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Main concepts of the "European approach" to karst-groundwater-vulnerability assessment and mapping

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Abstract In order to achieve some consistency in the establishment of groundwater intrinsic vulnerability maps in Europe, a new approach is proposed by Working Group 1 of the European COST Action 620 on "Vulnerability mapping for the protection of carbonate (karst) aquifers". A general procedure is offered which provides consistency while allowing the required flexibility for application to a continent and under conditions of varying geology, scale, information availability, time, and resources.

The proposed methodology is designed to be clearly more physically based than the existing vulnerability-mapping techniques. It takes the specificity of the karstic environments into account without necessarily excluding the applicability to other geological conditions. Combined "core factors" for overlying layers and for concentration of flow account for the relative protection of groundwater from contamination while taking into account any bypass of the overlying layers.

A precipitation factor is distinguished for describing characteristics of the input of water to the system. Differentiation is made between groundwater resource intrinsic vulnerability mapping and source intrinsic vulnerability mapping. For the latter, a factor describing the karst network development is relevant. This short technical note describes a first step in the work program of Working Group 1 of the COST Action 620. Future steps are now in progress to quantify the approach and to apply it in various European pilot areas.

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Résumé Pour atteindre, au niveau européen, une certaine cohérence dans l'établissement de cartes de vulnérabilité des eaux souterraines, une approche originale est proposée par le Groupe de Travail 1 de l'Action européenne COST 620 "Cartographie de la vulnérabilité pour la protection des aquifères carbonatés (karstiques)". La procédure générale présentée ici est très flexible afin de permettre des applications dans tout un continent, pour différentes conditions géologiques, à des échelles variables, et à l'aide de données et de ressources diverses.

La méthodologie proposée est conçue pour être plus compatible avec la physique des processus que ne le sont les méthodes existantes de cartographie de la vulnérabilité. Elle tient compte des spécificités des milieux karstiques sans pour autant exclure son applicabilité dans d'autres contextes géologiques. Des facteurs principaux tenant compte des couches supérieures et de la concentration des flux d'infiltration permettent de tenir compte du degré relatif de protection des eaux souterraines en tenant compte de toutes les infiltrations préférentielles possibles qui évitent les couches supérieures protectrices.

Un facteur dit précipitation est distingué pour décrire les caractéristiques de l'entrée d'eau dans le système. Une différence est faite entre les cartes de vulnérabilité intrinsèque des ressources en eaux souterraines et les cartes de vulnérabilité intrinsèque relatives à une source ou émergence. Pour ce dernier type de cartes, un paramètre décrivant le développement du réseau karstique est pris en compte. Cette note technique succincte décrit le premier pas de la démarche du Groupe de Travail 1 de l'Action COST 620. Des étapes suivantes concernant une quantification plus précise des paramètres et l'application pratique sur différentes zones pilotes européennes sont maintenant en cours de réalisation.

Resumen El Grupo de Trabajo 1 de la Acción Europea COST 620, dedicado a la confección de una "Cartografía de la vulnerabilidad para la protección de acuíferos carbonatados (kársticos)", ha propuesto un nuevo enfoque orientado a lograr más coherencia en el establecimiento de mapas de vulnerabilidad intrínseca de las aguas subterráneas en Europa. Se ofrece un procedimiento genérico que proporciona coherencia a la par que permite la flexibilidad suficiente para su aplicación en un continente y en condiciones variables de geología, escala, disponibilidad de información, tiempo y recursos.

La metodología propuesta se basa más en los fundamentos físicos del problema que las técnicas existentes de cartografía de la vulnerabilidad. Se considera la especificidad de los medios kársticos, sin excluir necesariamente su aplicabilidad a condiciones geológicas distintas. Se combina "factores fundamentales" de las capas superiores y de la concentración del flujo para tener en cuenta la protección relativa de las aguas subterráneas frente a la contaminación, incluyendo potenciales vías de flujo preferencial.

El método utiliza un factor de precipitación para describir las características del agua de entrada al sistema. Se diferencia entre cartografía de vulnerabilidad intrínseca de los recursos subterráneos y cartografía de la vulnerabilidad intrínseca de la fuente. En relación con ésta, hay un factor esencial que describe el desarrollo de la red kárstica. Esta breve nota técnica describe la primera fase de la labor del Grupo de Trabajo 1 de la Acción COST 620. Actualmente, se está desarrollando las fases siguientes con el fin de evaluar el enfoque y aplicarlo en distintas áreas piloto de Europa.

