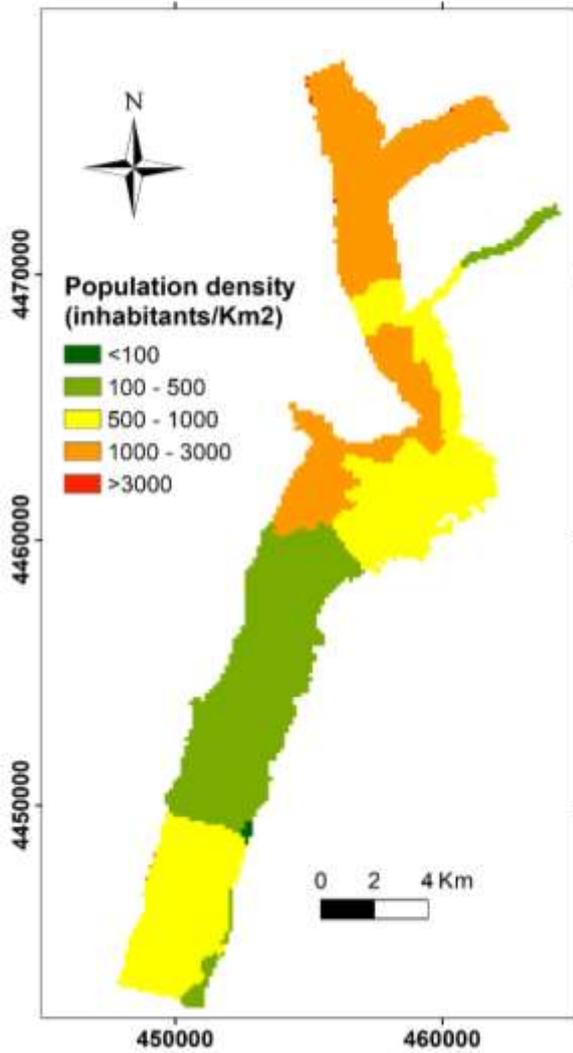
467 **Fig. 4.** Total consumption of groundwater in the study area. (a) Total groundwater uses in hm<sup>3</sup>/year.  
468 (b) Percentage of groundwater for different uses.

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470 **3.1.2 Vulnerability of exposed population ( $V_P$ )**

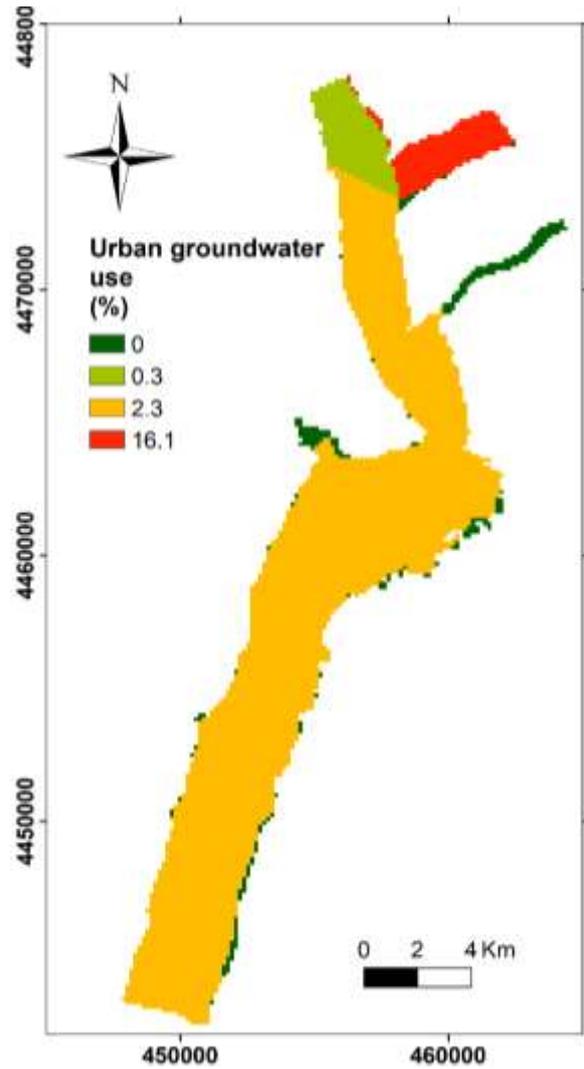
471 Fig. 5 and Fig.6 show the population density in the study area and its percentage of urban groundwater  
472 use, respectively. In general, the study area has a low population, as it is mainly an agricultural region.  
473 Therefore, urban development is low. The highest urban groundwater consumption is only 16% and  
474 occurs in a small area located at northeast (5% of the total area).

