Calculation of an interaction index between the extractive activity and groundwater resources

Collier, Louise; Barthelemy, Johan; Carletti, Timoteo; Moriame, Marie; Sartenaer, Annick; Hallet, Vincent

Published in:
Energy Procedia

DOI:
10.1016/j.egypro.2015.07.852

Publication date:
2015

Document Version
Publisher's PDF, also known as Version of record

Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 76 (2015) 412 – 420

Energy Procedia

European Geosciences Union General Assembly 2015, EGU

Division Energy, Resources & Environment, ERE

Calculation of an interaction index between the extractive activity and groundwater resources.

Louise Collier[a], Johan Barthélemy[b], Timoteo Carletti[b], Marie Moriamé[b], Annick Sartenaer[b], Vincent Hallet[a]*

[a]*University of Namur - Department of Geology. 61 Rue de Bruxelles, Namur B-5000, Belgium.*
[b]*University of Namur – Department of Mathematics and Namur Center for Complex Systems. 8 Rempart de la Vierge, Namur B-5000, Belgium.*

Abstract

Groundwater and stone are intensively exploited in Wallonia (southern region of Belgium). The water table located in the mined geological formation might be reached when the quarry is deepened. Dewatering is therefore performed to depress the water table below the pit bottom in order to continue the activity in dry conditions. This affects the regional hydrogeology and the productivity of the nearby water catchments for the public distribution. In order to recommend an adequate feasibility study and minimize the impact on the environment, an interaction index, based on the equation used in the assessment of natural disasters, was developed.

Peer-review under responsibility of the GFZ German Research Centre for Geosciences

Keywords: Water catchment; Dewatering; Classification; Hazard; Vulnerability.

* Corresponding author. Tel.: +32 81 72 44 74.
E-mail address: louise.collier@unamur.be

Peer-review under responsibility of the GFZ German Research Centre for Geosciences
doi:10.1016/j.egypro.2015.07.852

1. Introduction and objectives

There are two important underground resources in Wallonia (the southern region of Belgium). First, groundwater, a resource whose average annual recharge is about 1895 million m^3 [1] and exploited with a volume of 380.4 million cubic meters (in 2010) [2]. Secondly, stone whose average annual production amounts to more than 73 million tons [3].

Wallonia has significant groundwater capital due to a large and regular rainfall pattern and due to bed rock lithologies particularly favorable to the development of aquifers [4]. Because the quality of the groundwater is generally better than the surface water, most of the withdrawals are used for drinking water (305.5 million m^3 in 2010) [2]. All Walloon aquifers are exploited, even if the potential varies widely from one groundwater body to another, depending mainly on the geology. Water withdrawals for public distribution are relatively constant from year to year.

Despite a relatively small territory, Wallonia has a large quantity and a large variety of rocks. There are therefore many quarries, 160 of which are currently still active [3]. The production of stone is mainly composed of carbonate rocks (49.1 million tons of limestone/dolomite and 7.8 million tons of chalk), clastic rocks (5.3 million tons) and porphyry (5.2 million tons). The rest of the production consists of detrital rocks: flint, sand, clay and coticule [5].

Given the high population density and environmental pressures, the surface extension of the quarry is more and more difficult. As a consequence, when the deposit structure allows it, the only solution for the company is to mine deeper. In this context, the aquifer level is often reached and dewatering systems have to be installed to depress the water table below the pit bottom in order to continue to extract rock in dry conditions.

In general, regardless of the method used (sump drains, catchment devices, trenches) the effect is the same and manifests itself in the form of a depression cone in the water table centered on the excavation. This can affect successively the hydrogeological and the hydrological regimes and the productivity of the drinking water catchments [6]. Indeed, in Wallonia, 80.6% of the mined raw material comes from geological formations containing aquifers. These have high permeability, high water storage capacity and therefore are highly exploited for the drinking water production [7].

