

ATES: a geo-informatics decision aid tool for the integration of groundwater into land planning

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ABSTRACT

Groundwater is the primary source of drinking water for small municipalities and individuals. However, groundwater can be polluted by almost any land use. Consequently, many governments have acquired groundwater information in the aim of protecting the resource. Nevertheless, the resulting data are often ill-fitted to planning needs. In a previous study, a method was developed to help planners interpret hydrogeological data. It combines land planning and hydrogeological data through multicriteria analysis, in order to obtain groundwater contamination risk maps. The method proved efficient and useful. However, it could not be easily implemented by land planners, who do not always have training with these types of data and geographical information system (GIS). This paper presents how the method was integrated into a web-based interface called Aménagement du Territoire et Eau Souterraine (ATES). ATES allows planners to view groundwater basic maps, evaluate the present contamination risk for groundwater, and analyse new planning scenarios. ATES also suggests mitigation measures and offers tools to discuss the possible solutions. The tool has been developed, tested and validated with land planners. To our knowledge, it is the first geo-informatics tool developed especially for planners that aims at facilitating the incorporation of groundwater into planning. Moreover, an innovative approach called MACBETH was used for data aggregation, a novelty in groundwater management and spatial data integration.

Key words | groundwater protection, land planning, risk evaluation, web-based GIS tool

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ACRONYMS AND ABBREVIATIONS

ATES	Aménagement du territoire et eau souterraine, or land planning and groundwater	PACES	Programme d'acquisition des connaissances sur les eaux souterraines, program for acquisition of data on groundwater
COBARIC	Comité de bassin de la rivière Chaudière, Watershed organisation for the Chaudière River	RCM	Regional county municipality
GIS	Geographical information system	SCABRIC	Société de conservation et d'aménagement du bassin de la rivière Châteauguay, Watershed organism for the Châteauguay River
LID	Low impact development	US EPA	United States Environmental Protection Agency
L-THIA	Long-Term Hydrologic Impact Analysis		
MDDELCC	Ministère du Développement durable, de l'Environnement et de la Lutte contre les changements climatiques, or Ministry of sustainable development, environment and fight against climate change		
MULINO	Multi-sectoral integrated and operational decision support system for sustainable use of water resources at the catchment scale		

INTRODUCTION

Groundwater is an essential source of drinking water in many regions of the world. Half the people in the USA (51%) rely on

it for their daily water consumption (US Environmental Protection Agency 2010). In Canada, one-third of the total population relies on water originating from groundwater, but about 80% of the rural population depends entirely on it. Similarly, in the Province of Quebec (Canada), about 20% of the population is supplied by groundwater. However, that percentage is distributed over 90% of the land (Ministère du Développement durable de l'Environnement et de la Lutte contre les changements climatiques 2012), indicating that groundwater is the primary source of drinking water for small municipalities and individuals. Groundwater is generally of good quality and requires little treatment, an important advantage for small municipalities with limited infrastructures and financial resources. However, the local environment (type of soil, aquifer characteristics) can make groundwater vulnerable: practically every type of land use and anthropogenic activity can pose a threat to its quality (Granato & Smith 2002). Several examples of groundwater contamination confirm this statement. For instance, in 2000, in Walkerton, Ontario, the microbiological contamination of the municipal well from nearby agricultural lands killed seven people and made 2,300 others sick (O'Connor 2002). Along the US/Mexican border, incidences of water-borne diseases such as cholera, amoebiasis, hepatitis A and giardiasis have occurred because of inadequate solid waste treatment leading to contaminated groundwater (Kidd 2002).

In this context, several governments decided to produce hydrogeological data in order to better understand, protect and conserve their groundwater resources (Agriculture & Resource Management Council of Australia & New Zealand 1995; Government of Alberta 2006; US Environmental Protection Agency 2010; Government of British Columbia 2012; MDDEFP 2012). The data produced can range from simple vulnerability or recharge maps to complete atlases and databases characterizing the resource, including hydraulic conductivity, quality parameters, piezometry, recharge, geology, etc. In the Province of Quebec, Canada, the *Programme d'acquisition des connaissances sur les eaux souterraines* (PACES – program for acquisition of knowledge on groundwater) was launched in 2008. Its purpose was to produce complete hydrogeological atlases for the southern part of the province, which is the most populated region (Ministère du Développement durable de l'Environnement et de la Lutte contre les changements climatiques 2012). The

information resulting from these initiatives can be very useful in land planning. For instance, land development in municipalities or counties can be directed towards areas where groundwater is deemed sufficient (Acker & Lynch 2004; Wehrmann & Knapp 2006; Idaho Department of Water Resources 2009). In addition, by using such information, local authorities can turn to land use planning to promote strategies to prevent groundwater contamination (Giupponi et al. 1999; Collin & Melloul 2001, 2003; Thomsen et al. 2004). For example, land use planning can serve to define zones within a municipality where groundwater should be protected as a priority or identify sectors where potentially polluting activities could be acceptably located. However, it has been shown that hydrogeological data, as they are generally processed, disseminated and presented, are not suited to land planners' needs. The information provided lacks the interpretation needed for planners to be able to analyse it and make decisions (Lavoie et al. 2013, 2014).

Prior to developing the tool that will be presented in this paper, preliminary research steps were completed: a survey was conducted in North America to draw a picture of the integration of groundwater information into land planning (Lavoie et al. 2013); semi-directed interviews were conducted with planners in the Province of Quebec to better understand the local context (Lavoie et al. 2014); and a methodology was proposed to evaluate the risk of groundwater contamination from land uses (Lavoie et al. 2015). The semi-directed interviews were held with 22 planners from two different watersheds in Quebec (Lavoie et al. 2014). The watersheds were chosen because of the availability of the first two groundwater atlases in the province (Côté et al. 2006; COBARIC & Union des Producteurs Agricoles 2008). The atlases provide a great deal of information on groundwater, including recharge, vulnerability, hydraulic parameters, water quality and aquifer types, for instance. We previously discussed how useful this information can be for land planning. However, land planners from the two watersheds did not integrate the data into their planning to improve groundwater protection (Lavoie et al. 2014). The reasons underlying this situation were multiple. One reason was the fact that the data could not be incorporated into their own geomatic databases. However, several land planners also stated not being able to use geomatic tools, except for Google maps[®] (Google 2013). Moreover, the data needed to

be translated for use in land planning, in order for the planners to be able to refer to the information. Planners understood the maps, but could not identify their implications. They were most concerned about the quality of the water and how potentially polluting land uses could degrade it. On the basis of these observations, the idea of a geo-informatics tool emerged. The tool can serve to view the data, evaluate risks of groundwater contamination and help identify means to minimize said risks.

In a first step, a method was recently developed by the authors to produce maps to ascertain risks of groundwater contamination through land use (the development of this method is described in Lavoie *et al.* (2015)). The maps are evaluated by combining different aspects related to groundwater and land planning. This method has resulted in realistic outputs that provide a fair idea of the regional dynamics of groundwater. The maps have proven very useful for land planners. They allow planners to identify where the groundwater is threatened within their territory and to take action accordingly to minimize risks of contamination. They can also help delineate areas where the protection of water should be prioritized. However, although very useful, the procedure is complex. A geomatician, or at best someone with good knowledge of geographical information systems (GIS), is required to perform the tasks. In addition, it can take hours, if not days, to produce and analyse the results. This paper presents how the previously developed method has been integrated into ATEs (Aménagement du Territoire et Eau Souterraine, or land planning and groundwater), a geo-informatics decision aid tool that allows planners to examine groundwater contamination risk maps and analyse any new project on the basis of its impact on risk. The main novelty presented here is the programming of this method, which implies automatizing the MACBETH aggregation on spatial data and allows planners to use the developed method in a user-friendly environment. GIS-based decision support systems to help planners consider water while managing land have been developed before. Most focus on water quantity. The Long-Term Hydrologic Impact Analysis (L-THIA) tool (Engel & Theller 2011) analyses the impact of land use changes on average annual runoff volume as well as on potential storm water and pollutant reduction from low impact development (LID) measures. This helps planners understand the impact of land planning on water runoff and

