

C. Rentier
F. Delloye
S. Brouyère
A. Dassargues

A framework for an optimised groundwater monitoring network and aggregated indicators

Received: 20 January 2006
Accepted: 3 February 2006
Published online: 9 March 2006
© Springer-Verlag 2006

C. Rentier · S. Brouyère
A. Dassargues (✉)
Hydrogeology and Environmental
Geology, GEOMAC Department,
University of Liège, Liège, Belgium
E-mail: alain.dassargues@ulg.ac.be

C. Rentier · F. Delloye
Groundwater Direction, Water Division,
DGRNE, Walloon Region, Belgium

S. Brouyère
AQUAPOLE, University of Liège,
Liège, Belgium

A. Dassargues
Hydrogeology and Engineering Geology,
Geology-Geography Department,
Katholieke Universiteit Leuven,
Leuven, Belgium

Abstract The implementation of the Water Framework Directive (EU 2000) requires a groundwater quality monitoring. It is used for characterisation of the ‘good’ chemical status of each groundwater body and for the restoration or protection purposes of those bodies already at ‘good’ status. Interpretative aspects are lying in the design of monitoring network and in the way of building global indicators. Attention is given here to the global chemical status of the groundwater bodies and to the role of diffuse pollution, much of which is brought via groundwater to surface water. Monitoring ‘local’ pollution associated with individual sites is not addressed. Groundwater bodies with different contrasted hydrogeology conditions, land use and topography have been considered to

establish an approach for choosing an optimised monitoring network. Then, a quality assessment system has been developed and applied for qualifying the general status of each groundwater body. The use of non-dimensional indexes allows us to process with all kinds of chemical parameters in a normalised way and, by means of adequate aggregation rules, to qualify the general quality status of a groundwater body. The obtained diagnostic, even if not fully validated, is closely linked to the pragmatic objectives contained in the EU Water Directive.

Introduction

Groundwater is an essential component of the hydrological cycle. It supplies up to 80% of public water demand in Walloon Region of Belgium. Indeed, it also provides critical support to the wider aquatic environment and associated ecosystems. Like in many countries, much of the recent improvement in river water quality can be attributed to the reduction in the direct discharge of pollutants from point sources of contamination. The attention is now turning to the role of diffuse pollution, much of which occurs via groundwater (Ward et al. 2004).

The European Water Directive 2000/60/CE establishing a framework for Community actions in the field

of water policy aims at coordinating the Member states’ water management within the international river basin districts. The directive sets three general objectives concerning groundwater: (1) to prevent deterioration, (2) to enhance and restore in order to achieve good water status at the latest in 2015, and (3) to reverse any significant and sustained upward trend of any pollutant. Member States are requested to establish monitoring programmes to characterise groundwater chemical and quantitative status. All substances resulting from the impact of human activity must be controlled.

Understanding the spatial distribution of groundwater quality and determination of temporal groundwater quality trends is essential to design the monitoring tools,

to decide about the required networks, and to choose aggregation techniques for providing reliable 'indicators' at the groundwater body scale.

A strategic framework has been recently designed for groundwater quality monitoring in the Walloon Region of Belgium. The methodology that has been applied for optimising the monitoring of network and to calculate aggregated indicators at the groundwater body scale is described hereafter and illustrated on the example of the Hesbaye aquifer located near the city of Liège in Belgium.

Objectives

Natural groundwater quality is mainly dependent on the geochemical processes that take place when rain or surface water infiltrates the ground and reacts with the soils and rock-forming minerals. Impacts of human activities and the release of pollutants to the aquatic environment are superimposed on this natural quality status. However, it should be noted that the quality of rainwater may have already been strongly affected by human activities. Pollutants are various in nature and include synthetic organic chemicals, hydrocarbons, inorganic cations and anions, pathogens, radionuclides, etc. It is beyond the scope of this work to discuss about monitoring well design, equipment installation, well sampling in depth averaged conditions or multi-level sampling, and quality assurance of the chemical analysis, but all these issues may strongly influence chemical results. Within the framework described here, mainly the two following questions will be addressed. How can we select the sampling points in order to obtain a representative monitoring network? How can we aggregate the results in simplified but reliable indicators readable by decision makers?