Currently, more than a third of the quarries realize dewatering in Wallonia. Generally, the water pumped is largely released into the river system, after a possible partial use for industrial purposes (watering of the tracks, washing machines, etc.). A way for the quarry operators to enhance the pumped water is to collaborate with the water distributors withdrawing water nearby, or to recharge the aquifer by injecting the pumped water in the aquifer.

The objective of this study is to ensure that the stakeholders' interests are respected and to encourage synergies between them. So, a tool - an index - available to anticipate interaction by targeting situations where a hydrogeological study is needed was created to identify possible influences, remove uncertainties and minimize the impact of a quarry on its environment. Then, a more or less detailed investigation should be recommended depending on the value of this index.

2. Methods

2.1. Development of an interaction index

An interaction index between the extractive activity and the groundwater resources was developed on the basis of an equation used in the assessment of natural hazards [8]. That can be formulated as follows (1):

$$\text{Risk} = F\,(\text{Hazard, Vulnerability}) \qquad (1)$$

The hazard is a physical natural phenomenon or event that under specific conditions can lead to damage for humans and/or the environment and the vulnerability is a subjective concept that expresses the level of foreseeable consequences of a natural phenomenon on issues, namely the areas affected by a given hazard [9].

In this case, the risk corresponds to the interaction, which is a function of hazard and vulnerability. The hazard is defined from the parameters linked to the quarry and the vulnerability from the parameters related to groundwater resources, thereby providing the following equation (2):

Interaction = F (Quarry, Groundwater) (2)

Afterward, vulnerability and hazard were assessed using a parametric system such as the one used in the DRASTIC method [10]. The principle is to determine, using the geological and hydrogeological parameters which reflect the best, by their combination, the hazard in the studied system and its vulnerability.

Then, six parameters were determined: three for the hazard and three for the vulnerability. Each of them was divided into four categories, which provides a set of 4096 possible theoretical combinations. Some combinations are impossible in practice, which reduces the set to 3227. The studied quarry fits with a combination of these categories depending on its current state that can vary over time. Indeed, this methodology is able to easily update the interaction index as soon as a parameter changes.

2.1.1. Definition of the hazard parameters

The geological setting

The geological setting is defined by the lithological characteristics and the extension of the geological formation mined in the quarry and those of the neighboring geological formations that will govern the groundwater flow directions.

The categories identified for the geological setting are as follows (Fig.1):

- G1: The quarry is mined in a geological formation completely isolated by other formations with low permeabilities. Then, the dewatering effects are limited to the quarry. The aquifer extension does not exceed 5 km²;
- G2: The quarry is mined in a geological formation laterally limited by geological formations with low permeabilities or by the presence of a stream that consists of a "constant head" aquifer boundary [11]. For example, to the north and to the south, the dewatering effects are limited due to impermeable formations; to the east, the effects are limited due to the river (the water level is a constant head). The aquifer extension does not exceed 10 km²;
- G3: The quarry is mined in a geological formation of local extension, namely of an important extension but however laterally limited by geological formations with low permeabilities. For example, the dewatering effects are limited due to the north and to the south due to impermeable formations. The aquifer extension does not exceed 40 km²;
- G4: The quarry is mined in a geological formation of regional extension, then the dewatering effects are regional. The aquifer extension is greater than 40 km².

The hydrogeological setting

The categories identified for the hydrogeological setting are:

- H1: The quarry is located in an aquiclude formation (including aquiclude formation with aquitard levels);
- H2: The quarry is located in an aquitard formation (including aquitard formations with aquifer levels and aquiclude formation with aquifer levels);
- H3: The quarry is located in an aquifer formation;
- H4: The quarry is located in a "carbonate aquifer" formation.

The aquiclude, aquitard and aquifer names refer to clusters of geological formations according to their hydrodynamic characteristics in hydrogeological units [11]. The selected clusters and their names are those used in the hydrogeological maps of Wallonia [2]. However, a distinction was made between aquifers and carbonate aquifers (limestone, dolomite, chalk) whose hydraulic conductivity is increased by the dissolution of the rock and by the complexity of the karst environment [12].