promote LID (Hunter *et al.* 2010; Engel & Theller 2011). WEAP21 (Water Evaluation and Planning System) helps with water allocation. It serves to evaluate water resources, outputs and demand under different scenarios. The system provides information on supply sufficiency, average cost of delivered water, in-stream flow requirements, hydropower production and uncertainty of the data (Yates *et al.* 2005). Yang *et al.* (2011) have also developed a tool to facilitate water allocation, but in urban networks. The software provides hydraulic calculations of urban water supply networks (Yang *et al.* 2011). Chau *et al.* (2005) compared different models using hybrid algorithms in order to forecast floods in a channel of the Yangtze River. It could allow for quick and accurate flood forecasting, which is essential in flood-prone regions (Chau *et al.* 2005). Fewer examples of systems designed for groundwater management are available. Taormina *et al.* (2012) used artificial neural networks to predict hourly groundwater level variability in a shallow and very responsive aquifer and produce long-term simulations, based on observed data from rainfall and evapotranspiration as well as past predicted values of the groundwater head. Again, this could help with flood forecasting if the levels are beyond the safety thresholds and allow warnings to be issued when necessary (Taormina *et al.* 2012). Other initiatives focus on integrated water management. The MULINO (Multi-Sectoral Integrated and Operational Decision Support System for sustainable use of water resources at the catchment scale) decision support system (Giupponi 2007) helps users with the complex application of the European Union's Water Framework Directive. This system is designed to be used throughout the entire decision process to allow stakeholders to share a common conceptual framework and procedure, structure the problem, discuss the decision and communicate the solution. The MULINO methodology integrates socio-economic and water-related indicators to facilitate the evaluation of different scenarios during the participatory construction of integrated water management plans. Hellegers *et al.* (2012) also propose software that uses indicators to help with integrated water management. The tool evaluates the impact of land use changes on water productivity, water consumption, water availability and employment (Hellegers *et al.* 2012). The particularity of the tool that we propose here is that it focuses on the potential impact of land use on groundwater quality within the entire

territory. Moreover, ATES is designed especially for planners and was developed entirely with its future users, so it meets their expectations.

The first section of this paper summarizes the basics of the previously developed methodology for evaluating groundwater contamination risk. The process of developing the prototype and its interface is then presented. We discuss the validation of the tool through interviews and focus groups with land planners. Finally, we present the application's features and proposed interface.

METHODS

Evaluation of groundwater contamination risks

Before entering into developmental details underlying the tool, we will describe briefly how the evaluation of groundwater contamination risks is calculated (for more information, see Lavoie et al. 2015).

Groundwater contamination risks, as considered here, depend on two concepts: the likelihood of contamination and groundwater socio-economic value (Figure 1). Indeed, our concept of risk is derived from the common natural risk

analysis model (e.g., Manche 1997; Dilley 2005), where risk results from the product of hazard and vulnerability. In our case, since 'vulnerability' had a different meaning to hydrogeologists (the intrinsic physical vulnerability of groundwater), we decided to keep the hydrogeological meaning of this word. In the risk assessment method used here, *pollution likelihood* corresponds to what is usually referred to as hazard, and *groundwater socio-economic value* provides an idea of the potential consequences of pollution (traditionally called vulnerability). First, a pollution likelihood map is created on the basis of groundwater vulnerability and land use. If potentially polluting land use is occurring in an area where the water is vulnerable, the pollution likelihood will be high. However, not all pollution is equal. Indeed, pollution occurring in a place where the water is of mediocre quality and not used will have lesser consequences than a pollution occurring near a public well supplying hundreds of people. For this reason, the pollution likelihood is combined with groundwater socio-economic value. Groundwater value represents the water's significance for anthropogenic uses. Therefore, if the water has a high value, its contamination will have more dire consequences. Groundwater socio-economic value is evaluated on the basis of six criteria selected by a group of experts in water and land management: water use, water aesthetic

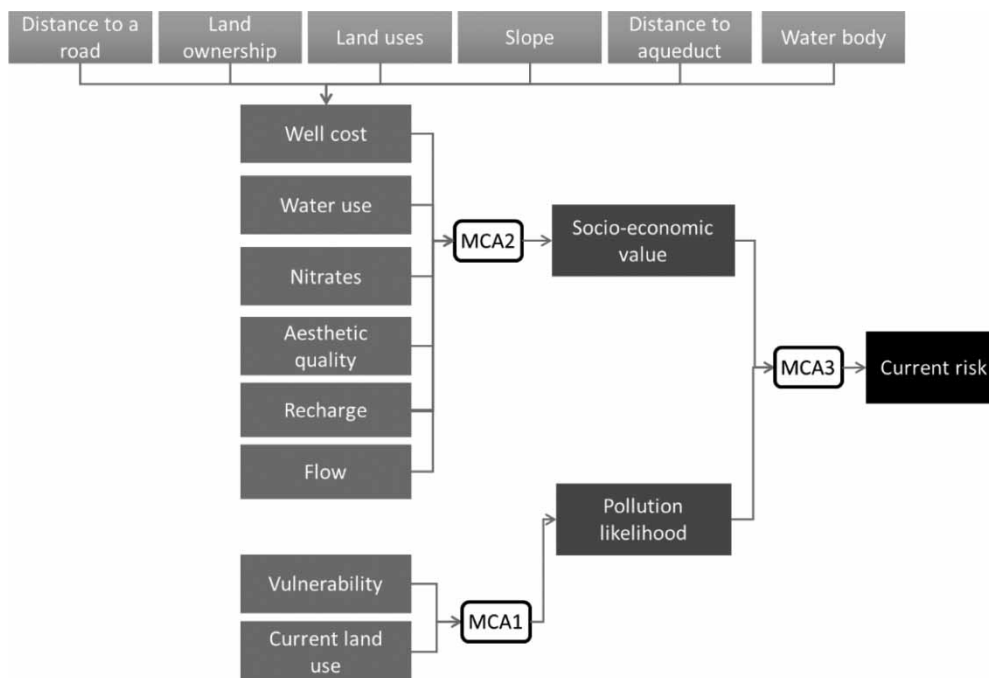


Figure 1 | Model for risk evaluation of groundwater contamination. 'MCA' refers to multicriteria analysis.

quality, nitrates, hydraulic conductivity (as a proxy of water flow), recharge and cost of a new municipal water well. The combination of the pollution likelihood and groundwater socio-economic value leads to groundwater contamination risks. The risk of contamination includes the possibility that the water is polluted and the potential consequences of contamination (Lavoie *et al.* 2015). Every criteria is evaluated using ArcInfo (Esri 2012) and all of the computations are done based on spatial data. The layers are aggregated using the MACBETH approach (Bana e Costa & Vansnick 1994; Bana E Costa *et al.* 2012). MACBETH is a multicriteria analysis method that helps elicit the preferences of a group of stakeholders in order to build a common value system and define the parameters of an index that represents the group's perception. MACBETH was chosen because it can combine information evaluated on qualitative and quantitative scales. It also produces rankings for each pixel used in order to classify them into risk categories. Moreover, MACBETH has recently been used in various areas for decision-making processes (De Mello *et al.* 2002; Clivillé *et al.* 2007; Montignac *et al.* 2009; Joerin *et al.* 2010; Sanchez-Lopez *et al.* 2012; Bana e Costa *et al.* 2014), and is especially designed to be user-friendly for decision-makers. The approach was used with different groups of stakeholders or experts depending on the analysis to be performed. An expert panel was put together for groundwater socio-economic value, the pollution likelihood was assessed with hydrogeologists, and the final risk was based on the perceptions expressed in the previous groups.

The resulting risk maps can be used by land planners to identify areas where groundwater is most threatened and take action to minimize pollutant infiltration. Another possible use would be to analyse the possible locations for a new project and authorize the project only where risks for groundwater are deemed acceptable.

As part of a previous study, the method was tested in the regional county municipality (RCM – a group of municipalities) of Acton (Province of Quebec) where a PACES project was underway. The RCM of Acton was selected for this study since it has both urban and rural land uses as well as diverse hydrogeological conditions, which allowed it to be seen how the tool reacts under a variety of contexts. Moreover, recent data were available at the time of the study and the planner was enthusiastic about the project, which was essential in this context since a considerable

involvement was required on his side. The RCM of Acton covers 578 km². It is located south of the St. Lawrence River and is mostly agricultural. It encompasses eight municipalities and 15,470 inhabitants (MRC d'Acton 2009).

As mentioned previously, the results of the risk assessment proved very interesting and useful for the planner. We were able to evaluate risks to groundwater within his territory and analyse new projects of interest to him. However, transforming the data, applying the calculations and verifying the data is not within the reach of every land planner (Lavoie *et al.* 2014). The next section explains how, in an effort to resolve the shortcomings identified in our previous work (Lavoie *et al.* 2015), the idea of integrating the risk assessment procedure into a web-based application emerged, and details the process behind the development of ATES.

