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Geostatistics tailored to address nitrates spatial uncertainty in groundwater (Douro watershed, Spain)

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Abstract

The management of water resources is a priority for development of the places and welfare of people that supply, especially in water bodies most affected by anthropic pressures. Moreover, the increasing of sudden and extreme climatic phenomena appearance urges to resource planning in specific situations. In this research, the evolution of the piezometric surface has been simulated as the basis of a flow model draft, in the karstic aquifer of Cuellar Moor, located in the Douro watershed, all along the hydrologic years between 2010 and 2012. The use of geostatistical tools has been the starting point for estimating the piezometric surfaces, based on the median values. From the point of view of planning two scenarios showing extreme situations have been simulated: one of them synthesizes the most favorable conditions, in which piezometric level is at the recorded highest median levels (wet scenario); and the other one synthesizes the toughest conditions with the lowest recorded median piezometric levels (dry scenario). It likewise shows the estimated nitrate concentrations surface.

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1. Introduction

The Douro watershed is the most extended in the Iberian Peninsula all along with 98.073 km² (Confederación Hidrográfica del Duero, 2015). It is a transboundary territory correspondingly 20% in Portugal and 80% in Spain. Geologically the units presented in Figure 1 were identified and corresponding to particular hydrogeological characteristics (Sánchez San Román, 2006). On the Tertiary detrital unit a set of calcareous moors, with an average height of about eight hundred and fifty meters above sea level, is registered. One of them is the Cuellar moor.

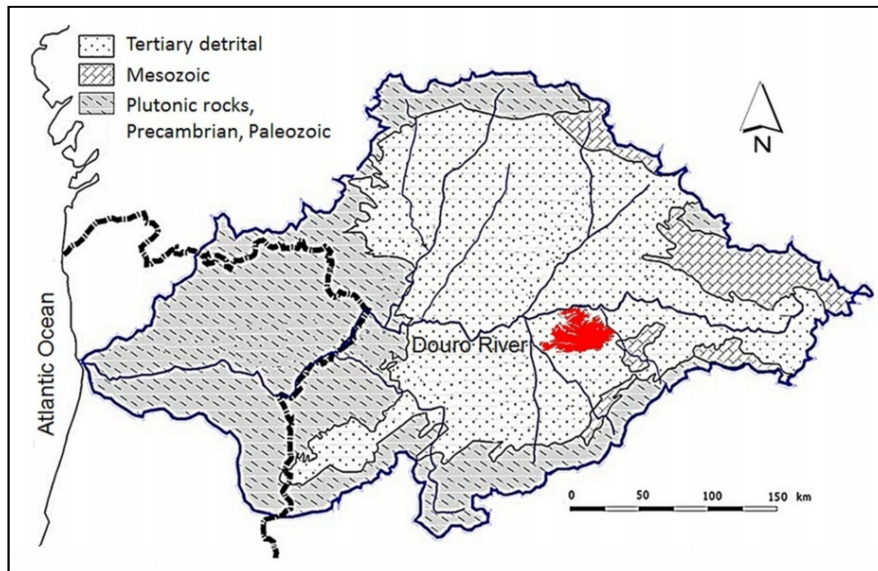


Figure 1. Geological map of Douro watershed where the Cuellar Moor aquifer is in red (adapted from Source: Sánchez San Román, 2006).

The Cuellar moor contains a “free” aquifer on top. Geographically, it is situated in the central part of the Douro watershed along 543.5 Km². It is bounded in the north by the Douro River, in the east by the Duraton River and in the southwest by Cega River. It is important to stress that in this area there are eleven villages where the urban water supply is made from the aquifer (Figure 2).

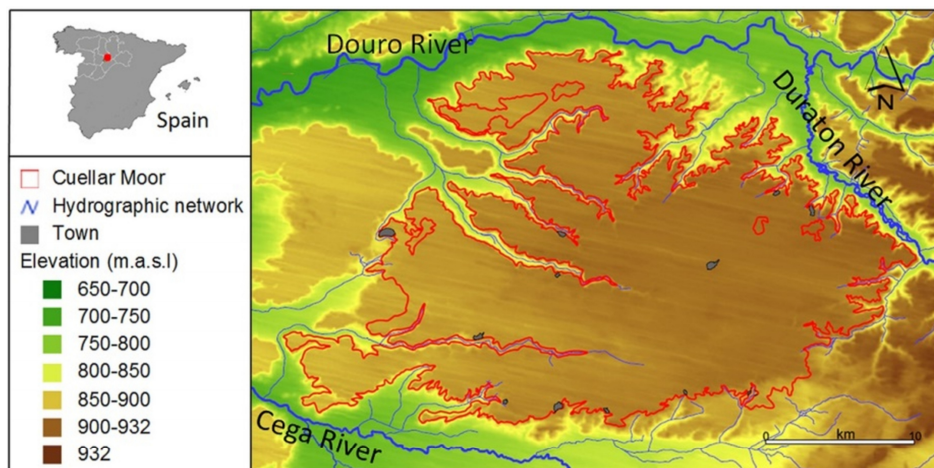


Figure 2. Cuellar Moor aquifer location, Spain.

