Environ Monit Assess (2018) 190:390
https://doi.org/10.1007/s10661-018-6758-4

Fuzzy-based assessment of groundwater intrinsic vulnerability of a volcanic aquifer in the Chilean Andean Valley

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Received: 1 August 2017 / Accepted: 31 May 2018

Abstract A fuzzy logic approach has been proposed to face the uncertainty caused by sparse data in the assessment of the intrinsic vulnerability of a groundwater system with parametric methods in Las Trancas Valley, Andean Mountain, south-central Chile, a popular touristic place in Chile, but lacking of a centralized drinking and sewage water public systems; this situation is a potentially source of groundwater pollution. Based on DRASTIC, GOD, and *EK*v and the expert knowledge of the study area, the Mamdani fuzzy approach was generated and the spatial data were processed by ArcGIS. The groundwater system exhibited areas with high, medium, and low intrinsic vulnerability indices. The fuzzy approach results were compared with traditional methods results, which, in general, have shown a good spatial agreement even though significant changes were also identified in the spatial distribution of the indices. The Mamdani logic approach has shown to be a useful and practical tool to assess the intrinsic vulnerability of an aquifer under sparse data conditions.

Keywords Aquifer vulnerability · Data scarcity · Fuzzy logic

Introduction

To know the spatial distribution of vulnerability of a groundwater system can be a useful input for assisting decision-making from regional to local levels, as these maps can be used for purposes such as land-use decision-making, sustainable development planning, water sources protection and planning, identification of sensitive areas, prioritization of areas for further monitoring, or protection and education of the general public

Article Impact Statement
This article describes a practical fuzzy logic approach to assess the intrinsic vulnerability index for groundwater under data scarcity.

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Published online: 11 June 2018

(Liggett et al. 2011). They have become one of the leading tools in the field of hydrogeological science and help in assessing, monitoring, and conserving groundwater resources (Prasad et al. 2011).

Water resources vulnerability is related to the susceptibility of a groundwater system to be damaged by external forces, the sensitivity of the system, and the ability of the system to respond (Plummer et al. 2012). However, Vrba and Zaporozec (1994) defined "intrinsic vulnerability" as an intrinsic property of a groundwater system and one that depends on the sensitivity of that system to human or natural impacts, whereas "specific vulnerability" was defined as the risk of pollution due to the potential impact of specific contaminants. There exist several methods to assess intrinsic vulnerability based on hydrogeological parameters methods, such as the DRASTIC method (Aller et al. 1987) and the GOD method (Foster and Hirata 1987; IGME 2004; Auge 2004) and the two-parameters *EK*v method (Auge 1995). Those indices can be spatialized to create vulnerability maps using GIS methods.

Intrinsic vulnerability assessment by traditional methods and GIS software requires a high density of field data. Moreover, uncertainties arise from errors in methods of obtaining spatial data—field and numerical approximation—as well as the natural spatial and temporal variability of the parameters in the field (Dixon et al. 2002); a fuzzy logic approach was used to face the uncertainty of results caused by sparse data, a common situation in many developing countries.

Las Trancas, a mountain town in the Renegado Valley in Central Chile, is the most popular touristic spot in the Bio Bio Region, but there are no centralized drinking water and sewage system. It therefore becomes important to assess the intrinsic vulnerability of the groundwater system that supports many springs used for drinking water by people located downstream of the study area. However, the hydrogeological data is sparse in this place.

Based on the foregoing, this study aims to propose an assessment method for the intrinsic vulnerability of a groundwater system based on the joint use of fuzzy logic and traditional methods, through the expert opinion and local knowledge, to face the uncertainty related to data scarcity of the study area. The results are complementary information that allows improving the decision-making related to territorial planning and public policies for aquifer protection. Furthermore, it is expected that this research will also be useful in other similar settings facing data scarcity problems.

Methodology

Study area

The study area encompasses Las Trancas Valley and the entrance of Shangri-La Valley, downstream of the confluence of the Renegado River and Shangri-La Creek, between latitudes 36° 53′ S and 36° 55′ S and longitudes 71° 28′ W and 71° 32′ W, in the Bio Bio Region of south-central Chile (Fig. 1). Las Trancas is the closest town to the main tourism spot in the Bio Bio Region and the biggest ski center in Chile. Therefore, the study area has the highest number of restaurants, hotels, houses, and stores in the area. As a reference, in July 2015, 19,791 visitors were registered in the so-called Chillán and Las Trancas Valley tourist destination (INE 2015).

Furthermore, there are no centralized sewage and drinking water systems in the area. As a result, home, restaurant, hotel, and store owners have to install their own sanitary systems.

The study area has altitudes ranging between 1100 and 1350 m.a.s.l. and is a typical Andean setting. The Renegado River and Shangri-La Creek rise from beneath the Nevados de Chillán volcanic complex on the western slope of the Andes Mountains at the beginning of the Nevados de Chillán Valley (Zúñiga et al. 2012; IGM 2008). Annual precipitation during the last 50 years has oscillated between 577 mm (2013) and 3690 mm (1982) (DGA 2016).

Geology and groundwater

The geology of the study area is described in detail by Dixon et al. (1999) and Naranjo et al. (2008), who explain the strong influence of the volcanic processes associated with the *Nevados del Chillán* volcanic complex. This volcanic complex is composed of several types of structures created by different processes that have occurred for approximately 650,000 years (Naranjo et al. 2008).

At the study area, three main geological units are identified (Naranjo et al. 2008). The first comprises Atacalco lavas (Pla) of the Middle-Upper Pleistocene, which correspond to one or more andesitic lava flows, with a layer thickness of 125 m (Rivera 2014).

The second unit is made up of alluvial-lahar deposits (Hal) of the Holocene, and the third one comprises Democrático Volcano lavas (LTd) of the Holocene,