Groundwater quality cannot be interpreted from a static point of view, i.e. assuming stationary conditions both at the site of infiltration and along the possible flow line, without reversals of flow patterns in time (Appelo and Postma 1993). It varies spatially in relation to residence time, aquifer mineralogy, chemical environment, spatial variation in land use and associated polluting activities. To understand the temporal as the spatial groundwater quality changes, a reliable understanding of the groundwater body is needed. So, hydrogeological characterisation is required before 'optimising' the monitoring network.

Specifically, the monitoring network must: (a) be compliant with Walloon and European commitments, (b) provide objective, reliable and comparable information, (c) define natural or 'patrimonial' groundwater conditions, (d) allow determination of trends, (e) provide early warning of groundwater pollution, and (f) identify hydraulic and geochemical interactions with surface water systems.

Selection of monitoring points

The EU working group on the implementation of the Water directive recommends a density of about 1 point/25 km², where the groundwater body is expected to be 'under pressure', and 1 point/100 km² otherwise. A spatial representativity within each body through scientific judgement is also recommended. A representativity index R_U has been proposed and it should reach a value of 80% (WFD-GW 2001):

$$R_U = \frac{37.7}{d} \sqrt{\frac{n}{A}} \quad [\%],$$

where d is the mean distance from any point of the groundwater body to the nearest sampling point, n , the number of sampling points, A , the total area of the groundwater body.

Rather than applying blind geostatistics, it is here preferred to give more importance to the conceptual model/understanding of the groundwater system and how pressures interact with that system. The proposed criteria for selection of sampling points are among others, the following:

- upward or downward position of the measurement point (with respect to the piezometric gradient);
- integrating/representative character of the measurement/sampling point;
- natural (or man induced) variability of already available historical measured data;
- absence of point contamination sources;
- accessibility of the measurement/sampling point;
- knowledge and reliability about the well equipment (position and length of the screens); and
- present status and ownership of the well.

The groundwater body of the Geer basin can be taken as an example. It provides about 60,000 m³/day of drinking water for the city of Liege and its suburbs (Dassargues and Monjoie 1993). The Hesbaye plateau extends over about 350 km². Altitudes range from 206 m in the southwest to 80 m in the north-eastern part of the region. From top to bottom, the substratum is made up of (Brouyère et al. 2004):

- a Quaternary loess of variable thickness, up to 20 m;
- a maximum of 10 m of a flint conglomerate, highly heterogeneous geological formation made of dissolved chalk residues (flints, sand, clay and local phosphate);
- locally, several meters of Tertiary sand deposits, mostly in the north of the Geer basin, where they take the place over the flint conglomerate;
- Cretaceous chinks forming the main reservoir of the Hesbaye aquifer, showing depths ranging from a few meters in the south up to 100 m in the north-eastern part of the basin; and

- at the bottom, several meters of smectite clay of low hydraulic conductivity, considered as the aquifer base.

The mean hydraulic gradient in the aquifer is north oriented, ranging from 0.01 in the south to 0.003 in the north, close to the Geer River (Dassargues and Monjoie 1993). The groundwater table is located at depths ranging from 10 m to more than 40 m below the land surface.

Most of the aquifer is unconfined, except in the north, where semi-confined conditions prevail under the Geer alluvial deposits. Fractured zones in the chalk also correspond to dry valleys visible in the surface morphology. Finally, dug in the lower part of the chalk, 40 km of galleries belonging to a local water company play a key role in the shape of the piezometric surface. Groundwater is drained in most portions of the galleries but an important quantity of water is also recharged from the galleries into the aquifer in other zones, depending on local differences between water levels in the aquifer and in the galleries. Apart from the galleries, the aquifer is exploited by pumping wells owed by water companies, local industries and agricultural settlements.

Since 1960, nitrate concentrations have risen annually at a rate ranging from 0.1 mg/l (as NO₃) in the semi-confined to 1 mg/l in the unconfined part of the aquifer. Presently, the mean concentration is around 35 mg/l, from 20 mg/l at the aquifer bottom to more than 175 mg/l in the contaminated zones from the upper aquifer (Brouyère et al. 2003).