Cuellar Moor aquifer is a karstic system. Geologically it is formed by limestone, with a maximum thickness reaching 60 meters. The recharge is essentially due to rainwater and reclaimed water routed to the subsurface. The

water comes out through evapotranspiration, pumping wells and springs which are always located along the moor’s perimeter and corresponding to the contact between the limestone layer and the clay/loam layer.

In Figure 3 it is possible to view a vertical log showing the aquifer limestone.



Figure 3. Geological vertical log.

Cuellar moor tectonics must be explained within the regional context of the Duero watershed. The most important issues concerning to the moor’s tectonics are the “Sistema Central” Mountains, especially in the eastern sector. In Figure 4, the main directions of flow that correspond to the major rivers by zone (A, B or C) are shown. In the B zone (Cuellar moor zone) rivers have as principal direction N 45° W (Babín Vich and Gómez Ortiz, 1997).

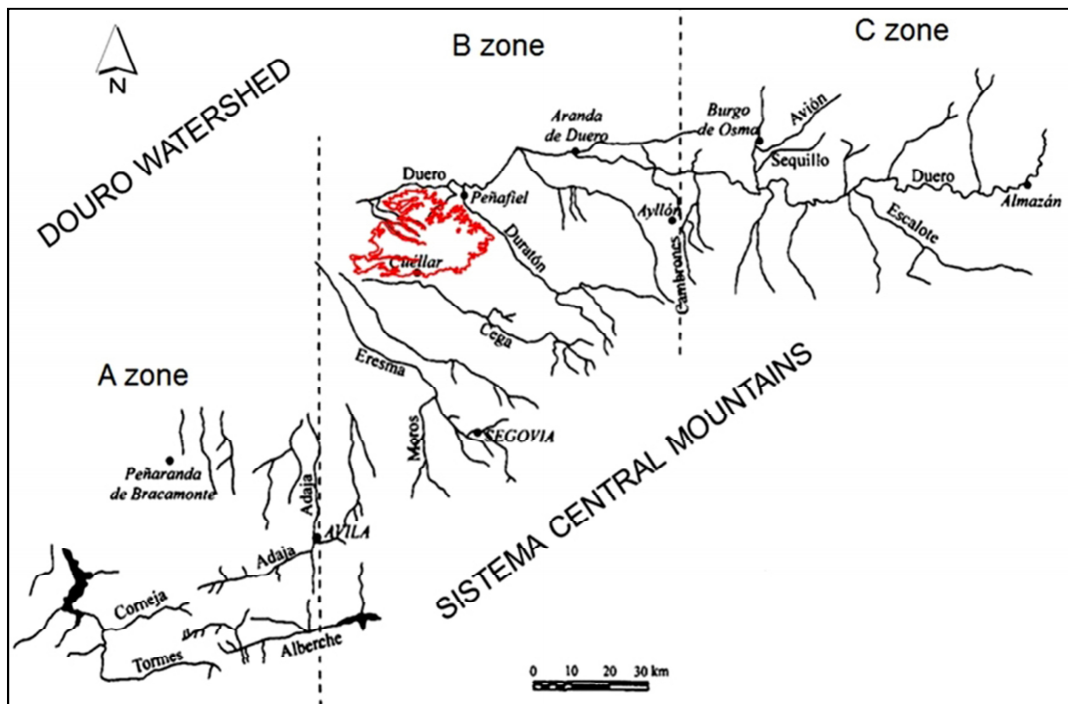


Figure 4. Disposition of the hydrographic network direction in the central-western area of “Sistema Central” Mountains. Cuellar Moor aquifer is in red (adapted from Source: Babín Vich and Gómez Ortiz, 1997).