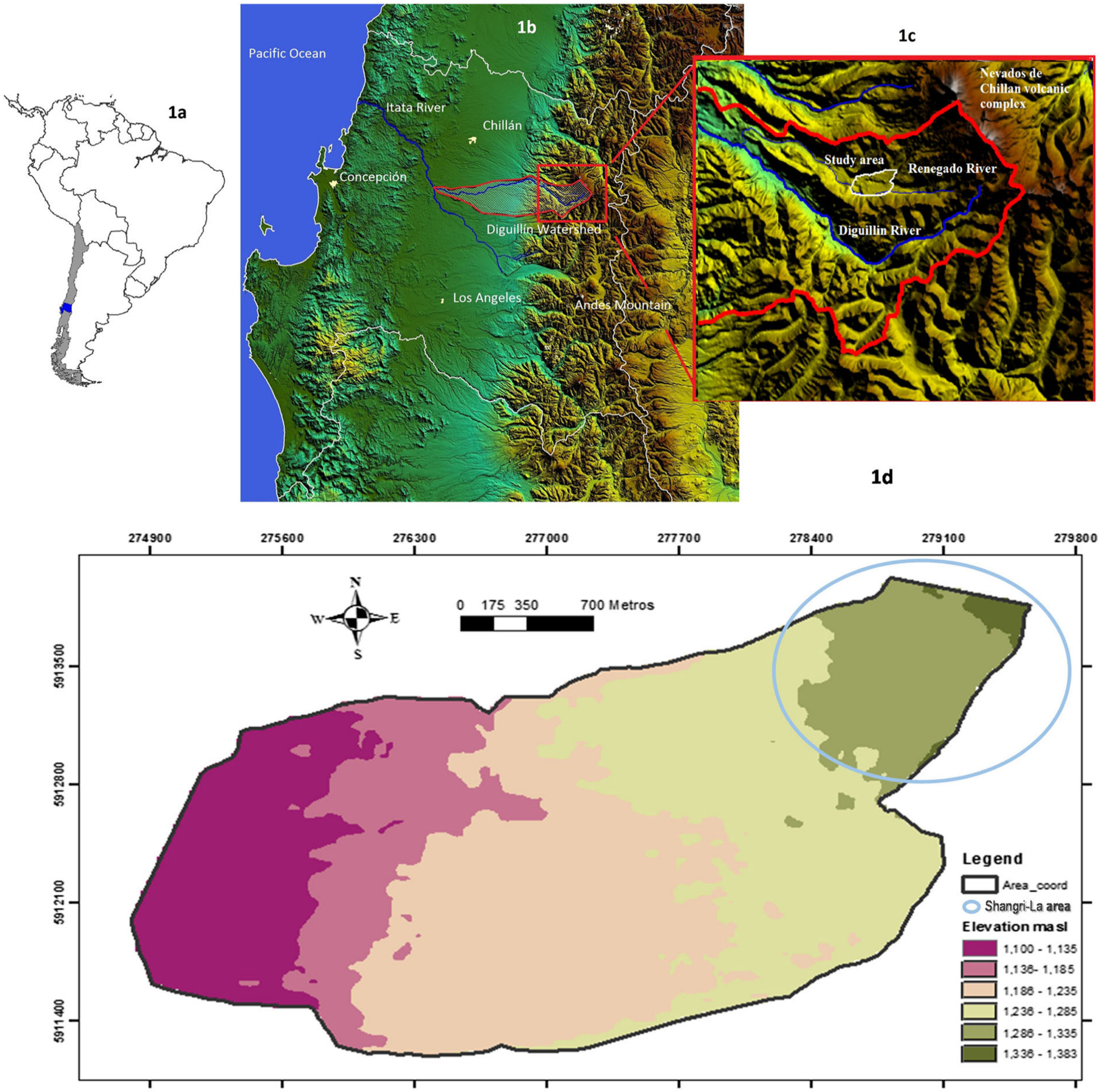

Fig. 1 Location of the study area (Las Trancas) related to **a** South America, **b** BioBio Region in Central Chile, **c** headwaters of the Diguillín River Watershed, and **d** study area

which are a fundamentally effusive structure of silicious, andesitic, to dacitic block lavas (Fig. 2).

From 33 to 42° S, alluvial aquifers present variable depths, ranging from a few meters in the pre-Andean areas, to a hundred of meters in the central graben (DGA 1986). Whereas for the fractured rock aquifer of the pre-Andean area, of interest to the current study, there is no information; it is worth highlighting that the main aquifer in the area of intrinsic of the current work corresponds to the Atacalco lavas geological unit. The Atacalco lavas exhibit 125 m and in some locations of the area of study is also covered by an alluvial deposits which reach 60 m of depth approx (Rivera 2014).

The water table is located in the Atacalco lavas geological unit where two springs were identified at 1100 m.a.s.l: the north spring, with a discharge of 1 m3/s, and the south spring, with 2 m3/s (Fig. 2). The groundwater flows from the east to the west. In addition, it was observed near both springs that the Atacalco lavas were extensively fractured, as the separation distances

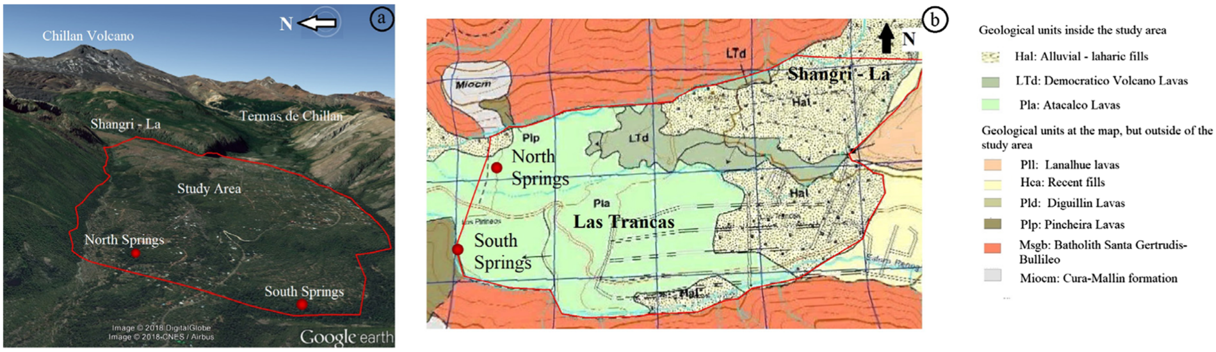

Fig. 2 **a** General view of the Renegado Valley showing the location of the Chillan Volcano and the springs. **b** Geological map of the area (modified from SERNAGEOMIN, 2008)

between the horizontal fractures were within a range of 30 to 65 cm, while the vertical fractures were within a range of 80 to 120 cm. The gap width of the fractures was between 0.5 and 2 cm (Fig. 3).

Vulnerability assessment methods

The assessment of the intrinsic vulnerability of groundwater system was based on the following parametric methods:

- *EK*v method: considers two variables, thickness of the vadose layer (*E*), and vertical hydraulic conductivity (*K*v). Both parameters range from 1 to 5 based on pre-defined ranges. The final *EK*v index (IV*EK*v) is obtained by adding both values (Auge 1995).
- ***GOD method****:* is an acronym that stands for the parameters associated with the type of aquifer: groundwater occurrence (*G*), overall lithology (*O*), and depth to the water table (*D*). Index, the indices determined for each parameter, which are defined on a scale 0 to 1, are multiplied together to calculate the vulnerability index (Foster and Hirata 1987).
- DRASTIC method: is an acronym that stands for seven parameters: depth to water (*D*), recharge (*R*), aquifer media (*A*), soil media (*S*), topography (*T*), impact of the vadose zone (*I*), and hydraulic conductivity (*C*). A value in a range of 1 to 10 is assigned to each parameter. The vulnerability index is calculated using the following equation:

$$\text{Vulnerability index} = DrD\text{w} + RrRw + ArAw + SrSw + TrTw + IrIw + CrCw \quad (1)$$

where r is the value of each parameter and w represents the relative weight assigned to each variable: $Dw = Iw = 5$, $Rw = 4$, $Aw = 3$, $Sw = 2$, $Tw = 1$, and $Cw = 3$.

