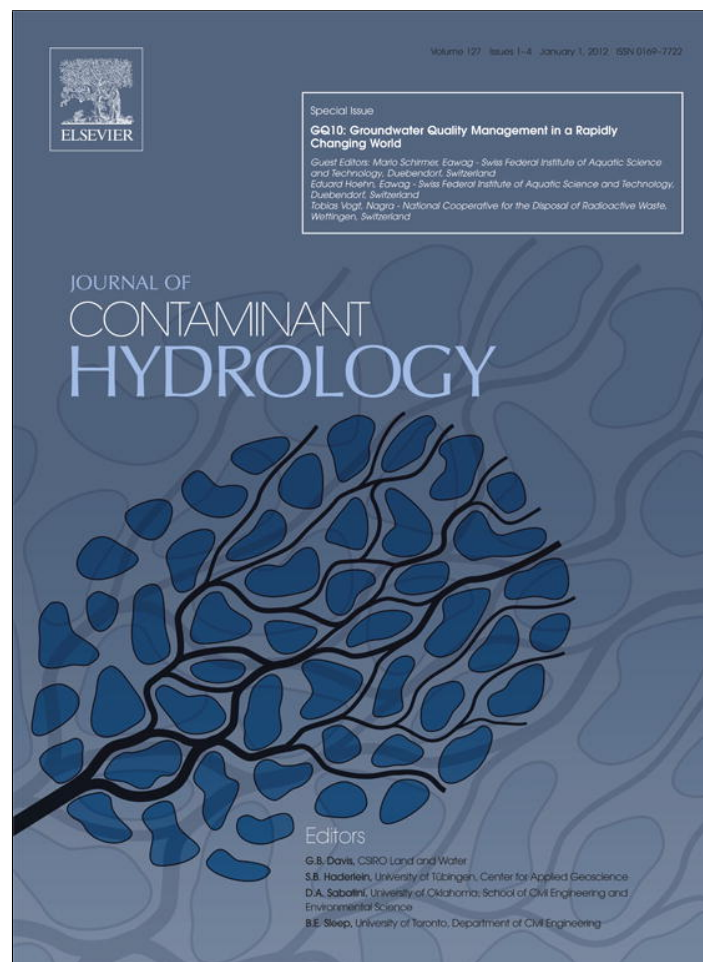


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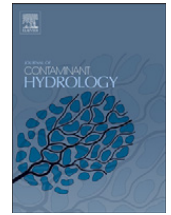
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A regional flux-based risk assessment approach for multiple contaminated sites on groundwater bodies [☆]

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ABSTRACT

In the context of the Water Framework Directive (EP and CEU, 2000), management plans have to be set up to monitor and to maintain water quality in groundwater bodies in the EU. In heavily industrialized and urbanized areas, the cumulative effect of multiple contaminant sources is likely and has to be evaluated. In order to propose adequate measures, the calculated risk should be based on criteria reflecting the risk of groundwater quality deterioration, in a cumulative manner and at the scale of the entire groundwater body. An integrated GIS- and flux-based risk assessment approach for groundwater bodies is described, with a regional scale indicator for evaluating the quality status of the groundwater body. It is based on the SEQ-ESO currently used in the Walloon Region of Belgium which defines, for different water uses and for a detailed list of groundwater contaminants, a set of threshold values reflecting the levels of water quality and degradation with respect to each contaminant. The methodology is illustrated with first results at a regional scale on a groundwater body-scale application to a contaminated alluvial aquifer which has been classified to be at risk of not reaching a good quality status by 2015. These first results show that contaminants resulting from old industrial activities in that area are likely to contribute significantly to the degradation of groundwater quality. However, further investigations are required on the evaluation of the actual polluting pressures before any definitive conclusion be established.

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1. Introduction

The EU Water Framework Directive (EP and CEU, 2000) requires management plans to monitor, to maintain and, if required, to restore the quality of surface water and groundwater bodies. In very urbanized and industrialized regions, water resources, and particularly groundwater, are subject to many pollution pressures related to different kinds of socio-economic activities and contaminants (UNEP/ADEME, 2005;

European Environment Agency, 2006). These plans cannot be defined without considering industrial sites potentially harmful to groundwater resources and, in this context, different questions arise. How can we take into consideration all these potential and actual sources of pollution in evaluating the risk of deterioration of groundwater quality and the efficiency of programs of measures defined to restore this quality? And, as a consequence of this, how can we evaluate groundwater quality at the regional scale of the groundwater body and the evolution with time of groundwater quality?

Classical risk assessment and management concepts for contaminated sites are usually based on a univocal relationship between a source of pollution and a potentially exposed receptor, commonly referred to as the source–pathway–

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receptor approach, with an evaluation of the receptor's exposure level and a comparison to environmental and health regulations (e.g. Ferguson et al., 1998; Fairman et al., 1999). This conceptual approach is convenient for pollution sources and receptors well located in space, such as local pollution “hotspots” and pumping wells nearby. By contrast, in heavily industrialized and urbanized areas, because of the spatial extent of groundwater bodies, many point or diffuse pollution sources may need to be considered in the analysis, with complex groundwater vectors for contaminant dispersion, and a meaningful regional risk assessment approach has to be considered (Gay and Korre, 2006; Critto and Sutter, 2009).

Several projects have been dedicated recently to the development of methodologies for contaminated megasite management, such as CLARINET (2002), NICOLE (2003), WELCOME (2004), INCORE (Ptak et al., 2003; Jarsjo et al., 2005), DESYRE (Carlon et al., 2007; 2008), and SAFIRA II (Schädler et al., 2007; Morio et al., 2008). These projects propose concepts and tools for a regional analysis of environmental issues related to contaminated sites, for regional risk assessment, for prioritization of investment and rehabilitation on industrial land parcels and brownfields or for cost–benefit socioeconomic analyses. Beside these megasite-oriented projects, other decision support systems have been developed (Béranger et al., 2006), based on GIS systems, e.g. SMARTe (Vega et al., 2009) or DECERNS (Sullivan et al., 2009) for data management and cartography and for regional scale risk assessment for contaminated sites, SADA (Purucker et al., 2009) or ERAMANIA (Semenzin et al., 2009) for ecological risk assessment, BOS (Tait et al., 2004; 2008; Chisala et al., 2007) for the management of groundwater in urban areas and BASINS (Kinerson et al., 2009), RISKBASE (Brils and Harris, 2009) or CatchRisk (Troldborg et al., 2008) for water pollution risk assessment and management at catchment scale. However, these projects do not really propose specific indicators for the quality of groundwater seen as a regional resource (Caterina et al., 2009). The objective here is to fill this gap by proposing a flux-based methodology to calculate a groundwater quality indicator that considers the cumulative effect of multiple, spatially-distributed pollution sources with multiple types of contaminants. This approach can be used for groundwater quality trend assessment and for groundwater pollution risk assessment on groundwater bodies.

The methodology and related tools are described in details and illustrated using a synthetic example and a first real scale application to a deteriorated groundwater body in Belgium.

2. Methodology for regional risk assessment

The methodology for regional risk assessment is summarized in Fig. 1. The scale of application corresponds to the groundwater body defined in the context of the EU water framework directive as the groundwater management unit for aquifers in Europe. The approach can also straightforwardly be limited and applied to parts of groundwater bodies where stronger deterioration of water quality is observed or to specific areas such as contaminated megasites. In the groundwater body of interest, the various potential sources of pollution are identified and geo-referenced into a specific geospatial database (Fig. 1a). For each of the selected contaminant sources, the

migration of contaminants within the aquifer is calculated using a numerical groundwater flow and transport model developed at the scale of the groundwater body. Repeating the same procedure for all identified sources of contamination provides a map of contaminants' plumes in the studied groundwater body (Fig. 1b) at different times. The generated plumes are classified in terms of groundwater quality classes on a normalized scale that accounts for threshold values defined specifically for each contaminant, using the SEQ-ESO evaluation system used in the Walloon Region (Rentier et al., 2006). This gives a global picture of the quality status of the groundwater body (Fig. 1c). Finally, a global quality index (I_{global}) is calculated for the groundwater body at each time step, using a weighting-average formula (Fig. 1d). The different modules composing the regional risk assessment system are described in details hereafter.

