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Groundwater pollution: a discussion about vulnerability, hazard and risk assessment

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Abstract
Three main stages in the development of groundwater pollution assessment since the 1970s are described. The first steps involved aquifer vulnerability assessment. In the second stage (from the late 1980s), three methodological approaches to risk assessment were developed. The latest stage (from the 1990s) has involved new technologies and approaches. At present, all three stages coexist, and their advantages and disadvantages are discussed. Experience highlights the need to account for the social vulnerability in risk assessment, particularly with respect to large cities in developing countries. Assessing groundwater pollution risk through an integrated approach appears to be the greatest challenge.

Keywords Groundwater management · Contamination · Aquifer vulnerability · Risk · Hazard

Pollution assessment in context

Throughout history, groundwater has been a major source of water for sustaining human life (Fienen and Arshad 2016). The relationship between water and cities is complex; within this context, water is a vital resource and, at the same time, can be perceived as a potential hazard. Such complexity is even greater in intermediary cities (population between 50,000 and 1 million), where dispersed patterns of urbanization are generated in the form of large peri-urban areas. Intermediary cities are home to 20% of the world's population and one third of the total urban population (Roberts et al. 2016). In developing countries these peri-urban areas consist of informal land-use patterns, accompanied by impoverished or practically nonexistent public services, with often inferior quality of housing and families living in poverty (Wandl and Magoni 2017). A large part of the population falls "below the radar" in terms of the United Nation's World Water Assessment Programme (UNESCO 2019). Thus, pollution assessment, prediction and prevention are the main tools to deal with this challenge and constitute the core of groundwater pollution risk management processes. This challenge presents different types of obstacles for technicians and decision makers: conceptual (for example, considering the aquifer as an isolated system), operational (access to reliable data and information), and political, including institutional factors and administrative arrangements (Foster et al. 2011; Vadiati et al. 2018). Particularly, groundwater pollution assessment (in a broader sense) is one of the proactive approaches to control or reduce pollution and it is one of the key criteria to identify the technical capacity of groundwater governance provision (Foster et al. 2010; Foster and Garduño 2013).

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Groundwater pollution assessment as a proactive tool

Since around 1970 there has been a continuous evolution of both conceptual and methodological groundwater pollution assessment, as a tool to help decision-makers. It is possible to identify three main stages in time, which in this essay are referred to as: "first steps", "developing a new branch" and "expanding the horizon". At present, these three stages coexist and the time frame developed within this paper depends on the country or region concerned; therefore, the dates mentioned should only be considered as a rough guide. Groundwater pollution assessment includes three main components that have been consolidated over time: aquifer vulnerability, hazard, and risk. Each one has its own assessment methodology (as discussed in the following). The basic logic used in these methodologies is quite similar: define the methodology to obtain an index (i.e. aquifer vulnerability index); define the territorial units to analyse and compare; obtain the index; identify classes or categories (e.g. low, intermediate and high); and build a final map that represents the spatial distribution of the index classes or categories (i.e. aquifer vulnerability map). Therefore "the map" has always been a good way to synthesize results and transfer knowledge. The versatility achieved by geographic information systems (GIS) has made maps into a remarkably precise instrument for processing and combining different "layers" of information, particularly over the last 25 years (Foster et al. 2002; Shrestha et al. 2017). It is important to mention that this paper is not a bibliographic compilation, so the references that are included are only an example and have been selected in order to represent different methodologies in the three proposed stages.

First steps: aquifer vulnerability assessment

The first stage started in the early 1970s, after Margat (1968) formally coined the term "aquifer vulnerability to pollution". During this time, many evaluation methods were proposed and many of them are widely known now, so no reference will be made to them in this essay; yet it is good to remember that as a common approach, the majority of these methods share an origin-pathway-target conceptual model (Gogu and Dassargues 2000; Civita and De Maio 2004; Machiwal et al. 2018). During this stage, and particularly in the 1980s, the main discussion focused on two topics. Firstly, alternatives between assessing intrinsic or specific vulnerability, each one of them bearing advantages and disadvantages (Vrba and Zaporozec 1994). It is interesting to mention that the approach towards the evaluation of specific vulnerability represents a direct "bridge" to the second stage, that is, the concept of hazard. Secondly, how to define more meaningful vulnerability categories (classes) and the limitations given by uncertainty (Foster and Hirata 1988).