In Las Trancas, the case study, it is difficult to obtain data for the "depth of the water table as well as the structure and composition of the vadose zone. However, in recent years, several hydrology studies have been undertaken, addressing water balance (Zúñiga et al. 2012), groundwater and surface water interactions (Muñoz et al. 2016), and spring characterizations (Arumí et al. 2016). Furthermore, the fieldwork during this study and the experience of the co-authors related to other research in the Renegado Valley and nearby areas. There is enough expert knowledge, which can be used to develop a fuzzy approach on the parameters related to the depth of water table and vadose zone. Key aspects of the fuzzy theory are given below.

Fuzzy system theory

The fuzzy system has been used in diverse areas of study related to polluted aquifers. Indeed, Dixon et al. (2002) and Dixon (2005) included a fuzzy system to determine the vulnerability of an aquifer based on a modified DRASTIC method; Muhammetoglu and Yardimci (2006) used the fuzzy logic approach to assess groundwater pollution levels below agricultural fields in the Kumluca Plain of Turkey and Nobre et al. (2007) used GIS modeling and a fuzzy logic tool to assess groundwater vulnerability and risk in an urban coastal aquifer in northeastern Brazil.

However, the proposals of Dixon (2004, 2005) have used a fuzzy logic approach with a new vulnerability method or with a main modification of the traditional vulnerability method; Dixon et al. (2002) were required

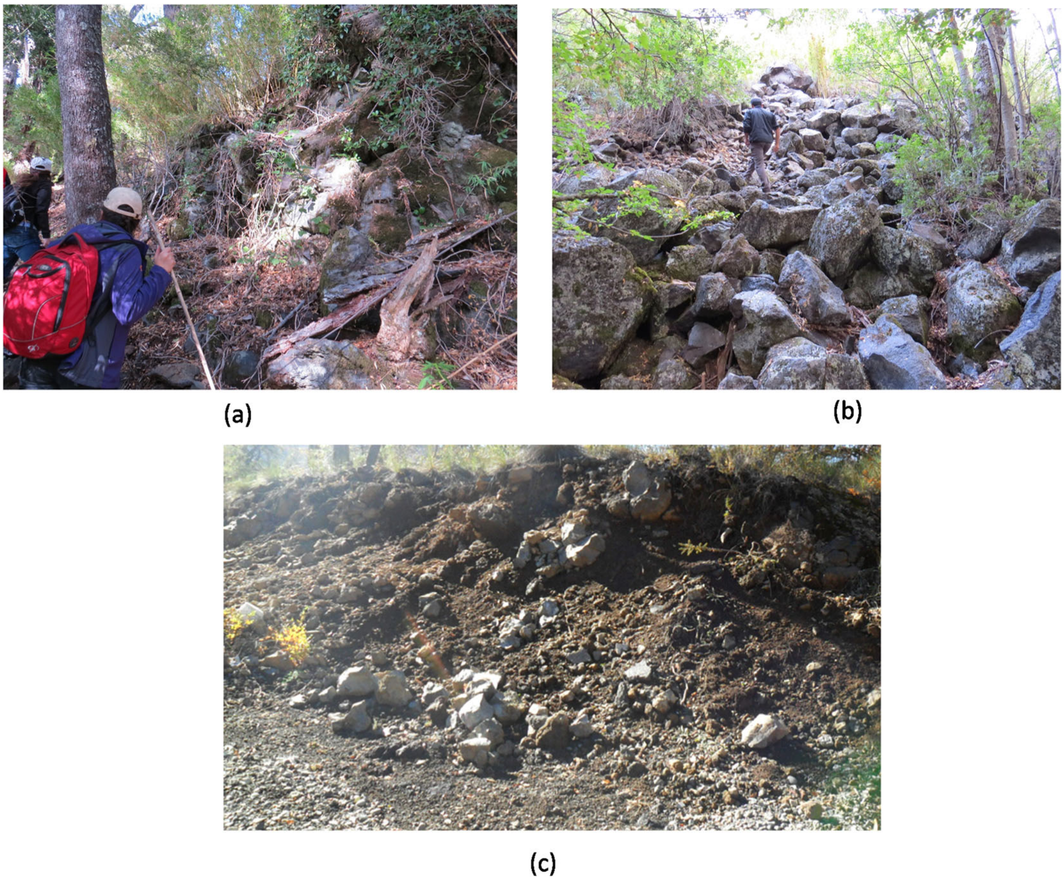

Fig. 3 **a** Atacalco lavas, near the south spring. **b** Democrático Volcano lavas, Las Trancas. **c** Alluvial deposits, Las Trancas

to validate. Moreover, other papers, Bárdossy et al. (2003) and Muhammetoglu and Yardimci (2006), included a fuzzy logic approach on groundwater pollution assessing causes by specific substances, which could be compared with the sampled contaminant data. While the novel part of our contribution is to assess the groundwater intrinsic vulnerability facing the uncertain, due to sparse data, based on validated and widely used methods, both for fuzzy logic, we used Mamdani and for vulnerability index, we applied DRASTIC, GOD, and EK_V. Therefore, this study aims to be a simple and useful proposal, which could be applied in different study areas based on expert knowledge and that allows decision-makers to have complementary information in the territorial planning and the establishment of public policies for aquifer protection under scarce data scenarios.

It is worth noting that one of the most widely employed fuzzy systems in the resolution of problems using fuzzy logic is the Mandami method (MathWorks 2015), which is considered adequate to work with complex situations that are dependent upon complex environmental systems (Bárdossy et al. 2003). Thus, although the fuzzy approach can be applied on all the parameters included in vulnerability indices, for this study, the fuzzy approach was applied only for the parameters with scarce data (The fuzzy parameters are *EK*v index: *E* (vadose zone thickness) and *K*v (vertical conductivity of the vadose zone); GOD index: *O* (overall) and *D* (depth), DRASTIC index: *D* (depth) and *I* (impact of the vadose zone)); the others parameters were calculated using the traditional vulnerability methods (GOD index: *G* (groundwater occurrence); DRASTIC index: *R* (annual recharge), *A*(mitigation capacity), *S* (Soil), topography (*T*), *C* (hydraulic conductivity)).

Fuzzy systems transform input values into fuzzy arguments using fuzzy and defuzzification rules (Bárdossy and Duckstein 1995). Fuzzy rules are composed of direct instructions (IF-THEN) with an antecedent (input data) and consequent (output data). The conceptual definition of fuzzy logic system is described in the Fig. 4. For this study, the setup of the Mamdani fuzzy rules was done by considering the original equations and the ranges of each traditional vulnerability index by MATLAB software based on expert knowledge opinion and data from another study in a close area (Arumí et al. (2016), Lavados (2015), Muñoz et al. (2016); Naranjo et al. (2008), Navarro (2016), Rivera (2014) and Zúñiga et al. (2012)) This allowed keeping the original relation between the parameters and vulnerability indices.

Moreover, the values between GIS software and Fuzzy logic Toolbox were extracted with a grid, which was set up on the study area. The parameters and index value were assigned to each point of the grid. Finally, the GIS maps were made using the Arcgis interpolation tool.

