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THEMATIC ISSUE

A decision tree tool supporting the assessment of groundwater vulnerability

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Abstract The Water Framework Directive and Groundwater Directive aim at preserving and improving the groundwater status. Groundwater bodies are classified as being or not being at risk of failing to meet these objectives. Those at risk are subject to more precise risk assessment where the concept of vulnerability is considered in the pathway part of the source–pathway–receptor scheme. However, no further details on implementation strategies are provided. In order to support groundwater managers and decision-makers in implementation of programs protecting groundwater, a systematic operational approach based on a decision tree is proposed, which leads the user through the stages of vulnerability assessment. First, a problem has to be formulated related to a threatening of the quantitative and/or qualitative status of a groundwater body. Next, the stated problem needs to be related to the intrinsic or specific vulnerability. Methods used for the intrinsic vulnerability assessment belong to two categories: subjective rating and objective methods. Method selection depends primarily on: data availability, knowledge and available resources. A key issue is the lag time associated with transport between a source/event of contamination and the water body. This lag time is primarily controlled by the temporal scale of water flow. It provides information about flow processes and at the same time also about timescales required for the implementation of strategies. Effects of any measures taken cannot be observed immediately but at the earliest after these estimated lag times emphasizing the need to also proactively safeguard groundwater resources and preserve their good status.

Keywords Vulnerability assessment · Groundwater management · Groundwater directive · Lag time

Introduction

The water supply of many countries around the world depends to a large extent on groundwater. However, the use of groundwater as drinking water depends on its availability and quality. Although the mere amounts of available water are currently not predicted to decrease in Northern and Central Europe, groundwater quality is under pressure. Mainly, this is caused by increasing inputs of contaminants to our global water resources posing a serious risk to human health and ecosystem functions (Balderacchi et al. 2013; Schwarzenbach et al. 2010). In Southern Europe, extended drought periods, mostly during summer, are expected to pose a stress to primary crop production (European Environment Agency 2010a). Water scarcity

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combined with increased input of contaminants will constitute many aquifers at threat, especially in coastal areas where seawater intrusion is an additional reason of concern. The pressure is expected to get even higher in the future due to the increasing appearance of (new) pollutants and chemicals of emerging concern in the water cycle (Lapworth et al. 2012). According to the European Environment Agency (2012), a high percentage of the European groundwater bodies still show a poor chemical status; for example, >30 % of groundwater bodies are of poor quality in Central Europe. Little is known about the ecological status of groundwater bodies due to missing ecological assessment schemes (Griebler et al. 2010) or about the chemical and ecological status of groundwater-dependent ecosystems (GDE). It is important to note that the Groundwater Directive (GWD) explicitly indicates groundwater-dependent ecosystems and water supply point for human consumption (wells, springs) as two important groundwater receptors with respect to which groundwater should be protected from deterioration and chemical pollution (EC 2006).

In the recent years, a paradigm shift has been initiated and a time frame has been set up for water quality improvements due to the aims raised in the GWD (EC 2006) and the Water Framework Directive (WFD) (EC 2000, 2010) of the European Union. In its Article 4, the WFD sets out five objectives for groundwater protection: 1. prevent or limit the input of pollutants; 2. prevent the deterioration of good status of groundwater bodies; 3. achieve good groundwater status (both chemical and quantitative); 4. implement measures to reverse any significant and sustained upward trend; and 5. meet the requirements of protected areas. The WFD (Article 5, Annex II) calls for the assessment of the degree to which groundwater bodies are at risk of failing to meet the above objectives. At the same time, there are no standardized, operational methods of groundwater vulnerability assessments and the most commonly used methods, such as DRASTIC (Aller et al. 1987), do not provide quantitative measures of vulnerability based on the knowledge of the physical processes that govern the interlinked processes of groundwater flow and pollutant transport. Furthermore, fulfillment of the requirements of WFD and GWD (setup of time frames for water quality improvements, need for observation of trends in water quality) is not possible without considering timescales of groundwater flow which are often underestimated when assessing the results of measures undertaken to improve groundwater quality (Filippini et al. 2013). It has been apparent that the time frame of the year 2015 set in the WFD for achieving a good status of groundwater bodies had been unrealistic, particularly when at the same time considering that most of the poor status is associated with farming which has to be continued. For example, nitrate concentration in groundwater has already exceeded the limits given in national groundwater directives for decades. Most importantly, the set time frame had been unrealistic due to the considerably long timescales of contaminant transport in groundwater systems. Due to long transit times in catchments, it was unlikely that any response to interventions would have been observable already in 2015 (Cherry et al. 2008). Consequently, the vulnerability assessment methods and the implementation strategies have to address temporal and transient aspects of contaminant spreading (Filippini et al. 2013). This emerging perspective of vulnerability assessments is related to monitoring of the results of measures undertaken to improve water quality in river basins. Here, despite restoration measures, the recovery of streams and rivers from eutrophication can be delayed for many years; it takes even longer for the ecosystem to return to a natural nutrient limited state (Hamilton 2012). The same applies to groundwater. Still, it is not commonly recognized among the policy makers, groundwater managers, and even among researchers that effects of reduced contaminant loads are reflected in groundwater receptors with some delay (i.e., the lag time), due to the wide spectrum of water travel times (Filippini et al. 2013). Further, decision-making requires the involvement of practitioners from different disciplines (managers, scientists, public officers, politicians) all having different perspectives and background. Collaborative interaction, however, also is a challenge requiring the right tools to increase the success of interdisciplinary teams and to find a common language among disciplines, which can be achieved by finding a consensus among team members through building knowledge structures (Benda et al. 2002).