The piezometric setting

The piezometric setting is defined by the piezometric level of the water table during the highest water period and the elevation of the pit bottom. The dewatering, set up as part of the deepening of some quarries, influences the level of the water table resulting in the formation of a depression cone.

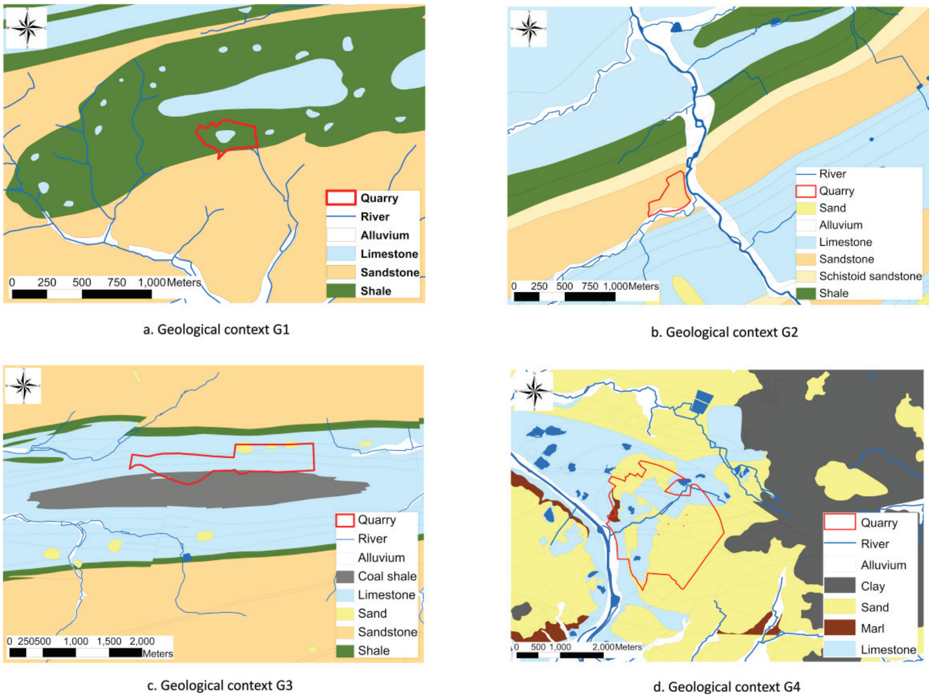

Fig.1. Maps illustrating the different geological settings.

Depending on the deepening of the quarry, there are four possible situations (Fig.2).

- P1: The altimetric level of the quarry floor is higher than the piezometric level;
- P2: The altimetric level of the quarry floor is lower than the piezometric level but higher than the thalweg of a river imposing the regional base level;
- P3: The altimetric level of the quarry floor is lower than the piezometric level and the altimetric level of the river thalweg which is the regional base level. The river defines the piezometric level along its thalweg (constant head condition);
- P4: The altimetric level of the quarry is lower than the piezometric level of the water table and the elevation of the river thalweg. The river does not define the piezometric level anymore and the depression cone spreads beyond the river (Fig.2d). The river becomes perched.

2.1.2. Definition of the vulnerability parameters

The relative position of the quarry and the catchments for public distribution

Catchments for the public distribution of drinking water are threatened by various sources of pollution. Nearer the catchment is, greater the impact of pollution might be. This is the reason why successive protection areas were set up around the catchment by the SPGE (Public Service of Water Management) based on the velocity of groundwater (transfer time) [13]. The geographical surface of each area is different depending on the local hydrogeology of the groundwater exploited and the nature of the soil (Fig.3).

- Zone IIa: the close prevention zone is the area inside which a pollution transported by groundwater would take maximum 24 hours to reach the water catchment.