Developing the geo-informatics tool

A first prototype of ATES was developed (Figure 2) on the basis of the results from interviews. Planners' needs and requests, as well as their resources and capacities regarding GIS, were taken into account. The tool had to allow easy map viewing and interpretation. Moreover, it had to help identify problem areas and suggest practical solutions to adapt land planning to groundwater characteristics (Lavoie *et al.* 2014, 2015). Programming was completed by a small firm specializing in geospatial intelligence.

Three land planners from different regions were selected to test the tool: one from each region where groundwater atlases existed and the one from the region under study (RCM of Acton). The three planners were first met in an interview where the prototype was presented and they could try it. We were especially interested in this first step to evaluate the usability of the tool. The interviews were recorded and the screen was also recorded during the problem solving exercise. Screen recordings, Think-Aloud protocol and user testing are often used for software usability evaluation (van den Haak *et al.* 2003; Kushniruk & Patel 2004; Følstad *et al.* 2012; Hasan *et al.* 2012; Wanderer *et al.* 2012). This method served to analyse every interaction the user had with the software and identify which aspects of the software were ill-designed. The users were assigned a task scenario to perform with little or no instructions or coaching on the use of the tool. They were asked to explain everything they were thinking

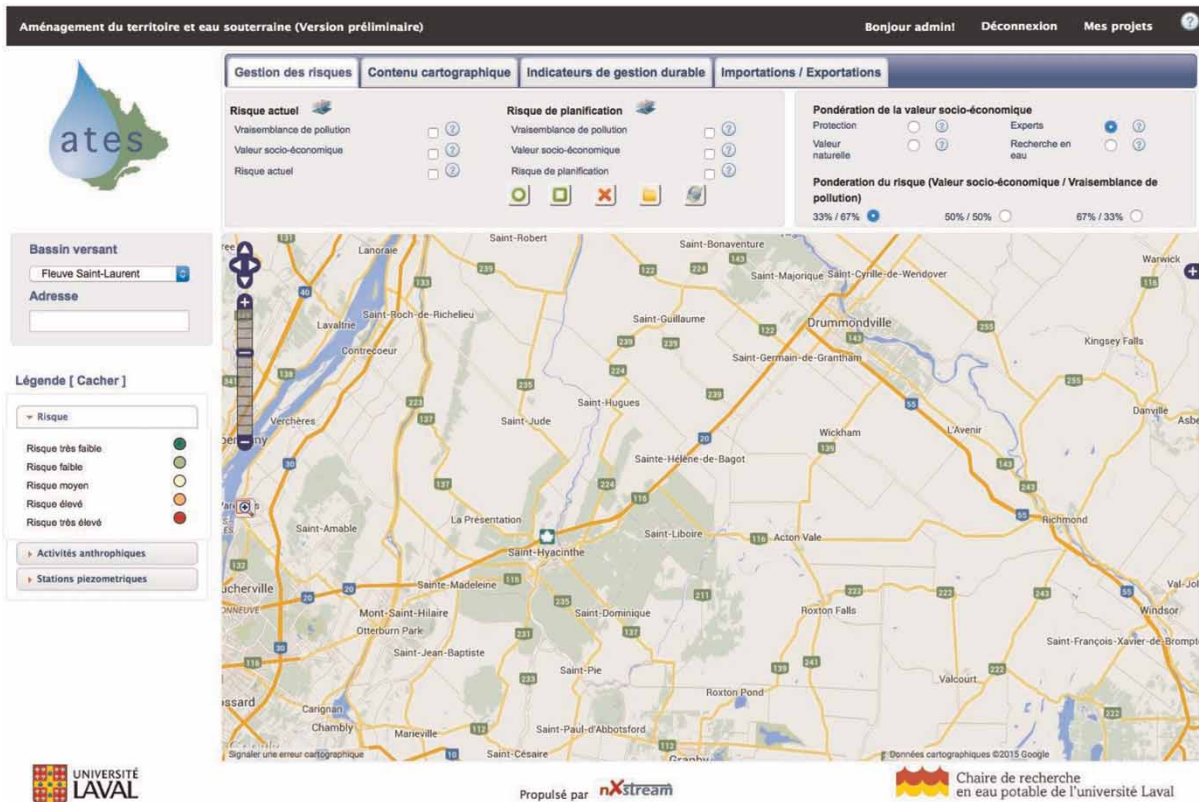


Figure 2 | First prototype of ATES.

about the software while trying to complete the task (Concurrent Think-Aloud Protocol (van den Haak et al. 2003; Lira et al. 2014)), and an observing evaluator (first author of this paper) filled in a questionnaire about how the software was used to solve the problem (see the evaluation grid in the Supplementary material, available online at <http://www.iwaponline.com/jh/017/031.pdf>). After this exercise, the user was briefly interviewed about his experience with the software. Two of the planners were accompanied by their map specialist. Using this methodology allowed the assessment, in an actual land planning problem-solving situation, of how the users would react and what they would want to do with the software. These validation workshops allowed us to improve the visual aspect and the functionalities of the tool. The content of the conversation and the use of the tool were then analysed resulting in the emergence of similarities. Content analysis (or thematic coding) consists of coding the transcriptions according to themes defined by the research context. It is regularly used to analyse perceptions in research projects (e.g., McNeese-Smith 1999; Walters et al. 2000; Lee &

Kim 2007; Lamarque et al. 2011; Otto-Banaszak et al. 2011). In this particular case, we were mostly interested in knowing what the participants liked and disliked about the tool, and what they thought should be improved. Thematic coding allowed us to gather all of the quotes on a particular aspect or functionality of the tool and the reaction of the planners to it. It appeared as the most simple and effective method to analyse the interviews in this context. The results from the three encounters clearly indicated that the planners were interested in the method for the evaluation of groundwater contamination risks, but the interface needed much work. The users remained confused about what to do, the different steps in the process and the location of the tools and functionalities. The experience proved frustrating for all participants. Two of them explicitly indicated that the interface was not user-friendly and that it would be very hard to work with it in the absence of the researcher.

A few significant changes were made to the prototype, and a project for a completely different interface was developed with a graphic designer (Figure 3). This second

interface was not programmed; it consisted instead of a series of slides. Changes to the prototype included

- adding more zoom functionalities;
- optimising the display for different screen resolutions;
- making sure that the software would be compatible with the most common operating systems;
- setting default parameters for the weighting;
- adding an example of a report with graphs;
- changing a few terms that appeared confusing to the planners;
- allowing to switch from map view to satellite;
- displaying information popups when pointing on functionalities;
- using all of the pixels, even partially selected, for the risk calculations;
- improving the look of the weighting functionality so that the cursors do not appear as if they could be moved; and
- displaying the land use associated with a zone after it has been selected for evaluation.

A second set of interviews was held with the same three planners. In this interview, they were presented the major changes made to the prototype and the new interface. They could try the improved prototype to see if the changes mirrored the differences they expected. They were also invited to react to the new interface and suggest improvements. The interviews were voice recorded only and notes were taken. They were analysed and compared. Fortunately, the second interface was much better suited to the planners' needs and habits. Indeed, the general comments were that the new proposal was more inviting to look at and the possibilities associated with the tool appeared more obvious. With the problems related to the interface seemingly less important, the planners were able to discuss the functionalities of the tool and how it might be a useful addition to their usual tasks.