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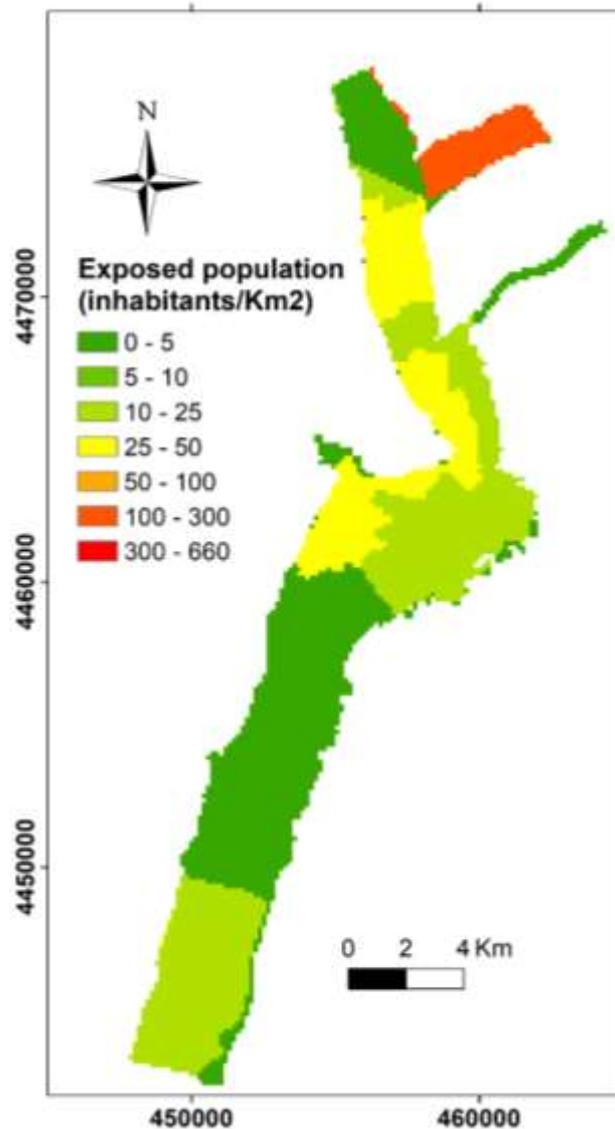
**Fig. 5** Population density of the study area.



**Fig. 6** Urban groundwater use in percentage of total groundwater in the study area

The distribution of the population exposed to the consumption of contaminated groundwater is shown in Fig. 7. By density, the population exposed is low. More than 90% of the study area presents an exposed population density of less than 50 inhabitants per square kilometre, due to the limited urban development in the area. For this reason, the vulnerability of the exposed population do not have a significant influence on the social vulnerability analysis of the study area.

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**Fig. 7** Density of population exposed to consumption of contaminated groundwater.

### 3.1.3 Socio-economic vulnerability ( $V_{S-E}$ )

As mentioned above, the price of land depends on the agricultural development and is highest where irrigated crops are present. Fig. 8a shows that about 60% of the area has a total land price below one million euros (the lowest value), which is consistent with most of study area having few irrigated crops and a significant portion of unproductive areas. Thus, the land classes map (Fig. 3) shows that most of the areas are unproductive, forested and rainfed crops zones. On the other hand, about 13% of the area has a total land value of more than ten million euros. This corresponds to the sector in the south, with a high development of irrigated crops as the Jarama river canal is providing water for irrigation. The crop production reached about four million euros in most of the study area (44% of the area), mainly by arable crops of corn and wheat and olive groves, located the central-southern part of the study area.