- Zone IIb: the remote prevention area is the area inside which a pollution transported by groundwater would take between 1 and 50 days to reach the water catchment.

- Zone III: the surveillance zone corresponds to the entire feeding area of the water catchment. It is generally not subject to special taxation

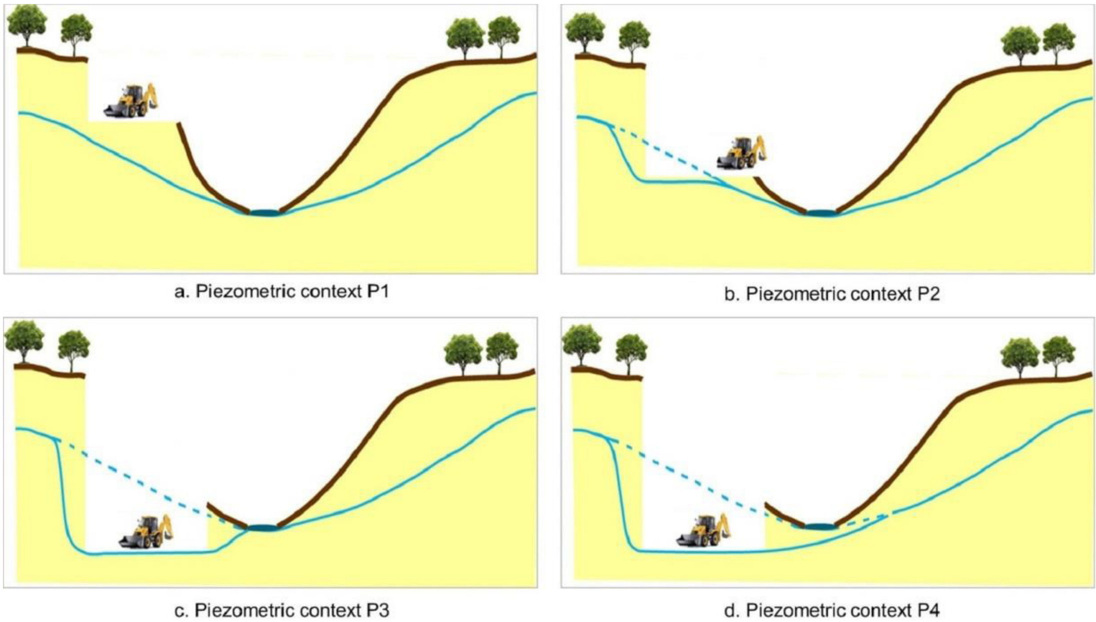

Fig.2. Maps illustrating the different piezometric settings.

Therefore, according to the position of the quarry and the water catchments, there are four possible cases:

- C1: The quarry is located outside the feeding area of the catchment but in hydrogeological continuity ;
- C2: The quarry is located in the feeding area of the catchment (zone III) ;
- C3: The quarry is located in the remote prevention area of the catchment (zone IIb);
- C4: The quarry is located in the close prevention area of the catchment (zone IIa).