Two focus groups were subsequently organized with eight and 15 regional planners, respectively. The first focus group took place in the region of Outaouais, in western Quebec. Outaouais is a 30,500 km² territory with approximately 372,300 inhabitants. It encompasses five regional county municipalities

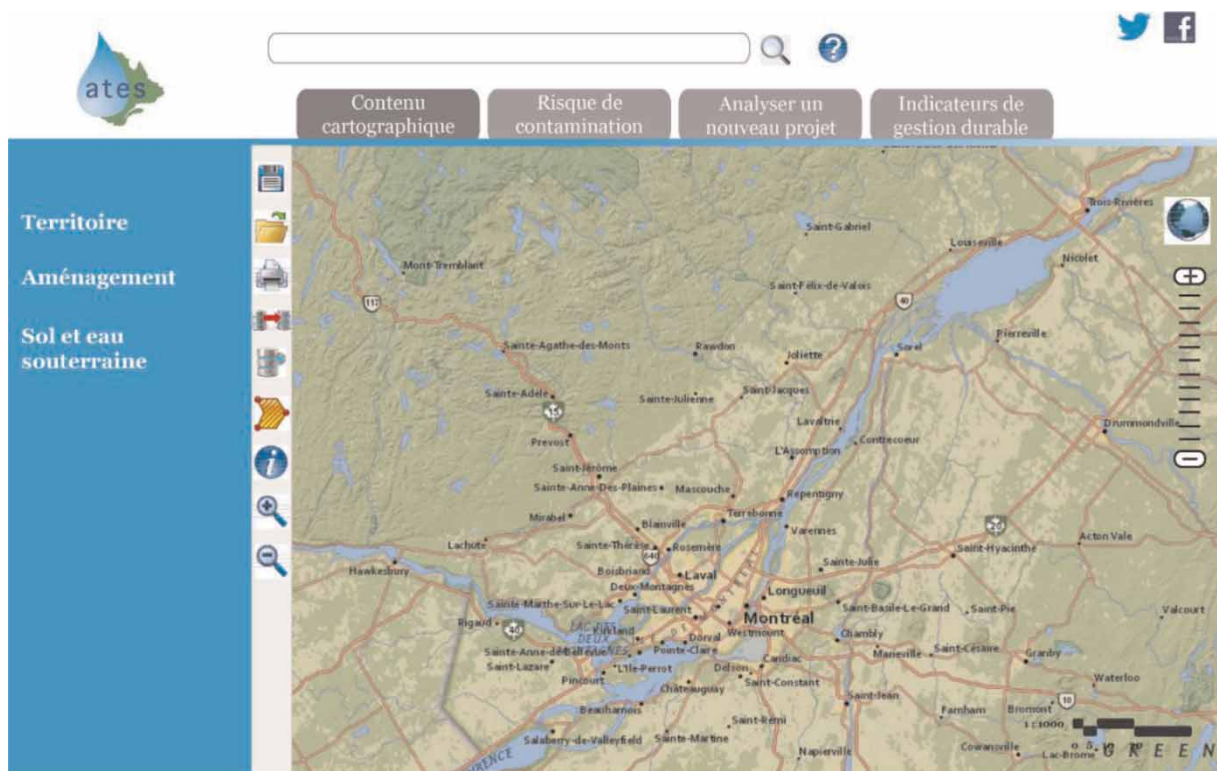


Figure 3 | Second interface of ATEs following changes made after the first set of interviews.

(RCMs: Gatineau, Les Collines-de-l'Outaouais, Papineau, La Vallée-de-la-Gatineau and Pontiac) that present great disparities. Gatineau is a city, with a density of 771.1 inhabitants per km², while Pontiac (density of 1.1 inh/km²) is a vast territory where forestry is the main economic activity. Significant economic activities in the region include finance and insurance, construction, healthcare and retail business. Forestry is the most widespread economic activity. The second focus group was held in Montérégie, in the southwestern region of the province. Montérégie covers 11,111 km² and includes 15 RCMs. Montérégie is one of the most populous regions of Quebec, with 1,470,300 inhabitants. The main economic activities include finance and insurance, construction, healthcare, retail, wholesale and food industries. However, most of the land is dedicated to agriculture. The focus groups were organized in two parts. The first one consisted of a presentation of the context, the tool and its functionalities. The second part included time for comments and a semi-directed discussion based on predefined questions (see Supplementary material, for complete list of questions: <http://www.iwaponline.com/jh/017/031.pdf>). During the presentation, participants were

encouraged to interrupt the presenter to react to the tool. The focus groups were recorded and analysed. This two-step focus-group procedure involving a relatively high number of planners allowed them to have sufficient time to understand the tool capacities and contribute to its improvement.

RESULTS

ATES is a user-friendly geo-informatics web-based tool that allows planners to easily understand groundwater conditions within their territory and integrate them into land planning. ATES first serves as a platform to access, view and download hydrogeological data from the PACES projects (Figure 4). The first set of PACES projects for groundwater data acquisition in Quebec ended recently in 2013 and the resulting data will be collected and standardized by the Ministère du Développement durable, de l'Environnement et de la Lutte contre les changements climatiques (MDDELCC – Ministry of sustainable development, environment, and fight against climate change). ATES will be connected directly to the

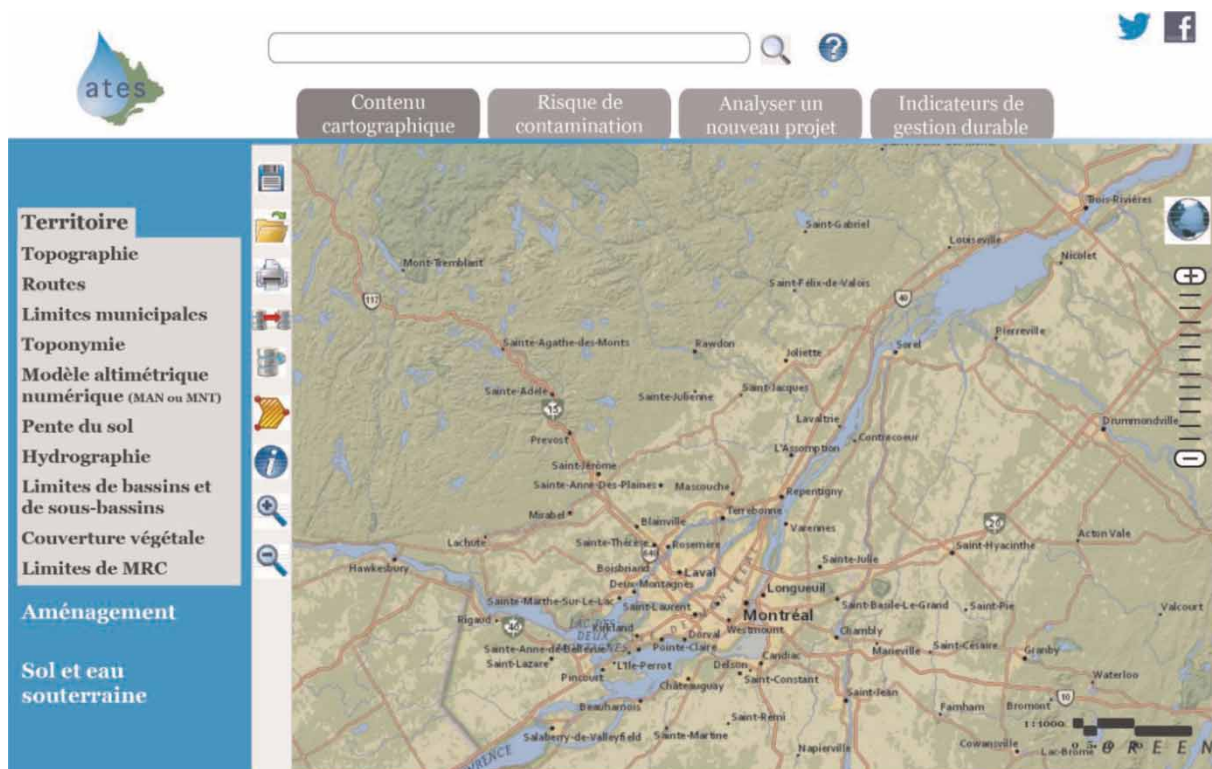


Figure 4 | Possibility of viewing hydrogeological data, using rollup menus.

Ministry's databases, so it will always be up to date. The originality of ATEs resides in the inclusion of a section to view the current likelihood of pollution of groundwater (Figure 5), socio-economic value (Figure 6) and contamination risk maps (Figure 7). The maps are re-calculated each time the database is modified, so they also represent the most recent data. Planners can also access each map used in the risk evaluation in order to understand which aspects play a major role in the results. Moreover, ATEs allows the user to test and analyse the impact of different scenarios on groundwater contamination risks. For instance, the planner in our region of study was tasked with the project of authorizing quarries in new areas of his RCM. He was able to use ATEs and analyse the potential impact of quarries in all agricultural and agro-forestal land allocations (Figure 8). To do this, he simply had to identify the areas where he could potentially allow quarries and associate the polygons to a specific land use (Figure 9). ATEs then integrates this information into the method and evaluates the potential risk of a quarry in the RCM. The resulting map revealed that in this particular

case, risks for groundwater would be lower in the northwestern part of the RCM.