2.1. Geospatial database for regional groundwater quality and pollution risk assessment

A geodatabase, organized according to the Source–Pathway–Receptor schema, has been developed to store and manage the important quantity of spatially distributed data required by the regional approach. This geodatabase has been developed under ArcMAP environment, with a specific menu in the graphical user interface, based on Visual Basic scripts and routines, and using shapefiles and attributes tables for handling environmental data. The conceptual schema of the geodatabase is shown in Fig. 2. The “Source” module gathers the information on potential contaminated sites. It is used to characterize the nature, size and location of industrial sites. The “Pathway” module organizes the information needed to characterize the physical environment, such as geology, hydrogeology, soils or land-use. The “Receptor” module gathers the information on potentially exposed receptors, which are first the groundwater resource but possibly also other receptors such as streams, pumping wells or springs.

At such a regional scale, it is unlikely to obtain all the information on existing pollution sources because all the contaminated sites are not necessarily known or characterized in details. The selection of pollutant sources considered in the analysis can also be based on registered industrial activities using a matrix “activity–pollutant” presented as two Microsoft Access-type linked tables connected with a shapefile listing all industrial plants. The first table is a dictionary of seventy-five selected pollutants with their main physico-chemical properties (e.g. solubility, octanol–water partitioning coefficients, Henry's constants ...) and contaminant threshold values used in the Walloon regulation (Walloon Soil Decree, 2008). The second table relates classified industrial activities and associated pollutants, based on previous similar works (e.g. MATE, 2000; SITErem, 2002). The “Industry” shapefile and the pollutant–activity matrix are linked using an activity code defined according to the European industrial activity classification NACE (European Commission, 2008) to create a shapefile of potential contaminant sources.

2.2. Groundwater flow and transport modeling concepts

In order to evaluate the impact of pollution sources on the quality of the groundwater resource, it is necessary to evaluate, at regional scale, how much and to which extent

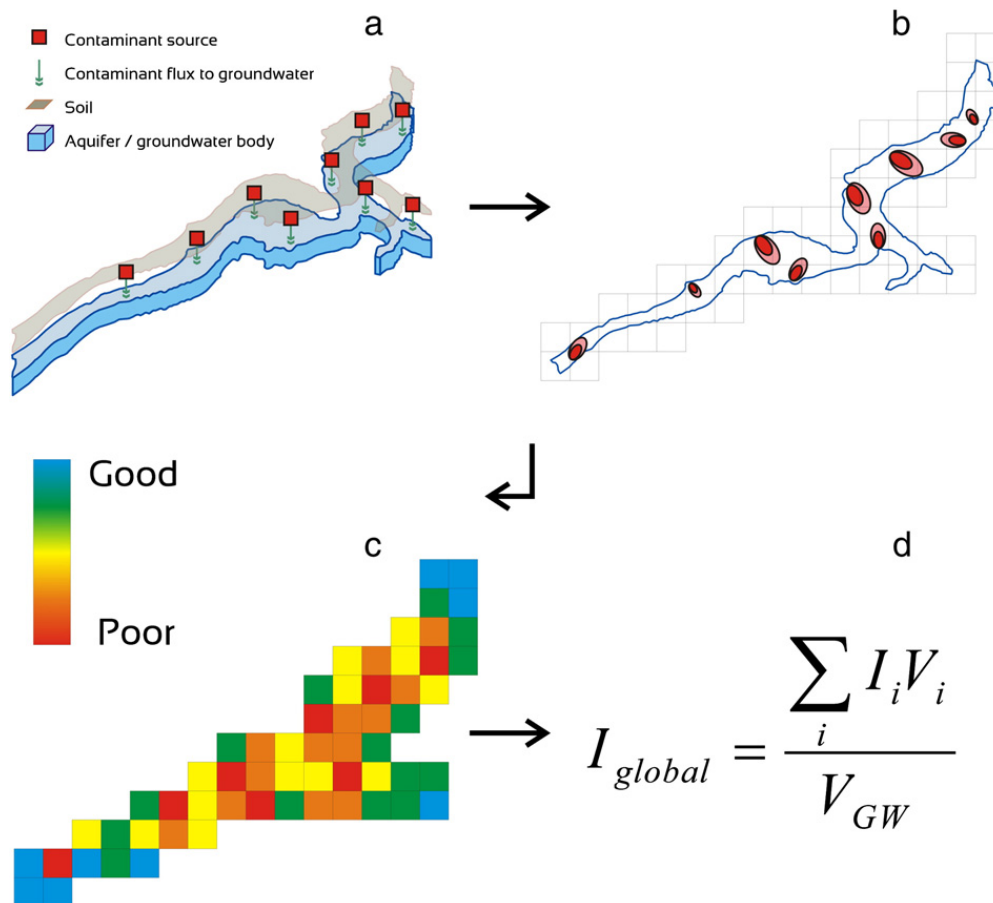


Fig. 1. Regional risk assessment methodology applied to a groundwater body. I_{global} : global quality index for the whole groundwater body at time t [–], V_{GW} : volume of groundwater comprised in the zone where the risk is assessed [L^3], V_i : volume of water into the cell i [L^3], I_i : quality index for the cell i [–].

groundwater is degraded from these sources. This requires quantifying contaminant mass fluxes to and through groundwater in order to determine the volumes of degraded groundwater and the severity of this degradation, *i.e.* the spatial extent of the contaminated plumes and concentrations of contaminants. Existing monitoring networks, usually based on piezometers, are unlikely to provide extensive and exhaustive information on groundwater pollution because they are very often limited to the neighborhood of identified polluted sites. The alternative is to use groundwater flow and transport models to calculate contaminant mass fluxes from the pollution sources to and through groundwater. The objectives of the groundwater flow and transport model is first to calculate the dispersion plumes of contaminants in the saturated zone, but also to evaluate the relative importance of specific pollutant sources within a regional contamination (*i.e.* site prioritization) and to test programs of measures defined for the restoration of groundwater quality for groundwater body management.

The extent and the boundaries of the concerned area (*i.e.* the model) have to be clearly defined before any other consideration. This step should be achieved with decision makers and stakeholders at the beginning of the risk assessment process. The most logical choice is to consider the whole groundwater body as defined by the EU Water Framework Directive, delineated according to geological, hydraulic and administrative factors and included into every EU member state legislations.

A comprehensive modeling approach requires calculating first the vertical leaching of contaminants from the pollution source to the groundwater table, then the horizontal dispersion of contaminants in the saturated zone. However, the pollution sources considered correspond mostly to historical contaminations having occurred when environmental regulations were less restrictive. Accordingly, it is assumed, as a first approximation, that contaminants have already reached the groundwater table and that the leaching of contaminants to groundwater can be modeled as a specified mass flux considering the recharge rate and the effective solubility of each contaminant.

The groundwater flow and transport model consists of a transient transport model based on a steady-state groundwater flow model. It serves to calculate groundwater fluxes and groundwater flow directions in order to route contaminants from the pollution sources through the groundwater body and, subsequently, to run transport simulations. Steady state simulations for groundwater flow are sufficient because the objective is to delineate contamination plumes over long time periods, and not to consider the influence of groundwater dynamics on these plumes.