2. Materials and methods

Piezometric data were gathered from the time series (1999 to 2013) of the Hydrographic Confederation of Duero (Confederación Hidrográfica del Duero, 2014) as well as from eight piezometers located in the Cuellar Moor aquifer. The obtained datasets showed heterogeneous values since they have not been measured in the same year or, even, in the same month. For this reason, the used dataset corresponds to the years of 2010, 2011 and 2012 as these three years are common with all the measured piezometers.

From piezometric data, two piezometric level surfaces have been simulated using Sequential Gaussian Simulation (SGS).

SGS was used for conditional stochastic simulation of the piezometric groundwater level distribution. SGS start by defining the univariate distribution of values, performing a normal score transform of the original values to a standard normal distribution. Simulation of normal scores at grid node locations was done sequentially with simple kriging (SK) using the normal score variogram and a Zero mean (Goovaerts, 1997; Deutsch, 2002) once all normal scores were simulated, they were back-transformed to original grade values. For the computation the Space-Stat software V. 4.0.18 (Biomedware, 2015) was used (Albuquerque et al, 2014; Faiz Rivas, 2009).

The outcome of a simulation is a twisted version of an estimation process, which reproduces the statistics of the known data, making a realistic look of the exemplar, but supplying a low prediction behavior. Even so, if a multiple sequence of simulation is designed, more reliable probabilistic maps is possible to obtain.

To capture spatial structure variographic study was carried in several directions to determine the flow behavior, that is, to obtain their preferred way. Variogram is a vector mapping, so it can be calculated in any direction in space, which facilitates the study of anisotropies in the spatial distribution of the variable (Chica, 2005). The 135° direction (N 45° W) has been determined like the most robust for main flow within the aquifer either for the dry as well as the wet season (Figure 5).

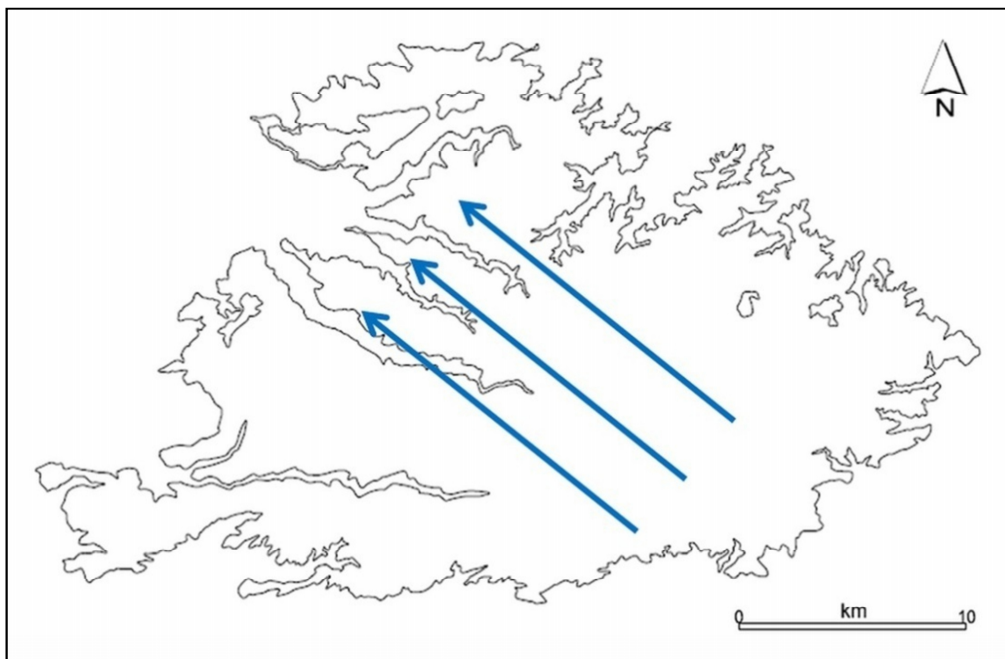


Figure 5. Preferential flow direction in the wet phase.

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). Experimental estimation of the function from the experimental data set is performed using the following formula:

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

Where $Z(x_i)$ and $Z(x_i + h)$ are the numerical values of the observed variable at points x_i and $x_i + h$, and $N(h)$ is the number of forming pairs for a h distance. It is, therefore, the mean value of the square of the differences between all pairs of points existing in the geometric field spaced at a h distance (Garcia Pereira, 1979).

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

The first average obtained scenario shows the wet season and the second one corresponds to the dry season scenario. To perform the simulated scenarios (SGS) for the Cuellar Moor aquifer, a first normal transformation, of the input data, was made. Simple kriging with back transform was used for interpolation. Twenty simulations were computed for each season in order to get the average scenario together with the spatial associated variance (Figure 6 and Figure 7).