According to the guidelines (Eurowaternet 1998), about 14 points were required. These 14 selected sam-

pling points, among 556 available points, are selected through a scientific hydrogeological judgement based on previous studies of this aquifer (Dassargues et al. 1988; Dassargues and Monjoie 1993; Hallet 1998; Brouyère 2001, Brouyère et al. 2003). The obtained spatial distribution is shown in Fig. 1.

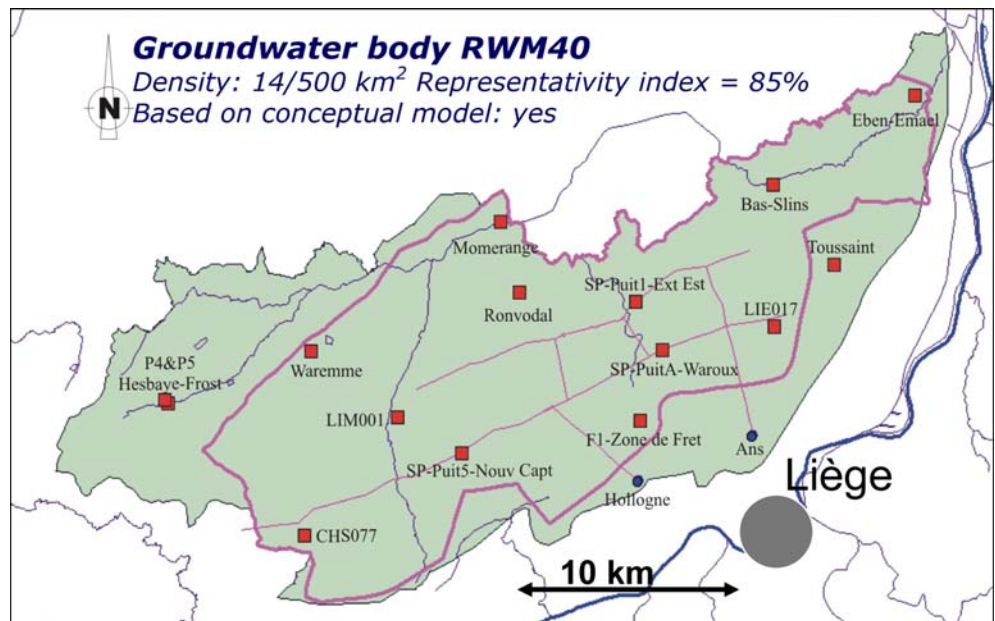
Among those 14 selected points, 7 correspond to pumping wells or outlets of draining galleries belonging to water companies, 7 are sampling piezometers.

Groundwater quality assessment system

All substances resulting from the impact of human activity must be controlled. A groundwater quality assessment system named SEQ-ESO (for 'Système d'Evaluation de la Qualité des Eaux Souterraines'), originally developed by the French Water Agencies (Agences de l'Eau 2002) has been adopted. The main principles of this system will be described hereafter. In order to satisfy the requirements of the Water Framework Directive, this system has been developed for qualifying the general hydrochemical status of groundwater bodies by means of aggregation techniques of groundwater quality measurements from a representative monitoring network.

In order to examine all compounds with a normalised scale, each value is converted into a non-dimensional index according to simple interpolation lines and curves between the thresholds. The parameters are then grouped together into consistent packages called 'alterations'. The quality class for each alteration is given by

Fig. 1 The 14 selected points of the monitoring network in the groundwater body of the Geer basin near Liège (Belgium)



the index of the most problematic compound of the group (security choice) for this considered alteration. This allows synthesising greatly the concept of groundwater quality. Not entering in to too much detail, the following alteration groups have been distinguished:

- mineralisation and salinity (pH, hardness, Cl, SO₄, ...);
- organic matter and nutrients (N, P, TOC, ...);
- filterable elements and particles (NTU, Fe, Mn, Al, ...);
- mineral micro-pollutants (Cu, Zn, As, B, Cn, Cd, ...);
- pesticides; and
- PAH (Polycyclic Aromatic Hydrocarbons) and other organic pollutants (PCE, TCE, HCB index, ...).

Basically, the SEQ-ESO provides an interpretation grid of a complete protocol analysis related to a single water sampling point. The system is based on the establishment of parameter thresholds defining quality classes.