Aquifer hydraulic conductivity defined in the regional model are essentially based on lithological entities using orders of magnitudes resulting from field measurements (pumping tests ...) for similar materials. Realistic estimates of groundwater recharge are important because it is the driver of

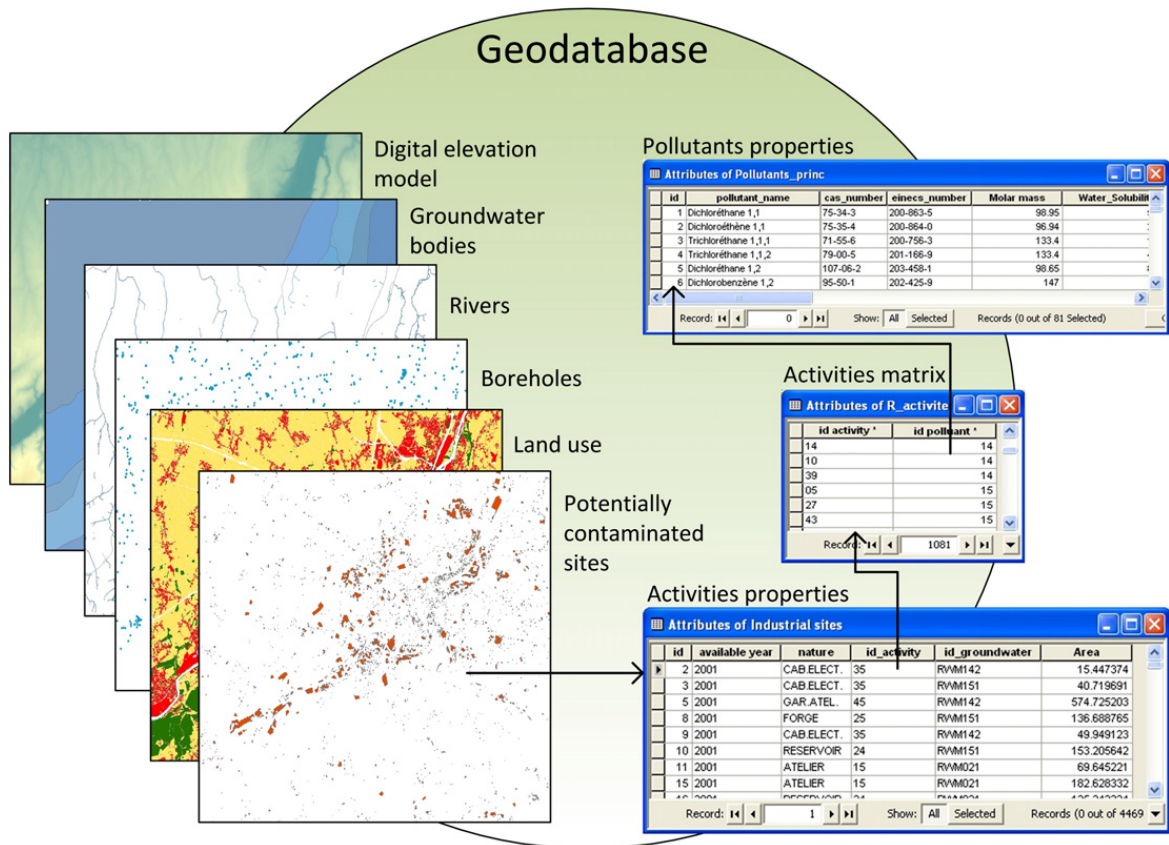


Fig. 2. General organization of the Geodatabase.

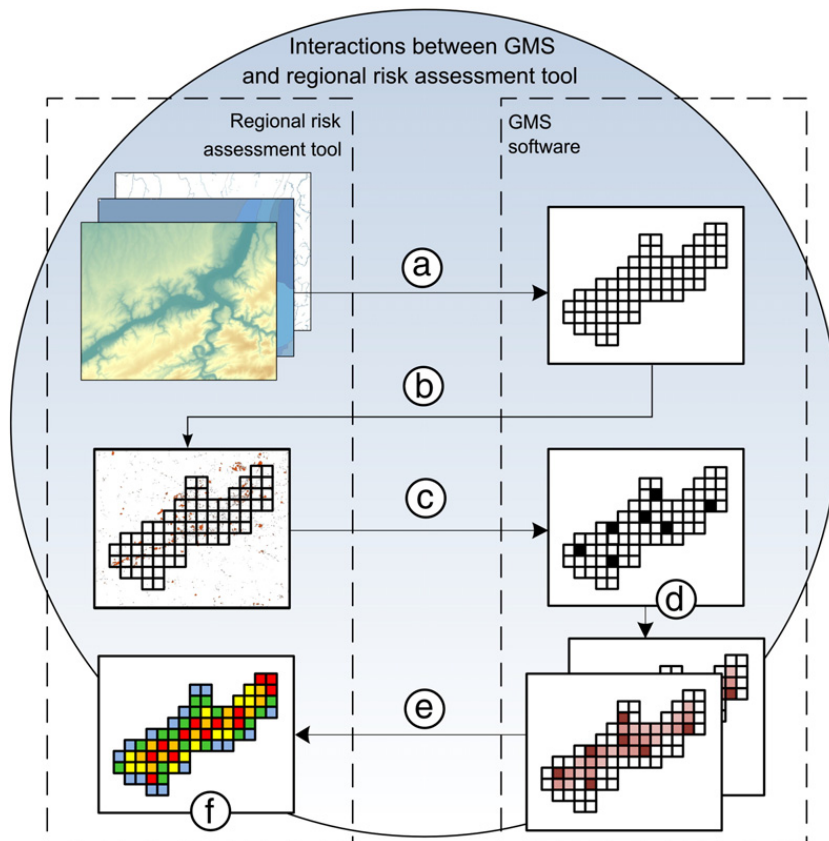


Fig. 3. Interactions between GIS and regional risk assessment tool.

contaminant fluxes to and in groundwater. In this context, a land cover mapping classification methodology has been developed from high resolution satellite data in order to distribute in space the recharge as a function of the land-use and soil imperviousness (Dujardin et al., 2009).

Practically, MODFLOW (Harbaugh et al., 2000) and MT3D (Zheng and Wang, 1999) numerical simulations are performed under GMS (Groundwater Modeling System) environment. Data and information exchanges between the modeling application and the regional risk assessment system are managed through specific communication modules developed in the GIS interface. The communication procedure is described in Fig. 3. The different shapefiles required for the hydrogeological conceptual model are prepared within the GIS system using data from the geodatabase and imported in GMS (Fig. 3a) using the 'GIS and Map Module'. Based on that, a regional finite difference grid is created and exported back to the GIS interface (Fig. 3b) where it is used to clip the pollution sources and related information (contaminant types and properties ...) to be again further exported in the appropriate GMS grid format (Fig. 3c) for contaminant transport simulations (Fig. 3d). Currently, the considered contaminant transport processes are advection, hydrodynamic dispersion, linear sorption and degradation (Eq. 1).

$$R \frac{\partial C}{\partial t} = \text{div}(\underline{D} \underline{\text{grad}} C - \underline{v}_e C) - \lambda RC + C^* \frac{q'}{n_e} \quad (1)$$

where C is the concentration [M L^{-3}], t : time [T], D is the hydrodynamic dispersion tensor [$\text{L}^2 \text{T}^{-1}$], \underline{v}_e is the groundwater effective velocity [L T^{-1}], λ is the first-order degradation constant (T^{-1}), q' : a source-sink term [T^{-1}], $C^* = C$ if $q' < 0$ (sink) and $C^* = C_{in}$ if $q' > 0$ (source), n_e is the effective (transport) porosity [–], R is the retardation factor equal to $1 + \frac{\rho_b K_d}{n_e}$ with ρ_b is the bulk density of the porous media [M L^{-3}] and K_d the distribution coefficient between aqueous and solid phase (linear sorption) [$\text{L}^3 \text{M}^{-1}$].

Once simulations are performed, modeling results (piezometric heads and contaminant concentrations at different time steps, one data set per contaminant) are imported into the GIS interface (Fig. 3e) for the calculation of the groundwater quality indicators (Fig. 3f), as described in the next section.