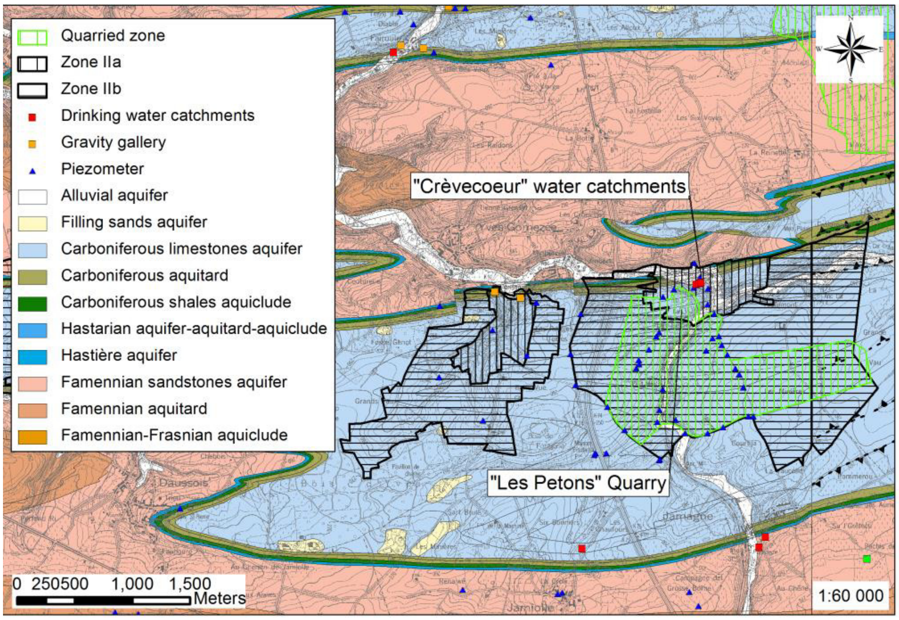

Fig.3. Map illustrating the exploitation of a quarry inside the zones IIa and IIb.

The production of the water catchments

In Wallonia, the Dix-Sous database [14] provides histories of annual volumes of drinkable groundwater collected in public water catchments and private wells. Using geocentric approach proposed on the website of Dix-Sous, it is easy to define the pumped volume in catchments for public distribution in the hydrogeological formation mined by the quarry. The size of the investigation radius is chosen depending on the watershed extension, defined thanks to the geological setting (parameter G) and the hydrogeological setting (parameter H). In Wallonia, the search radius is roughly between 500 meters and 5 kilometers.

Annual flow rates pumped in all the catchments for public distribution of drinking water in Wallonia were compiled in order to statistically classify the water catchments based on hourly flow rates ranges. Therefore, four categories were defined for the production of the water catchments:

- T1: Production of the water catchments between 0 and 2 m^3/h;
- T2: Production of the water catchments between 2 and 10 m^3/h;
- T3: Production of the water catchments between 10 and 30 m^2/h;
- T4: Production of the water catchments upper than 30 m^3/h.

The potential quality of the groundwater

The quality of the groundwater includes chemical, biological and physical parameters (temperature, color, taste, odor, turbidity). The Belgian system SEQ-ESO, based on the French system SEQ-EAU [15], is a reference tool to characterize the groundwater quality in the Walloon Region based on the notion of alteration. In the present study, the system SEQ-ESO was used to identify four classes of water quality for the production of drinking water [16]:

- L1: Water of poor quality;
- L2: Water with minor treatment;
- L3: Water of good quality;
- L4: Water of exceptional quality.

When water has an exceptional quality and so does not require any treatment, it is designated as a natural mineral water [17]. However, groundwater often contains undesirable products such as suspended particulates, dissolved salts or germs. Depending on its quality, the water treatment process will be more or less complex. It is therefore essential for the distributor to take representative water samples to properly determine and design the processing steps required for purification (physicochemical and bacteriological analyzes). For a water of good quality, treatment may be limited to three main stages: smooth filtration, chlorination and refining activated carbon.

Some particular cases can be more difficult to treat due to high turbidity, the presence of iron or manganese, a low pH acidic water, etc. and impose additional processing steps. These waters are classified as waters with minor treatment. In regions with high population density, groundwater contamination is often anthropogenic [18]. Indeed, human activities can alter the natural composition of groundwater by the deposit of microbial matter and chemicals products (nitrates and pesticides) on and in the soil surface or by injection of waste directly into the groundwater through karst losses. The pollution runs off and then has a direct access to contaminate the groundwater contained in the rock without having been previously filtered. These waters are classified as waters of poor quality.