Beyond the methodological discussion, aquifer vulnerability maps are today a widely used tool and still valid in different decision-making instances, especially when a good balance between representation, simplicity and utility is reached. Achieving this balance is a challenge for technicians and an essential aspect so that vulnerability assessment does not become an "impediment in promoting groundwater protection" (Foster et al. 2013).

Developing a new branch: hazard and risk of groundwater pollution

Stage 2 started in the late 1980s. The term geological hazard refers to the probability/possibility that a potentially negative event takes place in a certain time and space. On the other hand, the geological risk refers to the relation between a dangerous event (hazard) and the occurrence of certain damage, whether it be to health or the environmental or both (Baalousha 2017). Risk, hazard and damage make up variables that are directly proportional; their interaction is the key to the management process. These concepts, extensively studied for some risky processes (volcanism, seismicity) were progressively taken by hydrogeology to build equivalents in the process of groundwater pollution. Throughout its evolution, pollution risk assessment has become a useful tool for groundwater management (Aven 2016).

It is not easy to synthesize the approximations that have been and are still used in the assessment of groundwater pollution risk, although it is possible to identify at least three main lines:

Stage 2a. Incorporate a variable in the aquifer vulnerability index equations that is related to land use and its potential as a source of pollution (Secunda et al. 1998; Bartzas et al. 2015). This approach leads one to consider specific rather than intrinsic vulnerability.

Stage 2b. Use an approach closer to the toxicological one (considering risk to be the possible chance of harmful effects to human health or to ecological systems that are the result of being exposed to an environmental stressor; Fowle and Dearfield 2000).

Stage 2c. Evaluate risk as an interaction between hazard (probability that a potential pollutant load is generated and capable of contaminating groundwater), and damage (of the potentially affected population or the natural system). Hazard can be comprised of the combination of aquifer vulnerability and potential pollutant load. While intrinsic vulnerability is the more used in this approach, potential pollutant load is evaluated from the land use through different ways of establishing rankings (Zaporozec 2002; Foster et al. 2002). Evaluating damage, in economic terms, is always a difficult task. When it cannot be quantified in a practical way, a new vulnerability dimension appears, i.e. "social vulnerability", as a way of evaluating how susceptible the population is when exposed to the groundwater pollution (Massone and Sagua 2005). Thus, the combination between potential pollutant load and intrinsic aquifer vulnerability defines the pollution hazard, while the combination of pollution hazard and vulnerability of the exposed population is what defines the risk of pollution. This process shows clearly the conceptual difference between aquifer vulnerability, hazard and risk of pollution; greater aquifer vulnerability or greater hazard on their own do not necessarily imply greater risk (Baalousha 2017). Therefore, to talk about risk, it is necessary to take into account damage, or indirectly, vulnerability of the population exposed to the hazard. Figure 1 shows these interactions schematically and identifies the parameters most used to assess each variable. What stands out from this approach (or similar ones, Wang et al. 2012; Zhao et al. 2018) is the interaction of both socio-economic and natural variables (Ducci 1999; Simpson et al. 2014; Lavoie et al. 2015).

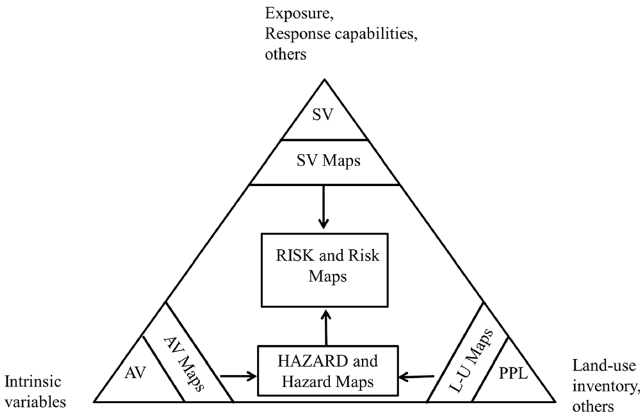

Fig. 1 Groundwater management risk triangle. SV social vulnerability; AV aquifer vulnerability; PPL potential pollution load; L-U land-use

Expanding the horizon: new technologies and approaches

Stage 3 (starting early-middle 1990s) involved a faster and more complex change in the evaluation of groundwater pollution. In parallel to the technological progress and with a greater accessibility to both software and hardware, the use of new technologies and approaches focused on three issues:

Stage 3a. Improve understanding and interpretation of complex problems through the use of computational intelligence, mainly fuzzy logic and artificial neural networks (Dixon 2005; Zhang et al. 2013).