Groundwater quality assessment is a relative concept depending on water use. As far as groundwater is concerned, the SEQ-ESO system considers three essential functions for groundwater:

1. *Water use*: the quality of water compared to the standards or needs corresponding to various uses is defined. The principal use introduced into the SEQ-ESO is the aptitude for Drinking Water Use (DWU). Other uses of water in such areas as industry, energy, the irrigation and the drenching can also be evaluated.
2. *Patrimonial status (PS)*: It expresses the degree of degradation of groundwater due to impacts of human

activities without reference to any specified use. This scale of deterioration of the groundwater quality is based on indicating solute concentrations not present at the natural state (organic and mineral micro-pollutants) or clearly identified as a result of specific human activities when lying above known thresholds (nitrates and pesticides).

3. *The chemical aptitude of groundwater for biology needs in surface water biotopes (BIO)*: In this function, different surface water physico-chemical quality status are taken into account for assessing the required groundwater quality. It thus makes the assumption of a 100% feeding of the river by groundwater.

At this stage of the research, this third function of water is not discussed. For each of the two other functions DWU and PS, specific threshold concentration values are chosen following the guidelines given in Table 1. Results of an application of these guidelines for the particular case of nitrates are shown in Fig. 2.

A major advantage of the SEQ-ESO consists in the possibility of combining two functions. Combining the DWU and PS functions, to obtain a general expression of the Groundwater Quality (GWQ), as illustrated in Fig. 2 for nitrate, it is observed that the two first thresholds for Groundwater Quality are dictated by the PS function when the others are prescribed by the DWU function.

Each GWQ threshold is then converted by interpolation into a general quality index (I_g) ranging from 100 (best quality) to 0 (worst quality).

Application of the SEQ-ESO system to the Geer groundwater body is illustrated in Fig. 3. At each sam-

Table 1 Guidelines in the choice of the considered threshold concentrations for the drinking water use (DWU) and for the patrimonial state (PS): application for nitrate is shown in Fig. 1

DWU	DWU-1 (blue/green)	Guide concentration value of EU Directive 80/778 related to drinking water quality, or choice of an intermediate value between 0 and the drinking water standard
	DWU-2	DWU-2 threshold does not exist for nitrates
	DWU-3 (green/orange)	Concentration value of EU Directive 98/83 relevant for raw water
	DWU-4 (orange/red)	Concentration value of EU Directive 75/440 relevant for water being treated in view of drinking water supply
PS	PS-1 (blue/green)	Corresponds as closely as possible to a 'natural status'. In practice, it is a 'reference status' set as the usual analytical detection limits for organic compounds, an expert judgement value (i.e. for nitrates = 10 mg/l) or reference values for minerals and metals according to the local Soil Conservation Law. It is based on estimated natural geochemical background in aquifers
	PS-2 (green/yellow)	Is fitted so that the complete set PS-1, PS-2, PS-3, PS-4 corresponds to an arithmetic or geometric series according to the considered pollutant (Agences de l'Eau 2002)
	PS-3 (yellow/orange)	Threshold value from which 'action' (prevention/control) is required to reverse the general current trend in groundwater quality (not yet definitively prescribed by EU). It is chosen here as 75% of DWU-3
	PS-4 (orange/red)	Remediation threshold taken from the Soil Conservation Law. A distinction is made here between diffuse pollutants (nitrates, pesticides) and point source pollutants like hydrocarbons and heavy metals. The chosen value is based on criteria considering the pollutant mobility in groundwater, the human health and eco-toxicity

Drinking Water Use (DWU)		General Quality			Patrimonial Status (PS)	
Best quality for drinking water; Directive 80/778 guide value	DWU-1 = 25 mg/l	Index = 80	GQ1 = 10	Very good	PS-1 = 10 mg/l	Pristine or natural quality content; geochemical background; no detection of organic compounds
Drinking water: concentration value of EU Directive 98/83 relevant for raw water		60	GQ2 = 25	Good	PS-2 = 25 mg/l	Anthropogenic contamination detected
Water unsuitable for drinking water supply	DWU-3 = 50 mg/l	40	GQ3 = 50	Medium	PS-3 = 37,5mg/l	Significant deterioration from "natural" status
Water unsuitable for a treatment to produce drinking water	DWU-4 = 100 mg/l	20	GQ4 = 100	Bad	PS-4 = 50 mg/l	Important deterioration from "natural" status
		0		Very bad		Very important deterioration from "natural" status; contaminated sites cleanup required

Fig. 2 Table of the General Quality Index for nitrate as deduced by consideration of Drinking Water Use (DWU) and Patrimonial Status (PS) thresholds

pling point of the monitoring network, the limiting compound with respect to the Drinking Water Use (DWU, Fig. 3a), to the PS (Fig. 3b) and finally to the general Groundwater Quality (GWQ, Fig. 3c) can be identified.