Based on the vulnerability index calculation methods described above and the MATLAB Fuzzy Logic Toolbox (MathWorks 2015), fuzzy sets were generated for each vulnerability model. Furthermore, the relationships between the parameters of each of the identified vulnerability methods were also considered as a basis for establishing fuzzy rules.

Input and output sets were established in order to maintain the representation of the ranges of the original vulnerability methods. The fuzzy approach was used for the *EK*v method with the *E* (vadose zone thickness) and *K*v (Vertical conductivity of the vadose zone) parameters; for the GOD method it was used on the *O* (overall) and *D* (depth) parameters; and for the DRASTIC method it was used on the *D* (depth) and *I* (impact of the vadose zone) parameters (Figs. 5, 6, and 7). The utility of carrying out the vulnerability evaluation using fuzzy numbers was that values could be assigned to vulnerability index parameters that exhibited uncertainty in their determination due to data scarcity in the study area. Thus, using expert judgment based on prior information, it was possible to estimate the value of the vulnerability index considering the possibility that the input values were related to the upper and lower parameters value. This was done in the fuzzy sets (Figs. 5, 6, and 7), where the ranges that the values of each parameter could take, their upper and lower limits, and the value each would most likely take was determined.

Regarding the input parameters for the *EK*v approach, the following fuzzy input sets were defined based on information derived from infiltration tests carried out by Navarro (2016): *K*v = 7.8 (m/day) for sectors with volcanic rock and *K*v = 3.8 (m/day) for sectors with lahar deposits.

For GOD, given the geology of the study area and the depth of the water table in the zones with lahar deposits, an unconfined aquifer ($G = 1$) was assumed and fuzzy sets were generated for the “overall” and “depth” parameters.

In the case of DRASTIC, fuzzy input sets were generated for the “depth” and “impact of vadose zone” parameters. The other parameters were defined as shown in Table 1.

It is worth noting that to extract the values between GIS software and Fuzzy logic Toolbox, it was created to grid on the study area. The parameters values were assigned to each point of the grid in base on ArcGis and Table 1. Then, the parameters related to the depth of the water table and vadose zone (parameters with sparse data) were processed by Mathlab Fuzzy Logic Tool Box to obtain the index value results. Finally, the index value results were processed by the Arcgis with nearest neighbor interpolation tool to make the vulnerability index maps.

The water table depth was determined following the methods and parameters described by Lavados (2015). Based on the geological description, the existence of lava strata in well-defined horizontal planes was identified (Rivera 2014), with no geological units that contribute significant heterogeneity. From the location of the springs indicated in Fig. 3, a water table profile was

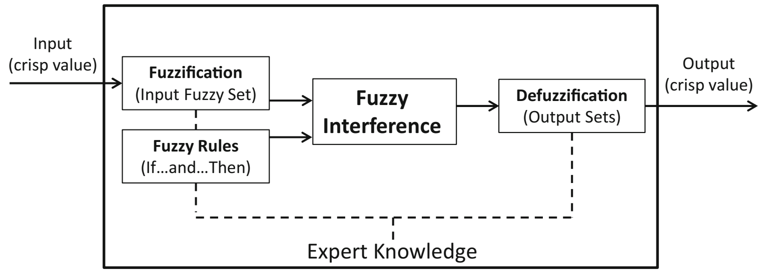

Fig. 4 Fuzzy logic system

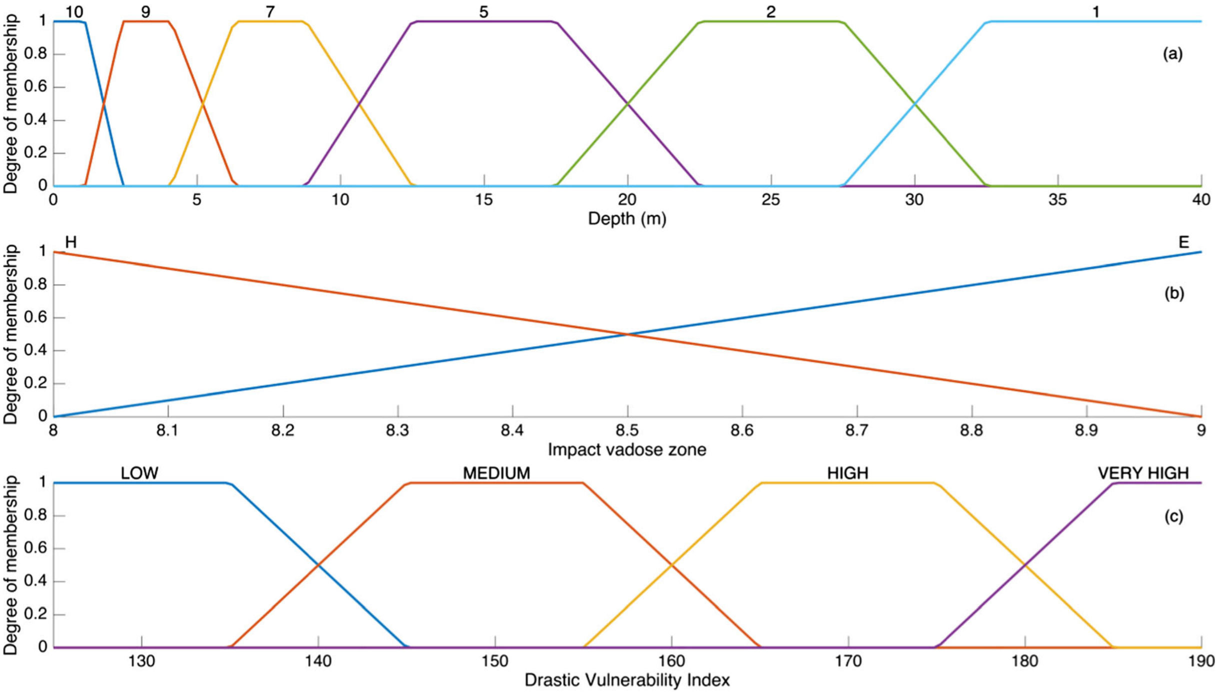

Fig. 5 Fuzzy sets developed using the *EK*v method. **a** Vadose layer thickness (E) (input variable). **b** Vertical hydraulic conductivity (*K*v) (input variable). **c** *EK*v vulnerability index (output variable)

projected assuming that the groundwater system behaves as a continuous saturated medium and that the springs located at the downstream end of the study area are the outlet point of the measured groundwater