2.3. Groundwater quality assessment using the SEQ-ESO indicator

The transport model provides concentrations of contaminants in groundwater at different times. However, these contaminants are of different nature, with specific physico-chemical properties and harmfulness for health or environment. To evaluate objectively the overall quality of groundwater and its level of degradation, it is necessary to normalize the concentrations of contaminants using a uniform classification procedure with classes that consistently reflect equivalent levels of degradation for the different contaminants considered (e.g. drinking water limit). To reach that objective, the SEQ-ESO indicator ('Système d'Evaluation de la Qualité des Eaux Souterraines', i.e. Groundwater Quality Evaluation System) used by the Walloon Region of Belgium to report on the Water Framework

Directive groundwater quality monitoring network (Rentier et al., 2004a; 2004b) has been selected and adapted. It is based on the SEQ-Eau ranking system initially developed by the French water agencies (Agences de l'Eau, 2002). The SEQ-ESO provides an interpretation grid for a complete protocol analysis related to a single water sampling point. Conversion from contaminant concentrations to a normalized non-dimensional index is based on interpolation functions between different threshold values that depend on the water uses. The final quality index, ranging from 100 (good quality) to 0 (very degraded) corresponds to the index of the most problematic compound (Rentier et al., 2006).

The calculation the SEQ-ESO quality index is performed in two steps. First, contaminant concentrations are normalized on a [0 = poor, 100 = good] scale considering different contaminant specific threshold values, as illustrated for benzene in Fig. 4. The threshold values are defined for each kind of contaminant with respect to different water uses. Three different water uses have been defined originally for the SEQ-ESO: patrimonial status (PS), drinking water use (DWU) and, biological impact on water courses (BIO). A global groundwater quality status, called SEQW, is also evaluated using a combination of PS and DWU thresholds (see example for benzene in Table 1). Four threshold values are defined for each pollutant with linear interpolation for the three first intervals (S0–S1, S1–S2 and S2–S3), antilogarithmic interpolation for the S3–S4 interval and negative exponential interpolation above the S4 threshold. In a second step, the quality index is set equal to the lowest quality index corresponding to the most degrading contaminant. In the regional risk assessment approach described here, the SEQ-ESO threshold values have been incorporated into the pollutant library of the database considering the different water uses (PS, DWU, BIO and SEQW). However, the SEQW indicator, which is assumed to better reflect the global quality of water, independently of any use, is effectively considered for the calculation of the regional indicator for groundwater quality. A specific SEQ-ESO module has been developed in the ArcMAP environment for calculation of the regional indicator of groundwater quality based on the SEQ-ESO methodology (Fig. 3d).

Results imported from the groundwater flow and transport simulations provide concentrations for each contaminant in each grid cell and at each time step. The SEQ-ESO procedure is applied in each cell of the grid to normalize the concentrations of contaminants and to convert them into groundwater quality indexes by considering the specific threshold values of each contaminant.

This provides, at each time step, a map of distributed groundwater quality indexes at the level of the grid. Finally, an overall indicator can be obtained at each time step, by spatial aggregation of the grid indicators weighted by the volumes of groundwater present in each cell (Eq. 2).

$$I_{global} = \frac{\sum I_i V_i}{V_{GW}} \quad (2)$$

where I_{global} is the global quality index for the whole groundwater body at time t [–], V_{GW} : the volume of groundwater comprised in the zone where the risk is assessed [L^3], V_i : volume of groundwater into the cell i [L^3] and I_i : quality index for the cell i [–].

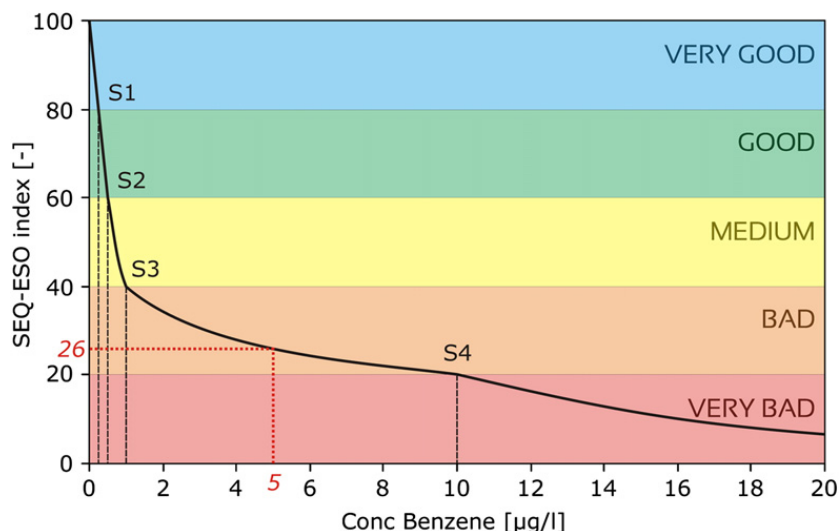


Fig. 4. Normalization from benzene concentration in groundwater to groundwater quality index according to SEQ-ESO method and SEQW thresholds (for example, groundwater contaminated at 5 µg/l of benzene corresponds to a quality index of 26).

The results of the SEQ-ESO application can be used in different ways. The maps of indicators can be used to identify most problematic sectors (contamination hot spots) with heavily contaminated groundwater volumes within a more generalized contamination. At the grid cell level, one can examine the global evolution with time of groundwater quality. Finally, the aggregated indicator can be used to report on the groundwater quality status of the groundwater body and for groundwater quality trend assessment. In this context, the indicator can be used as a referential for evaluating the risk of not reaching a good status and to test the efficiency of programs of measures defined to restore groundwater quality.

3. Illustrations

Two examples are proposed to illustrate the methodology and to show its usefulness for groundwater management in urbanized and industrialized areas: a synthetic example and the first results of a large scale application on a deteriorated groundwater body in Belgium.

3.1. Synthetic illustrative example

This simplified example reproduces the relatively frequent case of pollution of an alluvial aquifer by industrial contaminants emitted from an industrial plant located nearby a river

(e.g. [Batlle-Aguilar et al., 2009](#)). The studied domain corresponds to a polluted area of 500 by 400 m. The alluvial aquifer has a thickness of 15 m. The mean hydraulic conductivity of the alluvial sediments is 1×10^{-5} m/s. Groundwater is recharged by infiltration from rainfall ($135 \text{ mm/y} = 4.3 \times 10^{-9}$ m/s). The alluvial aquifer is drained laterally by the river. No-flow boundaries conditions are assumed at the external lateral boundaries (north, south, west) of the model, except at the riverbank (east) where a draining river boundary condition is defined (river stage: 55 m, hydraulic conductance of the riverbed: 2.5×10^{-4} m²/s). The pollution sources defined at three different locations in the contaminated land parcel are assumed to emit three different pollutants with contrasted physico-chemical properties representative of common contaminants in such contexts: a PAH-like pollutant (low mobility, moderate degradation), a BTEX-like pollutant (high mobility, high degradation) and a VOCl-like pollutant (high mobility, low degradation) ([Table 2](#)). Contaminants are assumed to leach into the aquifer at their maximum solubility in the recharge water for a period of 15 years, after which the sources are assumed to be removed and contaminant leaching is stopped. The contaminant transport model is run for 45 years from the beginning of the leaching of contaminants.

[Fig. 5a](#) shows the three contaminants plumes in terms of concentrations after 15 years. As expected, these plumes reflect the specific properties of the contaminants (solubility, sorptiv-

Table 1
Illustration of the combination of PS and DWU thresholds for the definition of SEQW threshold and origin of thresholds for benzene (example).

Benzene	Patrimonial status (PS)		Drinking water use (DWU)		SEQW
	Threshold	µg/l	Origin	µg/l	
S1	0.25	Reference value for natural groundwater quality including geochemical background.	0.5	Guidance value of the 80/778/CEE EU Directive concerning drinking water (CEU 1980).	0.25
S2	0.5	Linear interpolation between S1 and S3	1	Walloon drinking water standard	0.5
S3	0.75	Threshold value as defined in the Walloon Soil Decree	–	Does not exist	1
S4	4	Intervention value for cleaning as defined in the Walloon Soil Decree	10	Guidance value of the 75/440/CEE EU Directive concerning quality water before treatment of surface abstracted for drinking water (CEU 1975).	10

Table 2
Contaminants parameters used for the synthetic test case.

