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Vulnerability to groundwater contamination, SW Salamanca, Spain

R. Vidal Montes, A. M. Martinez-Graña, J. R. Martinez Catalán, P. Ayarza Arribas and F. J. Sánchez San Román

Department of Geology, Faculty of Sciences, University of Salamanca, Salamanca, Spain

1. Introduction

Water resources are indispensable for human development and progress, with proper management of these resources required for agricultural and livestock activities. Places where human activities are concentrated in limited areas face issues related to both water availability and quality. Different human activities generate leachates capable of altering water quality (Mohseni-Bandpei & Youseif, 2013), leading to pollution (e.g. wastewater, industrial or livestock leachates). The availability of potable water is a determining factor in the development of any territory. Thus, rational and sustainable planning is necessary in areas where human activities may have a negative impact on environmental factors, particularly water quality.

The vulnerability of an aquifer to pollution is defined as its susceptibility to external pollutants (Foster & Skinner, 1995). An intrinsic vulnerability is established when the environment is associated with a potential risk (geology, hydrology, etc.), whereas a specific vulnerability is defined when risks are posed by external factors (weather, polluting agents, etc.), which may also affect the intrinsic vulnerability. The DRASTIC method is likely the most widely used tool for vulnerability mapping (Aller, Bennet, Lehr, Petty, & Hackett, 1987). Vulnerability mapping or zoning is an important tool for regional management and planning and has to be taken into account in regard to authorizing all activities that may potentially cause pollution (Atta, Zuhairi, Yaacob, & Bin Jaafar, 2015; Awawdeh & Jaradat, 2010; Brito, Costa, Almeida, Vendas, & Verdial, 2006; López Vera, 2002; Martínez Navarrete et al., 2009; Martínez-Graña, Goy, De Bustamante, & Zazo, 2014; Martínez-Graña, Goy, Zazo, & Yenes, 2013). Sometimes, public administrations perform vulnerability mapping with little detail or treat rocky outcrops as non-permeable media without aquifers, analysing only detritic geologic formations in which the granular porosity implies a high susceptibility to aquifer pollution.

More recently, geographic information systems (GIS) have been widely used in groundwater vulnerability mapping (Boughriba et al., 2010; Evans & Myers, 1990; Hallaq & Elaish, 2012; Jasmin & Mallikarjuna, 2015; Martínez-Graña, Goy, & Zazo, 2013; Rapti-Caputo et al., 2006; Thirumalaivasan, Karmegam, & Venugopal, 2003). The use of a GIS has allowed the creation of groundwater vulnerability maps that are based on parametric mapping. These maps can be used for sustainable land-use planning and to determine the potential for regional aquifer pollution.

The goal of this study is twofold: (1) establish a mapping protocol using a GIS that takes into account all of the parameters established by DRASTIC to obtain a vulnerability map of groundwater pollution in an area with a non-permeable, but fractured, basement and (2) identify the hazards associated with human activities that may cause pollution (e.g. hospitals, livestock, quarries and trash dumps). The procedure presented in this study has been applied in southwestern Salamanca, a rapidly growing area that must be properly managed in terms of land protection and land-use planning (Figure 1).

2. Methodology

This vulnerability study was carried out using the parametric method called DRASTIC. This method
assumes (Ahmed, 2009; Aller et al., 1987; Neshat, Pradhan, Pirasteh, & Mohd Shafri, 2014; Babiker, Mohamed, Hiyama, & Kato, 2005; Hamza et al., 2015; Rahman, 2008; Sener, Sener, & Davraz, 2009; Wen, Wu, & Si, 2009) that contaminants seep into groundwater with precipitation. This assumption implies that contaminant mobility is based on that of water, which encompasses 0.4 km² of the study area. DRASTIC is based on the classification of 10 parameters that control the intrinsic vulnerability of the aquifer to pollution, although external vulnerability is also taken into account. Each pollutant is considered a non-pesticide.

A GIS is used to present the parameters using a weighed raster map of the area. These maps are overlaid using map algebra, resulting in a vulnerability map for groundwater contamination (Figure 2). In this map, each pixel has a value that represents the degree of vulnerability. DRASTIC parameters and typical weights are discussed in the following sections.

D – Depth to water table (weight 5): this parameter denotes the vertical distance from the ground surface to the water table. The lesser the distance, the greater the possibility of pollutants reaching the groundwater. The depth to the water table in aquifers was obtained from ‘Sondeos Balboa S.L’ and the ‘Diputación de Salamanca’ who consider the water table to be at least 40 m below the surface.