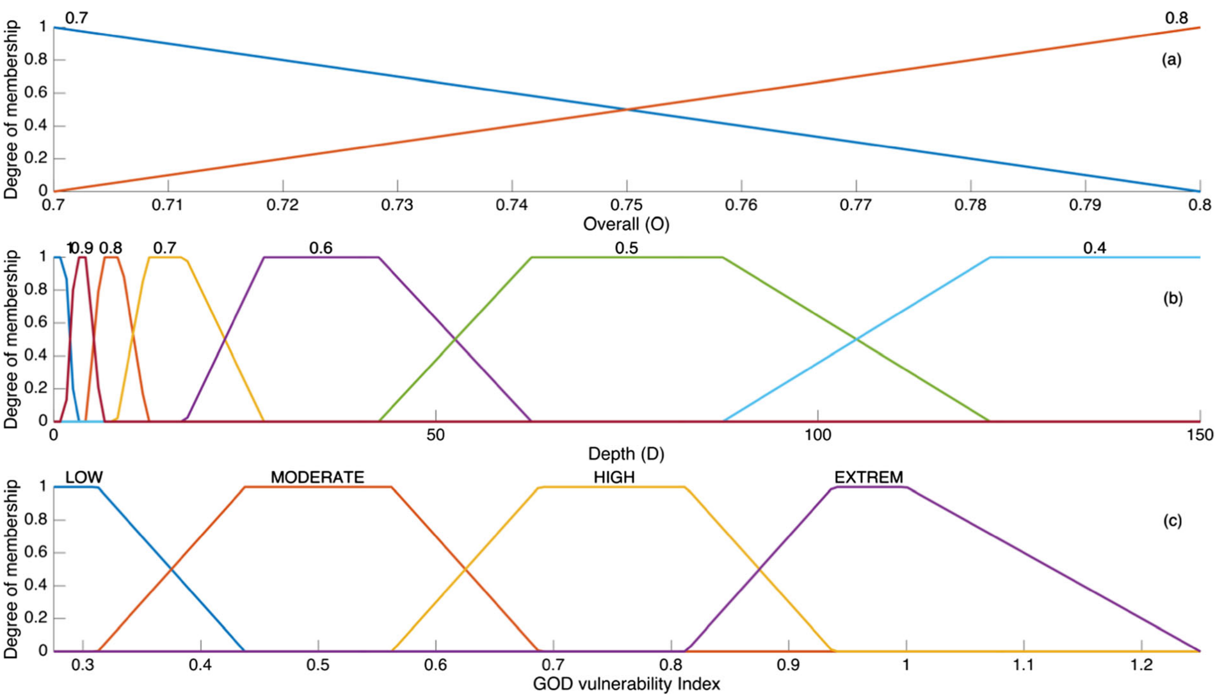

Fig. 6 Fuzzy sets developed using the GOD method. **a** Overall (*O*) (input variable). **b** Depth (*D*) (input variable). **c** GOD vulnerability index (output variable)

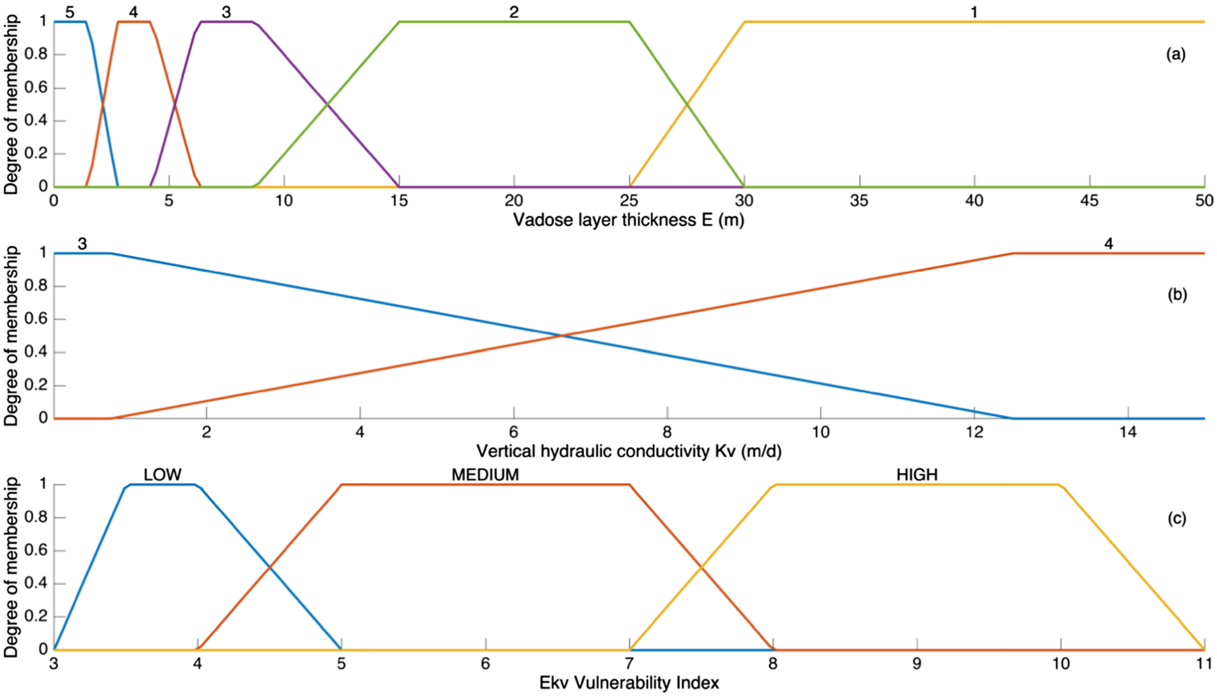

Fig. 7 Fuzzy sets developed using the DRASTIC Method. **a** Depth (*D*) (input variable). **b** Impact of the vadose zone (I) (input variable). **c** DRASTIC vulnerability index (output variable)

discharge. Therefore, the water table shape was defined by the following equations:

$$Q_{(x)} = Q_o - wxb \tag{2}$$

$$h_{(x)} = \sqrt{\left({h_o}^2 + \left(\frac{2Q_{(x)}x}{bk} \right) + \left(\frac{wx^2}{k} \right) \right)} \tag{3}$$

where:

- k Hydraulic conductivity of the aquifer ($k = 7.8$ m/day, Arumí et al. 2016)
- $Q_{(x)}$ Streamflow through the aquifer
- Q_o Streamflow at the downstream boundary of the study area ($Q = 270{,}000$ m3/day, Arumí et al. 2016)
- x Distance between two points (m)
- w Water recharge to the system per unit of area ($4.7 \times 10–3$ m day^{-1}, Arumí et al. 2016)
- b Average width of the study area (1900 m)
- h_o Elevation of the springs (1100 m.a.s.l, GPS field measurement)
- $h_{(x)}$ Elevation of the water table throughout the aquifer (m.a.s.l.)

At first, to determine the depth of water table shape, the streamflow through the aquifer and the water table profile throughout the study area were calculated from the downstream boundary of the study area (the straight line that connects the two springs) to the upstream boundary of the study area, using Eqs. 2 and 3 respectively, on a regular grid basis with 100-m-wide cells, based on known data at the line of springs; $h = 1100$ m.a.s.l, GPS field measurement). Then the depth of water table shape for the entire study area was calculated in ArcGis by subtracting the water table elevation from the terrain elevation (digital elevation model, Fig. 1d) (Fig. 8).

Furthermore, other digital maps for this study were generated by ArcGis Figs. 8 and 9.