538 The north of the study area had a low crop production of less than one million euros, by arable crops of  
539 barley, corn oat and fruit trees (38% of the study area). In the centre of the area, the production of  
540 arable crops of wheat, barley, corn, chickpeas, vineyard, olive groves and fruit trees reached around  
541 three million € (Fig. 8b).

542 About 80% of the study area produces one million euros or more from livestock, mainly bovine and  
543 ovine. However, this value is low compared with crop production (Fig. 8c).

544 The agricultural employment is the most influenced by groundwater uses. The economic value  
545 contributed by employment income was less than 300,000 euros/year, being lower than other economic  
546 variables. The employment income was higher in the south of the study area (Fig. 8d), due to higher  
547 agricultural development.

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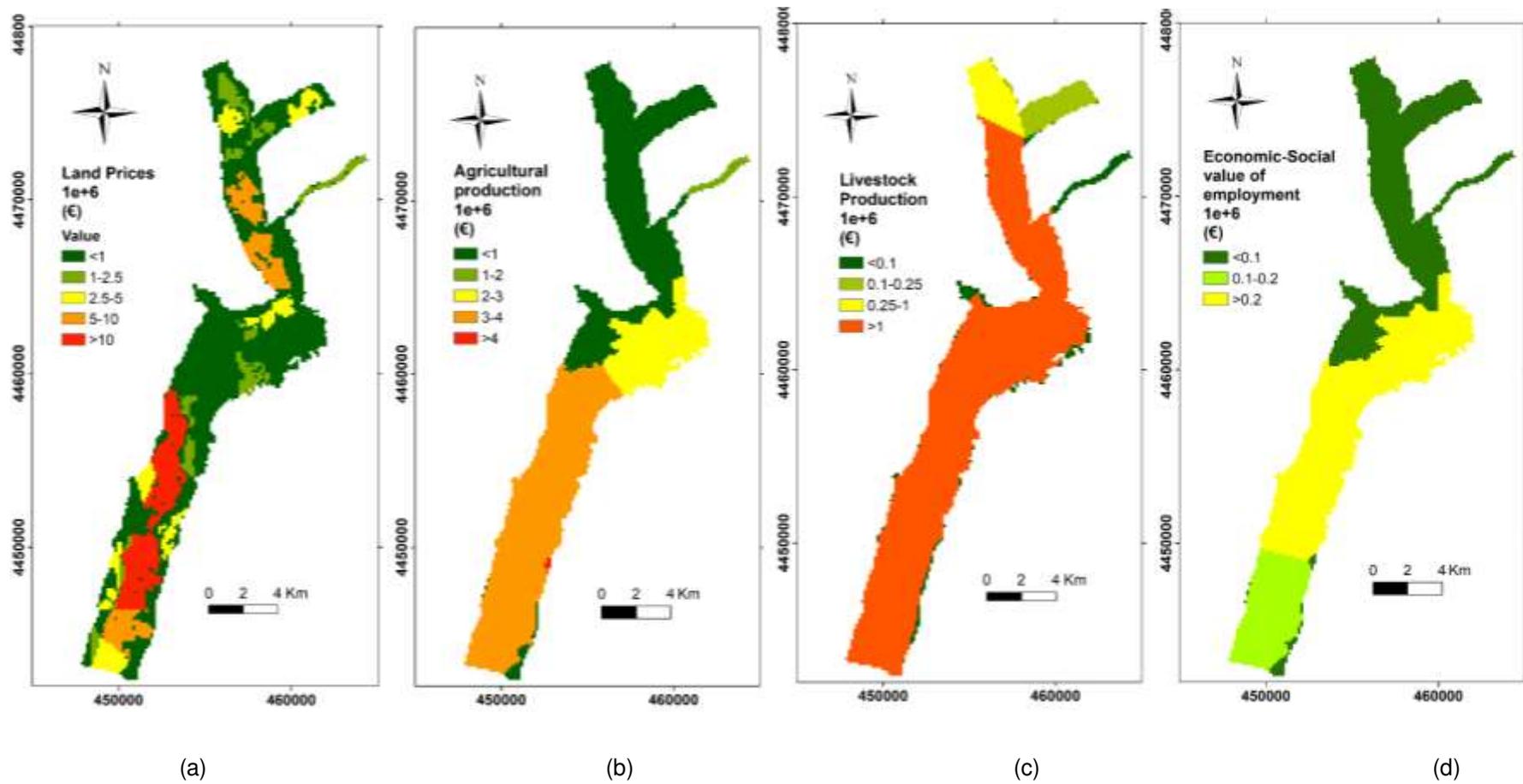
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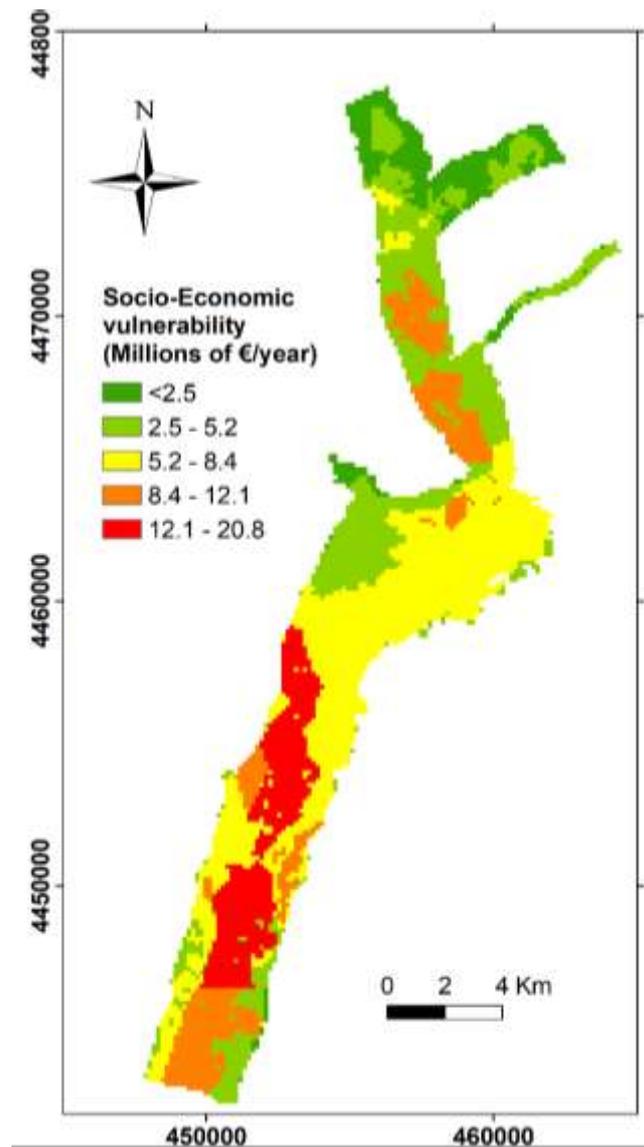
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**Fig. 8** Socio-economic vulnerability parameters. a) Land prices, b) Annual Crop production, c) Annual Livestock production, d) Annual agricultural employment income.

571 The highest values of socio-economic vulnerability were located in the south of study area (Fig. 9),  
572 mainly influenced by land prices and crops production, due to the availability of water to irrigate crops  
573 by the Jarama canal. Although in this zone the socio-economic vulnerability decreases due to the  
574 reduction factor (Fig. 2) by the irrigation facilities of the Jarama canal, it is still the zone with the highest  
575 socio-economic vulnerability. The lowest values are located in the north due to scarcity or absence of  
576 crops and low livestock production, which implies low agricultural employment in this zone. In the north-  
577 central area, the production of crops and livestock led a moderate socio-economic vulnerability.