Building of an aggregated indicator

In order to satisfy the requirements of the EU Water Directive, the SEQ-ESO has been developed to assess the global quality of groundwater in the whole groundwater body. The SEQ-ESO uses aggregation techniques through a simple arithmetic mean as prescribed by the directive. Data from each site of the monitoring network must be aggregated into a single global quality indicator (with respect to the water function). The two first steps of the aggregation are the following:

1. Each measured compound concentration is normalised using an index between 0 and 100.
2. For each compound and in each point, an arithmetic mean is calculated over a considered period of time providing a PMI (Point Mean Index).

Then, two different techniques may be worked out. A first one can be qualified as a 'compound aggregation technique', where:

- (c1) For each compound, averaging the PMI from the sampling points provides a BMI (groundwater Body Mean Index).
- (d1) For each alteration, the minimum of BMI values provides the final indicator (an index value per alteration and per groundwater body).

A second aggregation technique can be qualified as an 'alteration aggregation technique':

- (c2) For each point, the minimum among the PMI of a given alteration provides a PMA (Point Mean Alteration).
- (d2) The PMA arithmetic mean over the whole monitoring network provides the indicator (an index value per alteration and per groundwater body).

A synthetic example is given in Table 2 with a monitoring network composed of four points (X1, X2, X3, X4) and an alteration evaluated from three compounds (P1, P2 et P3). All PMI obtained after the first two steps are given within the three first lines of Table 2. This example clearly illustrates the difference. Results would be similar only if an alteration contains only one parameter, in all other cases the second technique (alteration aggregation) is penalising. It can be demonstrated that the indicator calculated by this last technique will always be smaller than the one calculated by the first technique. Moreover, this effect is accentuated if the point measurement variability is high. The compound aggregation gives an insight of the global contamination problem, whereas the alteration aggregation emphasises a possible local contamination not necessarily representative of the whole groundwater body. Therefore, it seems to be consistent to adopt the 'compound aggregation' as the standard aggregation technique.

General groundwater quality indicator

Tests have been performed on five very different groundwater bodies belonging to the hydrographic dis-