Keywords Groundwater vulnerability · Karst · Intrinsic vulnerability · Vulnerability mapping

Introduction

At present, each country in Europe has developed or is developing new regulations and decision-making frameworks for protecting groundwater quality. These are usually based on two main concepts: protection of the groundwater source and of the groundwater resource. In practice, these are often supported by source protection zones and groundwater vulnerability maps respectively (Gogu 2000).

Carbonate rocks, many of which are karstic, underlie 35% of Europe. Over wide areas, karst waters form the only available natural resource for drink-water supply. Karst is one of the most challenging environments in terms of groundwater and engineering problems, involving many uncertainties because the nature of the porosity and permeability of soluble rocks is not easily predicted. In fact, karstic aquifers are characterised by a dual or triple porosity and permeability, often in the matrix or intergranular voids and always in fractures and solutional conduits.

Carbonate aquifers are especially vulnerable to various human impacts because water can move rapidly through fissures widened by dissolution, sinking streams provide direct entry points to groundwater, with little or no attenuation of contaminants, and the soil cover is often thin or absent. Therefore, special strategies are required in order to preserve the optimum quantity and quality of karst waters. The management of this resource is recognised in Europe as a high priority.

Issued in 1991 and concluded in 1995, the COST Action 65 (COST is the acronym for "European Cooperation in the Field of Scientific and Technical Research") was devoted to the topic "Hydrogeological aspects of groundwater protection in karstic areas". Based on national studies, this action established a complete inventory of regulations and made recommendations for management measures.

Vulnerability maps have become more and more an essential part of groundwater protection strategies and a valuable tool in environmental management. However, applying different methods for mapping vulnerability at any one study site usually gives quite different results (Gogu 2000), showing the need for more flexible and physically based methods. An overview of different existing methods is given in Gogu and Dassargues (2000), and previously in Vrba and Zaporozec (1994). The following references pertain to each of the methods: EPIK, Doerfliger et al. (1999); DRASTIC, Aller et al. (1987); the so-called German method, Hölting et al. (1995) and von Hoyer and Söfner (1998); ISIS, Civita and De Regibus (1995); GOD, Foster (1987) and Robins et al. (1994); SEEPAGE, Navulur and Engel (1997); AVI, Van Stempvoort et al. (1993); SINTACS, Civita (1994); REKS, Malík and Svasta (1998); the so-called Irish approach, Daly and Drew (1999); the so-called Hungarian system, Madl-Szonyi and Fule (1998); and the so-called PI method, Goldscheider et al. (2000).

COST Action 620, which began in 1997 and which builds on the results obtained in COST Action 65, proposes an objective methodology for "intrinsic" and "specific" vulnerability assessment and mapping in karstic environments, taking into account potential risks. Another important goal of this Action is to achieve some European level of consistency in the establishment of vulnerability and risk mapping, taking into account specific regional environmental variations as well as the different stages of economic development and scientific investigation of karst.

General Concept of the European Approach

The European approach intends to be broad enough to encompass all European conditions but sufficiently flexible to be customised for individual karstic regions (COST 620 internal report 1999). Even if the method is karst-centred, it ought to have the potential to consider all aquifer types in a unified methodology. Last but not least, rather than being too prescriptive, the method should provide guidance for possible approaches, allowing for local conditions, information availability, time, and resources (COST 620 internal report 2000).

The suggested method for groundwater vulnerability assessment and mapping is based on the following definition of intrinsic vulnerability: Intrinsic vulnerability is the term used to define the vulnerability of groundwater to contaminants generated by human activities. It takes account of the inherent geological, hydrological, and hydrogeological characteristics of an area, but is independent of the nature of the contaminants.

Intrinsic vulnerability differs from specific vulnerability, the latter being used to define the vulnerability of groundwater to a particular contaminant or group of contaminants. It takes account of the properties of the contaminants and their relationships with the various components of intrinsic vulnerability.

Vulnerability is a concept which cannot be defined in a rigorous way. Nevertheless, the first objective is to differentiate "zones" of different degrees of groundwater vulnerability to contamination (or differing likelihood of contamination if a pollution event occurs). This implies a quantification of the concept, even if in practice it is not always possible to verify the results in the field.

As intrinsic vulnerability does not refer to a specific contaminant, only the properties which are relevant for all types of contaminants are considered. Conceptually, three basic aspects have to be considered in order to quantify intrinsic vulnerability: (1) advective transport time; (2) relative quantity of contaminants which can reach the target (a portion of the contaminants may never reach the target but might leave the catchment in surface runoff); and (3) physical attenuation (dispersion, dilution, dual porosity effects, etc.).