2.1.3. The discrete choice model

In order to correlate and properly weight the parameters in the interaction equation, a probabilistic model of statistical classification, the discrete choice model was used. A discrete choice model describes, explains and predicts the choice of an agent among a finite set of discrete alternatives [19]. The unity of decision-making (the agent) is assumed to be a person, although the concepts are applicable more generally. Indeed, in this study, choices are made by quarries and possible alternatives are the different parameters combinations that have been defined.

A discrete choice model links statistically the choice made by each quarry with the attributes thereof and the attributes of the alternatives available for a quarry. The model estimates the probability that a quarry chooses a particular alternative. The model will also be used to predict the change of the choice of the quarry following variations of an attribute of one or more alternatives.

2.2 The feasibility study requirement

Following the interaction index, four degrees of investigation, correspond to a study more and more precise, were established. Depending on the level obtained (low, medium, high or very high), the quarry will be included in one of these four classes.

2.2.1. Low Index (LI): a geological and hydrogeological contextualization

The geological and hydrogeological contextualization is a preliminary study synthesizing existing data, in which the following information is updated:
- The topographical setting;
- The geological setting;
- Piezometric data;
- Hydrodynamic data (pumping tests and tracer tests in the piezometers);
- Hydrographic data of nearby streams (flows, water chemistry, etc.);
- Data on the quarry (elevation of the pit bottom, lithology, structural geology, water inflows, etc.);
- Prospective geophysical investigations;
- Results of the geocentric approach;
- Data on the nearby karstic sites.

2.2.2. Medium Index (MI): LI and piezometric monitoring

Based on the information collected to establish the geological and hydrogeological setting, the location of additional piezometers in and around the quarry is defined. Continuous piezometric monitoring and several manual measurements on all the accessible regional piezometers are recorded in databases. Piezometric maps of the water table levels during highest and lowest water periods have to be drawn.

A hydrogeological balance helps to determine the water potential of a region by quantifying groundwater flow to or from the neighboring watersheds. Pumping in an aquifer modifies this balance. Its calculation requires the gathering of a series of information such as weather data (pluviometry, temperature, wind speed, hygrometry, insolation, etc.), rivers flows, pumped flow rates and groundwater reserves variations.

2.2.3. High Index (HI): MI and mathematical modeling in steady state

When an aquifer is sufficiently well known, the good management must include the construction of a mathematical model. After the conceptual model was conceived a steady state flow and transport model was created and calibrated based on the piezometric surface and the pumping tests. The model is then checked with a hydrogeological balance and different scenarios of the quarry mining and dewatering are simulated. These models are used in both quantitative and qualitative management of the groundwater.

2.2.4. Very High Index (VHI): HI and mathematical modeling in transient state

In the case of a steady state modeling, an average value for the piezometry might be enough. In the case of a transient modeling in steady state, the piezometry is no longer considered to be constant during the hydrogeological year, but varies seasonally during the periods of highest and lowest water levels. In other words, managers are required a greater rigor in the piezometric monitoring of the water table through the hydrogeological year. A good knowledge of the hydrogeological parameters to insert, such as the storage coefficient, leads to a better understanding of the aquifer hydrodynamism.

3. Results

The four following equations (3, 4, 5, 6) were obtained with the discrete choice model, Logit [20]:

$$L = 0 \tag{3}$$

$$M = -9.30 + (0 * H_1) - (0.05 * H_2) + (2.96 * H_3) + (2.96 * H_4) + (0 * P_1) + (2.24 * P_2) + (4.72 * P_3) + (4.61 * P_4) + (0 * G_1) - (0.62 * G_2) - (0.64 * G_3) - (0.68 * G_4) + (0 * C_1) + (3.29 * C_2) + (5.40 * C_3) + (5.40 * C_4) + (0 * T_1) + (0.46 * T_2) + (1.72 * T_3) + (4.55 * T_4) + (0 * L_1) + (4.12 * L_2) + (4.68 * L_3) + (4.83 * L_4) \tag{4}$$