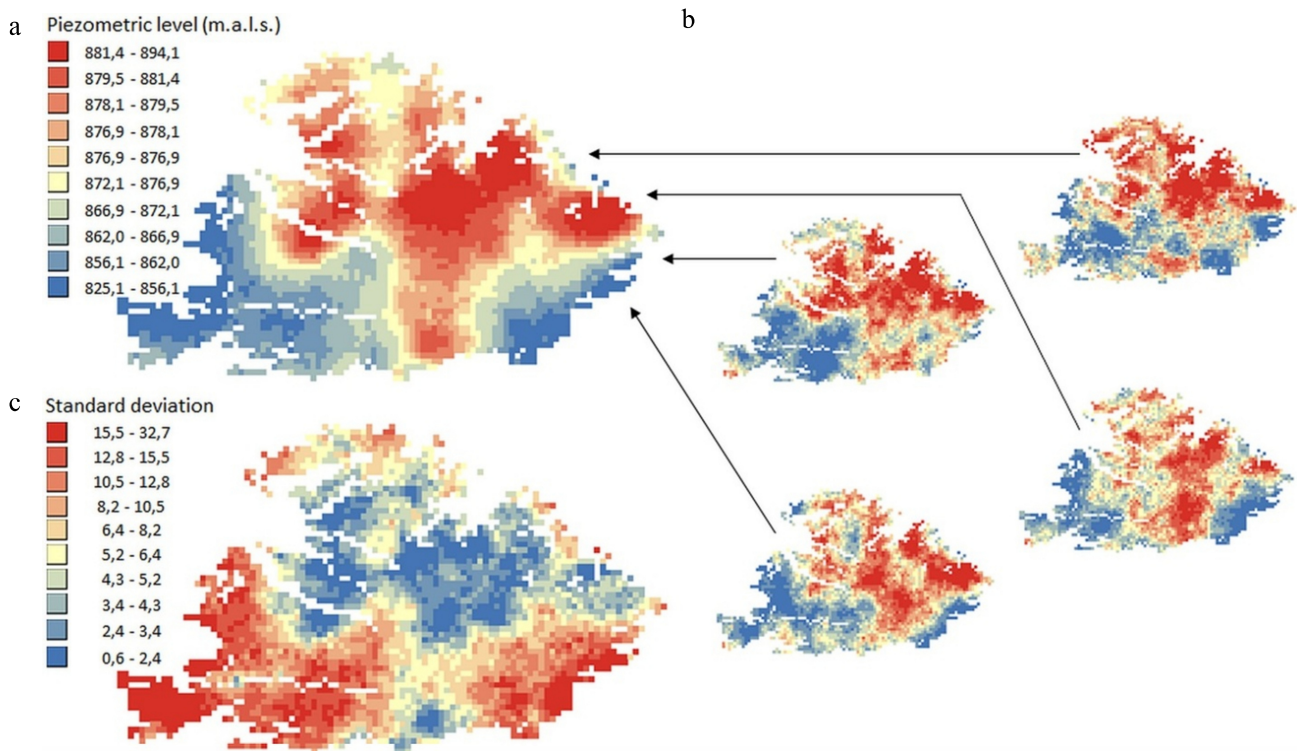


Figure 6. Wet season scenario; a) average piezometric level distribution; b) four of twenty simulated scenarios; c) spatial uncertainty.