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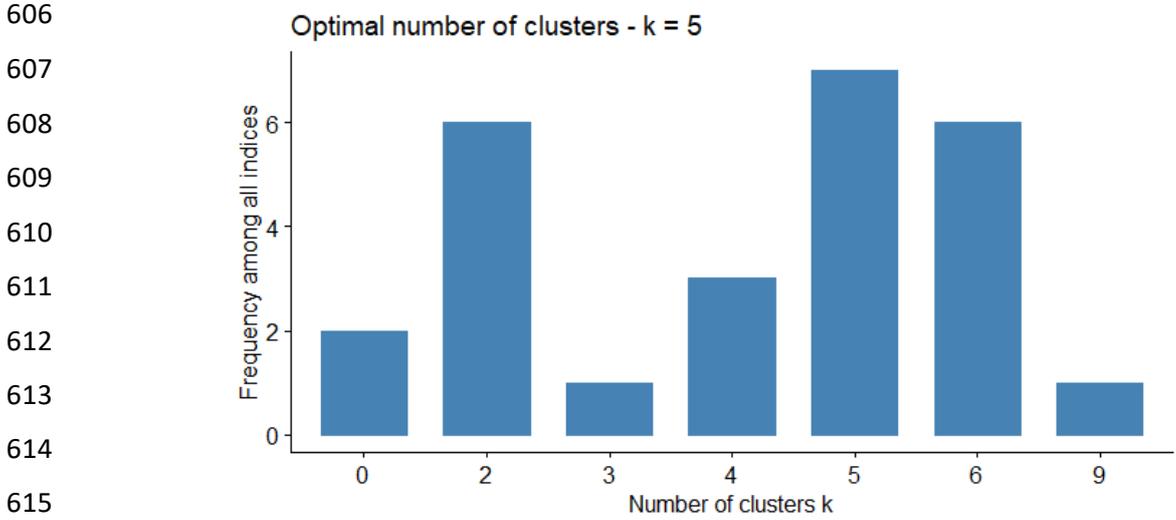


600 **Fig. 9** Economic-social vulnerability distribution (in millions of euros/year).

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604 **3.2 Social vulnerability by K-means cluster analysis**

605 The optimal number of clusters obtained by NbClust was five (Fig. 10).



616 **Fig. 10** Optimal number of clusters obtained by NbClust

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618 The results of the K-means cluster analysis are summarized in Table 14.

619

620 Table 14. Mean of each factor in the identified clusters.

Cluster	Points	%	$V_p$ (inhab/Km <sup>2</sup> )	$V_{GR}$ (hm <sup>3</sup> /year)	$V_{S-E}$ (million €/year)
			Mean	Mean	Mean
1	774	13.2	6.5	36.2	19.2
2	3263	55.9	15.9	36.2	5.6
3	589	10.1	2.2	3	2.2
4	898	15.4	17	36.2	10.3
5	318	5.4	166.1	58.7	1.8

621

622 Cluster 1 gave the highest value of socio-economic vulnerability due to the important agricultural  
 623 development located in the south of the study area. However, the reduction factor affecting this zone  
 624 due to the use of surface water to supply irrigation decreases the social vulnerability in this sector. In  
 625 fact, the groundwater resource has a moderate consumption in this area. In addition, the population in  
 626 this zone is small, which generates a reduced effect on human consumption. These conditions suggest  
 627 that this cluster belongs to the high vulnerability mainly influenced by socio-economic factors.

628 Cluster 3 represents the lowest values of groundwater resource vulnerability and population  
 629 vulnerability. In turn, social- economic vulnerability in this cluster is very low. These conditions  
 630 contributed to very low or no social vulnerability. This cluster includes areas where there are no

