Identification of groundwater quality trends in a chalky aquifer threatened by intensive agriculture

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ABSTRACT: Diffuse groundwater contamination related to agricultural practices is a worldwide environmental problem, particularly the continuous increase in nitrate concentrations. As a response to this threat, the European Union has adopted directives requiring that Member States take measures to reduce agricultural nitrate sources and stating that a "good" status of groundwater is required for all EU members. In order to achieve the environmental objectives for groundwater, the identification and reversal of any significant upward trend in the pollutant concentrations are required. Conclusions are drawn about the evolution of groundwater contamination by nitrates in the following decades with respect to the EU Water directive prescriptions. Measures have to be urgently taken in order to avoid major degradation of groundwater in 10 to 70 years. However, a good groundwater quality status cannot be expected for the 2015 EU Water Framework Directive (WFD).

KEYWORDS : Groundwater; Nitrate contamination; Trend analysis; Linear regression; Mann-Kendall test; Hesbaye aquifer; Geer basin.

1. Introduction

As a response to the continuous increase of use on fertilizers and pesticides in last decades related to agricultural practices, the European Union (EU) has adopted in 1991 the Nitrate Directive (91/676/EEC) requiring that member states take measures to reduce agricultural nitrate sources in high nitrate contaminated zones. More recently the "Water Framework Directive 2000/60/EC" (WFD) has been published, stating that a good status of ground water is required for all EU members and specific measures have to be adopted to prevent and control pollution of ground water, establishing the maximum allowable concentration of nitrate in drinking waters at 50 mg $NO_3^-\cdot l^{-1}$. In order to achieve the environmental objectives for groundwater, the WFD requires identifying and reversing any significant upward trend in the concentration of pollutants and a "good" groundwater status by the end of 2015 at the latest.

2. Methodology for statistical trend analysis

The methodology used in this research mostly follows the works of Grath *et al.* (2001) who proposed particular algorithms and techniques for the identification of pollutants trends in ground water. As suggested by Hirsch *et al.* (1991), a three-step procedure is considered: 1) normality test of the dataset; 2) trend detection; and 3) trend estimation.

2.1. Normality of the dataset

In order to select the trend detection method to be applied (parametric or non-parametric), the Shapiro-Wilk test or the Shapiro-Francia test, are used depending on the number of records of the dataset (Conover, 1980; Helsel and Hirsch, 1995).

2.2. Trend detection

For normally distributed datasets, a simple linear regression is applicable as a tool for trend detection. Trend detection is based on the calculation of the correlation coefficient r, also called Pearson's r, which is a quantitative measure of correlation between time t and concentration C.

For non-normally distributed datasets, trend detection is performed using the non-parametric Mann-Kendall test (Mann, 1945; Kendall, 1975).

The *MK*-test do not assumes any distribution form for the data and has the similar power as the parametric methods (Serrano *et al.*, 1999). The *MK*-test determines whether a trend is present or not with an indicator (T) based on the calculation of differences between pairs of successive data:

$$T = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sign\left(C_j - C_i\right), \tag{1}$$

where:

$$sign\left(C_j - C_i\right) = \begin{Bmatrix} 1 & if & C_j - C_i > 0 \\ 0 & if & C_j - C_i = 0 \\ -1 & if & C_j - C_i < 0 \end{Bmatrix}, \tag{2}$$

where C_j and C_i are concentration data at different time i and j, with $j > i$ and n is the size of dataset.

A 95% significance level has been used for the trend detection test (Helsel and Hirsch, 1995), corresponding to a threshold value of $T_{thresh} = 1.65$.

2.3. Trend estimation

The trend magnitude is expressed in units of increment of nitrate concentration per year ($mgNO_3^- \cdot l^{-1} \cdot year^{-1}$).

For normally distributed datasets, the magnitude of the trend is estimated using the slope b of the linear regression equation (EPA, 2000).

For non-normally distributed datasets, the trend magnitude is based on calculation of the Sen's slope estimator (Hirsch *et al.*, 1991) which is the nonparametric alternative to the linear regression slope. It consists in computing the slopes (b_{ij}) for all pairs of successive data as follows

$$bij = \frac{C_j - C_i}{t_j - t_i}, \tag{3}$$

where C_i *and* C_j are nitrate concentrations at time t_i and t_j, respectively. Finally, the value of the Sen's slope estimator (H) is the median of those slopes (EPA, 2000):

$$H = median\left(b_{ij}\right) \tag{4}$$

3. Geographical, geological and hydrogeological context

The Geer river is a tributary of the Meuse river downstream of the city of Liège. The basin, located in the Eastern part of Belgium and extends over about 480 km^2.

The Hesbaye aquifer, located in the Senonian chalk formations of the Geer basin, is an important ground water resource for drinking water supply for the city of Liège and its suburbs, which means around 30 million cubic meters per year (Brouyère *et al.*, 2004a). The land use is characterized by a dominant agricultural component, covering about 65% of the

catchment area, the remaining space remaining being divided between pastures (15%), housing (13%) and forests (7%) (Broers *et al.*, 2005).
The chalk formation is dipping northwards and presents continuity out of the basin. Most of the aquifer is unconfined except in the Northern part of the basin, where semi-confined conditions prevail on the left bank of the Geer river.

