AQUIFER VULNERABILITY MAPPING AND ASSOCIATED SPATIAL UNCERTAINTY

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Abstract

Quantitative estimation of water resources is indispensable when it comes to getting the sustainability of aquifers through planning. This becomes an essential aspect in areas whose primary economic activity is agriculture, in which ensure the availability of water means ensuring the sustainability of the societal and economic systems. This is the example of the Cuellar Moor karstic aquifer, located in the international Duero watershed, in which more than 80% of its surface is aimed to agricultural use.

The main goal of this research is the introduction of a new vulnerability index, which gathers together the hydrogeological covariates and the spatial uncertainty associated with the estimation of groundwater level and nitrate concentration. An optimized monitoring network to piezometric level and nitrate concentration control is required, as well as, to determine the vulnerability associated with pumping wells.

Key words: *Cuellar Moor, Karstic Aquifer, Vulnerability Index, Spatial Uncertainty, Monitoring Network.*

INTRODUCTION

The international Douro watershed, which extends between Spain and Portugal territories, is formed in its central part by a large extension of detrital materials. A set of calcareous moors, whose sedimentary origin is due to watershed clogging in the Pliocene, and which contain free karstic aquifers developed through an incipient dissolution of the cracking network. The Cuellar Moor aquifer is located between three rivers: the Douro on the north, Duraton on the east and Cega on the southwest. It extends over an area of 543.5 km^2, between the Spanish provinces of Valladolid and Segovia (Figure 1) (Alonso, et al., 2015).

More than 80% of the area of the Cuellar Moor aquifer is intended for agricultural activities, which is a diffuse source of nitrate pollution from fertilizers. Beside it, must be added the numerous farms, especially with porcine activity, which are distributed throughout the moor and act as pockets of nitrate point pollution from dung. Taking into account the high pressures on nitrate pollution, together with the Cuellar Moor aquifer being as a free aquifer, the risk of contamination is very high. Therefore, it is important to know the distribution of nitrate concentrations throughout the entire aquifer, in order to increase its monitoring in the most problematic areas and to establish future actions for its remediation.

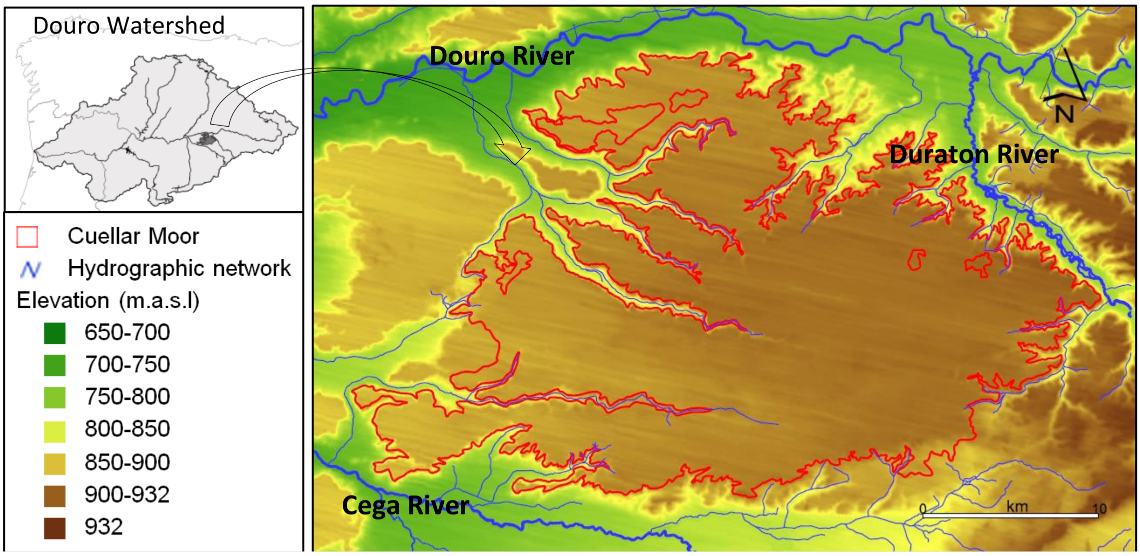

Figure 1: Cuellar Moor Aquifer location

In the present work, a new vulnerability index associated with spatial uncertainty is presented, through the use of Gaussian Sequential Simulation (SGS), in order to locate the areas in which a greater knowledge about the aquifer dynamics is required. The joint evaluation of the associated spatial uncertainty (standard deviation) to the average spatial distribution will allow to define an optimized monitoring network and to define strategies of sampling and remediation. There have been 100 simulations in which a different random initial number has been introduced for each of them.

