Karst groundwater vulnerability mapping: application of a new method in the Swabian Alb, Germany

Nico Goldscheider

Abstract Groundwater from karst aquifers is an important drinking water resource, which is, however, particularly vulnerable to contamination. Karst aquifers consequently need special protection. This paper discusses the concept of groundwater vulnerability mapping and the special characteristics of karst aquifers that are relevant in this context. On this basis, a new method of groundwater vulnerability mapping is proposed—the PI method. It can be applied for all types of aquifers, but provides special tools for karst. Vulnerability is assessed as the product of two factors: protective cover (P) and infiltration conditions (I). The method was first applied and compared with two other methods (EPIK and the German method) in a test site in the Swabian Alb, Germany. The results obtained with the different methods are discussed and an outlook on the role of vulnerability maps within an overall groundwater protections scheme is given.

Résumé L'eau souterraine des karsts est une importante ressource d'eau potable, cependant particulièrement vulnérable à la pollution. C'est pourquoi les aquifères karstiques nécessitent une protection particulière. Ce papier discute le concept de cartographie de la vulnérabilité de l'eau souterraine et les caractéristiques particulières des aquifères karstiques qui sont concernés dans ce contexte. Sur cette base, une nouvelle méthode de cartographie de la vulnérabilité de l'eau souterraine est proposée: la méthode PI. Elle peut être appliquée à tous les types d'aquifères, mais fournit des outils spécifiques au karst. La vulnérabilité est évaluée comme étant le produit de deux facteurs: les conditions de couverture protectrice (P) et d'infiltration (I). La méthode a été mise en oeuvre pour la première fois et comparée à deux autres méthodes (EPIK et la méthode allemande) sur un site test du Jura souabe (Allemagne). Les résultats obtenus avec les différentes méthodes sont discutés et le rôle des cartes de vulnérabilité dans un schéma général de protection des eaux souterraines est passé en revue.

Resumen Las aguas subterráneas en medios kársticos suponen un recurso importante para uso de boca, pero es particularmente vulnerable a la contaminación, por lo que los acuíferos kársticos requieren una protección especial. Este artículo discute el concepto de cartografía de vulnerabilidad de las aguas subterráneas y las características propias de los acuíferos kársticos que son relevantes en este contexto. Con esta base, se propone un nuevo método para cartografiar la vulnerabilidad de las aguas subterráneas, denominado "PI". Puede ser aplicado a todo tipo de acuíferos, pero proporciona herramientas especiales en medios kársticos. Se establece la vulnerabilidad como resultado de dos factores: la cubierta protectora y las condiciones de infiltración. El método ha sido aplicado por vez primera y comparado con otros dos enfoques (EPIK y el método alemán) en un emplazamiento ubicado en Swabian Alb (Alemania). Se discute los resultados obtenidos con estos métodos y se incide en cuál es el papel que desempeñan los mapas de vulnerabilidad en el contexto de los esquemas generales de protección de las aguas subterráneas.

Keywords Groundwater vulnerability mapping · Karst aquifer · PI method · Swabian Alb

Introduction

Groundwater from karst aquifers is among the most important resources of drinking water for the growing population of the world. Carbonate rock outcrops, of which a large part is karstified, cover about 7–12 % of the planet's dry, ice-free land and karst waters supply about 25 % of the global population (Ford and Williams 1989). In Europe, carbonate terrains occupy 35 % of the land-surface and a significant portion of the drinking water supply is abstracted from karst aquifers (Fig. 1). In some European countries, karst water contributes 50% to the total drinking water supply, and in many regions, it is the only available fresh water resource (COST 65 1995).

Received: 17 February 2003 / Accepted: 29 July 2003
Published online: 29 August 2003

N. Goldscheider (✉)
Hydrogeology Centre (CHYN),
University of Neuchâtel,
11 rue Emile-Argand, 2007 Neuchâtel, Switzerland
e-mail: nico.goldscheider@unine.ch

 DOI 10.1007/s10040-003-0291-3

Fig. 1 Map of carbonate rock outcrops in Europe. Karst features develop in most of them. The *black squares* show the location of the Engen area and the other sites where the PI method or modifications of it were tested by different groups of COST action 620. The *rectangle* shows the location of the inset map in Fig. 5 (modified after COST 65 1995)

At the same time, karst aquifers are particularly vulnerable to contamination: Due to thin soils, flow concentration in the epikarst (the uppermost, often intensively fractured and karstified layer of a carbonate aquifer) and point recharge via swallow holes, contaminants can easily reach the groundwater, where they may be transported rapidly in karst conduits over large distances. The residence times of contaminants are often short, and processes of contaminant attenuation, therefore, often do not work effectively in karst systems.