The next step was to determine the fuzzy sets for each vulnerability method in the MATLAB Fuzzy Logic Toolbox. The parameters related to the depth of the water table and vadose zone (parameters exhibiting data scarcity) were entered into the MATLAB Fuzzy Logic Toolbox for each vulnerability method as input data and the output sets were entered as the vulnerability index.

In addition, despite the data scarcity, the vulnerability of the aquifer was evaluated by the traditional methods using only the available data in order to compare the results with the fuzzy method.

Table 1 Value assigned to each parameter according to DRASTIC approach indications

Parameter value	Source
$R = 9$	Recharge = 1700 (mm/year) (Lavados 2015)
$A = 9$	Volcanic rock (Rivera 2014)
$S = 9$ and $S = 10$	Alluvial deposit and volcanic rock (Naranjo et al. 2008)
T: variable	Calculated using DTM and GIS software
$C = 2$	$K = 7.8$ (m/day) (Lavados 2015)

Finally, for the fuzzy method and the traditional vulnerability assessment methods, GIS maps were generated by nearest neighbor interpolation tool based on the values of the resulting vulnerability indices.

Results and discussion

As a first result, the water table depth map (Fig. 8) shows that groundwater is shallow in the area near the springs and gets deeper toward the East (as a reference, the depth reaches 30 m around 1 km from the springs).

For the three methods (EKv, GOD, and DRASTIC), the vulnerability index maps (Fig. 11a, c, e), based on the expert knowledge, were generated using a fuzzy approach in order to manage the uncertainty related to data scarcity. It should be noted that the application of a traditional vulnerability index approach with the few data available was still possible (Fig. 11b, d, f), but it was done to compare the results, as the traditional approach did not consider uncertainty.

In general, the vulnerability maps from both the fuzzy and traditional approach show that vulnerability reaches the highest value near the springs and decreases as distance from the springs increases, results that are consistent with the inferred depth of the water table (Fig. 10). In addition, the vulnerability results in the Shangri-La area, where there is a "low" vulnerability index for all the fuzzy maps (Fig. 11a, c, e) and for some of the traditional maps (DRASTIC (Fig. 11b) and GOD (Fig. 11f)), are influenced by the lower hydraulic