MATERIALS AND METHODS

To develop this study, two different piezometric scenarios have been simulated: the first one represents the maximum level of the piezometric level within a hydrological year (wet scenario), while the second one, represents the lowest level (dry scenario) (Alonso, et al., 2015). The second map used is the distribution of the nitrate concentration.

The initial nitrate concentration values have been taken from 43 points: 36 sources located in the perimeter of the aquifer and 7 quality control points of the water belonging to the Confederación Hidrográfica del Duero (CHD, 2016).

Variogram model

The variogram is a vector function applied to regionalized variables (Matheron, 1970), whose argument is the *h* distance vector which quantifies the variance of the increments of the first order function (Chica, 1987). The experimental estimation of the function of the experimental data set is performed using the following formula:

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [Z(x_i) - Z(x_i + h)]^2$$

Where $Z\ (xi)$ and $Z\ (xi + h)$ are the numerical values of the observed variable at points x*i*, and $xi + h$, and $N\ (h)$ is the number of pairs formed for a *h* distance. Therefore, it is the mean value of the square of the differences between all pairs of points, which exist in the geometric field, spaced at a *h* distance (Garcia Pereira, 1979; Goovaerts, 1997).

The graphical behavior study of the variogram provides an overview of the spatial variation of the variable structure (Chica, 2005). One of the parameters that provides that information is the nugget effect (C_0), which shows the behavior at the origin (Garcia Pereira, 1979; Goovaerts, 1997). The other two parameters are the sill (C_1) and the amplitude (a) that define, correspondingly, the inertia used in the interpolation process and the influence zone of the structure of the variable.

The graphical omnidirectional variogram obtained for the nitrate concentration, as well as, the parameters with which it has been fitted with a spherical model, can be observed in Figure 2.

Spherical Model

$C_0 = 30$

$C_1 = 1750$

$a = 4800$

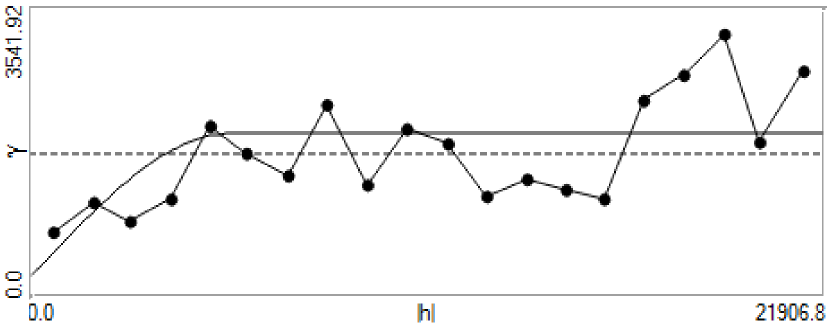

Figure 2: Variogram and adjustment parameters of the theoretical model.

Sequential Gaussian Simulation (SGS)

The SGS begins by defining the univariate distribution of the values, performing a normal transformation of the original values to a standard normal distribution. The normal values simulation at the grid node location is performed sequentially with a simple kriging (SK). Besides the normal value variogram and the mean Zero is used (Albuquerque, et al., 2014; Deutsch, 2002; Goovaerts, 1997).

Once all the normal values have been simulated, they have been transformed back to the original values. For calculating, the Space-Stat software V. 4.0.14 (Biomedware, 2017) was used.

A distorted version of an estimation process is the simulation result, which reproduces the statistics of known data, making a realistic-looking at the model, but providing a low prediction behavior. Even so, if a multiple simulation sequence is designed, it will be possible to obtain more reliable probabilistic maps.

To perform the simulated scenario (SGS) for Cuellar Moor aquifer, a first normal transformation of the initial data was made. Simple kriging with reverse transformation has been used for interpolation. One hundred simulations have been calculated in order to obtain an average scenario (mean image - MI), along with associated spatial variation.

This spatial variation is the spatial uncertainty, which will be used to work on the reclassification.