Karst aquifers consequently need special protection. However, protection zoning for karst is more complicated than for granular aquifers because karst systems are highly heterogeneous and anisotropic, the catchments may cover large areas and flow velocities may be as high as 500 m/h. For groundwater source protection in porous aquifers, many European countries use the travel time towards the source (well, spring) as the main criterion for the delineation of the so-called 'Inner Protection Zone'. Switzerland uses 10 days of travel time (GSchV 1998), Germany 50 days (DVGW 1995), Austria 60 days (ÖVGW 1995), and Ireland 100 days (DoELG/EPA/GSI 1999). Land-use is strongly restricted in these zones. If the same criterion were used for sources in karst aquifers, the protection zones would cover large areas, often the entire catchment. From the point of view of drinking water protection, this could be justified. However, it is most often not practical to demand maximum protection for large areas, as the resulting land-use restrictions would not be acceptable in many cases.

As a consequence, it is essential to protect at least those areas within a karst system where contaminants can most easily reach the groundwater. This leads to the concept of groundwater vulnerability that is not restricted to karst, but is most relevant and most complicated when applied to karst. The objective of vulnerability mapping is to identify the most vulnerable areas and prioritise those. A vulnerability map may thus help the decision makers to find a scientifically based balance between groundwater protection and socioeconomic aspects.

Therefore, it is necessary to define objective and applicable criteria to vulnerability mapping. For that reason, the Directorate General for Science, Research and Development of the European Commission set up the COST Action 620 on "vulnerability and risk mapping for the protection of carbonate (karst) aquifers". COST means cooperation in science and technology. The project was given additional impetus by the European Water Framework Directive (2000), which is intended to provide a common framework for water resource policy and management. A previous COST Action had worked out the basic "hydrogeological aspects of groundwater protection in karst areas" (COST 65 1995).

Within the framework of COST 620 and a project funded by the German Federal Institute for Geosciences and Natural Resources (BGR), a new method of vulnerability mapping was proposed—the PI method (Goldscheider et al. 2000). The acronym stands for the two factors that are considered: protective cover (P) and the infiltration conditions (I). The PI method was first applied

 DOI 10.1007/s10040-003-0291-3

and compared with two other methods at the test site "Engen", which belongs to the Swabian–Franconian Alb, Germany's largest coherent karst landscape.

The European approach to groundwater vulnerability mapping outlined by COST 620 (Daly et al. 2002) is partly based on the PI method, and in the final report of this Action (Zwahlen 2003), the PI method is proposed as a possibility for mapping karst groundwater resource vulnerability. To date, the method or modifications of it were applied in 12 karst test sites in seven European countries by various teams (Fig. 1). These applications are referenced and documented in Goldscheider (2002) and Zwahlen (2003).

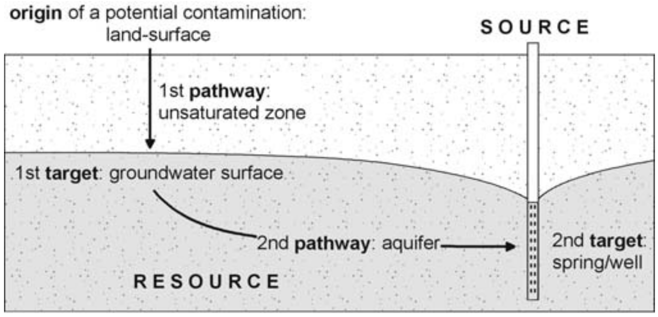


Fig. 2 Illustration of the origin-pathway-target model for groundwater vulnerability mapping and the concept of resource and source protection

Groundwater Vulnerability and Karst Aquifers

Background and Definitions

Margat (1968) introduced the term "vulnerability of groundwater to contamination". The terms "vulnerability to contamination" and "natural protection against contamination" can be used alternatively. High vulnerability means low natural protection.