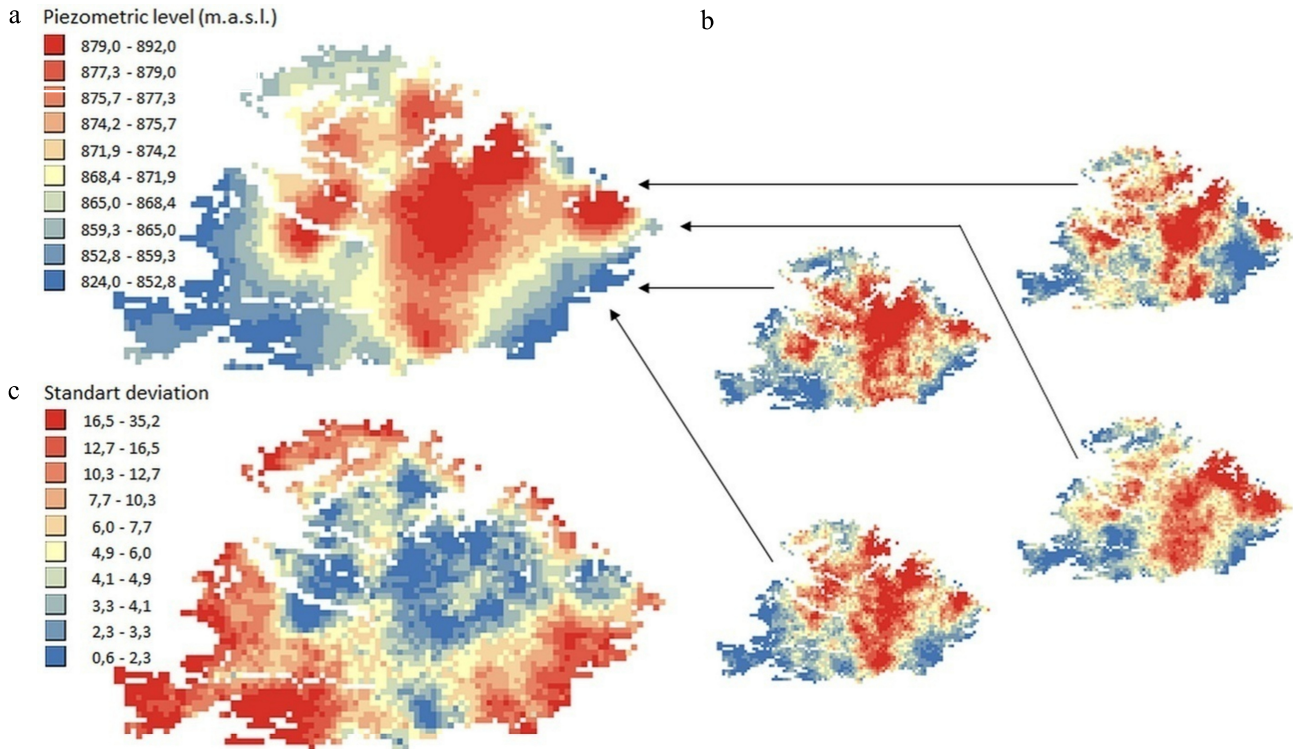


Figure 7. Dry season scenario; a) average piezometric level distribution; b) four of twenty simulated scenarios; c) spatial uncertainty.

Limestone wall aquifer has been obtained from interpolating depth data provided by the piezometers using Inverse Weighted Distance. There is a clear difference between the east, where the highest heights are located, and the west, where the lowest heights are located (Figure 8).

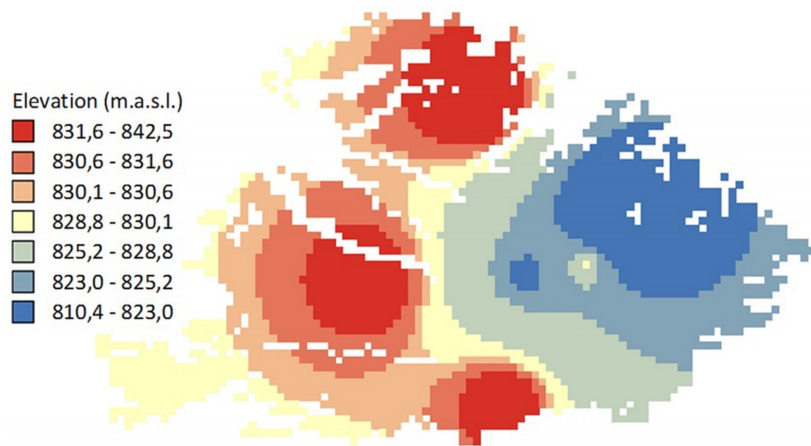


Figure 8. Estimated limestone wall.

The nitrate surface was calculated using as baseline data 23 measurements points obtained during 2011/2012 field campaigns. The obtained data showed no considerable variations throughout the all hydrological year so, average measurements for each spring was taken as representative. Interpolation was carried out by Ordinary Kriging (OK). The omnidirectional adjust variogram and fitted model parameters as well as the nitrate distribution are presented (Figure 9).