The user can use four different sets of weights for the assessment of groundwater's socio-economic value, in order to see how a change in the parameters of the analysis would impact the results. We chose to implement this functionality only for this aggregation, because it is highly related to values and, depending on the region's priorities, the planner might prefer another set of weights. The underlying implications of every set of weights are described in the weights selection interface. This functionality also allows it to be seen that, although the weights have a minor influence on the results, the risk level does not fluctuate a great deal, which also testifies to the stability of the results. At any time, the user can click on a pixel to obtain its specific value (a tool functionality that makes it easier to interpret results for specific areas). If done on a risk map, the user will be offered a more detailed view of the pixel. A window will then open with information on the risk level, contaminants associated with land use and their potential consequences in

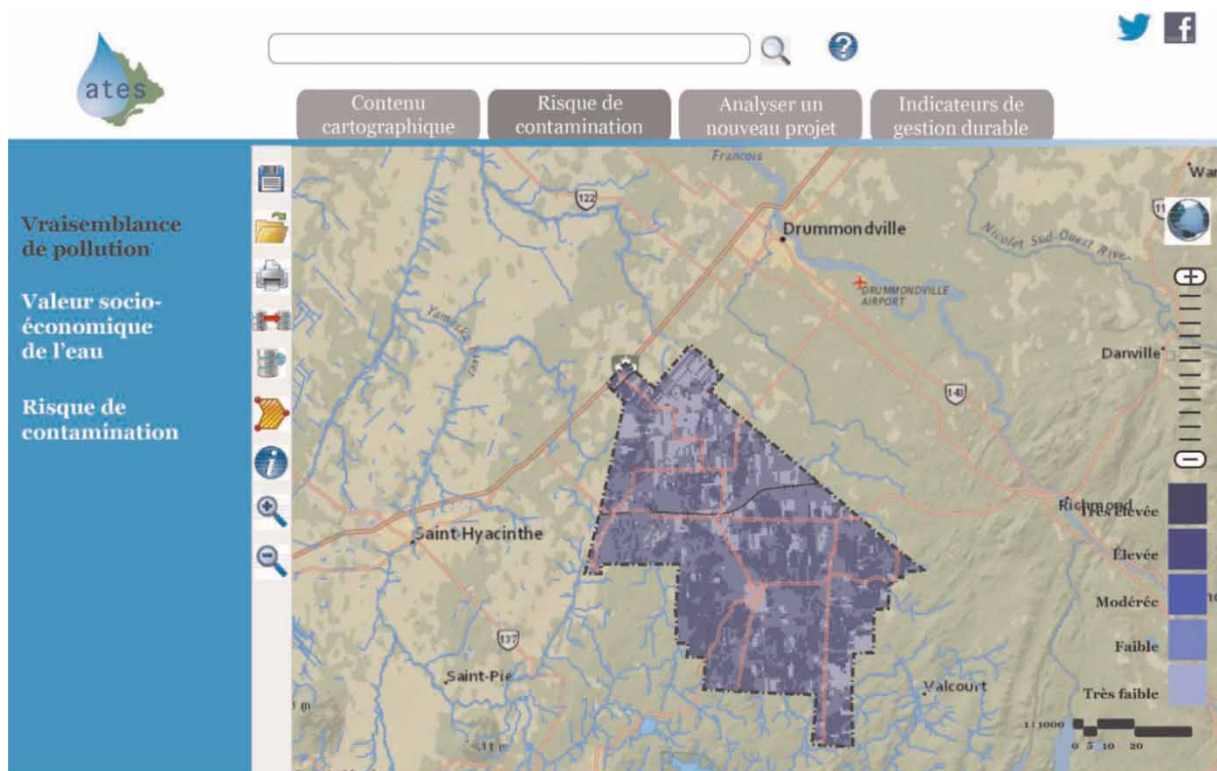


Figure 5 | Pollution likelihood.

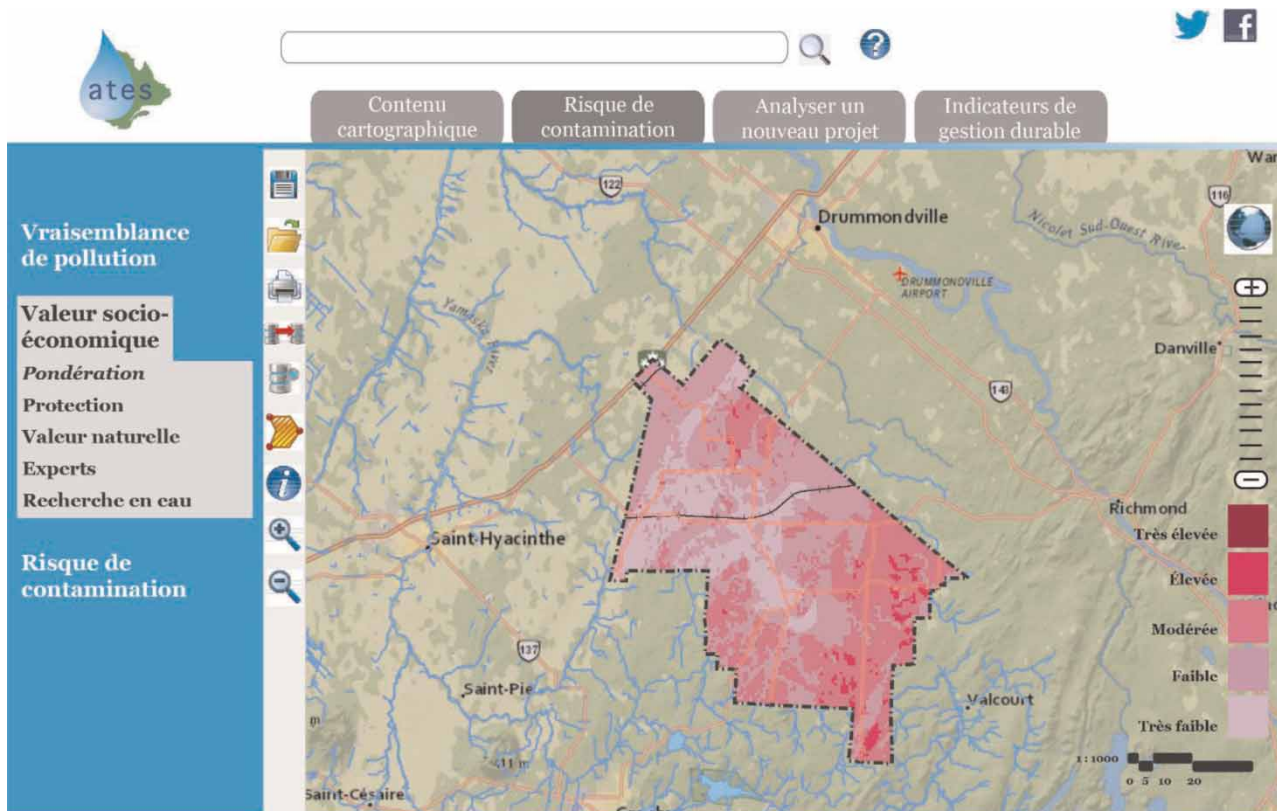


Figure 6 | Groundwater socio-economic value.

the event of pollution, graphics for the evaluation on each criterion entered in the calculation and possible actions that can minimize the risk level (Figures 10 and 11). This report, including the current map view with an indication of the selected pixel, can be saved in a .pdf document or printed out directly. Other functionalities include saving the current working session to keep track of the analysis and returning to improve or modify the proposal. Users can also print or save the current map view in .pdf format at their discretion.

It appeared essential for planners to have the possibility of importing and exporting GIS layers. Of course, when the planners have access to a geomatician or a geomatics system, they prefer to have all of the maps in their own database. This feature allows planners to modify the risk maps or add them to an existing map in order to create the right tools to support their decisions. The uploading of personal layers in ATES is used to superimpose known information to risk maps. For instance, it can serve to view land allocation maps in order to delineate new planning zones. Finally,

the planners insisted on being able to display satellite pictures as a base map. In fact, ATES uses Google maps[®] (for the figures here, a National Geographic base map has been used) as a base map, so it was possible to switch to the Google satellite view.