Stage 3b. Promote and improve effective communication with decision makers, mainly through the evolution of GIS, the application of decision support systems and spatial decision support systems, and the use of multi-criteria decision models (Lima et al. 2013; Lavoie et al. 2015; Aven 2016; Pierce et al. 2016).

Stage 3c. Achieve greater citizen participation, mainly through the evolution of GIS, expansion of the internet, and development of applications for mobile devices (Ducci 1999; Hoover et al. 2014; Sege et al. 2018).

Final words

Conceptual and methodological evolution of the process of assessing the risk of groundwater pollution has been enormously significant. The advantages and disadvantages of all the mentioned methodologies are documented in Table 1.

Three main aspects are highlighted in this paper: (1) it is important not to consider aquifer vulnerability, pollution hazard and risk as equivalent and interchangeable concepts; (2) while the presented methodologies can be grouped into three historical stages (from the most simple to the most complex), nowadays these three stages coexist and continue to be used; (3) there is a need to consider risk in its most integrating approach as the combination of aquifer vulnerability, potential pollution load and vulnerability of the exposed population (Fig. 1) taking into account the socio-economic reality of the population that live in a peri-urban area (particularly in intermediary cities of developing countries). Incorporating into the analysis the vulnerability of the

Table 1 Main advantages and disadvantages of the described stages/methodologies

Stage/methodology		Advantages	Disadvantages
1. First steps: aquifer vulnerability assessment		- Formalizes the beginning of a preventative vision in groundwater management - It is a simple tool that allows obtaining results even when there is little information available; when used well, this methodology is helpful in the decision-making process - First use of map overlay techniques showed it to have a great potential over time - Nowadays there is a great variety of assessment methodologies so it is possible to adapt them to different hydrogeological environments	- The use of qualitative labels (low, high, etc.) can result in confusion. Obtaining “classes” implies the need to define each one with as much precision as possible - Requires a lot of work in order to achieve a good balance between representation, simplicity and utility - It only includes hydrogeological variables
2. Developing a new branch: hazard and risk approaches	Hazard	- It allows the extension of the vulnerability assessment incorporating the potential pollutant load - It incorporates a social variable (land-use) and it therefore offers a broader vision - There are different methods of assessment, from the more qualitative to the more quantitative ones	- It makes the assessment process more complex since it is necessary to define how to carry out the combination of aquifer vulnerability and pollutant load - It presents difficulties in the assessment of potential pollutant loads, particularly in peri-urban areas, given the existence of multiple land-uses - The analysis does not take into consideration the social, economic, cultural or political variables that explain the vulnerability of people exposed to groundwater pollution
	Risk	- As above (2), there are different methods of assessment, from the more qualitative to the more quantitative ones - It includes assessment of the exposed population vulnerability (social vulnerability). It is therefore more effective and complete when, for example, guiding public policies related to water management	- As above (1), the use of qualitative labels (low, high, etc.) can result in confusion. Obtaining “classes” implies the need to define each one with as much precision as possible - As above (1), it requires a lot of work in order to achieve a good balance between representation, simplicity and utility - It requires the combination of hydrogeological and socio-economic data/information, more time of analysis, and the intervention of multidisciplinary teams
3. Expanding the horizon: new technologies and approaches		- It improves understanding and interpretation of complex problems - It allows the achievement of greater citizen participation	- It requires the combination of hydrogeological and socio-economic data/information with the use of artificial intelligence, web servers and other new technologies

exposed population, in terms (as an example) of the number of potentially affected people and the response capabilities, is imperative in the process of moving people from "below the radar" to "on the radar".

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