Reclassification

The three spatial uncertainty layers obtained through the SGS process (piezometric level in wet scenario, piezometric level in dry scenario and nitrate concentration) have been reclassified into three values each. The interquartile range (Q_3 - Q_1) has been chosen as the measure which splits data series into three values. In this way, data values lower than interquartile range have been reclassified as 1 ($X < Q_1 = 1$). Data values between interquartile range have been reclassified as 2 ($Q_1 < X < Q_3 = 2$) and data values above the interquartile range have been reclassified as 3 ($X > Q_3 = 3$) (Table 1).

Table 1: Reclassification roles and assigned value.

Reclassification rule	Value
$X < Q_1$	1
$Q_1 < X < Q_3$	2
$X > Q_3$	3

Once the three layers have been reclassified, have been added as follows: On the one hand, the wet piezometric scenario layer plus the nitrate concentrationand, on the other, the dry piezometric scenario layer plus the nitrate concentration layer.

Both sums results are a scale from 2 to 6, where 2 represents the minimum vulnerability, value associated with uncertainty, and 6 is the maximum value.

In this way, a vulnerability index is obtained with five values, as shown in Table 2.

Table 2: Reclassification values and assigned denomination.

Value	Denomination
2	Very low vulnerability
3	Low vulnerability
4	Average vulnerability
5	High vulnerability
6	Very high vulnerability

RESULTS AND DISCUSSIONS

The vulnerability index, associated with spatial uncertainty, measures the degree of uncertainty associated with the estimation of several surfaces as a whole. It also provides, a global point of view on the aquifer areas which need further study. In the case of the Cuellar Moor aquifer, the used uncertainties have been the associated with the piezometric level estimation, both wet and dry scenario, and the associated with nitrate concentration estimation.

The resulted uncertainty map is a tool that allows to study more in detail management actions which must be carried out on this aquifer.

This vulnerability index is not intended to indicate which areas are most vulnerable to pollution. However, its purpose is to point out areas where there is less knowledge about aquifer dynamics. For example, if a vulnerability index is used, it will indicate in which areas special measures to prevent or reduce the contamination must be taken. However, the vulnerability index associated with uncertainty is pointing to areas with a more accurate about nitrate pollution is required. Therefore, the first step to prevent or reduce pollution will be to increase the monitoring of areas in which there is a high uncertainty.

On the other hand, it is a more meticulous method that allows to accurately locate micro-zones within the aquifer in which specific monitoring is required, regardless of the overall aquifer dynamics.

High vulnerability associated with uncertainty areas suggests a high uncertainty relatively to estimated nitrate concentration and to estimated piezometric level. This is interpreted as a high uncertainty in the water flow micro dynamics in those specific aquifer areas.

Summarizing, the vulnerability index associated with spatial uncertainty, allows to locate areas in which further monitoring is required, in order to strengthen pollution control and prevention measures. Then, actions carried out on aquifer highest vulnerability areas should be restricted, at least, until more detailed knowledge is available.

In the specific case of the Cuellar Moor aquifer both scenarios wet and dry are very similar. (Figure 3). The highest vulnerability values associated with spatial uncertainty appear in the most peripheral areas of the aquifer. Special care should be taken in the northern area, where is located an environmentally protected area: the Site of Community Importance "El Carrascal" (Alonso et al., 2015). Moreover, it is one of the aquifer area with a significant mining activities andan increase in monitoring becomes even more necessary.