The planners met with during the focus groups had a very positive reaction to ATES (see Table 1, for a list of the ideas discussed by planners). The two regions where the meetings were held were to receive the results of PACES projects shortly and they remained uncertain as to how and for what reason they would use the data. The presentation of ATES indicated one way that groundwater information can be integrated into land planning and helped them grasp the implications of the new data. They were relieved to see that the tool would evaluate risks for them and that they would not have to collect, process and assemble the data. They found the interface user-friendly. Above all, they especially appreciated the content of the report and the advice on best practices to minimize risks for groundwater in particular. They also greatly appreciated

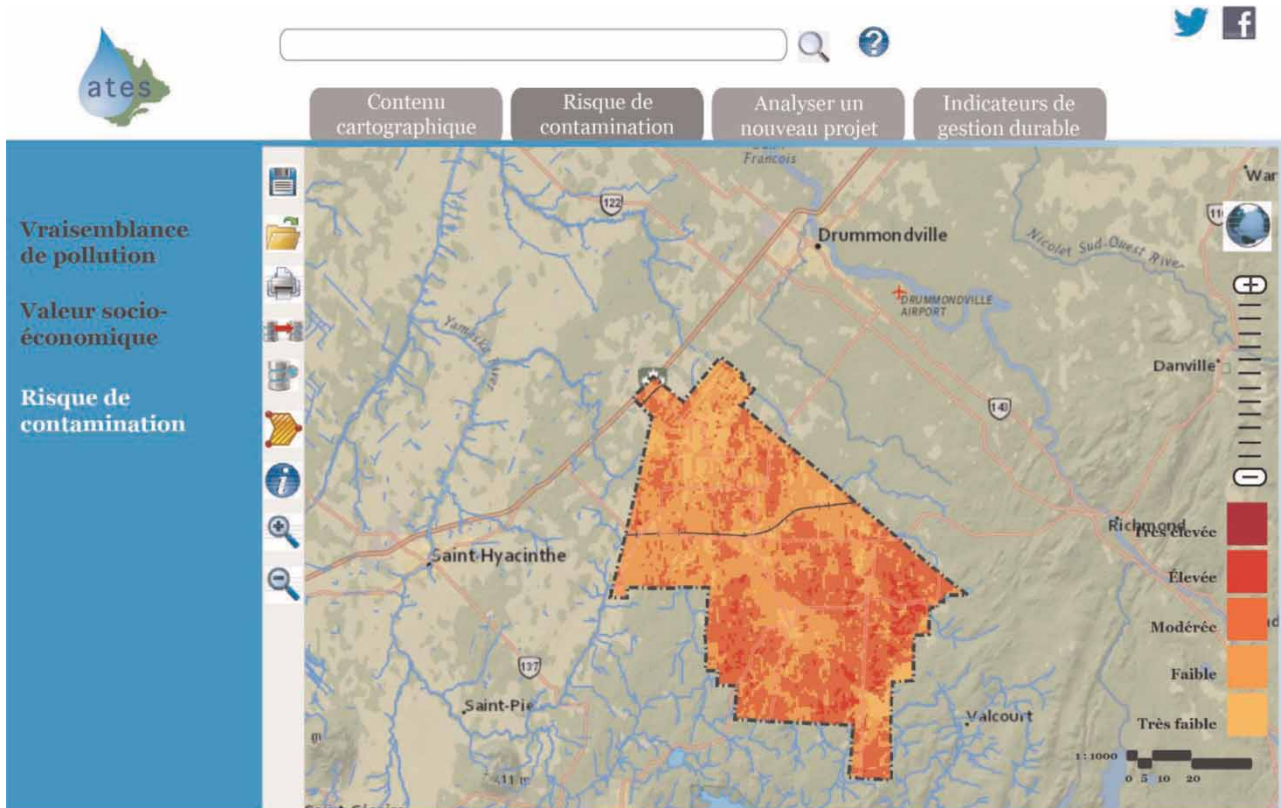


Figure 7 | Current contamination risk.

the possibility of exporting the results of the analysis to their own database.

Participants in the focus groups mentioned many opportunities for using ATES in their work. One of the most popular ideas was to manage the impact of agriculture on groundwater. Some indicated that the results could be included in agricultural zone development plans in order to identify high risk areas and favour best practice management or suggest that the development of potentially polluting activities would be done where risks for groundwater would be lower. An example of implementation would be a regulation on manure spreading where groundwater is most at risk. Almost all the planners agreed that the tool should be used for land planning, especially when preparing new development and planning documents. They stated that the results from ATES could affect land allocation by authorizing or prohibiting land uses based on their potential impact on groundwater. For instance, in the case of the extension of an urban area, ATES could be used to

evaluate whether the extension should move in one or another direction of the area. ATES could also be used for any new project of significance prior to its authorization. The tool would allow the incorporation of groundwater as a new evaluation criterion when assessing the projects. ATES could help as well with identifying means to protect groundwater to be included in new environmental strategies that will be developed within the next few years. The proposed software could also zero in on potential threats to public health. In short, planners definitely thought that ATES would provide them with arguments and tools to protect groundwater and explain their decisions to elected representatives and the population. It was also noted that ATES could help with the location of a new well by identifying the regions where water is best suited for exploitation and not too greatly threatened. Although ATES cannot identify the best spot for the well, it can direct the search towards the most suitable area and help a municipality save on exploration costs. Even though the moderator

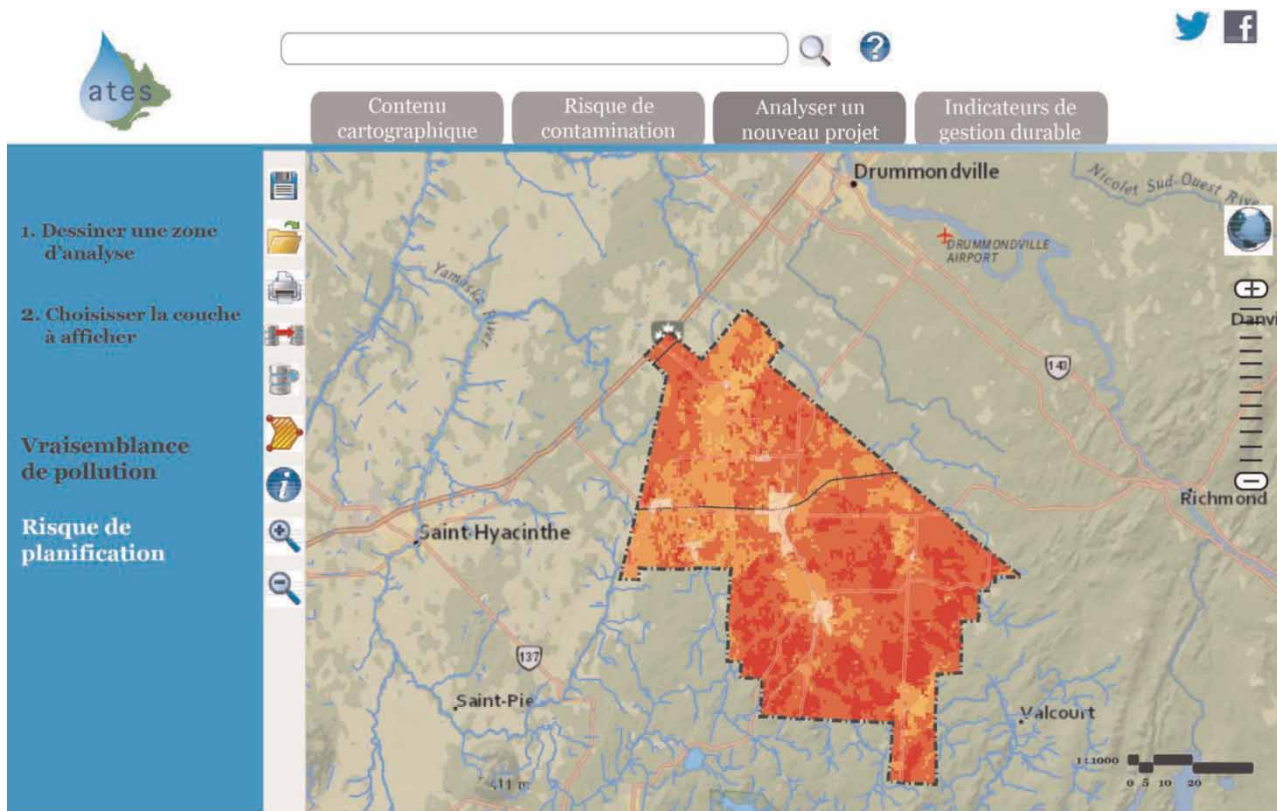


Figure 8 | Potential impact of quarries.

explicitly asked about weaknesses of ATES or potential improvements, very few negative comments were heard during the Focus Groups (Table 1). This is probably due to the fact that the participants could not try to use ATES. We therefore expect that, when a beta version of the tool is available to test, the planners will quickly venture critical comments about the shortcomings of ATES. Indeed, without having worked with the tool, it is harder to make comments about ergonomics, missing functionalities or other improvements. Still, some planners mentioned that they would like to see ATES improved by integrating the upcoming water policies and the regulatory framework into the tool, including more information on water catchments, providing more support to expose the results to elected representatives and especially allowing to correct the governments' data or adding one's local data layers. They also showed interest in other improvements that are not currently possible for technical and data availability reasons, such as the incorporation of surface water-

groundwater interaction models and the possibility of building and assessing detailed local land planning scenarios.