The proposed "European approach" is based on the hazard–pathway–target model:

1. Hazards are the activities and developments which pose a threat to groundwater. The "hazard" is taken to originate at the ground surface (potential release of a contaminant).
2. The "target" can be the groundwater resource as a whole, or a source/abstraction point. Accordingly, different vulnerability maps may be defined. This approach provides both a resource intrinsic vulnerability map and a karstic source intrinsic vulnerability map. For resource-vulnerability mapping, the groundwater of the karst aquifer as a whole is considered, with the target being the groundwater surface. This can be the water table where the potentiometric surface is within the limestone, or alternatively it may be the top of the bedrock where the water table or potentiometric surface is in overlying geological materials. For source-vulnerability mapping the target is a pumping well or a spring issuing from an aquifer (GSI 1999; Goldscheider et al. 2000).
3. The "pathway" includes everything between the ground surface (point of release of contaminants) and the target. All factors influencing vulnerability have to be evaluated. For resource vulnerability, the pathway is the vertical path through any overlying layers. For source vulnerability, horizontal-flow paths in the aquifer are also taken into account.

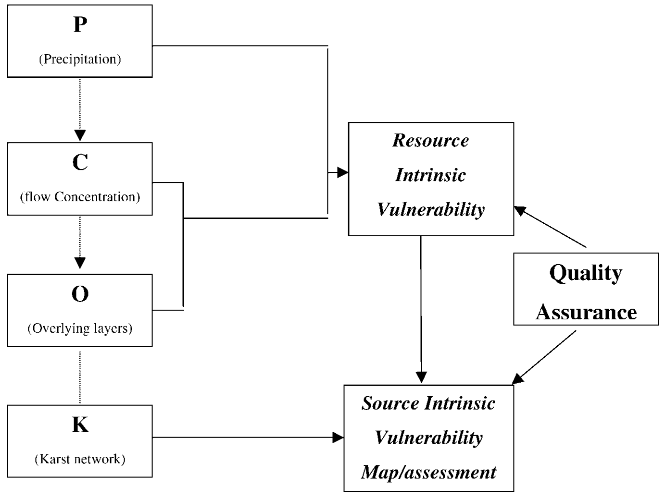

Fig. 1 Illustration of the "European approach" to mapping groundwater vulnerability: for resource-vulnerability mapping, the groundwater surface is the target; for source-vulnerability mapping, the spring or pumping well is the target. The precipitation regime (*P* factor) is responsible for water-flow rates within the system; the overlying layers (*O* factor) consist of up to four layers: (1) topsoil, (2) subsoil, (3) non-karstic bedrock, and (4) unsaturated karstic bedrock, combined with the concentration of flow (*C* factor), account for the relative protection of the groundwater from contamination, taking into account any bypass. In addition, the karst network development (*K* factor) is relevant for source-vulnerability mapping

System and Processes Conceptualisation

In describing the relative protective function of the different layers between the land surface and groundwater, the first factor takes into account the properties of any overlying layers in terms of advective transport time and physical attenuation. This is called the "overlying layers factor" (the O factor; COST 620, internal report 2000).

A pollution event occurring at the ground surface can reach groundwater in different ways (Fig. 1). The contaminant can move through the layers between the soil surface and groundwater by infiltration and subsequent percolation. Alternatively, preferential and concentrated infiltration can occur at swallow holes, thus bypassing the overlying layers. Also, in areas characterised by runoff (down slopes or where streams flow onto karstic aquifers from non-carbonate-rock areas), contaminated water can move to another location where it can infiltrate into the ground at swallow holes or dolines and bypass all or a part of the overlying layers. These processes are conceptualised in a factor called "flow concentration" (the C factor). The C factor of the European approach is almost identical to the I factor of the PI method (Goldscheider et al. 2000).

For source-vulnerability assessment, the advective transport time and physical attenuation must also be considered in the saturated zone. This is taken into account with a factor K describing the saturated karstic network behaviour.

Precipitation (the P factor) is an external "stress" applied to the geological environment. Except for surface water–groundwater interactions, no recharge and vertical seepage of water towards the groundwater is possible without rainfall or snowmelt. So this P factor will have to be combined with the factors C and O (or C, O, and K, depending on the target).

After adequate combination of these factors, a general validation of the results should be undertaken. This process, using data not used in the groundwater-vulnerability-assessment method and characterising the overall behaviour of the system, acts as quality assurance.

Overlying-Layers Factor: O

The overlying layers are those located between the land surface and the groundwater. They can consist of up to four types of layers (Hölting et al. 1995; COST 620 internal report 2000; Goldscheider et al. 2000):

1. Topsoil – the biologically active zone of weathering, composed of minerals, organic substances, water, air, living matter, roots (the A and B pedological horizons);
2. Subsoil – granular, unconsolidated material, like sand, gravel, and clay;
3. Non-karstic bedrock – non-karstic rock, like sandstone, schist, shale, and basalt;
4. Unsaturated karstic bedrock – the epikarst (if present) is considered as a part of this layer (COST 620, internal report 2000).

