A GIS open source application for the assessment of groundwater vulnerability to pollution: a case study in Serra da Estrela (Central Portugal)

Uma aplicação SIG open source para a avaliação da vulnerabilidade da água subterrânea à poluição: um estudo de caso na Serra da Estrela (Centro de Portugal)

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Abstract: Groundwater is more and more regarded as a crucial resource and its pollution is a major environmental concern at global scale. Geographical Information Systems (GIS) are often used to estimate groundwater vulnerability to pollution as it provides several efficient tools to manipulate and analyze a number of biophysical data types of hydrogeological relevance. The objective of this work was to use an improved GIS open source application for assessing groundwater vulnerability to pollution on the river Zêzere basin upstream of Manteigas (Serra da Estrela, Central Portugal), using two different indexes: DRASTIC and GOD. Vulnerability mapping was first carried out using a GIS open source application which incorporates the DRASTIC index. Subsequently, the application was improved by incorporating the GOD index. Finally, the resulting indexes maps were compared. It was concluded that, with this GIS application, the DRASTIC index provides more detailed and realistic results than GOD index in the assessment of groundwater vulnerability to pollution.

Keywords: Groundwater vulnerability, DRASTIC, GOD, GIS, QGIS.

1. Introduction

The demand for groundwater is growing every year, since it is a natural resource of great socioeconomic importance (Borevsky et al., 2004; Job, 2010). When a pollutant is imposed in the ground and the aquifer is affected, the sensitivity of the groundwater system corresponds to the aquifer pollution vulnerability (Foster, 1987).

So, groundwater vulnerability is the tendency or likelihood of contaminants reaching the groundwater system after introduction at some location above the uppermost aquifer (e.g., National Research Council, 1993; Majandang and Sarapirome, 2013). The assessment of groundwater intrinsic vulnerability may be carried out at different scales and presented in the form of vulnerability maps (e.g., Wachniev et al., 2016). It is also important to estimate the vulnerability based on the attenuation capacity of each study area (Foster et al., 2002). Groundwater vulnerability to pollution has been estimated through different methods such as DRASTIC (Aller et al., 1987), GOD (Foster, 1987), Aquifer Vulnerability Index (AVI) (Van Stempvoort et al., 1992), SINTACS (Civita and De Maio, 1997) and Susceptibility Index (SI) (Ribeiro, 2000, 2017).

In order to assess groundwater vulnerability, Geographical Information Systems (GIS) applications are often used because they provide the tools and algorithms required to manipulate geological and hydrogeological information (Shirazi et al., 2012). Several studies have been developed to assess and estimate groundwater vulnerability using proprietary software (Li and Merchant, 2013; Sener and Davraz, 2013; Mota Pais et al., 2012; Tilahun and Merkel, 2010).

The objective of this study was to assess the groundwater vulnerability to pollution in the Zêzere basin upstream of Manteigas village (Serra da Estrela, Portugal, Fig. 1), using two different indexes: DRASTIC and GOD. In an early phase of the research, vulnerability maps were created using a GIS open source application (Duarte et al., 2015), which incorporates the DRASTIC index. In a subsequent phase, the application was improved, allowing to assess groundwater vulnerability using the GOD index.
2. Methodology

2.1 Case study

The Serra da Estrela region (40°19’N, 7°37’W) is part of the Central-Iberian Zone of the Iberian Massif (Ribeiro et al., 2007). The main regional geological units are: Variscan granitic rocks, Precambrian-Cambrian metasedimentary rocks, alluvia and Quaternary glacial deposits (Fig. 1). The most important tectonic structure is the Bragança-Vilaraça-Manteigas fault zone (BVMFZ) with NNE-SSW orientation (Espinha Marques et al., 2013).

The Serra da Estrela climate is rather complex since this region is located in a transition zone between the influences of the Atlantic Ocean and the Mediterranean Sea. The mean annual precipitation is around 2500 mm in the most elevated areas. Mean annual air temperature is below 7 °C in most of the plateau area and may be as low as 4 °C in the vicinity of the Torre summit (Daveau et al., 1997; Mora, 2006; Pisani et al., 2017).

The study was conducted in the River Zêzere Basin upstream of Manteigas village (ZBUM, Fig. 1), a drainage basin with an area of 28 km² and elevation ranging from 875 m (Manteigas) to 1993 m (Torre). The dominant landforms of the ZBUM region are two major plateaus, separated by the NNE-SSW U-shape glacial valley of the Zêzere River (Daveau et al., 1997). Glacial landforms and deposits are typical of the upper Zêzere basin.
Groundwater vulnerability GIS open source application.

(Daveau et al., 1997; Vieira, 2004). According to Espinha Marques et al. (2013), the regional hydrogeological units in the ZBUM sector are: i) sedimentary cover; ii) metasedimentary rocks; and iii) granitic rocks (Fig. 1). In this area several pedological units occur (Espinha Marques et al., 2013): Humic, Leptic, and Skeletic Umbrisols, Lithic and Umbric Leptosols, Fluvisols and rock outcrops.

2.2 DRASTIC Index

The DRASTIC index is one of the most widely used methods to estimate groundwater vulnerability (Aller et al., 1987). The original DRASTIC index, encompasses eight controlling factors: Depth to groundwater (D), net Recharge (R), Aquifer media (A), Soil media (S), Topography (T), Impact of the vadose zone (I) and hydraulic Conductivity (C).