CONCLUSIONS

This research showed that a decision-making tool based on geo-informatics, in this case ATES, can considerably improve the ability of urban and regional planners to understand hydrogeological data. It is the first instance, in our knowledge, where the MACBETH approach was used with spatial data for automatized computations and it proved quite efficient. A literature review of the current state of the art did not show any other user-friendly tool especially designed to help planners evaluate the risk of contamination to groundwater. Above all, ATES facilitates the evaluation of groundwater contamination risks and provides easy-to-understand yet detailed explanations of the reasons for a given evaluation. With such a decision-making tool, planners

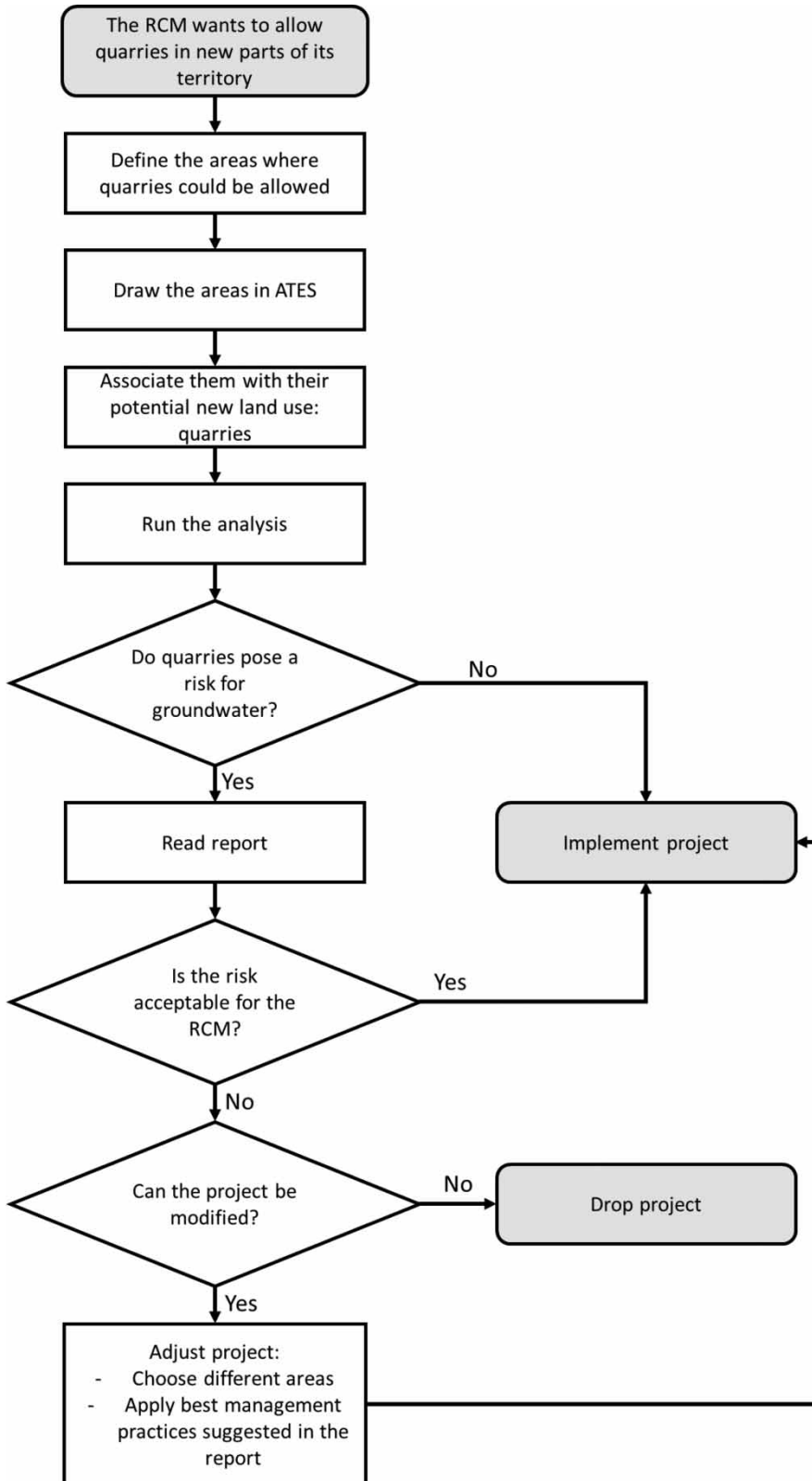


Figure 9 | Example of a decision process using ATEs. (Here, the example of the quarries was used.)

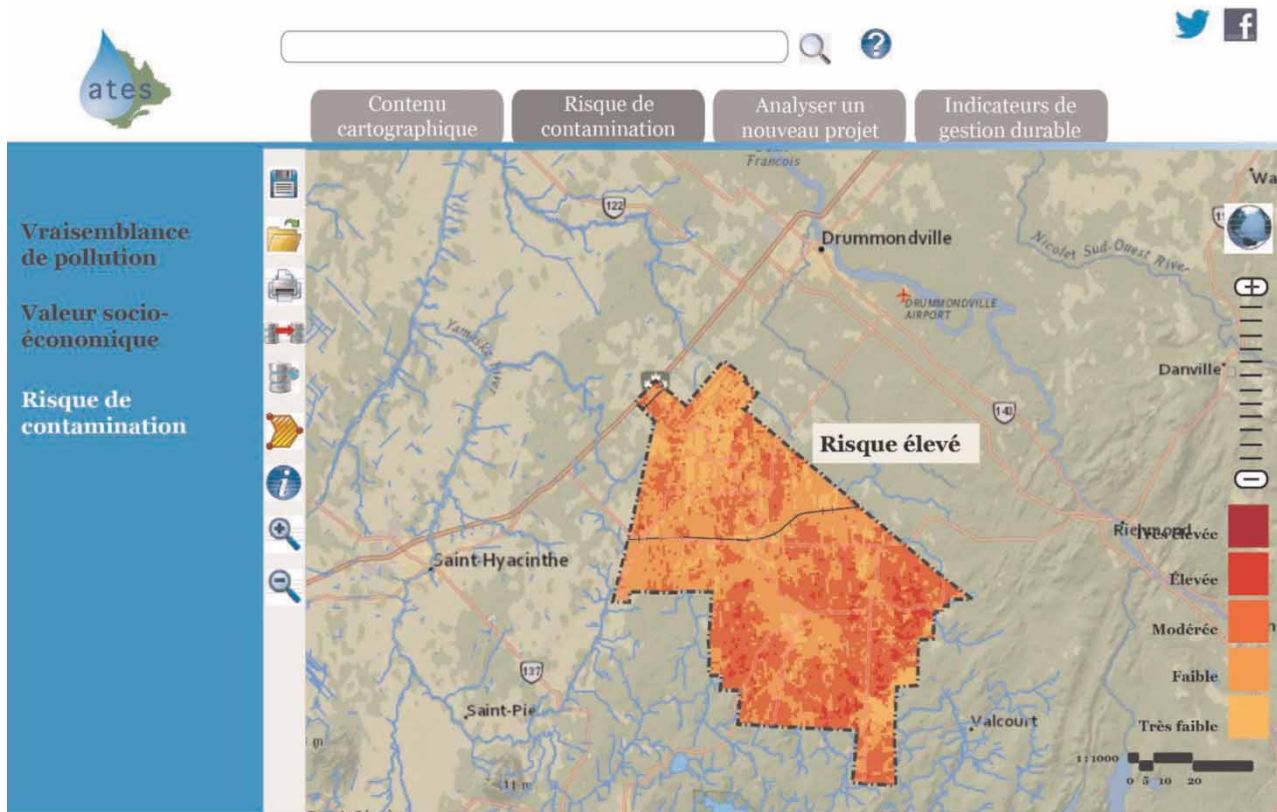


Figure 10 | When clicking on a pixel, a bubble identifies the pixel and, in the case of a risk map, more information is provided in a report.

can incorporate groundwater into their planning without having to hire a hydrogeologist or take days to understand and analyse hydrogeological data. The research results showed that the land planners involved in the entire process during the developmental stages of ATES were pleased with the results and eager to try the tool. They already see themselves using ATES in a variety of contexts, particularly in the preparation of their land development plans.