Each layer is not always present. A possible extreme situation could occur when only one karstified layer exists. There may be instances when some of these layers may be usefully separated into several sublayers.

The value to be given to the O factor must reflect the protective capacity of the overlying layers. Accordingly, the data to be collected are of two types: (1) key data (those which should actually be considered to directly assess the O factor): layer thicknesses, hydraulic-conductivity values (depending on water content), effective-porosity values (depending on water content), macroporosity and/or fissuring, fracturing/karstification (heterogeneity); and (2) other data (data from which the main data can be assessed): grain-size distribution, lithological content, soil type, vegetation indicators, drainage density.

Flow-Concentration Factor: C

Infiltration may occur in a relatively diffuse way through the overlying layers, without significant flow-concentration points at the soil (land) surface. On the other hand, and especially in karst systems, surface water and possible contaminants can very quickly reach the groundwater by concentrated recharge via dolines, shafts, and especially swallow holes. Consequently, the protective function provided by the overlying layers is completely bypassed at these places and partially bypassed within their catchments (COST 620, internal report 2000; Goldscheider et al. 2000).

The C factor represents the flow concentration, depending on (1) the presence of karst features or other places which concentrate infiltration flow; and (2) the parameters which control runoff, including slope, vegetation, and physical soil properties.

The C factor represents the degree to which precipitation is concentrated towards places where fast infiltration can occur. If the infiltration occurs diffusely without significant concentration of flow, the C factor is not an issue as the overlying layers are not bypassed. On the other hand, precipitation can be concentrated and the overlying layers can be completely bypassed by a swallow hole through which surface water and possible contaminants directly enter the karst aquifer. In such a case, the C factor is a significant issue in determining vulnerability. Catchment areas of sinking streams are assigned intermediate values of C. Basically, it is considered that the O factor should be multiplied by the C factor. Consequently, even an area covered with thick and low-permeability overlying layers (high O factor) turns out to be vulnerable if it discharges by surface runoff towards a swallow hole or sinking stream (low C factor). An approach to quantifying C could be to choose it in an interval between 0 and 1; however, the methods of quantifying the values of these parameters will be considered during the next stage of COST Action 620.

Karst-Network Factor: K

For assessing the karstic source (well or spring) intrinsic vulnerability, a factor taking into account the karst network of the mostly saturated aquifer is needed. The "vertical" pathway (from the soil to the groundwater) must be combined with the mostly horizontal pathway through the saturated karstic bedrock to the source being considered (GSI 1999; Goldscheider et al. 2000).

A classification system previously developed (COST 620, internal report 2000) for karst aquifers has been adopted. It is based on a general description of the bedrock, giving a range of possibilities from porous carbonate-rock aquifers to highly karstified networks (Table 1). By characterising the different types of flow (migration mechanisms) and the matrix-storage capacity (physical attenuation), a more detailed classification of the aquifer can be derived if required. This K factor is very similar to the K factor of the EPIK method (Doerfliger et al. 1999).

The description "slow active conduit network" reflects conduit systems which are not extensive and not very efficient in draining the aquifer. "Fast active con-

Table 1 Classification system for the karst aquifers (adapted from COST 620, internal report 2000). The increasing degree of karstification and concentration of flow within the aquifer is from left to right

Fractured and intergranular system			Solutionally-enlarged fissures			Conduit systems					
Inter-granular flow	Fractures		High matrix storage	Low matrix storage	No significant matrix storage	Slow active conduit network			Fast active conduit network		
	High matrix storage	Low matrix storage				High matrix storage	Low matrix storage	No significant matrix storage	High matrix storage	Low matrix storage	No significant matrix storage

duit system" implies an extensively developed karst network which is efficient in draining the aquifer. The matrix characteristics of the bedrock have been included, as the interaction between the conduits and the matrix may be sufficient to change the behaviour of the aquifer and hence the attenuation potential.

The means of assessing the karst network factor are the following: (1) geology, geomorphology; (2) cave and karst maps; (3) groundwater-tracing results; (4) pumping-tests results; (5) hydrochemistry, geochemistry; (6) remote sensing and geophysical prospecting; (7) borehole data and geophysical-logging results; (8) bedrock sampling and laboratory experiments; and (9) calibrated modelling results.