In the Duero Basin, surface water forms the Tormes River, which is located to the NE. All seasonally active
The resulting water balance allows us to determine which produced values between 680 and 800 mm. The climatic data were calculated using the Thornthwaite method, between 12°C and 14°C, and the annual rainfall ranges in the study area. The average annual temperature varies parameter is based on soil maps (Figure 2 and Main map S, Table 1).

Based on the locations of wells and the depth to the water table (Figure 2 and Main map D), we observe variations between 25 m in the water table at locations less than 10 m apart. However, we cannot define a water table ‘sensu stricto’ because this is not a continuous surface in fractured areas. In addition, the thickness of the non-saturated area is always more than 50 m.

R – Net Recharge (weight 4): Net recharge is the quantity of water that penetrates a unit area of land and consequently replenishes the groundwater. Hence, the higher the recharge, the higher the susceptibility to contamination. Net recharge is based on the Groundwater Aquifer Recharge (GAR) methodology FORGAES (Schosinsky, 2006). According to GAR, the recharge can be calculated from the water balance (WB), which is based on an area’s climate, and then multiplied by an infiltration coefficient (C). The latter is a dimensionless parameter based on the sum of the following three coefficients:

\[ C = K_p + K_v + K_{fc} \]

where Kp is the water fraction that infiltrates as a result of the slope and is obtained from the corresponding map (Figure 2 and Main map T); Kv is associated with the amount of water that infiltrates due to the effect of vegetation. In this case, data are based on the land-use values obtained from the Corine Project, which takes into account human activities that occur at the surface. Finally, Kfc refers to the water fraction that infiltrates as a result of the ground texture. This parameter is based on soil maps (Figure 2 and Main map S, Table 1).

The climate in the area has been characterized using weather station data (Figure 3) These climate data are interpolated using a Spline method (Esri ArcGIS v10), which specifies the values at each point in the study area. The average annual temperature varies between 12°C and 14°C, and the annual rainfall ranges between 360 and 450 mm. Potential evapotranspiration was calculated using the Thornthwaite method, which produced values between 680 and 800 mm. The resulting water balance allows us to determine the amount of water from precipitation that reaches the ground and infiltrates. The calculation of this balance, which ranges from 80 to 125 mm, is based on an analysis of the climatic parameters discussed above. Mapping the recharge area is the initial step in identifying the zones that are likely to be affected by pollutants. The largest recharge areas are the most susceptible to contamination.

A – Aquifer media (weight 3): This parameter defines the potential attenuation characteristics of the aquifer material. The higher the permeability, the weaker the attenuation capacity of an aquifer medium. This parameter is based on a geological map of the area (Figure 2 and Main map A), however, it does not consider shallow formations, which are considered part of parameter ‘T’. The study area includes a basement composed of Cambrian (Aldeatejada formation) and Ordovician metasediments (Armorican quartzite and Mid-Ordovician slates) as well as Neogene (Red Unit) and Quaternary surficial deposits consisting of gravels and clay. As mentioned previously, aquifers are located in the Ordovician quartzites and slates above the low permeability Aldeatejada formation (slates and siltstones).

S – Soil media (weight 2): This parameter is the topmost soil layer and weathered portion of the ground. Its characteristics control the movement of contaminants from the surface; thus, the higher the holding capacity, the longer the travel time.

The soil is the shallowest level of the subsurface where rainfall and other surface waters collect and flow. Water will infiltrate differently depending on the soil texture, resulting in pollutant transport variations. Soil types and their distributions were analysed through fieldwork at the 1:10,000 scale, as no soil maps exist for the study area. In the study area, we found leptosols, which are composed of thin unconsolidated soils or rock materials with less than 10% fine soil. In