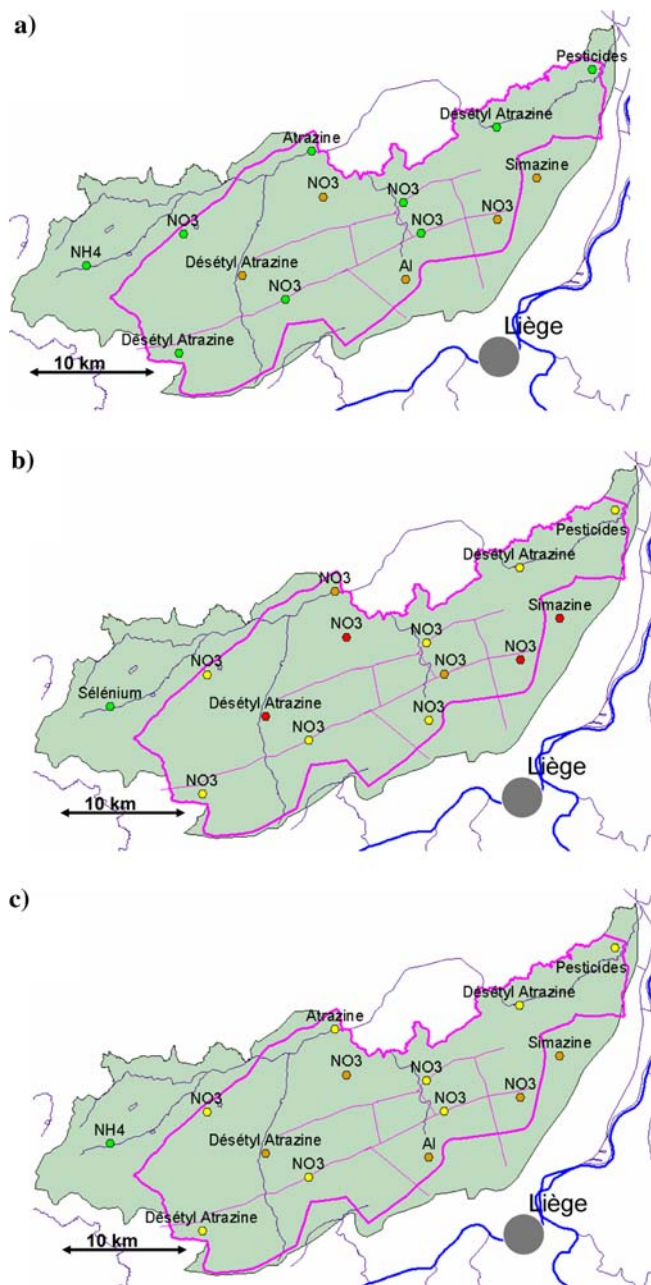


Fig. 3 Color index (cf. Table 1 and Fig. 2) and limiting compounds: **a** Color index and limiting compounds for Drinking Water Use (DWU), **b** Color index and limiting compounds for PS, and **c** Color index and limiting compounds for combined Groundwater Quality (GWQ) in the groundwater body of the Geer basin

tract of the river Meuse in the Walloon Region of Belgium (Rentier et al. 2004) and with different contrasted geological and hydrogeological conditions: Cretaceous chalk, Carboniferous limestone and Pleistocene gravel of the alluvial plain of the river Meuse.

Results obtained with the SEQESO for Cretaceous chinks of the Hesbaye groundwater body are given in the

Table 2 Calculation of the final index value (per alteration and for the whole groundwater body) using both ‘compound aggregation’ and ‘alteration aggregation’ techniques

PMI	X1	X2	X3	X4
P1	82	85	19	75
P2	76	74	78	69
P3	54	42	55	40

Compound aggregation

Step c1: BMI(P1) = 65 ; BMI(P2) = 74 ; BMI(P3) = 48

Step d1: BMI_{min} = 48 (P3)

Medium quality class (yellow) with P3 as the global problematic compound

Alteration aggregation

Step c2: PMA(X1) = 54 (P3) ; PMA(X2) = 42 (P3) ; PMA(X3) = 19 (P1) ; PMA(X4) = 40 (P3)

Step d2: PMA_{mean} = 39 (P1)

Bad quality class (orange) with P1 as the local most problematic compound

example in Fig. 4 as a summary quality sheet. It appears that the minimum index is found for alteration ‘nutrients and organic matters’ due to relatively high monitored nitrate concentrations. This minimum index is automatically taken as the global index and a ‘medium status’ is assessed for this groundwater body.

Conclusions

A framework is described for designing a groundwater quality monitoring network. It is fully compliant with the EU commitments. The last step, leading to the “water quality characterisation” of a groundwater body in the frame of the EU Water Directive, can be performed with the use of a decision sheet as the one described in Fig. 5.

The SEQ-ESO system is a powerful tool to evaluate the chemical status of a groundwater body. From the examination of the groundwater uses and other functions, in particular the concept of PS, a general quality assessment scale has been built. The use of non-dimensional indexes allows the processing of all normalised concentration values gathering them into groups called ‘alterations’, and, by means of proper aggregation rules, to qualify the general status of a groundwater body from the data of a representative network of groundwater in the water-framework directive.

A first set of thresholds, corresponding to the different quality levels are now operational. However, the SEQ-ESO can be considered as an instrument that can evolve. For example, one can reinforce criteria for certain compounds accounting for the biodiversity in the dependent surface ecosystems. It is as obvious that the key thresholds could still be retuned in function (for example) of new groundwater quality standards.