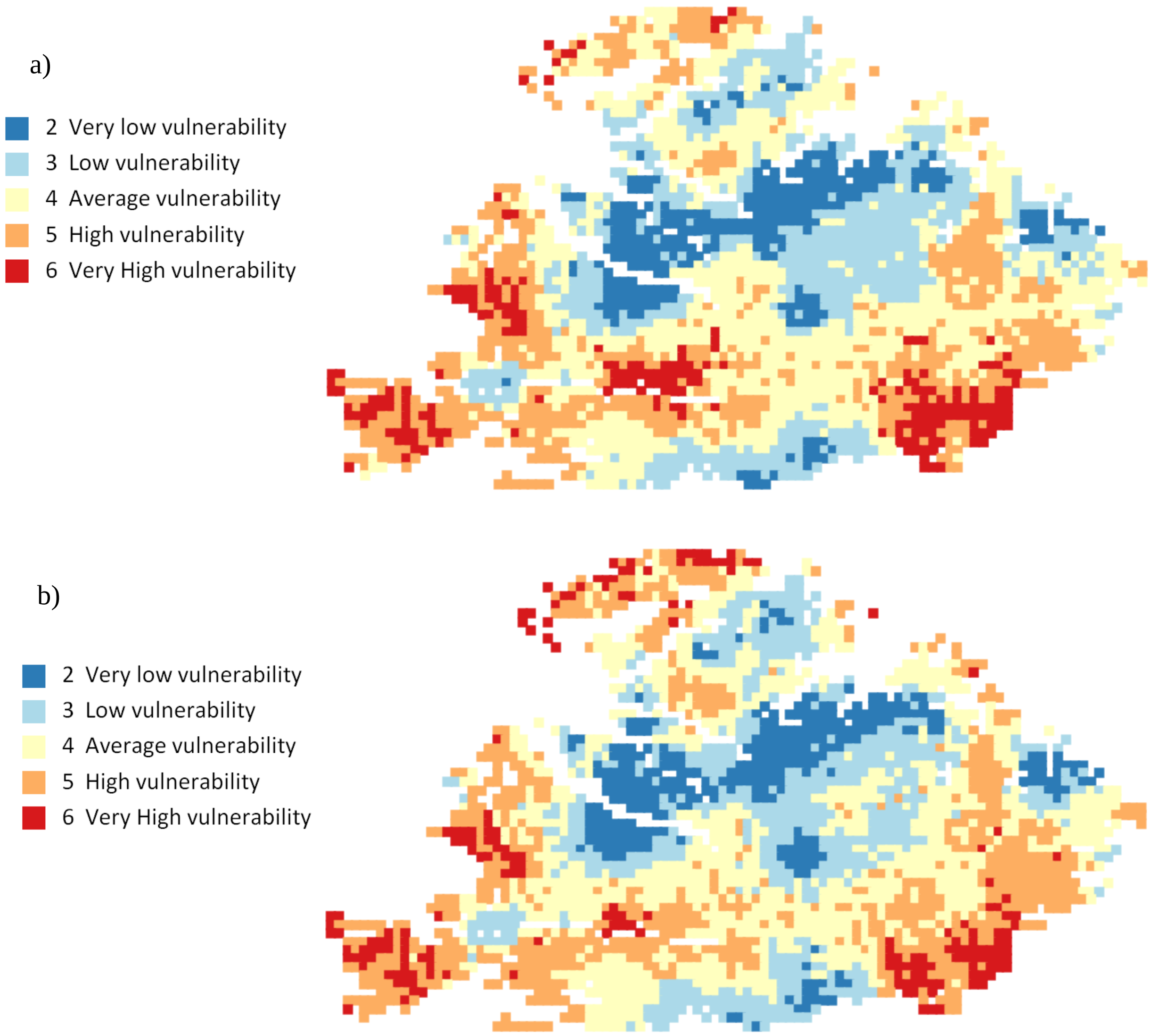

Figure 3: Vulnerability associated with uncertainty: a) in wet scenario; b) in dry scenario.

On the opposite side of the aquifer, in southeast, there is an highest vulnerability area associated with spatial uncertainty (Figure 3). Monitoring this area with a good planning is essential insomuch as the preferential water flow within the aquifer occurs from southeast to northwest (Alonso et al., 2015). Therefore, nitrate contamination resulted in that area, will be carried to the environmentally protected area “El Carrascal” by the preferential water flow.

On the contrary, the lowest vulnerability area associated with uncertainty corresponds to the central zone of the aquifer (Figure 3), as the area with the greatest thickness of limestone (Alonso et al., 2015). This area has the highest hydrogeological interest and consequently the most monitorization actions.

Karstic aquifers function as a complex system in which actions in certain areas can influence other parts of the aquifer, without the need for the two points to be located in a nearby area. For this reason, a good knowledge of each point of the aquifer is so necessary in order to ensure that areas with a greater hydrogeological interest maintain a good status, both qualitative and quantitative.

CONCLUSIONS

The following conclusions have been drawn from this study:

1. The vulnerability index associated with the spatial uncertainty is used to indicate areas with a less knowledge of aquifer dynamics.
2. The areas with highest vulnerability index must be monitored in order to have a better understanding of nitrates dispersion.
3. In the Cuellar Moor aquifer, the highest vulnerability associated with spatial uncertainty

occurred in the southeast area, coincident with water flow arises.

4. Monitoring must be increased in the environmentally protected area "El Carrascal", since it has a high vulnerability and receives a preferential water flow from the high vulnerability area located on the southwest.
5. The lowest vulnerability areas, associated with the spatial uncertainty, are located in the centre of the moor, and are associated to a greater knowledge of the aquifer dynamics.

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