Vrba and Zaporozec (1994) state that vulnerability is a qualitative, relative, non-measurable and dimensionless property. They suggest distinguishing between intrinsic and specific vulnerability. The former only depends on the natural properties of an area, while the latter also takes into account the properties of the contaminant. COST Action 65 (1995) presented an overview on definitions of vulnerability that had been proposed until then. COST 620 evaluated this issue and proposed the following definitions (after Daly et al. 2002):

– The intrinsic vulnerability takes into account the hydrogeological characteristics of an area, but is independent of the nature of the contaminants and the contamination scenario.
– The specific vulnerability takes into account the properties of a particular contaminant (or group of contaminants) and its relationship to the hydrogeological system.

The PI method is an approach to intrinsic vulnerability mapping. It is based on an origin-pathway-target model (Fig. 2). 'Origin' is the term used to describe the location of a potential contaminant release. The 'pathway' includes the passage of potential contaminants from the point of release to the 'target' (receptor), which may be the groundwater surface or a drinking water abstraction point. There are two general approaches to groundwater protection: resource protection aims on protecting the whole groundwater body and source protection aims on protecting a particular source, which may be a spring or well (DoELG/EPA/GSI 1999). However, the two concepts are closely related to each other—protecting a source usually involves providing protection for the resource as well. Resource vulnerability maps take the groundwater surface as the target, and the pathway consists of the mostly vertical passage through the layers above the groundwater surface (the unsaturated zone). For source vulnerability mapping, the well or spring is the target and the pathway includes additionally the mostly horizontal flow route in the saturated part of the aquifer (Goldscheider et al. 2000).

The PI method is made for resource vulnerability mapping and, thus, takes the groundwater surface in the uppermost relevant aquifer as the target.

The Special Situation in Karst

Although the concept of groundwater vulnerability is applicable for all types of aquifers, it is essential to develop a method that takes into account the nature of karst. There are two possibilities to do so: develop a method that is only dedicated to karst, or develop a method that can be used for all types of aquifers, but provides special tools for karst. There are three reasons why the second possibility appears more appropriate. Firstly, there are transitions between purely fissured and karstified carbonate aquifers. Secondly, there are transitions between porous and karst aquifers, e.g. intensively fractured dolomites. Thirdly, there are often several types of interacting aquifers in one hydrogeological system.

The following characteristics of karst systems are relevant with respect to groundwater vulnerability and should consequently be taken into account (compiled from Ford and Williams 1989; Drew and Hötzl 1999; Klimchouk et al. 2000; Goldscheider 2002):

– Each karst system has its individual characteristics; generalisation is problematic.
– Karst systems are heterogeneous and anisotropic; interpolation of data is thus difficult and the reliability of a vulnerability map can be lower for karst than for other areas.
– There is both diffuse and point recharge. Adjacent non-karst areas may generate surface flow that may enter the karst aquifer via swallow holes (allogenic recharge).
– The epikarst, if present, controls the infiltration into the aquifer. It may store water and concentrate flow.

 DOI 10.1007/s10040-003-0291-3

The structure and function of epikarst is often difficult to assess.
– Karst aquifers may comprise conduits, fissures and intergranular pores. Contaminants can be transported very fast in the conduits or stored in the fissures and pores (matrix).
– Karst systems show strong hydraulic and physico-chemical reactions to hydrologic events.
– The water table and hydraulic gradient are often difficult to define, particularly in shallow and conduit systems.
– Karst catchments are often large and hydraulically connected over long distances. Karst catchments may overlap and the flow paths (proved by tracer tests) may cross each other.

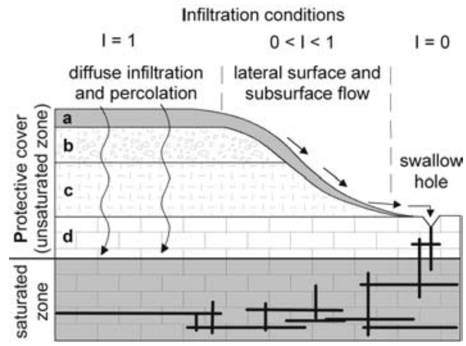


Fig. 3 Illustration of the PI method. The P factor takes into account the effectiveness of the protective cover as a function of the thickness and hydraulic properties of all the strata between the ground surface and the groundwater surface. The protective cover consists of up to four layers: *a* topsoil, *b* subsoil, *c* non-karst rock, and *d* unsaturated karst rock. The I factor shows the degree to which the protective cover is bypassed by lateral surface and subsurface flow that occurs in the catchments of sinking streams