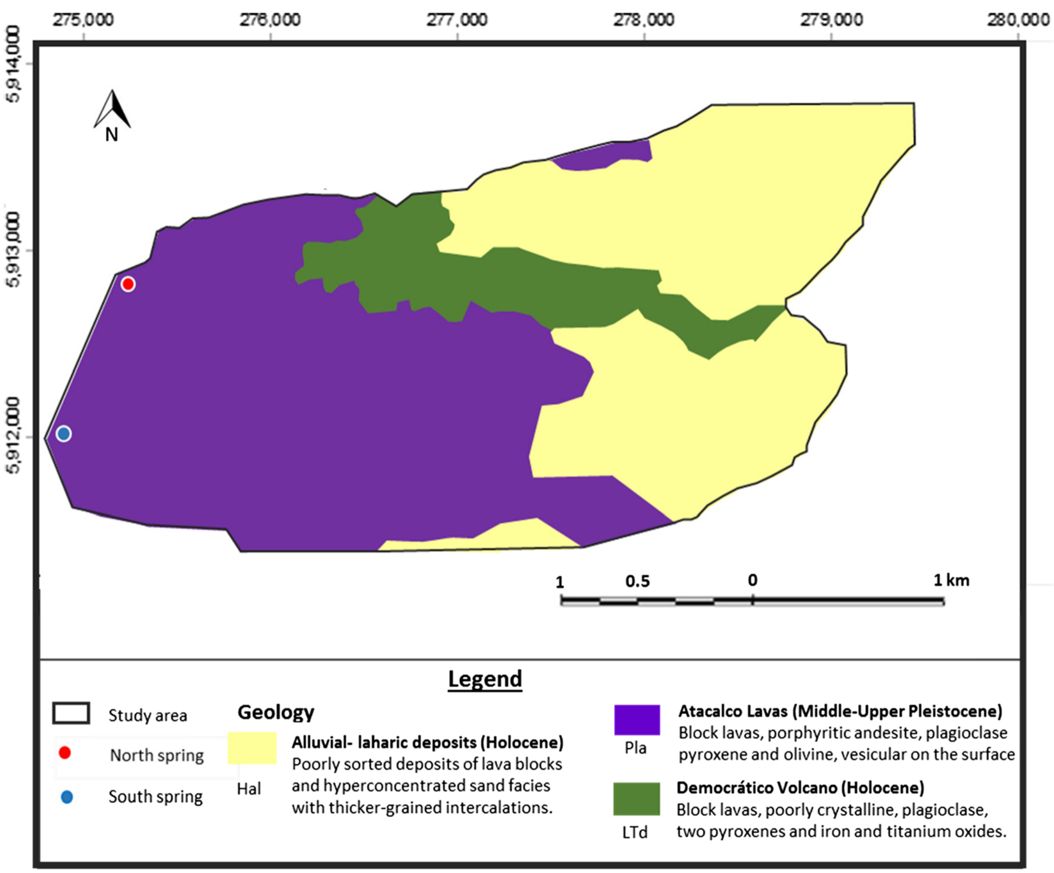

Fig. 8 Geology map of the study area by GIS

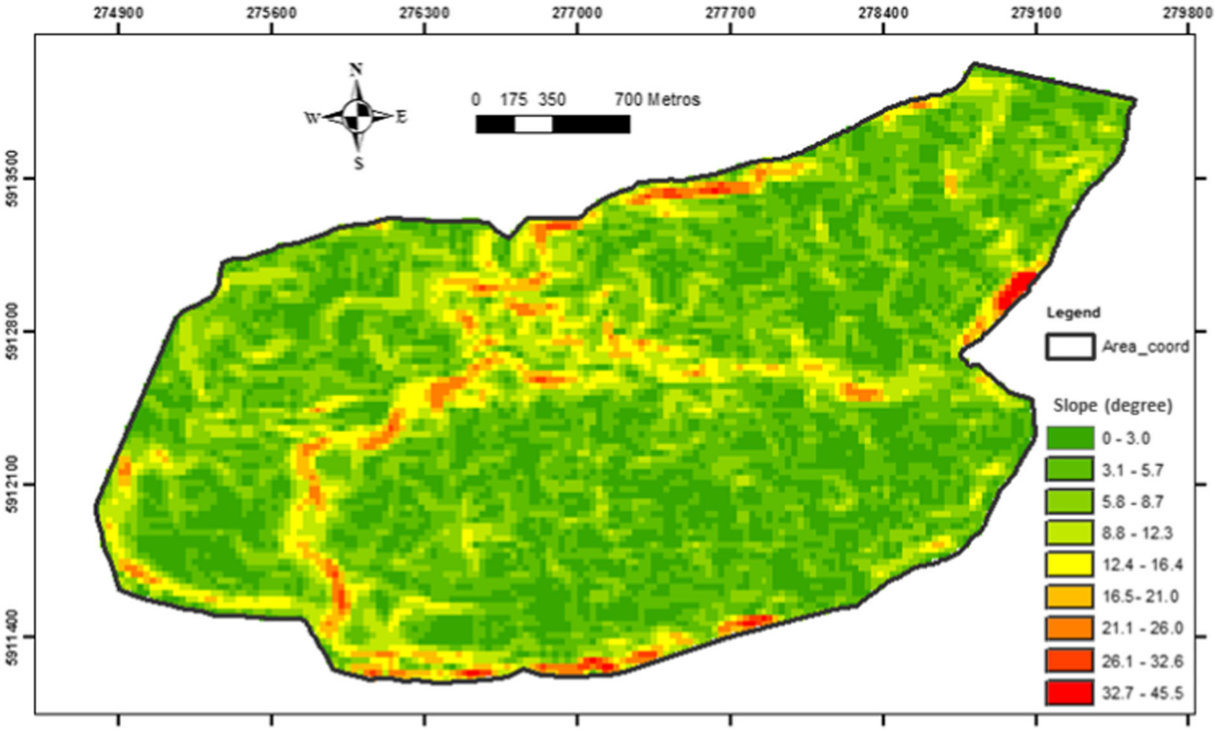

Fig. 9 Slope map of the study area

conductivity of the vadose zone. These results suggest that Shangri-La has a "low" index and the areas near the springs have "extreme" or "high" indices.

Furthermore, the fuzzy and traditional approaches of each method were compared. First, the results of the vulnerability assessment with the *EK*v method (for this method, both parameters, *E* and *K*v, were processed with the fuzzy approach) presented a substantial difference compared to the traditional *EK*v approach, with the fuzzy approach exhibiting a "low" index at the eastern part of the study area and the traditional approach exhibiting a "moderate" index there. Furthermore, "high" vulnerability areas were detected for both the fuzzy and traditional *EK*v approaches, but with different shapes.

Second, for the GOD method (where the overall and depth parameters were processed with the fuzzy approach), the vulnerability index maps made with both the fuzzy and the traditional approaches had similar distribution of the different vulnerability classes. However, the fuzzy GOD map shows a larger area with the highest index and smaller area with a "low" index compared the traditional approach.

Third, the results of the DRASTIC method (for this method, the depth and impact of vadose zone parameters were processed with the fuzzy approach) are very similar in both the distribution and magnitude of the vulnerability index areas. Nevertheless, in areas near the springs, the fuzzy map shows a large area of "very high" vulnerability. Another issue to consider for the DRASTIC maps is the mosaic (pixelated) effect that was produced when the topographic layers (slopes) were added using the map algebra tool in GIS. This situation generated coarser areas for the vulnerability index, which could present a difficulty for land-use planning purposes, as the limits of the vulnerability index areas there are not sharply defined.

Considering the above, the fuzzy approach proved to be a practical alternative to the traditional vulnerability assessment approach when there is uncertainty due to lack of data, given that the results were consistent with the spatial distribution of the water table depth shape and the distribution of vadose zone type in the study area. In general, they were also consistent with the distribution of vulnerability index areas, although differences in specific distribution and magnitude of the vulnerability index areas were identified between the two approaches. Because the differences would not have been possible to detect using only a traditional approach, the proposed approach could be considered

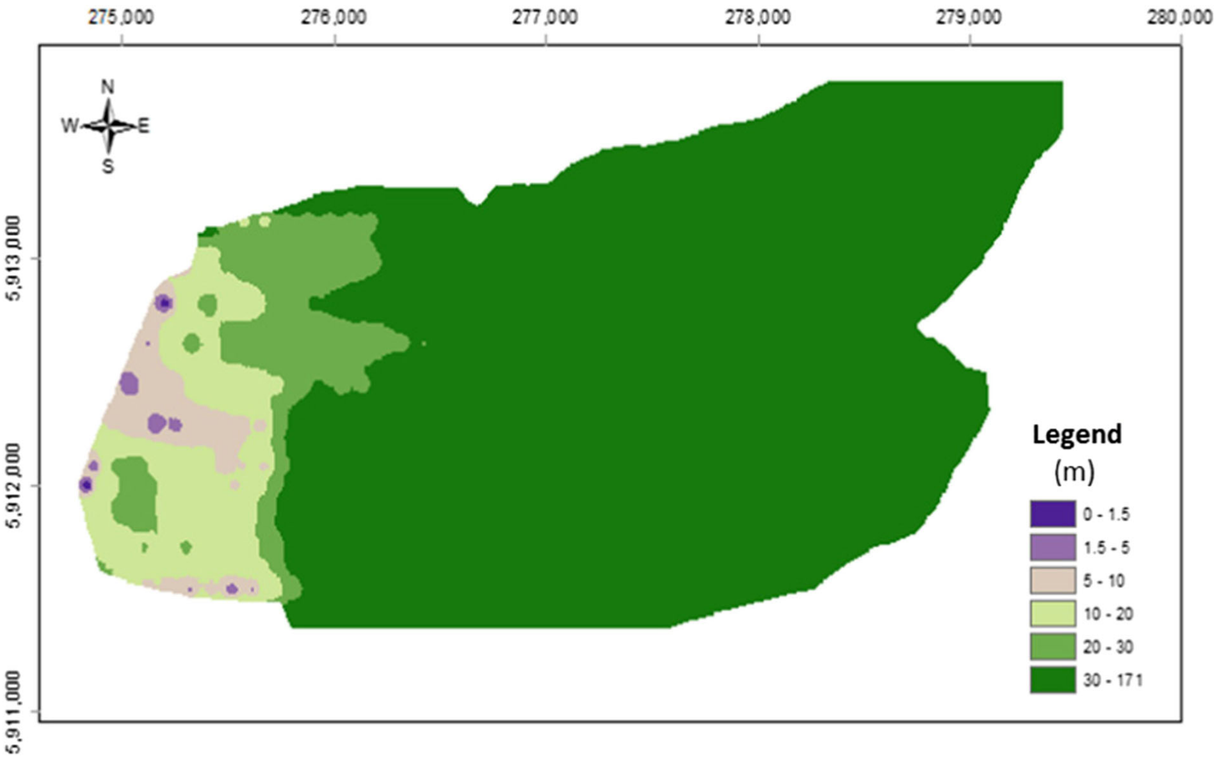

Fig. 10 Depth map of the aquifer of the study area by GIS

an additional analysis tool to determine the distribution and magnitude of the vulnerability index in a study area.

It should be stressed that the differences above concur with the selection of the fuzzy membership function, which were established under expert knowledge of the study area, because the spatial distribution vulnerability indices variations are related to the coincidence ranges between the adjacent fuzzy sets; indeed, the input values that there are out of the coincidence ranges in the fuzzy approach maintain the same value with traditional methods, due to the fact that the fuzzy approach was developed based on the equations structures, indices ranges, and parameters of each traditional method used in this study to assess the intrinsic vulnerability.