$$H = -2.09 + (0.82 * H_1) - (0 * H_2) + (5.15 * H_3) + (5.15 * H_4) - (5.36 * P_1) + (0 * P_2) + (3.93 * P_3) + (3.82 * P_4) + (0.5 * G_1) + (0 * G_2) - (0.02 * G_3) - (0.03 * G_4) - (6.94 * C_1) + (0 * C_2) + (5 * C_3) + (5.36 * C_4) - (3.57 * T_1) + (0 * T_2) + (2.98 * T_3) + (6.5 * T_4) - (7.23 * L_1) + (0 * L_2) + (1.92 * L_3) + (3.24 * L_4) \tag{5}$$

$$VH = 24.6 - (7.45 * H_1) - (9.13 * H_2) + (0 * H_3) + (0 * H_4) - (17.2 * P_1) - (7.89 * P_2) + (0 * P_3) - (0.11 * P_4) - (0.49 * G_1) + (0.02 * G_2) + (0 * G_3) + (0.04 * G_4) - (23.9 * C_1) - (8.62 * C_2) + (0 * C_3) + (0.788 * C_4) - (13.2 * T_1) - (6.28 * T_2) + (0 * T_3) + (2.52 * T_4) - (14.1 * L_1) - (3.73 * L_2) + (0 * L_3) + (3.36 * L_4) \tag{6}$$

These equations are resolved with a binary system. A value of 0 or 1 is assigned to the four categories of each parameter, 0 if the quarry does not fit that category or 1 if it does. Then, the computation of these equations delivers probabilities for each value of the interaction index: low, medium, high and very high. The equation whose probability is highest attributes its index interaction to the quarry. The probabilities are expressed as follows (7):

$$\begin{aligned} P(L) &= \frac{e^L}{e^L+e^M+e^H+e^{VH}} \\ P(M) &= \frac{e^M}{e^L+e^M+e^H+e^{VH}} \\ P(H) &= \frac{e^H}{e^L+e^M+e^H+e^{VH}} \\ P(VH) &= \frac{e^{VH}}{e^L+e^M+e^H+e^{VH}} \end{aligned} \tag{7}$$

Where e is the Euler number (or the Napier constant), which is approximately 2.71828.

4. Conclusions

The methodology developed to calculate the interaction index between the extractive activity and groundwater resources, using simple geological and hydrogeological settings, is an useful tool for the stakeholders' decision-making. Indeed, it opens the discussion about the feasibility study and thereby helps to reach a consensus between quarry operators and water producers.

The interaction index takes into account various parameters, combined and weighted according to their influence, in an equation based on the one used for the assessment of natural hazards. This corresponds to a function of a "hazard" (the quarry) and the "vulnerability" of a resource (the groundwater). Every quarry in its current mining state is a combination of these parameters. A modification due to a change of either the parameters relating to the quarry or the parameters relating to the groundwater resources causes an update of the interaction index.

Thanks to the level of the interaction index, which can be low, medium, high or very high, stakeholders will be advised to conduct less or more advanced investigations (on the field and in laboratory), namely a geological and hydrogeological contextualization, a piezometric monitoring, a modeling in steady flow state and a modeling in transient flow state.

However, while this index has the advantage of an easy contextualization of a quarry by clearly summarizing the existing information, it is very important to realize that it only provides a relative assessment tool. It was not established to give absolute answers or to estimate the feasibility of extending or deepening a quarry.

Acknowledgements

This study is part of a project with the support and funding of the Public Service of Wallonia (SPW), in collaboration with the FEDeration of the Extractive Industry of Belgium (FEDIEX) and the professional union of the water public operators of Wallonia (Aquawal).