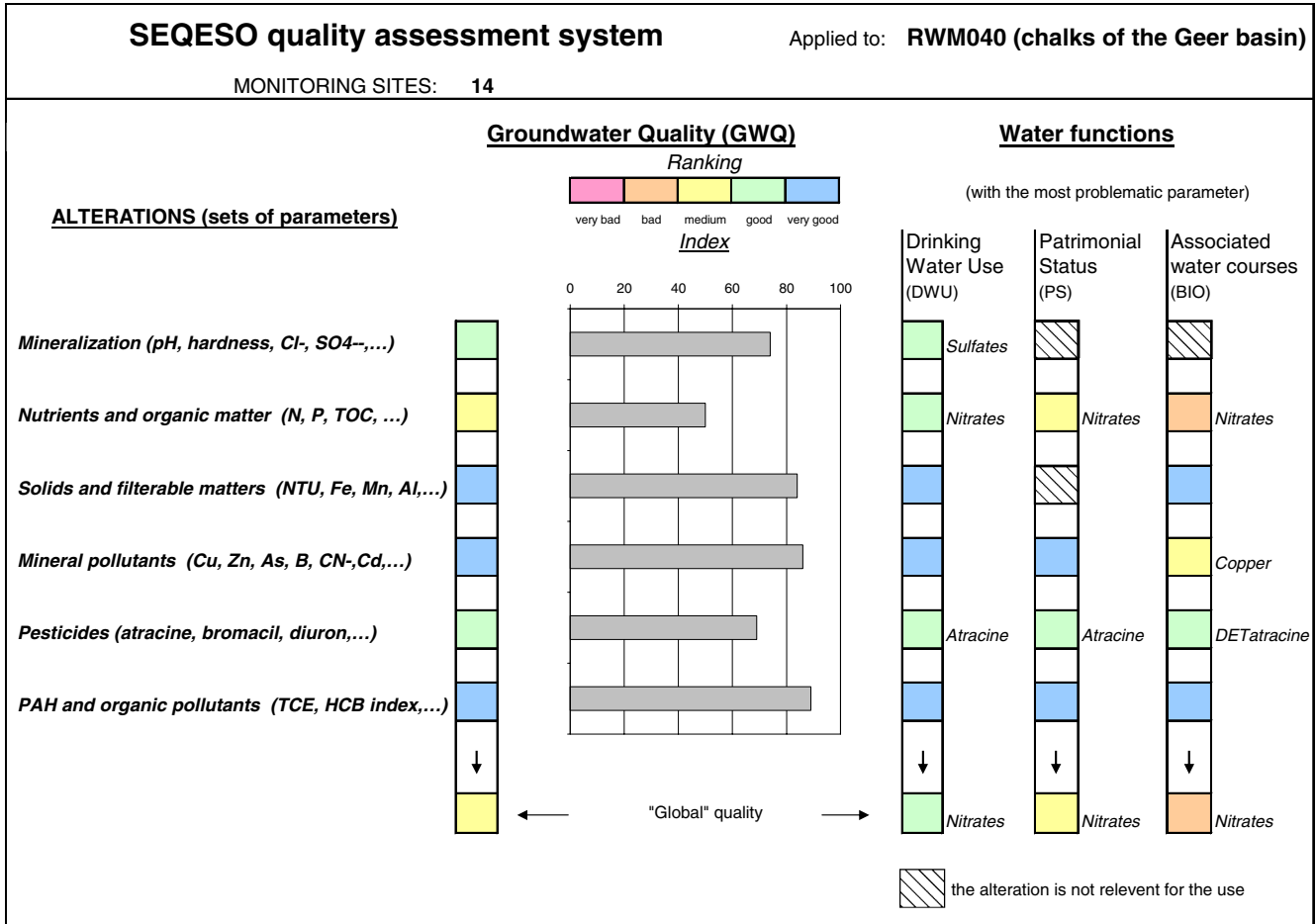
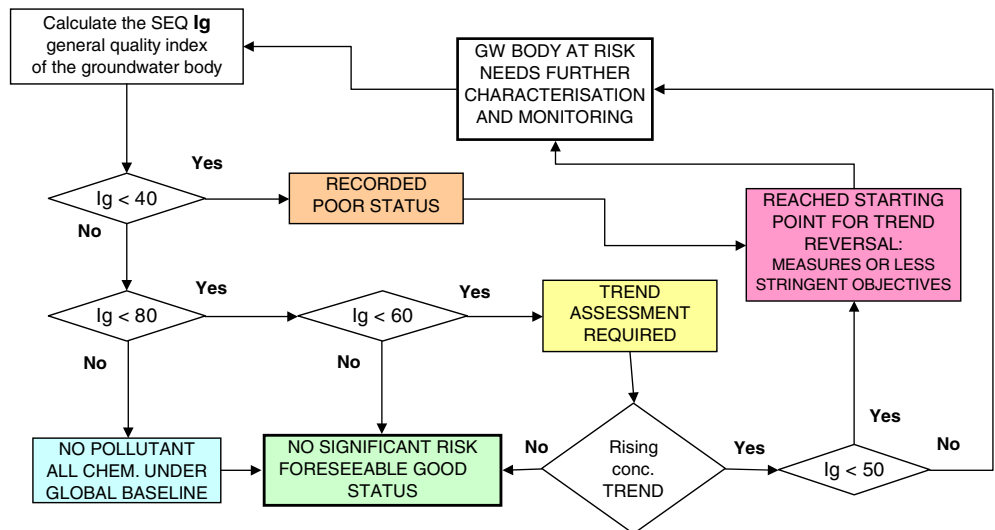