Therefore, the objective was to facilitate the decision-making process by developing a systematic operational approach which includes the establishment of intrinsic vulnerability indices and which is presented in a form of a *decision tree*. This *decision tree* leads the users through the stages of vulnerability assessment and further development of implementation strategies for achieving a good status of groundwater bodies. It is helpful for building knowledge structures and recognizing scientific limitations for assessing intrinsic groundwater vulnerability. A crucial step of vulnerability assessment is the precise formulation of a problem related to a threat to the quantitative and/or qualitative status of a groundwater body. Therefore, some examples covering typical questions related to vulnerability assessment are presented. Further, the *decision tree* highlights vulnerability methods including timescales as one of the fundamental parameters to describe the pathway in the source–pathway–receptor concept and to develop indices for vulnerability mapping. The use of these methods will allow the identification of lag times associated with contamination and thus a successful implementation of protection strategies.

General decision tree

The central part of the *general decision tree* (Fig. 1) builds on the implementation of the WFD and the GWD with regard to assessing the vulnerability of groundwater and GDE. According to the WFD, groundwater bodies are classified as being or not being at risk of fulfilling to meet these requirements. Those found to be at risk are subject to more precise risk assessments outlined in the Common Implementation Strategy Guidance Document No. 26 "Guidance on risk assessment and the use of conceptual models for groundwater" (EC 2010) where the concept of vulnerability is placed into the context of the source–pathway–receptor paradigm (SPR) of groundwater risk assessment. Within this conceptual framework, vulnerability is related to the pathway part of the risk assessment scheme; however, its identification cannot be abstracted from only knowing sources, characterizing pressures on the groundwater body (CIS Guidance No. 3; EC 2003) or identifying the impacted receptors (CIS Guidance No. 18; EC 2009). Identification of the source(s) and receptor(s) is thus an indispensable component of the problem statement (Filippini et al. 2013; Wachniew et al. 2016). The CIS Guidance Document No 26 (EC 2010) underlines the role of conceptual models of different complexity in identification of the components of the SPR model and their relations. It needs to be considered that climate change or land use changes can impact both sources and pathways (European Environment Agency 2010b; Kløve et al. 2014a).