| Table 1. Weighting of the different parameters for the coefficient of infiltration. |
|---|
| Slopes | Kp |
| 0–5% | 0.40 |
| 5–15% | 0.15 |
| 15–30% | 0.10 |
| 30–50% | 0.07 |
| 50–70% | 0.05 |
| >70% | 0.01 |
| Use of soil | Kv |
| Forests | 0.20 |
| Agroforestry systems | 0.20 |
| Pastures | 0.18 |
| Industrial or commercial areas | 0.18 |
| rail and road networks and lands associated | 0.18 |
| Continuous urban areas | 0.18 |
| well-drained terrains permanently | 0.15 |
| Discontinuous urban areas | 0.10 |
| Terrains systems in drylands | 0.10 |
| Type of soil | Kfc |
| Soils of fine texture | 0.10 |
| Soils of medium texture | 0.15 |
| Soils of coarse texture | 0.20 |
Figure 3. Characterization of the climatic parameters: temperature, rainfall and evapotranspiration, for the calculation of water balance.
particular, we identified dystric leptosols (with a base saturation lower than 50% in the 5 cm located above a lithic contact) and eutric leptosols (with a base saturation higher than 50% in the 5 cm located above a lithic contact). We also found albisol with high aluminium content, high acidities and high activity clays. In addition, we identified luvisols, which are characterized by the lower layer concentrations of materials from upper layers that are transported downward. These luvisols include chromic-calcium (based on a calcic horizon or concentrations of secondary carbonates between 0.5 and 1 m deep), chromic, haplic and vertic (clay subsurface horizon caused by continuous expansion and contraction) luvisols. In some places, there are fine texture eutric and dystric regosols, which develop above loose or hard rock greater than 30 cm deep. Both eutric and dystric cambisols have been found above altered materials. Finally, we identified dystric, eutric and calcaric fluvisols, which result from river deposits, with organic matter content that decrease irregularly or are high in deep areas. Different types of soil associations were noted as follows (Figure 2 and Main map S): I (quartzite outcrops characterized by dystric leptosols with coarse surface textures), II (hypoosmoric and chromic alfisols, and calcium luvisols, which occur in quartzite deposits on slopes and have medium surface textures), III (haplicromic and calcium luvisols consisting of colluvial materials in quartzite and red sediments with medium surface textures), IV (regosols, leptosols and eutric cambisols formed by slates with medium surface textures), V (calcium, chromic luvisols and vertisols formed by red sediments with medium surface textures) and VI (dystric, eutric and calcium fluvisols formed by alluvial deposits with medium textures).

T – Topography/slope of terrain (weight 1): This parameter represents the gradient or slope of the terrain. The steeper the angle of inclination, the greater the run-off rate and the lower the recharge ability of the aquifer, and vice-versa. A 170 m drop exists between the top of ‘The Montalvos’ (935 m), a topographically high area characterized by quartzite, and the Tormes River. The slope map (Figure 2 and Main map T) shows that the steepest slopes are found on the upper hillsides and slopes decrease closer to the valleys. The slope map is created from a Digital Elevation Model (DEM) by dividing the elevation change between DEM pixels by the distance between pixels using a GIS.

I – Impact of unsaturated zone (weight 5): This parameter represents the texture of the soil between the water table and the unsaturated soil cover. This parameter is obtained from a geomorphologic analysis (Figure 2 and Main map I) based on morphostructural studies, the morphogenetic processes associated with the terrain or models determined from the surface formations.

At a morphostructural level, alternating quartzite and slate layers, together with a favourable structural arrangement in isoclinal folds, gives rise to strong dips, causing an Appalachian morphostructure with ridges aligned in an E–W direction. One such topographic feature is the ‘Montalvos Hill’, which is a syncline that developed on the Armorican quartzite.

We distinguish five different morphogenetic system models as result of the external modelling agent: fluvial, polygenic, gravitational, hillside and anthropic models. Fluvial modelling is characterized by the development of terrace systems, some of which comprise alluvial fans formed by sands, slates and quartzites. These fans form triangular shapes facing the heads of ravines and spread towards valley bottoms, including at the mouths of small streams that feed major river systems. Polygenic modelling include erosion surfaces (S1 and S3), which are typical of the plains, alteration deposits that slate metasediments pass through and important kaolinitic argillization, with numerous segregations of iron and silica. Debris flows occur on hillsides due to deposit instabilities and gravity. Morphostructural modelling consists of tectonic and fluvial escarpments developed in the study area and adjacent areas. Finally, anthropic modelling is represented by debris accumulations, which alter the relief and slopes.

C – Hydraulic Conductivity (weight 3): This parameter represents the aquifer transmissivity. The higher the conductivity, the more vulnerable the aquifer.

The hydraulic permeabilities or conductivities of different lithologies were determined based on the geological units that host the aquifers. Thus, different groups of discontinuities are analysed to establish a correlation between their spacing and their hydraulic conductivities (Bell, 2000) (Table 2). Outcrops chosen for this task were sufficiently far apart to adequately represent the entire study area (Figure 4). Hydraulic conductivities of deep lithological formations are based on the spacing between discontinuities in the aquifers themselves (Bell, 2000).