Overview on Existing Methods

There are various methods of groundwater vulnerability mapping. DRASTIC (Aller et al. 1987), GOD (Foster 1987) and SINTACS (Civita and De Maio 2000) are among the most commonly known. Vrba and Zaporozec (1994), COST 65 (1995), Gogu and Dassargues (2000), Magiera (2000) and Goldscheider (2002) reviewed various existing methods, which can be classified as follows: hydrogeological complex and setting methods, index models and analogical relations, parametric system models, mathematical models and statistical methods. It is also possible to classify the methods on the basis of scale (site, local, regional) or purpose (e.g. risk management, protection zoning), and to distinguish intrinsic and specific vulnerability maps, and source and resource vulnerability maps.

Most methods do not provide special tools for karst and, thus, lead to unsatisfactory results when applied to karst. EPIK (Doerfliger and Zwahlen 1998) was the first method especially dedicated to karst. The acronym stands for the four factors that are considered: epikarst, protective cover, infiltration conditions and karst network development. The method is used for source protection zoning in Switzerland according to the Water Protection Ordinance (GSchV 1998). However, it can only be applied in karst areas, which leads to problems in complex hydrogeological systems comprising different aquifer types. The method contains some drawbacks that often lead to contradictory results (Goldscheider 2002).

In Germany, the protective function of the layers overlying groundwater is assessed using a method proposed by Hölting et al. (1995). This ’German’ method presumes diffuse infiltration into the soil and subsequent vertical percolation through the unsaturated zone towards the groundwater. This precondition is generally fulfilled in porous aquifers. However, in karst systems, water may enter the aquifer through dolines, vertical shafts and swallow holes (point recharge). There is also often lateral inflow from adjacent non-karst areas that focus runoff towards a stream that later sinks into the karst aquifer (allogenic recharge). The above-mentioned precondition is thus often not fulfilled in karst areas. The application of the ‘German’ method consequently leads to contradictory results. For example, an area where the karst aquifer is covered by several metres of clayey sediments will be classified a ’very low vulnerability’ area, even when this particular area generates surface runoff towards an adjacent swallow hole. This was the starting point to develop the PI method, which is based on the German method, but includes tools for the application in karst.

The PI Method

The PI method is a GIS-based approach to mapping the intrinsic vulnerability of groundwater resources (Goldscheider et al. 2000). It can be applied to all types of aquifers, but provides special methodological tools for karst. The conceptual model of the method is based on an origin-pathway-target model. The land surface is taken as the origin, the water table in the aquifer is the target, and the pathway includes all layers in between. Vulnerability is assessed as the product of two factors: protective cover (P) and infiltration conditions (I) (Fig. 3).

The detailed assessment schemes for the two factors can be found in Goldscheider et al. (2000), Goldscheider (2002) and in the final report of the European COST Action 620 (Zwahlen 2003). The following paragraphs, therefore, give a brief description only.

The P factor describes the protective function of all layers that may be present between the ground surface and the groundwater table: the topsoil (biologically most active uppermost layer of the earth crust; pedologically the A and B soil horizons), the subsoil (non-lithified sediments below the soil and over the bedrock; most often Quaternary deposits), the non-karst rock and the unsaturated zone of the karst rock. Protectiveness is assessed on the basis of the effective field capacity (eFC) of the soil, the grain size distribution (GSD) of the subsoil, the lithology, fissuring and karstification of the non-karst and

 DOI 10.1007/s10040-003-0291-3

	vulnerability map vulnerability of groundwater		P-map protective function of overlying layers		I-map degree of bypassing	
	description	π-factor	description	P-factor	description	I-factor
red	extreme	0-1	very low	1	very high	0.0-0.2
orange	high	>1-2	low	2	high	0.4
yellow	moderate	>2-3	moderate	3	moderate	0.6
green	low	>3-4	high	4	low	0.8
blue	very low	>4-5	very high	5	very low	1.0

Fig. 4 Common legend for the vulnerability map, the P and the I map. The colours do not apply for the figures in this paper, but are to be used on printed maps

karst rock, the thickness of all strata, the mean annual recharge and artesian pressure in the aquifer. The total score range is divided into five classes, from P=1 for an extremely low degree of protection to P=5 for very thick and protective overlying layers. A decadic logarithmic scale is applied, so that a ten times higher protectiveness (e.g. 10-m-layer thickness instead of 1 m) makes the P factor one class higher. The distribution of the P factor is shown on the P map.