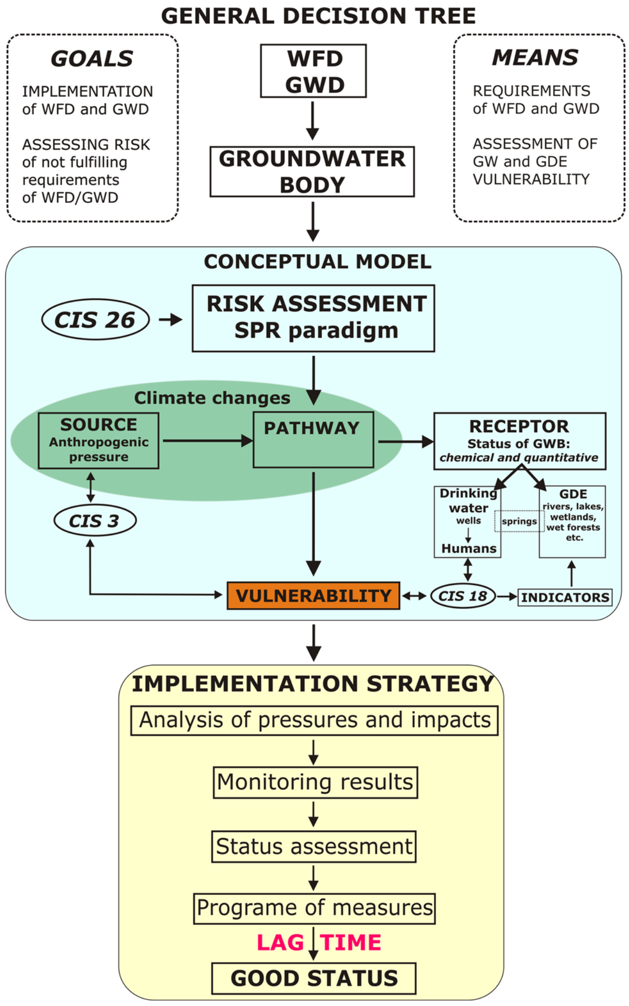

Fig. 1 General decision tree illustrating the main steps of assessing the risk of groundwater bodies and implementing protection strategies

In most cases, a comprehensive assessment of the actual quantitative and qualitative status of a particular groundwater body is not feasible due to insufficient availability of monitoring data and/or complexity of groundwater systems (CIS Groundwater risk assessment report; EC 2004). Instead, GDE vulnerability indicators or groundwater vulnerability indices can be identified and mapped in order to reflect the actual or to predict the potential severity of human-induced deterioration in GDE or groundwater quantity and quality (e.g., Bottero 2011).

Next to analyzing the pressure and impacts and collecting data for status assessment, most crucial to consider are the timescales required for the implementation of strategies for achieving a good status of the water body. Effects of any measures taken cannot be observed immediately but at the earliest after these estimated lag times. Therefore, the knowledge about lag time between a source/event of contamination and the water body (receptor) is fundamental. This lag time is controlled by the temporal scale of water flow and can be identified through vulnerability assessment which is the key element of the WFD implementation strategy. Therefore, a more detailed guidance using different vulnerability concepts is given in the detailed part of the *decision tree* in the next chapter (Fig. 2).

Detailed decision tree

A crucial step of vulnerability assessment procedure is the precise formulation of a problem related to a threat to the quantitative and/or qualitative status of a groundwater body. Some typical examples of questions related to vulnerability assessment and associated with practical problems in hydrogeology are presented in Fig. 3 (the questions related to qualitative and quantitative status of the groundwater body (GWB) are marked with red and blue color). The next step is to identify whether the stated