631 groundwater bodies (at the boundary of the study area and in a narrow branch located in the northeast),  
632 which reduces the impact on the water resources. In addition, the groundwater use in the northwest of  
633 the “Aluvial del Jarama: Guadalajara-Madrid” groundwater body has the lowest urban, industrial and  
634 agricultural consumption (Table 13), resulting in the lowest population and socio-economic vulnerability.  
635 Cluster 2 and 4 show low population vulnerability values due to the low urban development in these  
636 areas. However, the groundwater resources vulnerability overlaps in the range of index values between  
637 these clusters, with values being between the highest and lowest ranges. This suggests that clusters 2  
638 and 4 represent low and moderate social vulnerability, but it is not clear which corresponds to which.  
639 The socio-economic vulnerability is used to clarify the classification and assign clusters 2 and 4 to their  
640 corresponding social vulnerability level. Cluster 4 has the highest values of socio-economic vulnerability  
641 and cluster 2 the lowest ones. For this reason, cluster 2 stands for low vulnerability and cluster 4 stands  
642 for moderate vulnerability. In this case, both population and groundwater resource vulnerabilities have  
643 been more influential in creating clusters and the socio-economic vulnerability has allowed the  
644 classification to be refined.

645 Cluster 5 includes the highest values for the vulnerability of the exposed population and the vulnerability  
646 groundwater resources, therefore a very high social vulnerability would be expected. However, as  
647 mentioned above, the population vulnerability did not have a relevant influence on social vulnerability  
648 due to the low population. Furthermore, the socio-economic vulnerability was the lowest value, which  
649 means that despite the higher impact on the population and groundwater resource, the economic losses  
650 due to an eventual groundwater contamination would be low. For this reason, cluster 5 was considered  
651 representative of high social vulnerability, similarly to cluster 1.

652 According to previous discussion, no very high social vulnerability was identified in the clusters  
653 analyzed.

654 The clusters distribution and the social vulnerability maps using K-means analysis are shown in Fig. 11.

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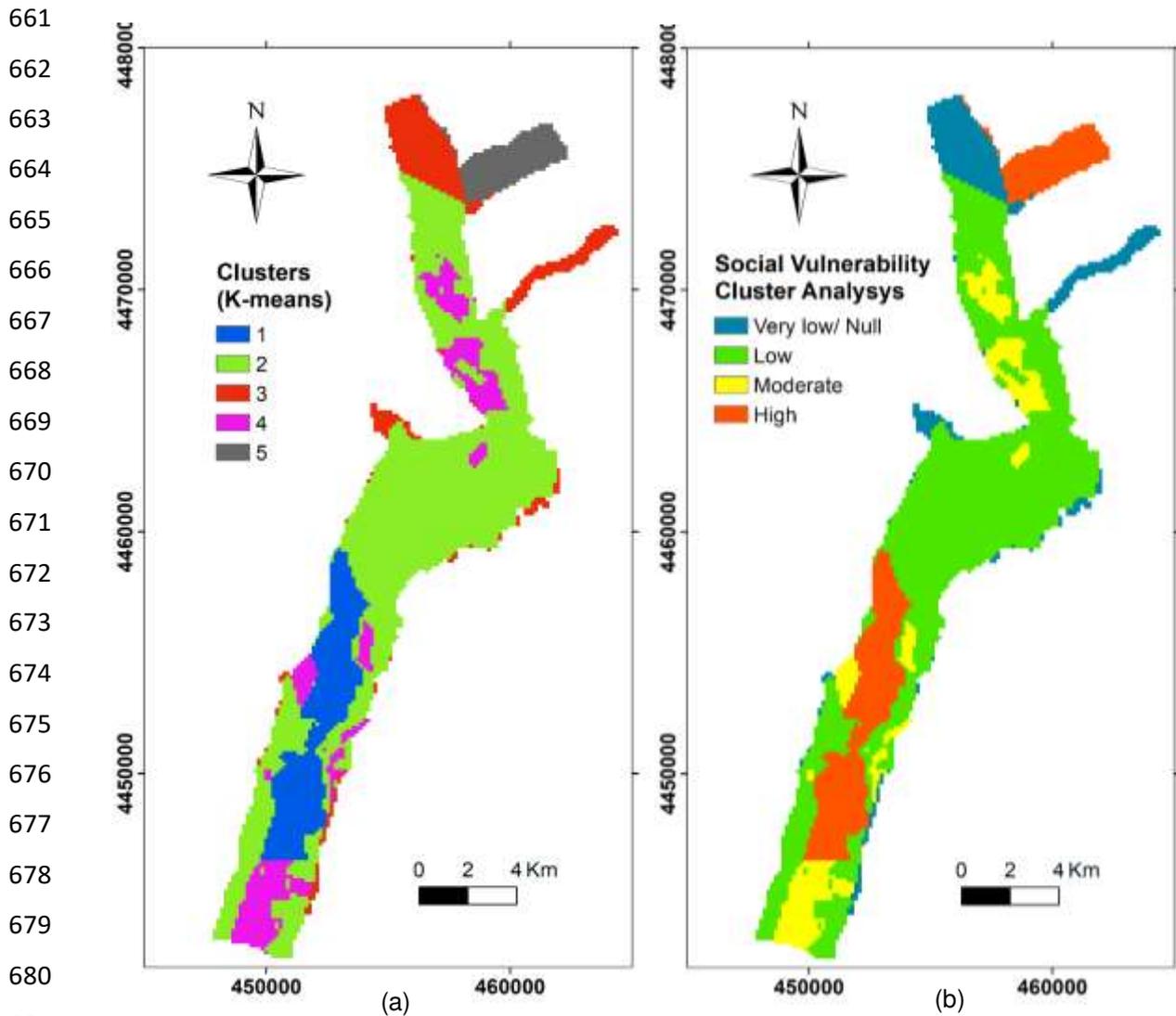
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682 **Fig. 11** Social vulnerability results from K-means analysis. (a) Spatial clusters distribution. (b) Map of  
683 social vulnerability to groundwater contamination obtained through K-means cluster analysis