Parameters	Units	Benzene-like species	PAH-like species	VOC-like species
Concentration in recharge	mg/l	1830	10	1100
Kd	m ³ /mg	4.15×10^{-11}	4.77×10^{-7}	3.50×10^{-11}
Degradation	s ⁻¹	1×10^{-7}	1×10^{-9}	1×10^{-9}

ity and degradability). PAHs are almost immobile and do not disperse into groundwater. VOCI are very mobile and BTEX are mobile but their plume extent is reduced because of degradation processes. However, these pictures do not give any clear insight on the actual degradation level of the groundwater resource in the area. Fig. 5b shows the SEQ-ESO map of indicators for the three contaminants concentrations scaled into in a single groundwater quality index. This shows that most of the groundwater is heavily contaminated in the plumes. Finally, Fig. 5c shows the evolution of the spatially aggregated groundwater quality index for each contaminant considered separately and the global SEQ-ESO indicator for the whole aquifer. During the period of contaminant leaching, groundwater quality is progressively degraded with time, the VOCI contaminant being the most significant contributor (approximately 40%) to this degradation. The BTEX contaminant contributes to a subsequent degradation of groundwater (approximately 10%) during the first 25 years. After 25 years, the contribution of BTEX to groundwater quality degradation becomes negligible because of the progressive removal of the remaining quantity of BTEX by biodegradation in contrast with VOCI that does not degrade and keep a strong impact on groundwater quality after 45 years. The PAH contaminant is very sorptive and insoluble and it remains captured near the source from where it never effectively contaminates groundwater.

3.2. Real-scale application in the alluvial aquifer of the River Meuse

The Meuse River flows in the Walloon Region of Belgium along 128 km from the French to the Dutch borders. The alluvial aquifer located in the deposits of the river contains an important groundwater resource which is exploited for water distribution and industry thanks to many water catchments located in the alluvial plain (Haddouchi, 1987; Brouyères et al., 2006). In the region of Liège, heavy industries related to coal extraction, metallurgy and chemistry have been developed for more than two centuries. These industries were preferentially settled in the alluvial plain, near the river, for facilitating transportation by boat of primary and final products. This, together with a growth in the urbanization, has resulted nowadays in the existence of numerous potentially contaminated sites and a generalized contamination of groundwater in the alluvial aquifer.

The portion of alluvial aquifer corresponding to the industrial area, located North-East of the Meuse Belgian stream (Fig. 6a), has been explicitly defined by regulators as a distinct groundwater body (named RWM073) from the rest of the alluvial aquifer to allow defining specific measures

related to the issue of deterioration in groundwater quality in this part of the alluvial aquifer.

The problem of regional groundwater contamination is known and documented through water analyses at different locations, but important questions remain. There is no real global estimation of the actual level of water quality degradation at the scale of the groundwater body and of the actual contribution of industrial activities to this degradation as compared to other possible contamination sources, such as groundwater rebound after coal mine closure or diffuse atmospheric pollution. There is also no integrated referential for land cleanup prioritization and cost-efficiency assessment. To answer these questions, a referential for groundwater quality at the scale of the groundwater body is essential. An application of the regional-scale risk assessment approach has been initiated on this groundwater body. At the following, the first steps and results are described. At this step of the analysis, the objective of the real-scale application is not to provide a definitive value of the indicator of groundwater quality for the investigated groundwater body but to test and validate the concepts at real scale and to identify the priorities for further investigations.

The Meuse river alluvial gravel groundwater body RWM073 stretches on 40 km. The alluvial plain has a mean width of 3 km. The usual top-bottom geology consist of 2 to 4 m of backfill deposits, 1 to 4 m of silt sand clay deposits and approximately 8 m of alluvial gravels lying on a shaly bedrock that constitutes the impervious lower boundary of the aquifer. A data mining on the hydraulic properties of the aquifer has revealed hydraulic conductivity values ranging from 10^{-3} to 10^{-6} m/s with a mean value of 8×10^{-5} m/s. Along most of the river course, groundwater is drained by the Meuse River and it flows more or less perpendicularly to the river bank with a mean hydraulic gradient of 0.003 m/m. The aquifer recharge has been calculated using remote sensing imagery integrated in a modeling procedure. From medium resolution satellite imagery, the land-cover mapping is drawn and serves, along with soil type, topography and other physical parameters, in a hydrologic model to produce a high resolution spatially distributed groundwater recharge (Dujardin et al., 2011). Groundwater abstraction in the alluvial aquifer is limited to few industrial pumping wells which do not significantly affect regional groundwater patterns. As a first approximation, these pumping wells have been disregarded.

Groundwater flow and transport simulations are performed using MODFLOW (Harbaugh et al., 2000) and MT3D (Zheng and Wang, 1999). The model is developed using the finite difference method with a constant cell size of 20 by 20 m. The top of the model is given by a DTM and the cell thickness is assumed constant (15 m). The external boundary conditions are represented by specified fluxes at the lateral limits of the alluvial plain to consider groundwater flowing from the hill slope of the valley, by the infiltration recharge and by the River Meuse acting as regional drain of the aquifer. The groundwater flow model is calibrated in steady state mode using piezometric head measurements available in the area (Fig. 6b). Transport parameters are defined based on previous experiments and scientific works in the Meuse alluvial aquifer (Derouane and Dassargues, 1994; Brouyère, 2001; Batlle-Aguilar, 2008; Batlle-Aguilar et al., 2009). Transport simulations are run over a 20 years period.

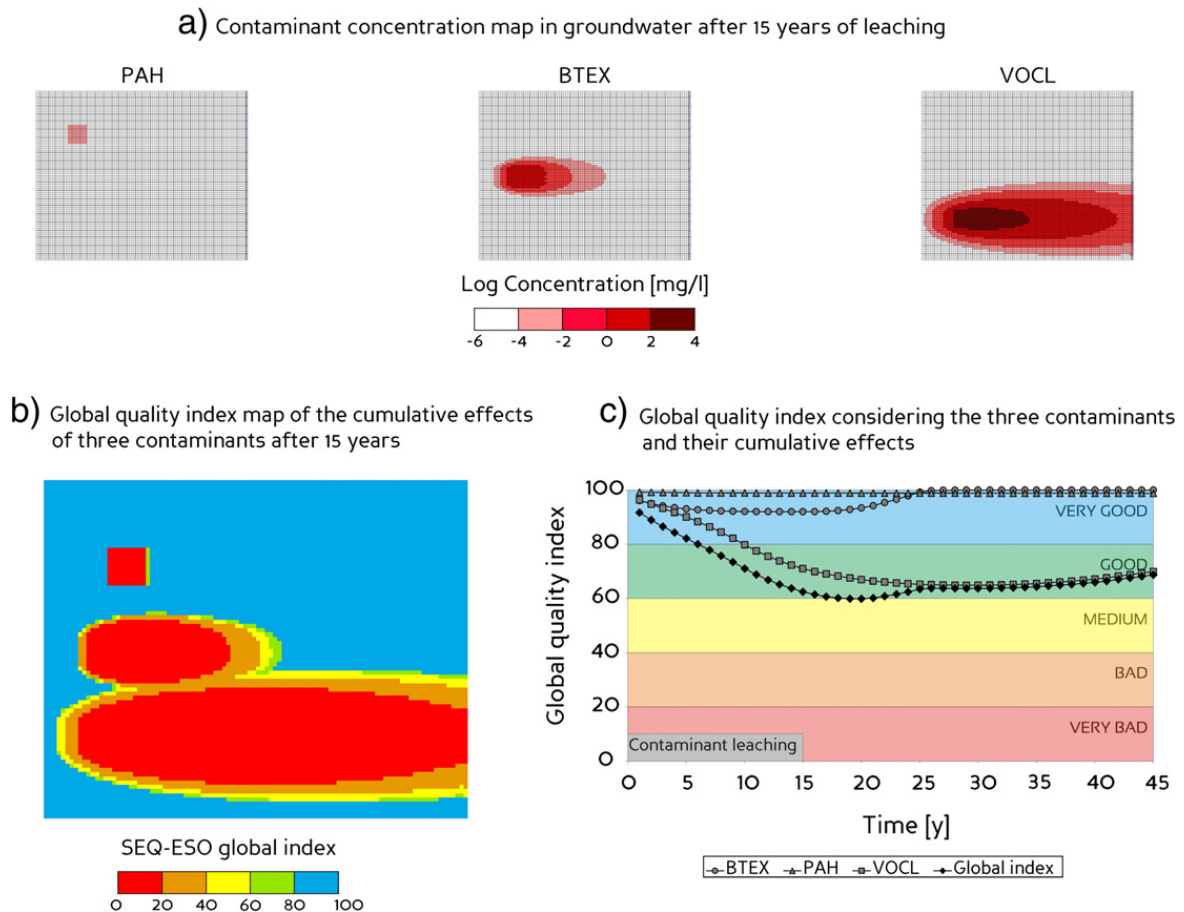


Fig. 5. (a) Contaminants concentration after 15 years, (b) map of groundwater quality index after 15 years and (c) evolution with time of the global quality index using SEQ-ESO after spatial integration.