References

[1] Bonniver I & Hallet V, 2013. Rapport final de l'étude: Convention de recherche d'intérêt général et pluridisciplinaire relative à l'évaluation des ressources en eau souterraine de la Wallonie. Département de Géologie de l'UNamur. DGARNE.
[2] SPW-DGO3, 2014. Etat des nappes d'eau souterraine de Wallonie. Edition: Service public de Wallonie, DGO3 (DGARNE), Belgique. Dépôt légal D/2014/11802/11 - ISBN 978-2-8056-0142-2. http://environnement.wallonie.be/de/eso/atlas.
[3] Poty E, Chevalier E & Caudron M, 2002. Inventaire des ressources du sous-sol de la Région wallonne et des besoins à terme (1995-2001). Ministère de la Région wallonne, Direction générale de l'Aménagement du Territoire, du Logement et du Patrimoine, Namur.
[4] Dassargues A & Walraevens K, 2014. Watervoerende lagen en grondwater in België/Aquifères et eaux souterraines en Belgique. Gent: Academia Press, 455 p.
[5] Poty E & Chevalier E, 2004. L'activité extractive en Wallonie. Situation actuelle et perspectives. Ministère la Région wallonne, Direction Générale de l'Aménagement du Territoire, du Logement et du Patrimoine. D/2004/5322/30.
[6] Environment Agency 2007. Hydrogeological impact appraisal for dewatering abstractions. Using science to create a better place. Science Report – SC040020/SR1.
[7] Collier L & Hallet V, 2013. Rapport final de l'étude: Examen des interactions entre les ressources en eau et l'industrie extractive en Région wallonne. Département de Géologie de l'UNamur. SPW–DGO3.
[8] Dauphiné A, 2003. Risque et catastrophes: Observer, spatialiser, comprendre, gérer. Collection UGéographie. Éditeur Colin, A. 283 p.
[9] Smith K, 2013. Environmental hazards: Assessing risk and reducing disaster. 6th edition. Editor Routledge. 504 p.
[10] Aller L, Lehr JH & Petty R, 1987. DRASTIC: a standardized system to evaluate ground water pollution potential using hydrogeologic settings. National water well Association Worthington, Ohio 43085. Truman Bennett. Bennett and Williams, Inc. Columbus, Ohio 43229.
[11] Fetter CW, Applied Hydrogeology, fourth edition 2011. University of Wisconsin – Oshkosh. Upper Saddle River, New Jersey 07458.
[12] Ronayne MJ, 2013. Influence of conduit network geometry on solute transport in karst aquifers with permeable matrix. Advances in water resources. Elsevier. Volume 56, pg 27-34.
[13] Vernoux JF, Wuilleumier A & Dörfliger N, 2007. Délimitation des bassins d'alimentation des captages et leur vulnérabilité vis-à-vis des pollutions diffuses. Guide méthodologique, rapport BRGM/RP-55874, 75 p.
[14] Banque de données « Dix-Sous », MRW-DGRNE. Direction des eaux souterraines. 15, Avenue Prince de Liège. http://carto1.wallonie.be/10SousInt/Default.asp.
[15] BRGM 97-D-211, 1998. Système d'Evaluation de la Qualité des Eaux souterraines. Tests cartographiques sur quelques aquifères. R39924.
[16] Rentier C, Delloye F, Brouyère S & Dassargues A, 2006. A framework for an optimized groundwater monitoring network and aggregated indicators, Environmental Geology, 50(2), pp. 194-201, DOI: 10.1007/s00254-006-0200-x.
[17] 80/777 European Directive of the 15.07.1980 relative to the approximation of the laws of the member states relating to the exploitation and the marketing of natural mineral waters.
[18] Brouyère S, Orban P & Ruthy I. Rapport analytique 2006-2007 sur l'état de l'Environnement wallon. L'état quantitatif et qualitatif des eaux souterraines en Région wallonne. Département ArGEnCo, Faculté des sciences appliquée, ULg.
[19] Train K, 2009. Discrete choice methods with simulation, Second edition. Cambridge University press, 383 p.
[20] Barthélemy J, Carletti T, Collier L, Hallet V, Moriamé M & Sartenaer A, 2015. Development and comparison of two interactions indexes between extractive activity and groundwater resources, to be submitted.