684

685 According to the results, more than 50% of the study area has a low social vulnerability, mainly located  
686 in the central zone and in some parts of central north and on the southern edges of the aquifer, due to  
687 the low population located in these areas as well as low agricultural development, which implies a low  
688 economic production. Additionally, about 10% of the area has little or no groundwater use, which  
689 resulting in very low or no social vulnerability. This condition is observed in the northwest sector of the  
690 "Alluvial del Jarama: Guadalajara-Madrid" groundwater body, which only consumes 5% of the  
691 groundwater resource in the study area. Some localities are not associated with a groundwater body  
692 and therefore in these localities social vulnerability is null. A small part of the study area (11%) located  
693 in the centre-north and in some areas at south, shows moderate social vulnerability, mainly influenced

694 by the economic impact on agricultural development. It is important to note that the influence of surface  
695 water supplied by the Jarama water canal in the south of the study area reduces the impact of  
696 groundwater contamination (irrigation use of surface water is as high as 23% in some localities). Finally,  
697 almost 20% of the area presents high social vulnerability, distributed in two different sectors in the study  
698 area and influenced by different factors. In the north, the high social vulnerability is due to the high  
699 groundwater resource (~50% of the groundwater consumed in the study area) and the impact of the  
700 exposed population (~166 inhabitants per square kilometres). In the south of the study area, the high  
701 social vulnerability is due to the impact on the social and economic sectors such as agricultural  
702 production, employment, and land prices, although this impact is partially reduced by the use of  
703 irrigation water from the Jarama water canal. Despite this, the groundwater consumption in this area  
704 represents the 36% of the total groundwater resource of the area, which represents a significant amount  
705 of the resource used for irrigation needs that negatively affects the economic and social development  
706 in the area.

707 These results demonstrate the advantage of using K-means cluster analysis in the assessment of social  
708 vulnerability, since it was not necessary to assign numerical ranks and weights to the considered  
709 vulnerability factors because the similarity in the data set grouped the information required to classify  
710 the social impact.

711

## 712 **Conclusions**

713 The interaction between contaminated groundwater, nature and society requires an assessment of the  
714 risk and the damage that a contamination event could cause in a region. In this work, the assessment  
715 of social vulnerability allowed the delimitation of zones for an adequate prevention of damage to society  
716 by contaminated groundwater. To assess the social vulnerability, three factors were considered: the  
717 groundwater resource ( $V_{GR}$ ), the exposed population ( $V_P$ ) and the socio-economic impact ( $V_{S-E}$ ).