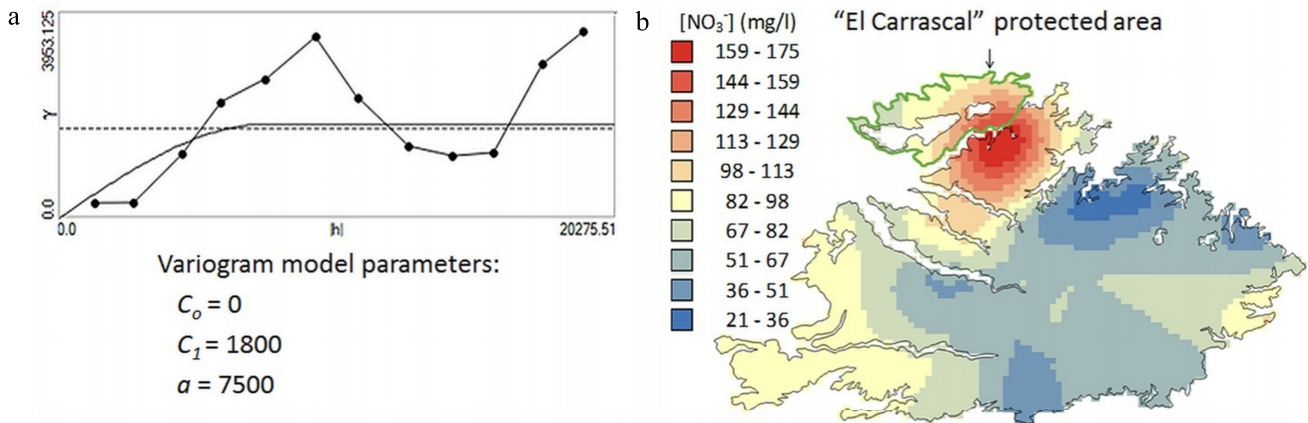


Figure 9. Nitrates estimated map: a) variogram and fitted model parameters; b) estimated map.

The OK estimator (Matheron, 1970; Journel and Huijbregts, 1978) used to extrapolate a value is a linear weighting of the experimental values $Z(x_i)$ by unknown coefficients λ_i (Chica, 2005):

$$Z_{OK}(x) = \sum_{i=1}^n \lambda_i Z(x_i) \quad (2)$$

3. Results and discussions

The estimated piezometric level surfaces, both the wet scenario and dry scenario results from the mean of the 20 simulations performed showed the presence of three domes located in the central and northeast zone of the aquifer where the highest levels are recorded. On the contrary, it is in the southeast and southwest sectors where lower piezometric levels are recorded (Figure 6a and Figure 7a).

In the wet scenario the greatest spatial uncertainties have been observed in the southeast and southwest zones, decreasing gradually towards the center of the aquifer (Figure 6c). Spatial uncertainty associated with dry scenario is very similar to the wet since the points through which the surface has been interpolated are the same (Figure 7c). However piezometric level domes, in both seasons, coincide with lower uncertainty zones, which ensure the preference flow starting in these domes heads.

Respecting to the limestone wall, the greater thickness and therefore, greatest water potential are located in the central and northwest area (Figure 8).

On the other hand, high spots of nitrate pollution are confined to the northern sector of the moor (Figure 9b), in which is located a protected site called "El Carrascal". The presence of a protected area near high levels of nitrate concentration additionally showing a high uncertainty associated, makes key statement the implementation of a monitoring network to determine whether the nitrate pollution is increasing or, on the contrary, the aquifer hydrodynamics (Figure 5) prevent dispersion allowing self-deportation. Other important areas to monitor and assess correspond to the isolated points, in the west and east of moor, where high nitrate spots were mapped the northeast and south of the aquifer, which are the areas coincident to the highest piezometric levels.

4. Conclusions

As key conclusions should be emphasized:

1. The way of preferential flow to the aquifer of Cuellar Moor is N 45 ° W which is likewise the known regional hydrographic network that includes the moor.
2. The highest volume of water is located in the central and northwest of the aquifer region.
3. The lowest spatial uncertainty is overlapping these areas which allows an accurate approach for the distribution

patterns obtained for the simulated piezometric levels (wet and dry seasons).

4. The aquifer presents the maximum thickness of limestone in the central and northwest sector.
5. The nitrates dispersion is not a problematic issue. The highest concentrations are found northwest and since the main flow direction is southeast-northwest, the key problem is the implantation of a monitoring net in order to assess the associated risk.

As future developments are aimed:

1. Improve the sampling design, especially in the southwest and southeast of the moor, where the highest spatial uncertainties were observed;
2. Constructed a vulnerability map, taking into account land use as an ancillary variable in the nitrate's concentration surface simulation;
3. Improve a detailed monitor net in order to determine whether corrective actions are needed in the "El Carrascal" protected area.

Acknowledgements

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