The D factor is related with the distance that pollutants travel until reaching the aquifer. This factor considers depth values measured in wells and creates an interpolation surface. The R factor relates the groundwater vulnerability to pollution with the aquifer recharge. The A factor is defined by the influence of the geological material on groundwater vulnerability to pollution. The S factor involves the influence of soil characteristics on the attenuation of pollution. The T factor is related with the influence of terrain surface slope in the infiltration of the pollutant in the soil. The I factor is related with the way how the geological material controls the pollutant attenuation. The C factor comprises the hydraulic conductivity values.

The DRASTIC index results of the sum of the seven factor ratings being multiplied by the corresponding weights as defined in equation 1, according to Aller et al. (1987):

\[
\text{DRASTIC} = DR \times DW + RR \times RW + AR \times AW + SR \times SW + TR \times TW + IR \times IW + CR \times CW
\] [1]

The R and W indexes correspond to the rating and weight for each factor, respectively. The ratings and the weights are assigned according to the relative importance of each factor. The higher the DRASTIC index value, the higher the groundwater vulnerability to pollution. In order to interpret the results, a classification was assigned according to Melo Junior (2008).

2.3 GOD Index

Foster (1987) proposed an empiric methodology to evaluate groundwater vulnerability to pollution involving three successive parameters: Groundwater occurrence (G), Overall aquifer class (O) and Depth to groundwater table (D).

The G factor expresses the level of groundwater hydraulic confinement. It measures the extent of hydraulic confinement of the water circulating within the aquifers and ranges from 0 to 1. The O factor represents the bulk nature of the overlying strata. It describes the features of the materials overlying the aquifers with respect to their capacity to prevent the flow of contaminants. The D factor represents the depth to the water table (it is similar to the DRASTIC D factor). The GOD index is often the method of choice due to its simplicity (Foster et al., 2002). It can be calculated through the product of the three factors as expressed through Eq. 2, according to Foster (1987):

\[
\text{GOD} = G \times O \times D
\] [2]

Figure 2 presents the methodology applied to estimate the vulnerability to pollution through the GOD index. GOD index

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Figure 2. GOD index methodology (adapted from Foster et al., 2002).

Figura 2. Metodologia do índice GOD (adaptado de Foster et al., 2002).
values range from 0 to 1, considering a very low vulnerability when the index value is lower than 0.1 and very high vulnerability when the index value is higher than 0.7 (Foster et al., 2002).

2.4 GIS Application

In order to create the maps required to assess groundwater vulnerability to pollution, a GIS open source application was used (Duarte et al., 2015). The first version of this application incorporated DRASTIC index. During this research, a tool for computing the GOD index was added. The application was developed under the QGIS 2.14.3 Essen software.

3. Results

A number of maps illustrating the spatial distribution of controlling factors and vulnerability index results were created with 25 m of spatial resolution.

The D parameter (for both indexes) was obtained from a Digital Elevation Model (DEM). According to field observations, the depth of water table is at least 20 m in hilltop areas whereas it reaches the topographic surface under river and stream valleys (Fig. 3). Given the lack of water table depth measurements, the following rule was adopted: at the vicinity of rivers and streams, the depth to water table is 0 m, and its raises to a maximum of 20 m, at 200 m of distance. For distances greater than 200 m, the water table depth assumes a constant value of 20 m. Figure 3 presents the conceptual model to determine the depth to water table.

The R parameter map was based on the DEM and also on the fact that the spatial variability of precipitation is mainly controlled by altitude. A regression model from Espinha Marques et al. (2011) was used: \( y = 0.99x + 542.22 \), where \( y \) stands for mean annual precipitation (in mm) and \( x \) stands for altitude (in m).

The A, S and I parameters were obtained from the geological map of Serra da Estrela Natural Park at scale 1/75 000 from Ferreira and Vieira (1999) as well as from hydropedological information (Espinha Marques et al., 2007, 2011, 2013). The user assigns the appropriate ratings to each geological material and the application automatizes the process in order to create the respective map.

The T parameter was obtained from DEM, which was derived from topographic maps in the scale of 1/25 000. The hydraulic conductivity values (C parameter) were assigned through typical hydraulic conductivity values due to the lack of data in the region (Freeze and Cherry, 1979; Domenico and Schwartz, 1990): \( 10^{-4} \) cm/s to igneous and metamorphic rocks and \( 10^{-2} \) cm/s to glacial deposits.

In the case of GOD index, the G and O factors were determined according to hydrogeological information from Espinha Marques et al. (2013). The D factor was obtained the same way as the D parameter from DRASTIC index. The method is similar, however the classification values were assigned according to the literature adopted for GOD index.

The G factor map was assigned with a unique value (0.6) as all the study area has the same confinement (unconfined aquifer). The O factor map was created based on the occurrence of three different lithologies in the study area: sedimentary cover (0.7), igneous rocks and metasedimentary rocks (0.6). The resulting groundwater vulnerability maps (for DRASTIC index and GOD index) are presented in figure 4.

The application of different groundwater vulnerability assessment indexes has produced somewhat contrasting results.
vulnerability corresponds to the closest vicinity to the drainage network (besides the river Zêzere and the Candeira valleys) while the low vulnerability extends until the distance of 200 m away from the drainage channels. At distances greater than 200 m the very low vulnerability class prevails. This transition could be partially explained by the 200 m limit adopted in the D (Depth to water table) factor. The DRASTIC index map was obtained based on the procedure presented in Duarte et al. (2015). This application has been improved with a new tool which also applies the GOD index. Future developments of the application will encompass other groundwater vulnerability indexes as well as other functionalities.

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