Results show that (Table 3) the Armorican quartzite features spacing between discontinuities of 200–600 mm, with an aperture of less than 13 mm. When filled,
Figure 4. Analysis of discontinuities in the principal geological formations.
the dominant materials are small fragments of altered quartzite, with a weathering degree of two. Thus, these spaces allow water circulation and behave as moderately permeable masses. Middle Ordovician slates are assumed to have the same spacing as the quartzites, although the maximum aperture was 10 mm. These spaces were generally occupied by altered slates, with a weathering degree of two. In some cases, they were characterized as small quartz dikes. Thus, the permeabilities of these types of slate spaces were estimated at between 5–10 and 2–10 m/s. The hydraulic conductivities of the remaining geological formations are based on laboratory tests (Table 4). Each unit on the geological map is assigned a corresponding hydraulic conductivity (Main map C), resulting in a map of permeabilities (Figure 2).

Finally, the DRASTIC index is calculated in each cell/pixel of the vulnerability map using map algebra. This calculation multiplies the characterization factors (parametric maps) by the DRASTIC weight parameters and sums the resulting values.

### 3. Results

In the resulting maps, each pixel has a vulnerability degree described by a number (Table 5). If we assume that the vulnerability degree of an aquifer is associated with a pollution risk, then this method can be used to evaluate the hazard (Martínez Navarrete et al., 2009). Finally, we assess the susceptibility of the aquifer to groundwater contamination by integrating and classifying the values obtained based on five degrees of vulnerability (Foster & Skinner, 1995): very low (confined aquifers that receive no significant groundwater flow), low (areas vulnerable to persistent pollution or with continuous pollutant release or leaching), moderate (sectors that are vulnerable to contaminants that are released or leached), high (areas vulnerable to a variety of contaminants, except those that are absorbed or are rapidly transformed) and very high (most vulnerable areas to water pollution). Thus, we obtain the vulnerability map of groundwater contamination (Figure 2 and Main map of vulnerability).

The map of vulnerability to groundwater contamination (Figure 2 and Main map of vulnerability), shows four sectors with different vulnerability degrees. The lowest vulnerability sector is located where the Aldeatejada formation outcrops. No aquifers exist

### Table 3. Results of discontinuities analysis.

| Formations                  | ID stations | Family | Orientation | Spacing (mm) | Continuity (m) |
|-----------------------------|-------------|--------|-------------|--------------|---------------|
| Armorican quartzites        | I Road west of the Montalvos Hospital (Figure 3.19) | S0 29/233 | 260–600     | <1           | 1–3           |
|                             | J1 68/128   |        | 250–320     | <1           | <1            |
|                             | J2 75/227   |        | 400–580     | <1           | <1            |
|                             | J3 5/220    |        | 190–380     | 1–3          | 3–10          |
|                             | J1 65/4     |        | 90–420      | <1           | <1            |
|                             | J2 72/228   |        | 100–300     | <1           | <1            |
|                             | J3 79/292   |        | 150–370     | <1           | <1            |
|                             | J1 77/124   |        | 70–160      | <1           | <1            |
|                             | J2 70/188   |        | 50–120      | <1           | <1            |
|                             | J3 45/201   |        | 50–140      | <1           | <1            |
|                             | J1 20/125   |        | 150–540     | 3–10         | <1            |
|                             | J2 55/208   |        | 210–540     | 1–3          | 1–3           |
|                             | J3 82/294   |        | 170–320     | 1–3          | 1–3           |
|                             | J0 19/22    |        | 200–520     | 1–3          | 3–10          |
|                             | J1 70/105   |        | 20–430      | <1           | 1–3           |
|                             | J2 79/169   |        | 50–100      | <1           | <1            |
|                             | J0 53/319   |        | 320–580     | 1–3          | 3–10          |
|                             | J1 83/28    |        | 200–600     | <1           | <1            |
|                             | J2 66/259   |        | 160–550     | <1           | <1            |
|                             | J0 21/340   |        | 200–220     | 1–3          | <1            |
|                             | J1 84/6     |        | 640–750     | <1           | <1            |
|                             | J2 61/74    |        | 30–70       | <1           | <1            |
|                             | J0 12/266   |        | 90–240      | 1–3          | <1            |
|                             | J1 80/346   |        | 130–370     | <1           | <1            |
|                             | J2 86/240   |        | 190–400     | <1           | <1            |
|                             | J3 78/273   |        | 60–320      | 1–3          | <1            |