The GIS-based regional risk assessment application has been used to extract the most common industrial activities recovered on the groundwater body, *i.e.* industrial plants included in the categories “mining”, “gas station” and “metallurgy”. Only important plants with a spatial extent larger than 5000 m² have been considered. In this example, benzene is the only contaminant taken into consideration, with a worst case scenario assuming that all potential sources are active. The sources of contaminant are assumed to leach continuously in the recharge to the aquifer at their maximum solubility and contaminant spreading in groundwater is modeled considering advection, dispersion, sorption and degradation processes (Table 3). In the reality, the different sources have certainly started to leach at different times and with different discharge rates and the contamination history should be reconstructed in order to produce a more representative sketch of the time evolution of groundwater contamination (e.g. Troldborg et al., 2008).

Once the simulation is performed in GMS, results files are exported to the GIS application to calculate maps of the SEQ-ESO indicators and the global quality index at each time step.

Fig. 6b shows the map of benzene concentrations in the alluvial aquifer and Fig. 6c a map of the global quality index, both after 10 years. This map highlights highly contaminated zones.

The last graph (Fig. 6d) shows the evolution with time of the SEQ-ESO global quality index for the whole groundwater body.

Contaminant plumes reach steady state and equilibrium between source leaching and contaminant dispersion, attenuation and drainage to surface water after approximately 5 years. All the simulations performed here show that, a single polluted site does not have a significant effect on the overall quality of that whole groundwater body but that, with reasonable assumption and despite the turnover of groundwater and the degradation of pollutants, multiplication of industrial contaminated sites can have a strong effect on groundwater quality at the scale of the groundwater body.

However, simulations were run considering strong assumptions that constitute a worst case scenario for benzene for which a large amount of contaminant is probably released into the groundwater body. A real case is for sure much more complex. Many different contaminants with different physico-chemical properties (sorption, degradation) are usually released to groundwater at different times and for different durations. Source strengths are usually smaller because the contaminated soils are usually restricted to some parts of extents of the industrial sites. However, leaching can be greater in case of non-aqueous phase liquids. Based on these considerations, it can be concluded from the first simulations that the industrial pressure on the Meuse alluvial aquifer is likely to be important but no definitive and quantitative conclusions can be drawn at this level of the analysis. Further data on contaminated sites characterization remain necessary for refining the regional risk assessment.

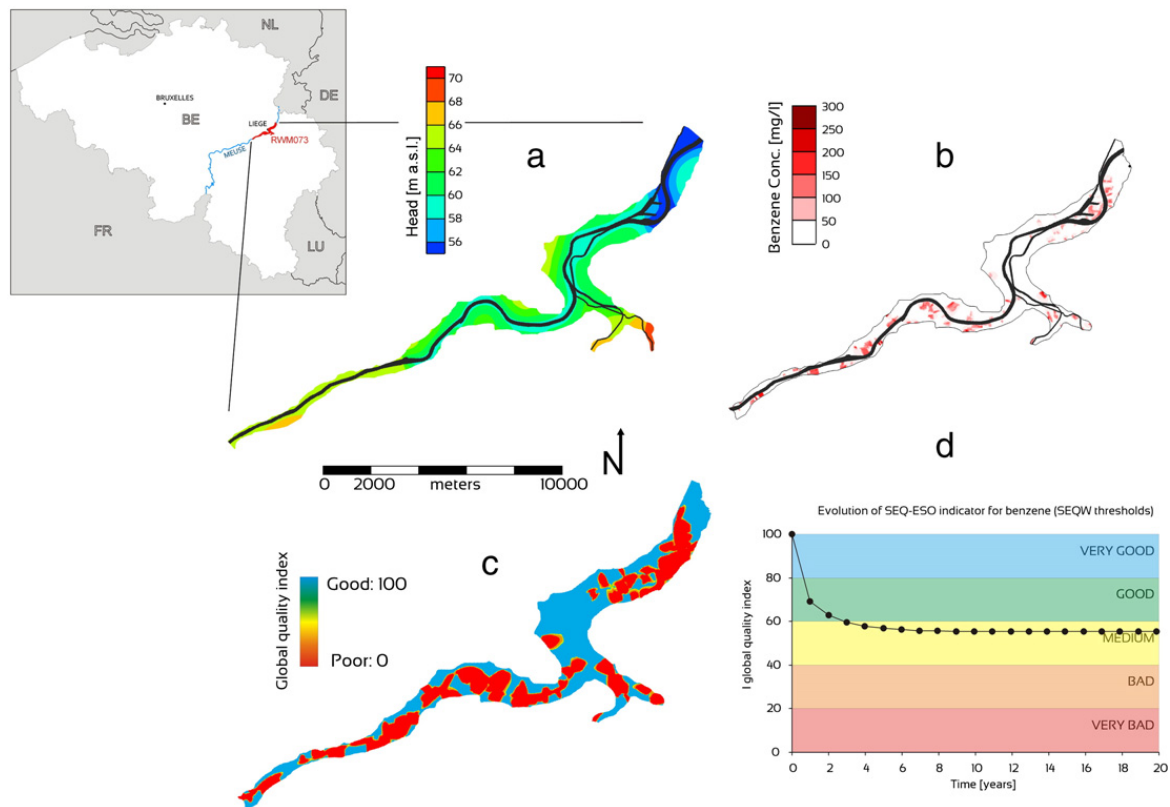


Fig. 6. Preliminary results of regional risk assessment on groundwater body RWM073 considering industrial activities releasing benzene into the groundwater. The resulting SEQ-ESO indicator suggests a “medium” quality status of the groundwater body.

Table 3
Contaminants parameters used for real application case.

Parameters	Units	Benzene
Concentration in recharge	mg/l	1830
Kd	m ³ /mg	4.15×10^{-11}
Degradation	s ⁻¹	1×10^{-7}
Longitudinal dispersivity	m	5
Transversal dispersivity	m	0.5
Effective porosity	–	0.05

3.3. Conclusions and perspectives

A regional scale risk assessment methodology for groundwater bodies is proposed as a flexible approach for evaluating the pressure exerted by various sources of contamination of groundwater resources. The methodology is based on the aggregation of various cumulative sources of contaminants of different chemical natures, properties and toxicities into a set of “easy to use” spatially distributed or aggregated indicators.

The spatially-distributed indicators (maps of indicators) can be used to identify most problematic sectors (hot contamination spots) with larger volumes of heavily contaminated groundwater and the evolution with time of groundwater quality at different locations in the catchment. The spatially-aggregated indicator can be used to report on the global status of groundwater quality in the groundwater body, for groundwater quality trend assessment and as a referential for site prioritization and for the evaluation of programs of measures

aiming at restoring groundwater quality in the groundwater body, using cost-efficiency approaches.

Thanks to these capabilities, the regional risk assessment methodology is compliant with the ongoing legislation in the Walloon region, based on the SEQ-ESO and it fits very well with the guidelines of the EU Water Directive which promotes the use of aggregated indicators able to reflect status and trends in groundwater quality and to evaluate in a rigorous way the risk of not reaching a good status by specific milestones such as 2015.