The I factor is new and crucial for the application of the method in karst areas. It describes the infiltration conditions and, in particular, the degree to which the protective cover is bypassed as a result of lateral surface and subsurface flow that enters the karst aquifer at another place, for example via a swallow hole. The factor ranges between 0.0 and 1.0. It is 1.0 on a horizontal, highly permeable soil, where all recharge will occur in a diffuse way, i.e. by infiltration and subsequent percolation. In contrast, the I factor is 0.0 on a steep slope made of low permeability soil that focuses surface runoff towards a sinking stream. In such a situation, the protective cover will be completely bypassed. All other areas are assigned intermediate values (0.2, 0.4, 0.6, 0.8), depending on the soil properties controlling the predominant flow process, the vegetation and slope gradient, and the position of a given point inside or outside the catchment of a sinking stream.

The final protection factor π is the product of P and I. As proposed by Vrba and Zaporozec (1994), five classes of vulnerability (or protectiveness) are distinguished and symbolised by colours ranging from red to blue (dark to light grey in this paper): A protective factor of $\pi \leq 1$ indicates a very low degree of protection and an extreme vulnerability to contamination, symbolised by a red colour (dark grey). A value of $\pi=5$ means a very high degree of protection and a very low vulnerability, symbolised by a blue colour (light grey). The distribution of the π factor is shown on the vulnerability map. Small I and P maps should be printed as insets on the PI vulnerability map, in order to show in which way the vulnerability of a particular area is influenced by the two factors. The legend for the P map and I map also comprises five colours from red to blue (dark to light grey; Fig. 4).

Description of the Engen Test Site

The test site covers an area of 36 km^2 and belongs to the Swabian Alb in Southwest Germany. The test site is part of the drinking water protection area for the city of Engen. As the karst spring catchments in the Swabian Alb are large (hundreds to thousands of km^3), the test site does not cover the complete catchment of a particular spring, but was delineated rather arbitrarily following administrative boundaries. However, for groundwater resource vulnerability mapping, it is not necessarily to respect spring catchment boundaries.

The altitude of the test site ranges between 470 m in the southern lowlands and 690 m in the north. Half of the area is forested, 44% is used for agriculture, and 6% are settlements. The mean annual air temperature is 8.1 °C and the precipitation is 818 mm.

The Swabian Alb is made of Upper Jurassic carbonate rocks with a total thickness ranging between 300 and 400 m. Towards the south, these formations dip below the Tertiary Molasse foreland basin of the Alps. The Engen area is located in the transition zone between these two units. The carbonate rocks (bedded and reef limestones, interstratified with marl) are partially overlain by Molasse sediments and, locally, volcanics. Glacial deposits of two alpine glaciations cover large areas and alluvial sediments are present in the valleys (Fig. 5). In the test site, the Jurassic strata dip towards the S and SE at about 3° and are cut by faults with three predominant directions: NW–SE, N–S and W–E (Schreiner 1997).

As the carbonate rocks are widely covered with sediments and soils, karst landforms such as dolines and karren are rare and often not noticeable. However, quarries allow study of the epikarst development (Fig. 6). Rainwater that infiltrates diffusely into the soil is concentrated in the epikarst, which is drained by vertical shafts. The only relevant visible karst landforms are dry valleys. Due to the widespread low permeability sediments, there are many watercourses that seep diffusely or sink via swallow holes into the karst aquifer.

The karst aquifer has been studied in detail while investigating the famous Danube–Aach-System (e.g. Batsche et al. 1970; Hötzl 1973; Villinger 1977; Vogelsang and Villinger 1987). Water from the Danube River sinks via swallow holes into Oxfordian limestone and flows more than 10 km southward to springs that are tributary to the Rhine River. The main outlet of the system is the Aach spring (outside the test site) with a mean discharge of 8.5 m^3/s (Fig. 7). As the dip of the strata is steeper than the dip of the land surface, the karst water rises across the stratification on its way to the Aach spring, which discharges from Kimmeridgian limestone. Tracer tests proved flow velocities of up to 250 m/h, indicating the presence of a well-developed and connect-