### Table 4. Results of the hydraulic conductivities of lithologies, obtained by laboratory test.

| Formation                                                                 | Hydraulic conductivity (cm·s⁻¹) |
|----------------------------------------------------------------------------|---------------------------------|
| Aldeatejada formation                                                      | 1×10⁻⁵                         |
| Altered slates                                                            | 4.6×10⁻⁶                       |
| Formation of Sandstones of Salamanca, very silicified                      | 10⁻¹⁷–10⁻⁷                     |
| Red Unit: soils                                                           | 2.4×10⁻⁶                       |
| Red Unit: rocks                                                           | 1×10⁻⁷                         |
| Quaternary materials (plains of flood, bars and deposits of fund of valley and landfills) | 1.5×10⁻²                       |
| Terraces                                                                  | 9.6×10⁻⁶                       |

### Table 5. Vulnerability from the value DRASTIC.

| Vulnerability | DRASTIC value |
|--------------|--------------|
| Very low     | 23–64        |
| Low          | 65–105       |
| Moderate     | 105–146      |
| High         | 147–187      |
| Very high    | 188–230      |
and soils are resistant to penetration by contaminants. The low vulnerability sector is characterized by non-permeable geological formations regardless of having, in places, higher hydraulic conductivities than other sectors. This group also includes areas of steeply sloping aquifer outcrops, that is, areas used for communication/transportation or mountainous areas. These two vulnerability sectors (very low and low) strongly resist groundwater contamination by run-off. However, these areas are more prone to surface water run-off, which affects streams and rivers.

The moderate vulnerability sector consists of areas where contamination occurs irregularly. These areas require more controls because they include aquifer regions with detritic cover that permits leachate penetration. In this group, we have distinguished between moderate and moderate-high vulnerabilities. The latter group includes soils with high textural permeability, which promotes pollutant infiltration into groundwater.

Finally, anthropic activities are identified and separately mapped on the vulnerability map. First, we include a hospital whose main source of contamination is sewage from a septic tank. We also include two cattle farms, with more than 50 cows each, with extensive regimes, that is, free during most of the day and locked in the farms at night. Here, the potential hazard is associated with the organic load spilled on the ground and the likelihood that it reaches the aquifers, especially in the highest concentration areas, that is, the farms. In addition, an old, abandoned mine that used quartzites as aggregates may cause contamination associated with quarry activities and mine dams. The final anthropogenic hazard is a construction and demolition waste landfill. These materials may contain pollutants or harmful substances that can enter the groundwater system when mixed with rain water (Figure 1).

The three activities associated with the highest pollution hazards are as follows: farm II, the landfill and the hospital centre (Figure 1), which are all located in the moderately vulnerable sector. Moreover, the landfill is located in the moderate-high vulnerability sector. The quarry affects sectors with different degrees of vulnerability because it is located on the boundary between the Aldeatejada formation and the Armorican quartzite. In fact, its most significant hazard is related to the steep slopes of the quarry walls. Finally, farm I and the mining dams are located in areas with low or very low hazard vulnerabilities.

4. Conclusions

We present an efficient and low cost protocol for assessing groundwater vulnerability and so planning human activities. This methodology has been implemented with a GIS and analyses the effects of human activities and their sustainability, taking into account the environmental resistance (lithology, soils, hydrogeology, etc.) to groundwater pollution.

The vulnerability map of groundwater pollution in the study area, which was created using the DRASTIC method, allows us to identify sectors with very low and low vulnerabilities that do not contain threats to aquifers but do influence surface run-off. A moderate vulnerability sector was also observed near aquifer outcrops, featuring fractures and cracks that allow direct and fast connectivity. This area requires special attention, as non-persistent pollutants may influence water quality. Based on the presented data set, we can conclude that the activities that pose the largest threats to groundwater due to their intrinsic characteristics and locations are as follows: farm II, the construction and demolition waste landfill and the hospital centre.

Software

We used Esri ArcGIS v.10.3, the Spatial Analysis and 3D Analysis extensions, and scripts to perform algebra calculations and produce the final map. The reference system used was Universal Transverse Mercator UTM Datum ETRS 89 in zone 30.

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ORCID

A. M. Martinez-Graña  http://orcid.org/0000-0003-2242-5192

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