4. Nitrate dataset

Nitrate datasets used in this study come mainly from the Nitrate Survey Network (NSN) established by the Walloon Region water authorities and form VMW (Vlaamse Maatschappij voor Watervoorziening), the Flemish water supply company.
The nitrate network considered in the study is made of 57 sampling points, among which 24 have been considered a priori as containing suitable records (i.e. a minimum of 10 nitrate records over time) for trend analysis. The remaining 33 points could not be used for trend analysis because of either too small number of records or non detected presence of nitrate (mostly in the north-western part of the basin corresponding to the confined zone).

5. Description of the point-by-point trend estimation

A total of 17 sampling points are characterized by an upward trend (71 % of the points), the annual increase of nitrate concentration ranging between 0.3 and 0.8 $mg{\cdot}L^{-1}{\cdot}year^{-1}$. The remaining points (7 over 24), which do not show any evidence of upward or downward trend, generally corresponds to sampling points with limited nitrate records, irregularly distributed in time. One can notice that these datasets are made of 8 and 9 records, distributed on 6 and 4 years respectively. These results indicate that in context similar to that of the Geer basin, a minimum of 20 samples, distributed over a period of 10 years (frequency of 2 samples/year) is required in order to reliable sampling location for statistical trend analysis.

6. Trend extrapolation

Because changes in agricultural practices have started recently, it can be considered that the trends observed nowadays are likely to remain for years. Based on this assumption, a “simple” trend extrapolation is relevant in order to estimate the time remaining before ground water be unusable for public water supply (Figure 1).
A rough estimation of the time remaining before the threshold concentration of 50 $mg{\cdot}l^{-1}$ would be reached in various parts of the chalk aquifer, has been calculated based on a point-by-point extrapolation of nowadays nitrate contamination levels using nitrate trend estimates in this research. To do so, the present contamination level has been estimated at 36 of the 57 available points (excluding in the North where nitrate have not been detected) based on a point-by-point calculation of mean nitrate concentration over the period 1999-2003, assimilated to year 2001. Then, using the trend estimated value at the nearest available point, an estimation of the time remaining to reach the water-drinking limit was performed.

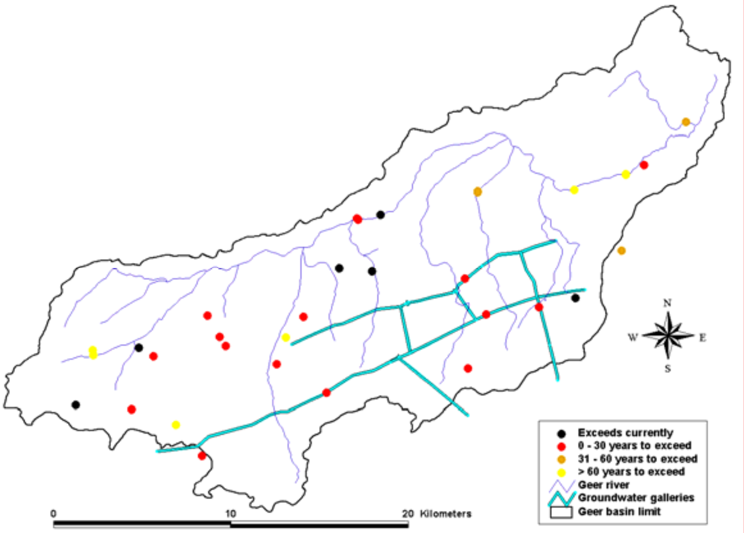

Figure 1. Foreseen time before excess of nitrates with regards to the 50 mg $NO_3^{-}\cdot l^{-1}$ threshold value. Black circles show points with critical concentrations of nitrate over the drinking limit; red circles denote points reaching this value in a period of 30 years; orange circles denote points reaching the threshold value between 31 and 60 years, and yellow circles show points reaching the drinking limit after 60 years.

7. Conclusions and perspectives

It has been showed that in cases where parametric and non-parametric methods can be applied, results are similar for both methods, concluding that non-parametric methods (*MK*-test in this case) are perfectly applicable for datasets normally distributed, making this test suitable for the WFD application.
Taking into account the foreseen time extrapolation and the transit time (approximately 1 $m\cdot year^{-1}$ as deduced by Brouyère *et al.*,(2004b)) of nitrates across the thick unsaturated formations (from 10 to 70 m) to reach the groundwater, means that measures taken today will have an observable effect with a delay of 10 to 70 years. It gives thus more than time to react.

At present, geostatistical analyses are in the way in the Geer basin to propose an optimized monitoring network well adapted to the needs of the basin.
On top of that, a regional ground water model is being developed. This model will be used for nitrate trend analysis and forecasting in the Geer basin. For this purpose, nitrate trend results obtained in the present study will be aggregated and used as calibration and validation datasets for the ground water flow and transport model.

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