It is worth noting that the approach presented and followed in the current work represents an alternative way to deal with data scarcity issues when attempting to assess groundwater pollution vulnerability (through intrinsic vulnerability index assessments), as it uses a formal and well-proved fuzzy approach to address the uncertainty related to data scarcity. When the quality and quantity of collected data is suitable enough, the uncertainty decrease and the number of fuzzy parameters also decreases. Thus, fuzzy methods are a valuable tool when spatial and temporal uncertainty is high, but also provides a way to account for uncertainty, especially when results are envisioned or required for environmental assessment procedures, for land use planning, and for public policies development. Indeed, in the current work, the application of fuzzy sets allowed identifying areas with high vulnerability that were not detected by using the traditional approaches. Finally, we expect the proposed approach could be used and tested under different conditions, in order to better constrain its range of applicability, advantages, and shortcomings.

Conclusions

The assessment of the vulnerability of the aquifer in Las Trancas, south-central Chile, with the fuzzy approach allowed uncertainty due to data scarcity to be managed. The results obtained are related to fuzzy sets and rules, which are based on the structure of the parametric methods and expert knowledge on the area.

In general, the results of working jointly with fuzzy numbers and vulnerability methods are coherent among the three methods. They showed variability in the study

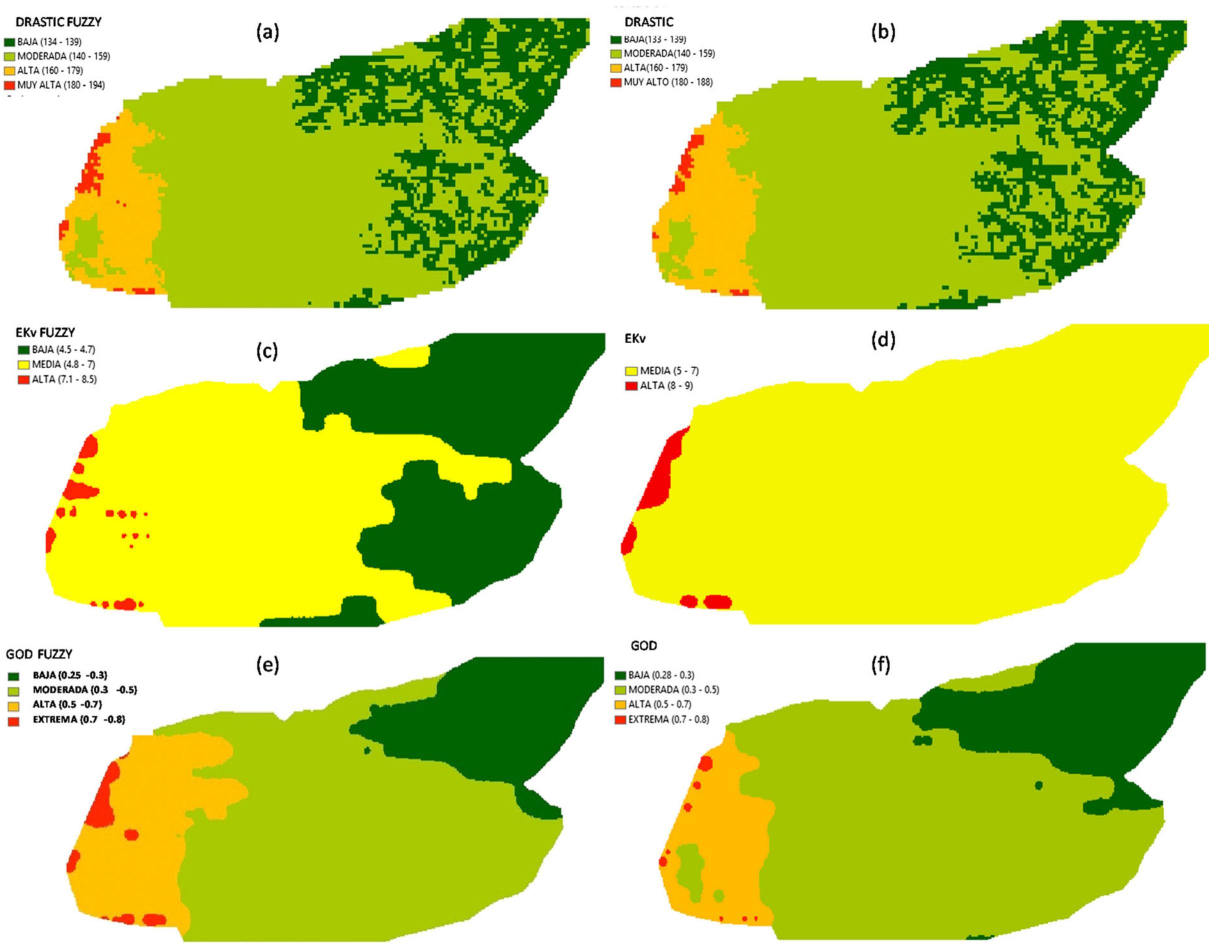

Fig. 11 Vulnerability GIS maps of the study area generated by fuzzy (**a**, **c**, **e**) and traditional methods (**b**, **d**, **f**)

area and indicated that vulnerability indices are higher in the western sector of the study zone (close to the springs), while they decrease toward the east. With the DRASTIC method, greater heterogeneity in the vulnerability index results was observed, which is attributable to the calculation of the slope through DTM and the GIS platform.

Moreover, the vulnerability map shows that the zones with the highest values (Extreme for GOD, Very High for DRASTIC and High for *EK*v) are closest to the line of springs, where the water table has the lowest depth value, whereas the largest part of the study area, where the greatest number of buildings are located, is characterized by a medium vulnerability index and the Shangri-La sector is characterized by the lowest vulnerability indices. Furthermore, when using the GOD and DRASTIC methods, the vulnerability index decreases in the sectors with alluvial sediments compared to those with volcanic rock terrain.

Considering that the vulnerability index distribution (GIS maps) shows that the zones closest to springs present high and medium vulnerability indices, that there is a significant population increase in certain times of the year (ski season and summer), and that there are wastewater discharges upstream of where drinking water is extracted from springs, it would be beneficial to have a year-round spring water quality sampling program and evaluate the necessity of implementing a community drinking water and sewage system.

Besides, when applying this proposal, it is fundamental to consider an adequate knowledge about the study area, which allows establishing a fuzzy logic approach under expert criteria on study area.

Finally, the differences in the vulnerability index results between the fuzzy and traditional methods provide additional useful information for making spatial planning decisions. They confirm the vulnerability values in the areas with equal ranges and, when they identify areas with different vulnerability ranges, tell us that these values could belong to a lower or higher range if there were more precise information on the land under study. Thus, this study presents a practical approach to evaluate or improve vulnerability index values calculated under data uncertainty, a rather common situation in rural settings of developing countries.

Funding information The authors express their gratitude to Conicyt for the funding provided through the Conicyt/Fondap/15130015 and Fondecyt 1150587 grants.

Compliance with ethical standards

Conflicts of interest The authors declare that they have no conflict of interest.

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