 DOI 10.1007/s10040-003-0291-3

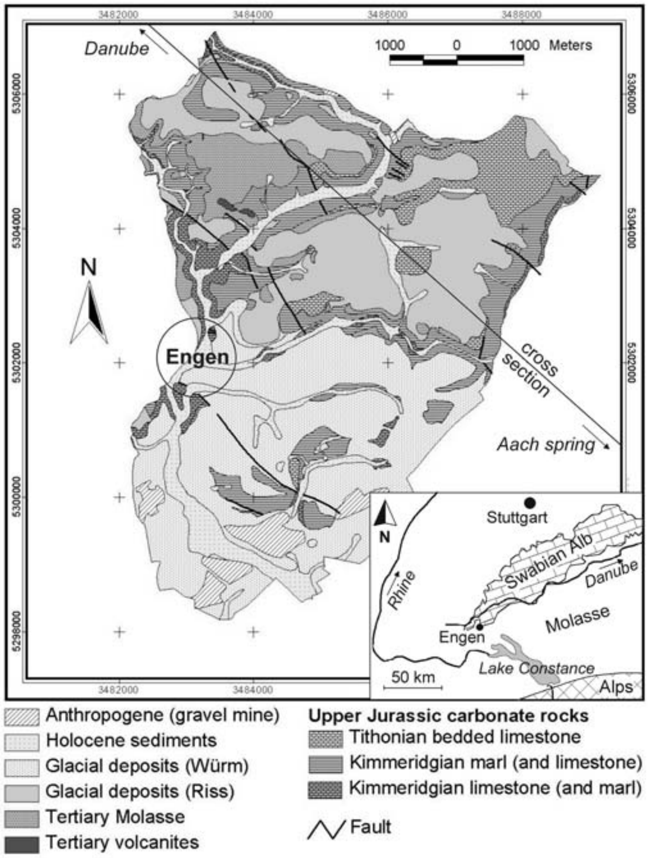


Fig. 5 Generalised geological map of the Engen area. The *inset map* shows the location of the test site within the Swabian Alb (see also Fig. 1). The *line* shows a part of the cross section in Fig. 7

Fig. 6 A quarry in carbonate rocks in the Engen area shows a well-developed epikarst layer with a funnel-shaped doline that is connected with a vertical shaft (the given scale is an approximation)

ed system of wide and open conduits. Some of the tracers reached the wells and springs in the Engen area.

In the test site, there are locally higher aquifers above the main karst aquifer: four small perched aquifers in the north, and a porous aquifer in the south, which developed in 30–50-m-thick glacial sand and gravel with a separating clayey layer. Tracer tests proved that karst water rises into this porous aquifer. The springs in the south thus discharge a mixture of water from the karst and the porous aquifer (Batsche et al. 1970; Schreiner 1997).

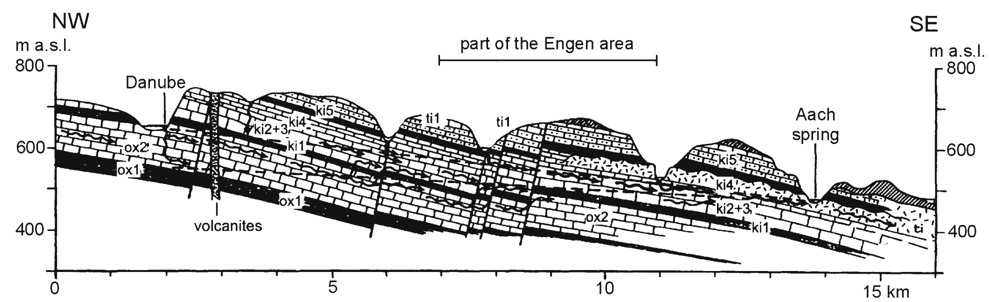
In the test site, the soils on Jurassic carbonate rocks are characterised by low to medium effective field capacity (eFC; 50–140 mm) and high hydraulic conductivity (40–300 cm/day). In old glacial deposits in the northern part of the area, there are a large variety of deep, loamy soils. The eFC is medium to high (90–200 mm) and the conductivity is often very low (<1 cm/day). The soils on the young glacial deposits in the south of the area had less time to develop and are thus less deep. These soils show medium to high eFC (90–200 mm) and moderate hydraulic conductivities (10–40 cm/day). Soils on sand and gravel are characterised by low to medium eFC (50–140 mm) and very high conductivity (>300 cm/day; LGRB Freiburg unpublished data, 1999).