A synthetic example and a first illustrative application have been developed for the alluvial aquifer of the Meuse River in the region of Liège (Belgium). These examples confirm that the approach provides a useful referential for decision-making in relation with regional contamination of groundwater. The synthetic test case demonstrate that the approach is able to turn a complex multiple contamination into a simple global quality index, evolving with time and easily incorporated or compared to a risk index.

The application on the RWM073 allows also defining the weakest points and drawbacks of such a regional approach and the priorities for further developments. First, the approach is data demanding. However, this is the case for all these regional scale approaches that require relatively important preparatory works for data acquisition, organization and processing. This drawback is partly overcome by the use of a geospatial database and specific interfacing tools between the GIS system, the groundwater flow and transport modeling application and the regional SEQ-ESO calculation module. In this context, further work is ongoing on developing customized user-interfaces for a better integration of the whole procedure.

Secondly, there are many sources of uncertainties in the different data feeding the approach. In particular, the pollution sources are not always perfectly identified and characterized and hydrogeological parameters and contaminant properties remain difficult to identify and to quantify at the regional scale. Further investigations are required on the reconstruction of the history of contamination of the groundwater body and on a better evaluation of source strengths. A key next step will be to implement a statistical approach for handling all the uncertainties that remain at regional scale. More particularly, it is expected to obtain, in a near future, statistics on contaminant leaching in relation with different industrial and environmental factors such as characterization of contaminated site (industrial activity, area, land use) and properties of the soil (groundwater flow, lithology). To reach that objective, information on contaminated sites available in the French database ADES (Chery et al., 2008) developed and managed by BRGM, will be used. This database contains analyses for contaminants in groundwater for most industrial plants in France as requested by the regional environmental agencies.

Finally, the regional flux-based risk assessment approach is now used as a referential for a cost–benefit assessment of total or partial remediation of the contaminated groundwater body, according to different management scenarios. This analysis starts from the actual groundwater body quality state for which groundwater restoration scenarios (based on natural attenuation or active remediation) are suggested. The regional risk assessment method is then applied on these scenarios to evaluate the improvement of the groundwater quality index when management plans are applied. This allows evaluating, in monetary terms, the costs for given improvements in the groundwater body quality status.

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References

- Agences de l'Eau, 2002. Groundwater Quality Evaluation System "SEQ-Eaux Souterraines". Bureau de Recherches géologiques et minières, France. 72 pp.
- Battle-Aguilar J., 2008. Groundwater flow and contaminant transport in an alluvial aquifer: *in-situ* investigation and modelling of a brownfield with strong groundwater – surface water interactions. PhD thesis, Faculty of Applied Sciences, Université de Liège, Liège, Belgium, 249p.
- Battle-Aguilar, J., Brouyère, S., Dassargues, A., Morasch, B., Hunkeler, D., Diels, L., Vanbroekhoven, K., Seuntjens, P., 2009. Benzene dispersion and natural attenuation in an alluvial aquifer with strong interactions with surface water. *Journal of Hydrology*. Hydrol. 369 (305–317), 2009.
- Béranger, S., Blanchard, F., Archambault, A., Allier, D., 2006. Utilisation des outils d'aide à la décision dans la gestion des mégasites, Rapport BRGM/RP-55223-FR. <http://www.brgm.fr/publication/pubDetailRapportSP.jsp?id=RSP-BRGM/RP-55223-FR> 2006114p.
- Brils, J., Harris, B. (Eds.), 2009. Towards Risk-Based Management of European River Basins: Key-Findings and Recommendations of the RISKBASE project, EC FP6 reference GOCE 036938, December 2009. Utrecht, The Netherlands.
- Brouyère, S., 2001. Study and modelling of transport and retardation of solutes in variably saturated media. PhD Thesis, Faculté des Sciences Appliquées, Laboratoire de géologie de l'ingénieur, d'Hydrogéologie et de Prospection géophysique, Université de Liège, Liège, Belgium, 307 p.
- Brouyères, S., Orban, Ph., Rothy, I., 2006. Quantitative and qualitative state of the groundwater in the Walloon Region. (L'état quantitatif et qualitatif des eaux souterraines en Région wallonne) (in french). Scientific Report for the Walloon Environmental State 2006–2007. University of Liège, Liège, Belgium. 76p.
- Carlou, C., Critto, A., Ramieri, E., Marcomini, A., 2007. DESYRE: decision support system for the rehabilitation of contaminated megasites. *Integr. Environ. Assess. Manag.* 3, 211–222.
- Carlou, C., Pizzol, L., Critto, A., Marcomini, A., 2008. A spatial risk assessment methodology to support remediation of contaminated land. *Environ. Int.* 34 (3), 397–411.
- Caterina, D., Brouyère, S., Jamin, P., Battle-Aguilar, J., Dassargues, A., Dejonghe, W., Diels, L., Crèvecoeur, S., Thomé, J.-P., Dujardin, J., Batelaan, O., Canters, F., Hérivaux, C., 2009. Flux-Based Risk Assessment of the Impact of Contaminants on Water Resources and Ecosystems "FRAC-WECO". Final Report. Brussels: Belgian Science Policy, Science for a Sustainable Development Research Program. http://www.belspo.be/belspo/ssd/science/FinalReports/rappSDterr_fr.stm – 59 pp.
- Chery, L., Martin, A., Legrand, H., 2008. National access to water database: a case study with the ADES portal. TSM (Techniques Sciences Méthodes, genie urbain et rural) (in french), No 2, pp. 85–92.
- Chisala, B.N., Tait, N.G., Lerner, N.G., 2007. Evaluating the risks of methyl tertiary butyl ether (MTBE) pollution of urban groundwater. *J. Contam. Hydrol.* 91, 128–145.
- CLARINET, 2002. Review of Decision Support Tools for Contaminated Land Management: an Overview. http://www.commonforum.eu/publications_clarinet.asp 2002192p.
- Critto, A., Sutter II, G.W., 2009. Environmental risk assessment. In: Marcomini, A., Critto, A., Sutter II, G.W. (Eds.), *Decision Support Systems for Risk-Based Management of Contaminated Sites*. Springer Science + Business Media, pp. 29–52.
- Derouane, J., Dassargues, A., 1994. Modélisation mathématique appliquée à la délimitation des zones de protection: cas du site de captage de Vivegnis (plaine alluviale de la Meuse, Belgique) (in French). *Bulletin du Centre d'Hydrogéologie de l'Université de Neuchâtel (Suisse)* 13, 53–68.
- Dujardin, J., Boel, S., Anibas, C., Batelaan, O., Canters, F., 2009. Improving surface–subsurface water budgeting for brownfield study sites using high resolution satellite imagery. EGU General Assembly 2009, Vienna, Austria. <http://adsabs.harvard.edu/abs/2009EGUGA..11.7052D>.
- Dujardin, J., Jamin, P., Batelaan, O., Canters, F., Brouyère, S., Dassargues, A., 2011. Regional flux-based risk assessment of contaminants in a groundwater body using remote sensing imagery integrated in a modeling procedure. EGU General Assembly 2011, Vienna, Austria. <http://meetingorganizer.copernicus.org/EGU2011/EGU2011-5826.pdf>.
- European Environment Agency EEA, 2006. Guidance Document for the implementation of the European PRTR. <http://www.eea.europa.eu/data-and-maps/explore-interactive-maps/promotions/european-pollutant-release-and-transfer-register-2014-e-prtr> 2006148 pp.
- Council of the European Union, 1975. Directive 75/440/CEE concerning the quality required of surface water intended for the abstraction of drinking water in the Member States (further amended by Council Directive 79/869/EEC and Council Directive 91/692/EEC). http://ec.europa.eu/environment/water/water-drink/index_en.html 1975.
- Council of the European Union, 1980. Directive 80/778/EEC relating to the quality of water intended for human consumption as amended by Council Directives 81/858/EEC and 91/692/EEC (further amended by Council Regulation 1882/2003/EC). http://ec.europa.eu/environment/water/water-drink/index_en.html 1980.
- European Parliament, the Council of the European Union, 2000. Directive 2000/60/EC establishing a framework for the Community action in the field of water policy. http://ec.europa.eu/environment/water/index_en.htm 2000.
- European Parliament, the Council of the European Union, 2008. Regulation 1893/2006 establishing the statistical classification of economic activities NACE. http://ec.europa.eu/environment/water/index_en.htm. 2008.
- Fairman, R., Mead, C.D., Williams, W.P., 1999. Environmental risk assessment: approaches, experiences and information. Environmental issue report No 4., EEA (European Environment Agency). <http://www.eea.europa.eu/publications/GH-07-97-595-EN-C2/riskindex.html>, 251 pp.
- Ferguson, C., Darmendrail, D., Freier, K., Jensen, B.K., Jensen, J., Kasamas, H., Urzelai, A., Vegter, J., 1998. Risk assessment for contaminated sites in Europe. Scientific Basis, LQM Press, Nottingham, UK, Volume 1. <http://www.lqm.co.uk/pages/publications.html>, 165 pp.
- Gay, J.R., Korre, A., 2006. A spatially-evaluated methodology for assessing risk to a population from contaminated land. *Environ. Pollut.* 142, 227–234.