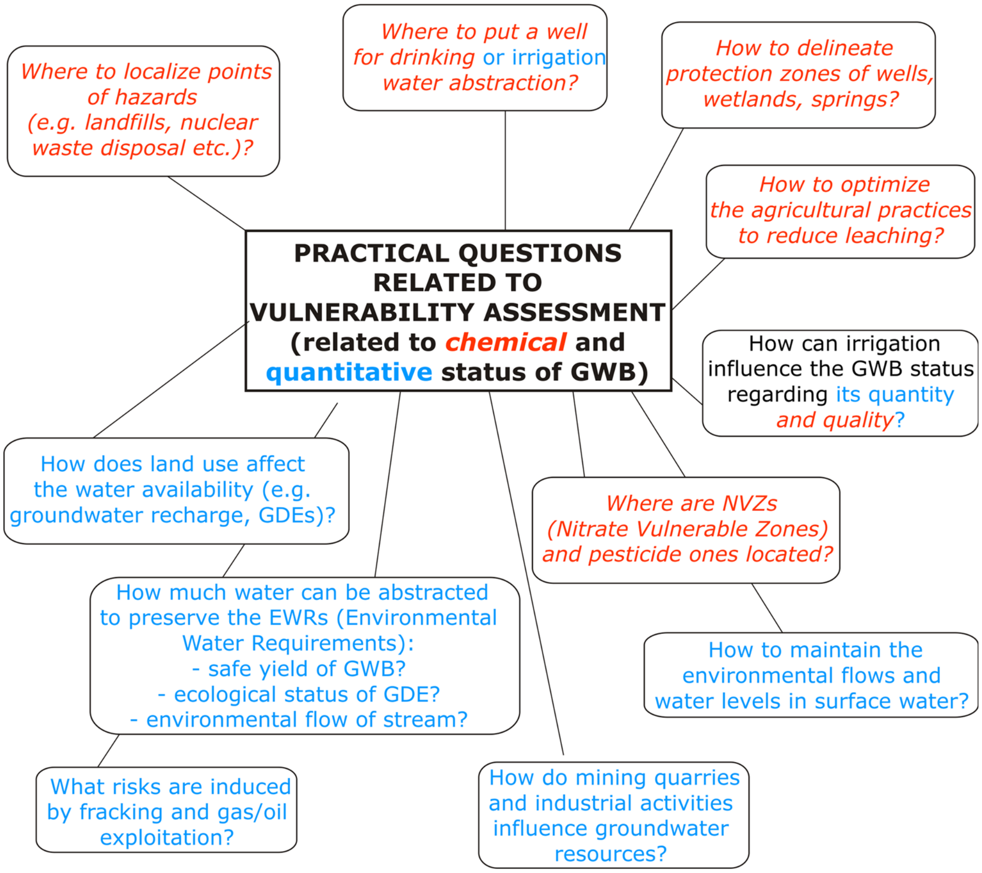

Fig. 2 Detailed decision tree illustrating the identification of vulnerability with a particular focus on methods using timescales as indices

problem is related to intrinsic or specific vulnerability. Although there is no obligatory definition of groundwater vulnerability (Wachniew et al. 2016), the distinction between intrinsic (natural) and specific vulnerability proposed by Vrba and Zaporozec (1994) is generally accepted. Considering water supply for human consumption as the receptor, the intrinsic vulnerability results from those properties of groundwater systems that control subsurface water flow; specific vulnerability encompasses the compound-specific physical and biogeochemical attenuation processes that control the fate of particular contaminants (Zwahlen 2004). Transport of conservative contaminants is dominated by the water flow. In that case, specific vulnerability assessment can be performed in the same way as for intrinsic vulnerability. For transport of nonconservative contaminants, the assessment of specific vulnerability requires to account for sorption and degradation processes in addition to intrinsic properties. Issues related to GDE as the receptor of chemical and quantitative anthropogenic pressures require the specific vulnerability assessment in combination with conceptual models (Kløve et al. 2014b).

There are different methods available for assessing the intrinsic vulnerability that have been reviewed by many authors (e.g., Faybishenko et al. 2015; Focazio et al. 2002; Gogu and Dassargues 2000; Liggett and Talwar 2009; Margane 2003; Marín and Andreo 2015; Plummer et al. 2012; Vrba and Zaporozec 1994; Wachniew et al. 2016; Zwahlen 2004). These methods belong to two major categories: objective (comprising the physically based and statistical methods) and subjective methods; sometimes, HYBRID methods, a combination between the two categories, are used (Pisinaras et al. 2016; Yu et al. 2010, 2012). Selection of the method depends primarily on the data availability, knowledge and available resources. The greatest significance among the physically based (process-based) methods is attributed to those using timescales as an indicator of intrinsic vulnerability (Wachniew et al. 2016). In the *detailed decision tree*, the use of objective vulnerability assessment methods that are based on estimation of residence (transit) times of water is recommended. The benefit of assessing the timescales of water flow and conservative transport is that, at the same time, knowledge is provided on the lag time required for achieving a good status of groundwater bodies when implementing management strategies. One has to distinguish between estimating the mean residence (transit) time, MRT (MTT), or the distribution of residence (transit) times, RTD (TTD). The first is crucial for