Because ATES is a first prototype, many aspects remain to be improved. Some of the tool's limitations are due to the difficulty of modelling certain characteristics of groundwater. Indeed, we would have liked to include piezometry and the interactions between groundwater and surface water in ATES. However, current models and the availability of the data do not allow this. In the near future, however, surface water and the protection of source water supplies will be incorporated into ATES. The hydrogeological data is evaluated with $250\text{ m} \times 250\text{ m}$ pixels that are not precise enough for local planning, but ATES still offers a

good regional perspective of groundwater and allows the identification of trends. Even with this limitation, planners found ATES useful for zoning, larger projects and planning the development of their land. Another limitation is that the history of land use is not documented; thus, these data cannot be incorporated into the tool. This means that if a previous anthropogenic activity contaminated the soil and represents a potential source of pollution for groundwater, ATES will not consider it. We hope that with the new databases from the PACES projects, such cases will eventually be on file and that we will be able to incorporate them into ATES. We were also told by planners that land use databases occasionally contain errors. In some cases, the wrong code is indicated for a plot. Therefore, ATES should include a means to correct these errors and re-evaluate risks for groundwater. One of the proposals was that since planners use a standardized canvas for these databases, they could enter their own data in the risk calculations.

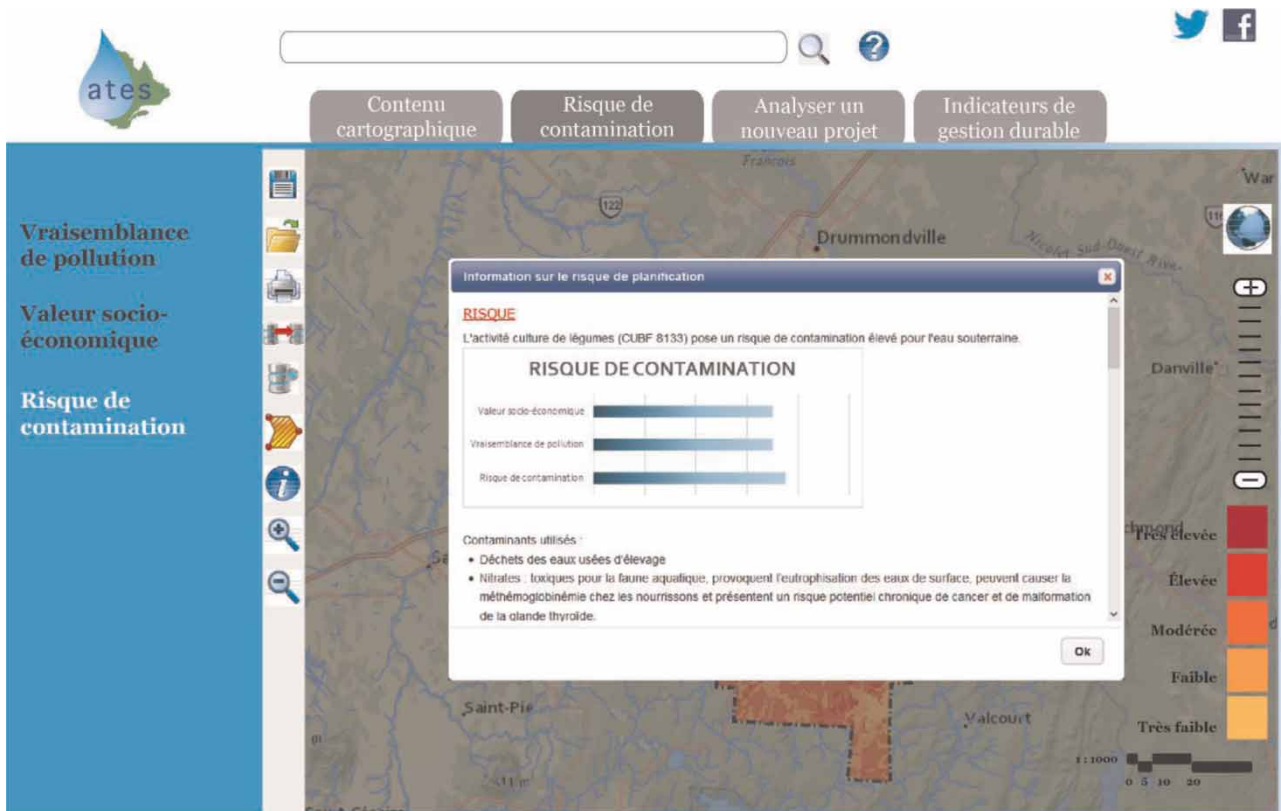


Figure 11 | Example of a window with a report.

In the future, many aspects of ATES will be improved. First, for ATES to be used, it must be tied in with provincial government legal requirements regarding groundwater. A regulation indicating who should protect groundwater, and how, was strongly recommended by all the planners interviewed. In fact, the Quebec Government is currently preparing a new regulation framework for source water protection (Gouvernement du Québec 2012, 2013) that will be included in ATES. Legal and regulatory tools that allow planners to protect groundwater will also be identified in a database and associated with relevant cases through reports in ATES. For example, the new regulatory framework in Quebec requires that municipalities delineate their water supply catchment area. This information will be integrated into ATES to evaluate the potential consequences of land use management on the quality of drinking water sources.

The reports, which include a map with risk levels, graphs explaining the calculations that led to the risk assessment and suggested mitigation measures, appeared as one of the main features for the planners. The

database with possible measures to minimize risks for groundwater based on each land use will be developed in the near future. It would also be a great improvement if ATES could help with planning scenarios. For instance, for agricultural activities, planners could build their scenario with percentages of cultivated lands and fertilization methods and ATES would evaluate the particular plan and propose alternatives. Similarly, ATES could propose areas for the location of a new potentially polluting activity when the first proposed plot proved problematic.

Finally, the planners' job involves proposing plans and defending them before other planners, elected representatives and citizens. They need to be well equipped for this task. The participants in this project expressed the desire for assistance with the contextualization of the results of ATES. They would like to clearly understand the implications of hydrogeological data and the consequences of action or non-action. In short, there is still a great deal to work on in order to improve the tool proposed in this

Table 1 | Themes put forward by the planners during the Focus Groups discussion**(a) Land planning tools that could be used for the incorporation of groundwater**

Zoning plan
 Land planning and development plan
 Land occupation density
 Complementary document
 Land allocation
 Authorized land uses grids
 Civil security planning
 Regulations on soil permeability and manure spreading
 Agricultural area development plan
 Criteria for the evaluation and authorization of new projects

(b) Improvements for future development of ATEs

Integration of new government water policies into the tool
 Include more information on water catchments
 Model interactions between groundwater and surface water
 Include support to expose the results to elected representatives
 Allow the correction of a wrongly coded land use
 Allow the replacement of the government's land use data layer by the user's layer
 Integrate data from the contaminated soil repertoires
 Develop the possibility to build local land planning scenarios and analyse them

(c) Examples of the use of ATEs

Elaboration of the zoning plan
 Analysis of a new project
 Orient the search for a new water catchment location
 Help direct future land development where groundwater's potential risk is lower
 Analyse the potential impact of a new or extended urban area
 Analyse the potential impact of a new or extended industrial park

study. In the near future, surface water and the protection of drinking water sources will be integrated; a functionality allowing planners to either correct known errors in the database or use their own data will be implemented; and the new regulations on groundwater protection will be better incorporated into the tool as well as the proposed risk reducing measures. On a longer time frame, we would like to add a module to allow for local planning scenarios, and provide more contextual information to help planners explain groundwater-related issues to elected representatives.

ATEs is still a prototype, but we can already see the great potential of such a tool. Planners who have hydrogeological data are keen to use it and countless research avenues will stem from it. In the next few years, ATEs will become a much more complete water management tool for land planners.

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