718 The vulnerability of groundwater resources factor ( $V_{GR}$ ) implied the consideration of an environmental  
719 factor due to the possibility of incorporating contaminated water into the Jarama river (and its canal)  
720 from the aquifer, causing significant damage to flora and fauna and socio-economic losses. The results  
721 point out that the vulnerability of groundwater resources represents an important and influential factor  
722 in the assessment of social vulnerability. This factor was estimated from the sum of different uses of  
723 groundwater in the region (urban, agricultural and industrial). The agricultural uses account for more  
724 than 50% of the groundwater use, as agricultural activities are the most important productive sector in

725 the region that depend on groundwater resources. On the other hand, a high value of groundwater use  
726 was identified due to agricultural, industrial and urban activities in the northeastern part of the study  
727 area. Although small, this area revealed an important influence on the assessment of social  
728 vulnerability.

729 The study area is sparsely populated due to its significant agricultural development, which reduces the  
730 risk of people exposed to contaminated groundwater consumption. In fact, less than 50 inhabitants per  
731 square kilometre are exposed in most of the study area (more than 90%). For this reason, the exposed  
732 population has a low influence on social vulnerability.

733 The socio-economic vulnerability is closely influenced by the main productive activity in the region.  
734 Agricultural activities involve crops and livestock production that affect land prices and agricultural  
735 employment. The highest socio-economic vulnerability was observed in the south of the study area,  
736 despite the fact that the Jarama canal is located in this area. This effect reduces the socio-economic  
737 vulnerability by 10-20% due to the use of a combination between surface water and groundwater for  
738 irrigation. However, the social vulnerability in this area remained high. This area covers ~14% of the  
739 study area, representing a small zone but significantly affected area.

740 The K-means cluster analysis made it possible to assess and delimit areas to classify the social  
741 vulnerability without using weighting and rating values for the three factors considered, thus reducing  
742 the subjectivity of the methodology. Five clusters were obtained, revealing four levels of social  
743 vulnerability: Very low (Cluster 3), low (Cluster 2), moderate (Cluster 4) and high (Clusters 1 and 5)  
744 social vulnerability, respectively.

745 Most of the social vulnerability in the study area is low, which means that an eventual groundwater  
746 contamination would not cause a major impact in society. However, in the south (14.2% of the area)  
747 and in the northeast (5.7% of the area) there are small zones that could be highly affected with a more  
748 important impact. In the northeast due to the exposed population and groundwater resource, and in  
749 the south due the socio-economic factor related to agricultural development. In turn, in the northwest  
750 of the study area there is a small area (10.9%) that is not affected by a groundwater contamination at  
751 the social level. The small and scattered areas in the centre-north and south present moderate social  
752 vulnerability, due to the groundwater resources factor (they represent the 36% of the total of  
753 groundwater consumption) and the socio-economic factor related to the agricultural development. The

754 K-cluster analysis clearly demonstrated the advantage of using this technique in the assessment of  
755 social vulnerability to groundwater pollution.

756

### 757 **Authors Contributions**

758 All authors contributed to the study conception and design. Material preparation, data collection and  
759 analysis were performed by Marisela Uzcategui-Salazar. The first draft of the manuscript was written  
760 by Marisela Uzcategui-Salazar and Javier Lillo and all authors commented on previous versions of the  
761 manuscript. All authors read and approved the final manuscript.

762

### 763 **Declarations**

764 **Ethical Approval** This article does not contain any studies with human participants or animals  
765 performed by any of the authors.

766 **Consent to participate** Not applicable.

767 **Consent to publish** Not applicable

768 **Competing Interests** The authors declare no competing interest.

769 **Financial interests:** The authors declare they have no financial interests.

770 **Funding** No funds, grants, or other support was received.

771 **Availability of data and materials** The datasets used and/or analysed during the current study are  
772 available from the corresponding author on reasonable request.

773

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