- Haddouchi, B., 1987. Etude géologique et hydrogéologique de la plaine alluviale de la Meuse en Belgique. PhD Thesis, Faculté des Sciences Appliquées, Laboratoire de géologie de l'ingénieur, d'Hydrogéologie et de Prospection géophysique, Université de Liège, Liège, Belgium, 307 pp.
- Harbaugh, A.W., Banta, E.R., Hill, M.C., McDonald, M.G., 2000. MODFLOW-2000, the U.S. Geological Survey modular ground-water model – user guide to modularization concepts and the Ground-Water Flow Process. Open-File Report 00–92. U.S. Geological Survey. <http://water.usgs.gov/nrp/gwsoftware/modflow2000/ofr00-92.pdf>, 121 pp.
- Jarsjo, J., Bayer-Raich, M., Ptak, T., 2005. Monitoring groundwater contamination and delineating source zones at industrial sites: uncertainty analyses using integral pumping tests. *J. Contam. Hydrol.* 79, 107–134.
- Kinerson, R.S., Kittle, J.L., Duda, P.B., 2009. BASINS: better assessment science integrating point and nonpoint sources. In: Marcomini, A., Critto, A., Sutter II, G.W. (Eds.), *Decision Support Systems for Risk-Based Management of Contaminated Sites*. Springer Science + Business Media, pp. 375–398.
- MATE, 2000. (Potentially) polluted sites management. Ministère de l'Aménagement du Territoire et de l'Environnement. Classeur "Gestion des sites (potentiellement) pollués" (in french), version 2. éditions du BRGM.
- Morio, M., Finkel, M., Schädler, S., Hartmuth, G., Rügner, H., 2008. Improving mega-site revitalisation strategies by trading off benefits from future land use and clean-up costs. Proceedings of the conference Groundwater Quality 2007, Securing Groundwater Quality in Urban and Industrial Environments. IAHS Publ. 324, Fremantle, Australia, pp. 555–562.
- NICOLE, 2003. Sharing Experience in the Management of Megasites: towards a sustainable approach in land management of industrially contaminated sites. Report of the NICOLE Workshop, 29–31 October 2003. <http://www.nicole.org/documents/DocumentList.aspx?l=1&w=n>, 55 pp.
- Purucker, S.T., Stewart, R.N., Welsh, C.J.E., 2009. SADA: ecological risk based decision support system for selective remediation. In: Marcomini, A., Critto, A., Sutter II, G.W. (Eds.), *Decision Support Systems for Risk-Based Management of Contaminated Sites*. Springer Science + Business Media, pp. 239–256.
- Ptak, T., Ertel, T., Teutsch, G., 2003. An integral approach for the quantification of subsurface contamination. In: Annokkée, G.J., Arendt, F., Uhlmann, O. (Eds.), *ConSoil 2003, Wissenschaftliche Berichte, FZKA 6943*, Forschungszentrum Karlsruhe in der Helmholtz-Gemeinschaft, pp. 3322–3329.
- Rentier, C., Delloye, F., Brouyère, S., Dassargues, A., 2006. A framework for an optimised groundwater monitoring network and aggregated indicators. *Environmental Geology* 50 (2), 194–201.
- Rentier, C., Delloye, F., Dassargues, A., 2004a. 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 (in french). Unpublished report University of Liege, Walloon Region, p 215.
- Rentier, C., Delloye, F., Dassargues, A., 2004a. Réseaux de surveillance des masses d'eau souterraine en Région Wallonne. *Tribune de l'Eau* 631–632, 11–21.
- Schädler, S., Morio, M., Finkel, M., 2007. Land use related cost estimates for contaminated site development: consequences of uncertainty to planning and investment decisions. Proceedings of the conference Groundwater Quality 2007, Securing Groundwater Quality in Urban and Industrial Environments. IAHS Publ. 324, Fremantle, Australia, pp. 539–546.
- Semenzin, E., Critto, A., Rutgers, M., Marcomini, A., 2009. DSS-ERAMANIA: decision support system for site-specific ecological risk assessment of contaminated sites. In: Marcomini, A., Critto, A., Sutter II, G.W. (Eds.), *Decision Support Systems for Risk-Based Management of Contaminated Sites*. Springer Science + Business Media, pp. 205–238.
- SITERem, 2002. Inventory of the relationships between plants/activities and soil contaminations risks. Inventaire des relations entre les activités/installations et les risques de pollution du sol (in French). Convention Région Wallonne (RW) – SITEREM S.A. 78 pp.
- Sullivan, T., Yatsalo, B., Grebenkov, A., Linkov, I., 2009. Decision Evaluation for Complex Risk Network Systems (DECERNS) software tool. In: Marcomini, A., Critto, A., Sutter II, G.W. (Eds.), *Decision Support Systems for Risk-Based Management of Contaminated Sites*. Springer Science + Business Media, pp. 257–280.
- Tait, N.G., Davison, R.M., Leharne, S.A., Lerner, D.N., 2008. Borehole Optimisation System (BOS) – a case study assessing options for abstraction of urban groundwater in Nottingham, UK. *Environmental Modelling and Software* 23, 611–621.
- Tait, N.G., Davison, R.M., Whittaker, J.J., Leharne, S.A., Lerner, D.N., 2004. Borehole Optimisation System (BOS) – a GIS based risk analysis tool for optimising the use of urban groundwater. *Environmental Modelling and Software* 19, 1111–1124.
- Troldborg, M., Lemming, G., Binning, P.J., Tuxen, N., Bjerg, P.L., 2008. Risk assessment and prioritisation of contaminated sites on the catchment scale. *J. Contam. Hydrol.* 101, 14–28.
- United Nations for Environment Programme/Agency for the Environment and Energy Management, 2005. Identification and Management of Contaminated Sites – A Methodological Guide. 132p.
- Vega, A., Argus, R., Stockton, T., Black, P., Black, K., Stiber, N., 2009. SMARTe: an MCDA approach to revitalize communities and restore the environment. In: Marcomini, A., Critto, A., Sutter II, G.W. (Eds.), *Decision Support Systems for Risk-Based Management of Contaminated Sites*. Springer Science + Business Media, pp. 179–204.
- Walloon Soil Decree, 2008. Soils management decree. Décret relatif à la gestion des sols (in French). <http://environnement.wallonie.be/LEGIS/solsoussol/sol003.htm> 2008(05.12.2008 - M.B. 18.02.2009 - add. 06.03.2009).
- WELCOME, 2004. Integrated Management Strategy for the Rotterdam megasite. Welcome Extensive Summary. 27 pp.
- Zheng, C., Wang, P.P., 1999. MT3DMS, a modular three-dimensional multi-species transport model for simulation of advection, dispersion and chemical reactions of contaminants in groundwater systems (Release DoD_3.50.A). Documentation and User's Guide, U.S. Army Corps of Engineers. 239p.