Precipitation Factor: P

This factor should reflect not only the total quantity of precipitation, but also the frequency, duration, and intensity of extreme events, which can have a major influence on the quantity and rate of infiltration. Through the dependency of the hydraulic-conductivity and effective-porosity values on the water content, the advective transport times and physical attenuation processes are influenced by the prevailing precipitation characteristics in the region concerned.

Four possible general scenarios can be considered: humid climate with extreme events, humid climate without extreme events, dry climate with extreme events, and dry climate without extreme events.

Quality Assurance: Validation

The philosophy underlying such analysis, which is supposed to assess the whole system, is that it acts as an independent evaluation to be used as a means of comparison with the vulnerability maps. It is a "reality check" utilising tools which evaluate the whole system. It also provides a means of incorporating data from methodologies which have traditionally been used in karst hydrology (COST 620, internal report 2000). The use of data which were not previously used in the factors evaluation allows this general validation procedure to be carried out.

In practice, quality assurance is introduced to consider how the vulnerability assessment reflects what is known of the entire hydrological system supplying the source. The quality assurance or validation assessment can be done with the use of different kinds of data, such as (COST 620, internal report 2000) (1) hydrograph, graphs of chemical properties, bacteriology; (2) tracer techniques; (3) water balance; (4) calibrated numerical simulations; and (5) analog studies.

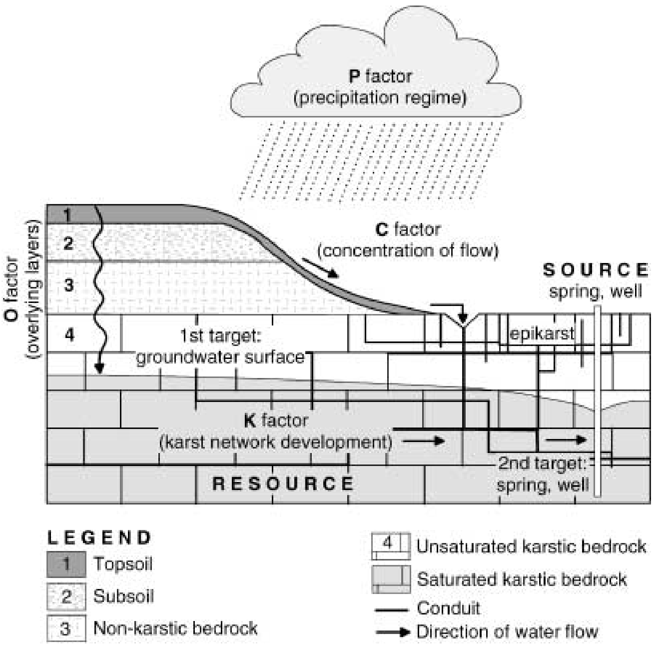

Fig. 2 Diagrammatic cross section showing distribution of factors which result in the production of intrinsic vulnerability maps (modified after Goldscheider et al. 2000)

Intrinsic-Vulnerability Maps

The resource-intrinsic-vulnerability map is obtained by applying the system stress factor P on the combination of the O and C factors (core factors). Vulnerability assessment at a site is also achieved by combining these factors. The additional combination with the K factor provides the source (karstic) intrinsic vulnerability map. Fig. 2 is a diagrammatic cross section showing the distribution of the factors which result in the map. The quality-assurance test is used a posteriori for checking the vulnerability assessment and mapping.

Next Steps to be Considered in the "European Approach"

Now the work is directed to the following developments:

1. Methods of quantifying/categorising factors;
2. Defining a way of combining and weighting the different factors with respect to the underlying physical processes (i.e. migration and physical attenuation processes);
3. Defining the different meteorological scenarios and their respective influence for combining P, on one hand, with O and C factors on the other hand;
4. Applying the proposed method to various European test sites which have different meteorological, hydrological, geological, and hydrogeological conditions; the approach allows data of varying quality/reliability to be used in individual cases, and it is necessary to be able to estimate how good the assessment of vulnerability is, based on the quality of the data input;
5. Using the assessment of the factors to compartmentalise the range of hydrogeological settings and conditions into 4–5 vulnerability categories;
6. Revising the approach based on the results from the test sites.

Concluding Comments

The main concepts of the "European approach" for karst groundwater-vulnerability assessment and mapping outlined in this report represent a consensus view of hydrogeologists and karst specialists from about 15 European countries. It provides a simple, yet sound, conceptual framework for vulnerability assessment and mapping for both karst and non-karst hydrogeological environments. It also provides a broad framework which takes account of the variability and conditions within Europe, although it is also likely to be applicable outside Europe. It may assist in the implementation of the EU Water Framework Directive (Directive 2000/60/EC) by providing a consistent approach to considering and describing the vulnerability component of river-basin district characterisation.

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