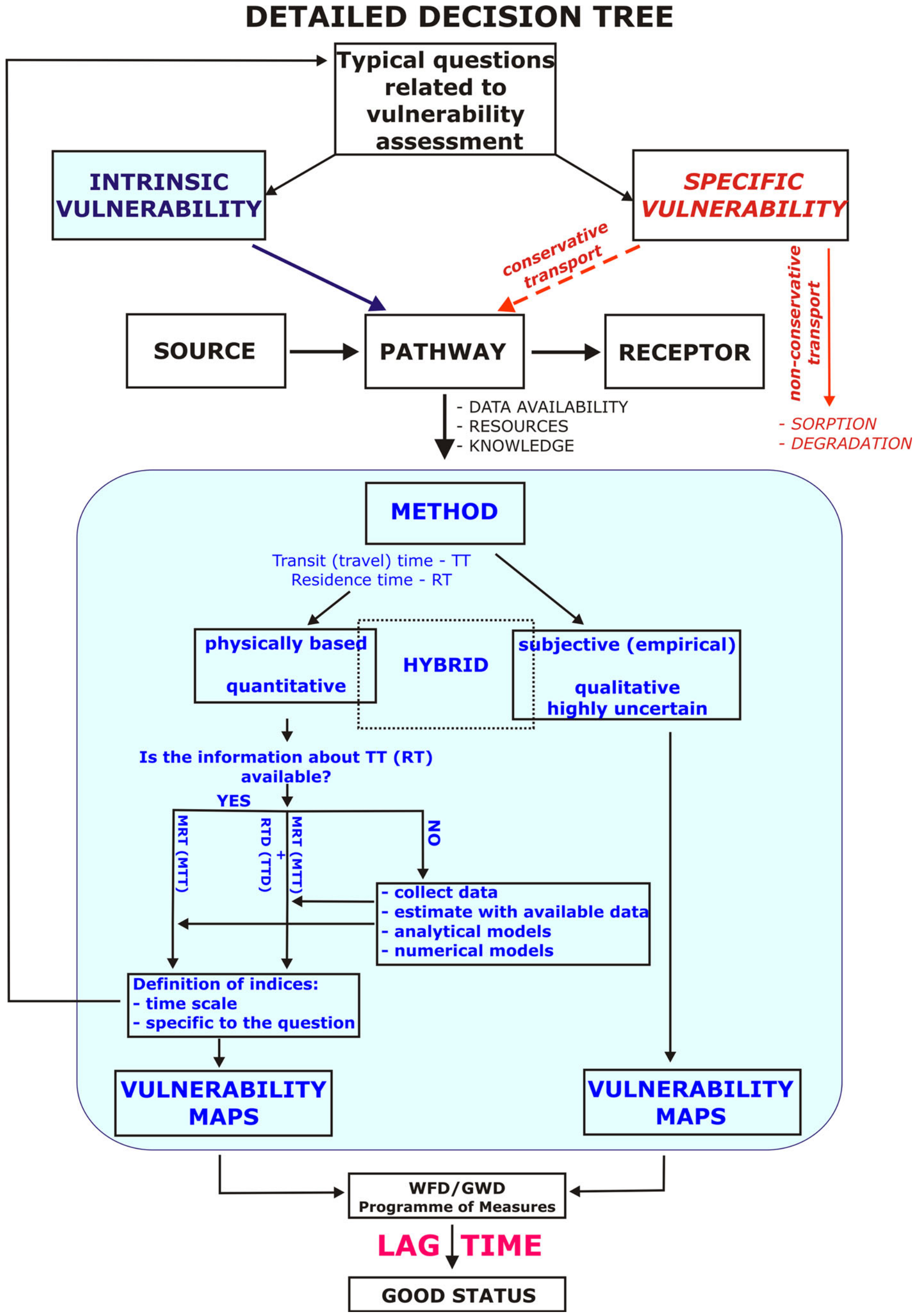

Fig. 3 Examples of practical questions for vulnerability assessment related either to chemical (*red*) or quantitative (*blue*) status assessment of groundwater bodies (GWB)

homogeneous systems and advection dominated transport or if only little data are available for investigations. If data are available, the distribution of residence (transit) times gives more detailed information and is recommended in particular for heterogeneous media. A summary of different approaches including analytical and numerical modeling is given in Wachniew et al. (2016). Various indices of groundwater vulnerability can be designed from MRT or RTD at different points of the investigated groundwater system or at the receptor. Intrinsic vulnerability assessments are conducted at various scales. At catchment scale, information is provided about the basic hydrological unit according to the WFD (Gogu et al. 2003; Yu et al. 2010). At the aquifer level, vulnerability assessment gives details for operational management of specific aquifers, such as water allocations to various users or delineation of groundwater protection zones (Fritch et al. 2000; Pisinaras et al. 2016). As a result of vulnerability assessment, vulnerability maps are presented and addressed to authorities and water managers to support the implementation of measures for achieving a good status of groundwater bodies.

Summary

A general and a *detailed decision tree* was introduced providing a systematic operational approach for vulnerability assessment and for the development of implementation strategies to achieve a good status of groundwater bodies according to the requirements of the WFD and the GWD. The *decision tree* is based on risk assessment using the source–pathway–receptor concept. Here, the pathway is directly linked to the vulnerability of water bodies. Particularly, timescales associated with transport along the pathway are crucial and are defined by the intrinsic properties of the groundwater body. The benefit of methods estimating timescales, like MRT or even better RTD, is that the timescales provided give information about the time required for successfully implementing protection strategies. Therefore, the *general* and *detailed decision tree* supports groundwater managers and decision-makers in the implementation of such programs to protect groundwater resources.

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