Fig. 4 Summary sheet relative to the groundwater body of the Geer basin. It shows how the nitrate concentrations induce a general index of groundwater quality that leads to a 'medium status'

Fig. 5 Example of a decision flow sheet for groundwater quality aspects leading to the characterization of a groundwater body in the frame of the EU Water Directive



References

- Agences de l'Eau (2002) Système d'évaluation de la qualité des eaux souterraines «SEQ-Eaux souterraines». Version 0, Ministère de l'Aménagement du territoire et de l'Environnement, Bureau de Recherches géologiques et minières (France), p 72 (in French)
- Appelo CAJ, Postma D (1993) Geochemistry, groundwater and pollution. Balkema, Amsterdam, p 536
- Brouyère S (2001) Etude et modélisation du transport et du piégeage des solutés en milieu souterrain variablement saturé (study and modelling of transport and retardation of solutes in variably saturated media), PhD Thesis, University of Liege, Faculty of Applied Sciences, p 572 (in French)
- Brouyère S, Dassargues A, Hallet V (2003) Migration of contaminants through the unsaturated zone overlying the Hesbaye chalky aquifer in Belgium: a field investigation. *J Contam Hydrol* 72:135–164
- Brouyère S, Carabin G, Dassargues A (2004) Climate change impacts on groundwater reserves: modelled deficits in a chalky aquifer, Geer basin, Belgium, *Hydrogeol J* 12(2):123–134. DOI 10.1007/s10040-003-0293-1
- Dassargues A, Monjoie A (1993) In: Hydrogeology of the Chalk of North-west Europe, Chapter 8: Chalk as an aquifer in Belgium, Oxford University Press, Oxford, pp 153–169
- Dassargues A, Radu JP, Charlier R (1988) Finite elements modelling of a large water table aquifer in transient conditions. *Adv Water Resour* 11(2):58–66
- Eurowaternet (1998) Technical guidelines for implementation. Technical report no. 7, ETC/IW Ref: P031/98/1
- EU (2000) Directive 2000/60/EU of the European Parliament and of the Council of 23 October 2000, Official Journal of the European Communities, L327
- Hallet V (1998) Etude de la contamination de la nappe aquifère de Hesbaye par les nitrates: hydrogéologie, hydrochimie et modélisation mathématique des processus d'écoulement et de transport en milieu saturé, PhD thesis, University of Liège, p 361 (in French)
- Rentier C, Delloye F, Dassargues A (2004) Mise au point d'un réseau de mesure et de surveillance des eaux souterraines en vue de la mise en œuvre de la Directive-cadre et du système d'évaluation de la qualité des eaux (SEQ-Eaux souterraines) en Région wallonne. Unpublished report University of Liège, Walloon Region, p 215 (in French)
- Ward RS, Streetly MJ, Singleton AJ, Sears R (2004) A framework for monitoring regional groundwater quality. *Q J Eng Geol Hydrogeol* 37:271–281