Vulnerability Mapping

Overview

Two other methods of vulnerability mapping were applied in the test site before developing the PI method: Dickel, Sokol, Watzel and Weinzierl (1993, unpublished report) applied the German method (Hölting et al. 1995); Goldscheider, Klute, Surm and Hötzl (2000, unpublished report) applied EPIK (Doerfliger and Zwahlen 1998) and compared the two maps (Fig. 8). A brief description of the two methods is given in the section Overview on Existing Methods. None of the two methods produced completely consistent results. EPIK classifies all areas without visible karst features and sinking streams as "moderately vul-

Fig. 7 Hydrogeological cross section of the Danube–Aach system; the Engen area is a part of this (compare Fig. 5). *ox* Oxfordian; *ki* Kimmeridgian; *ti* Tithonian (modified after Schreiner 1992)



 DOI 10.1007/s10040-003-0291-3

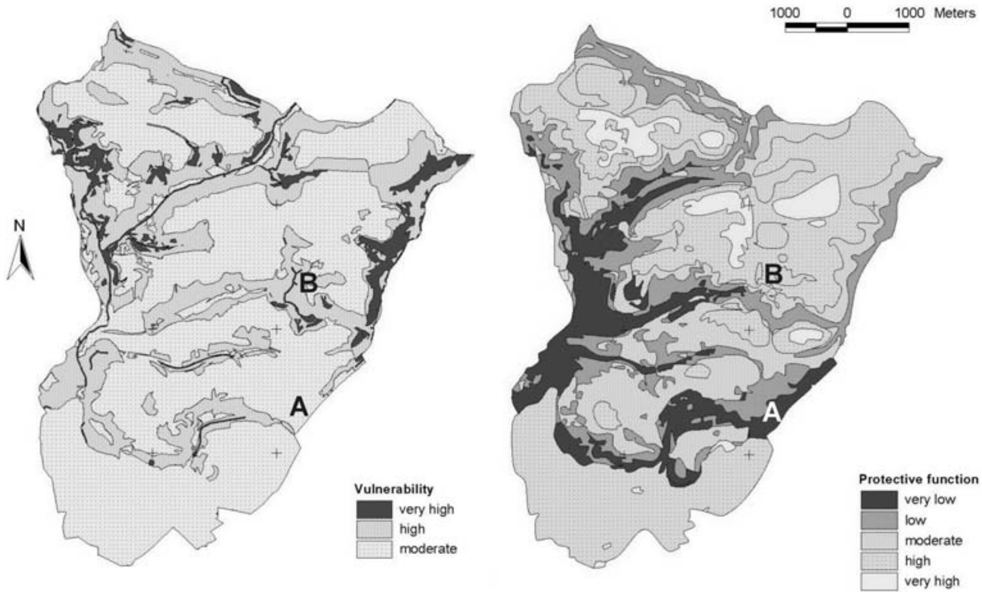


Fig. 8 Vulnerability maps for the Engen test site using EPIK (*left*) and the German method (*right*). The vulnerability assessment at points A and B is discussed in the section Comparison of the Maps and compared with the results obtained using the PI method (Fig. 9)

nerable" even when the karst aquifer is overlain by only shallow soils or highly permeable gravel. The German method always presumes diffuse recharge and subsequent vertical percolation. It consequently fails in areas made of low permeability formations, which generate surface runoff towards a sinking stream. This was the motivation to develop the PI method and compare it with the two other methods in the test site. Sturm (1999, unpublished diploma work) contributed to the mapping of the P factor, while Klute (2000, unpublished diploma work) worked on the I map. All maps were made using a GIS (ArcInfo and ArcView).

Determination of the P Factor

The P map shows the protective function of the layers overlying groundwater as a function of their thickness and properties (Fig. 9). As above mentioned, the P factor is assessed using a modified version of the German method. As this method had previously been applied in the test site, it was possible to use the existing data. Two significant changes were made:

– A decadic logarithmic classification was used. The P map consequently shows a more generalised distribution than the map made with the German method.
– In contrast to the German method, the new method always takes the uppermost relevant groundwater as the target. All areas with higher aquifers thus had to be re-evaluated: the four perched aquifers and the porous aquifer that overlies the karst aquifer in the southern lowlands. On the map made with the German method, this lowland is classified as an area of "high natural protection", due to artesian pressure in the karst aquifer. On the P map, it appears as an area of "low to moderate protection" as the porous aquifer is taken

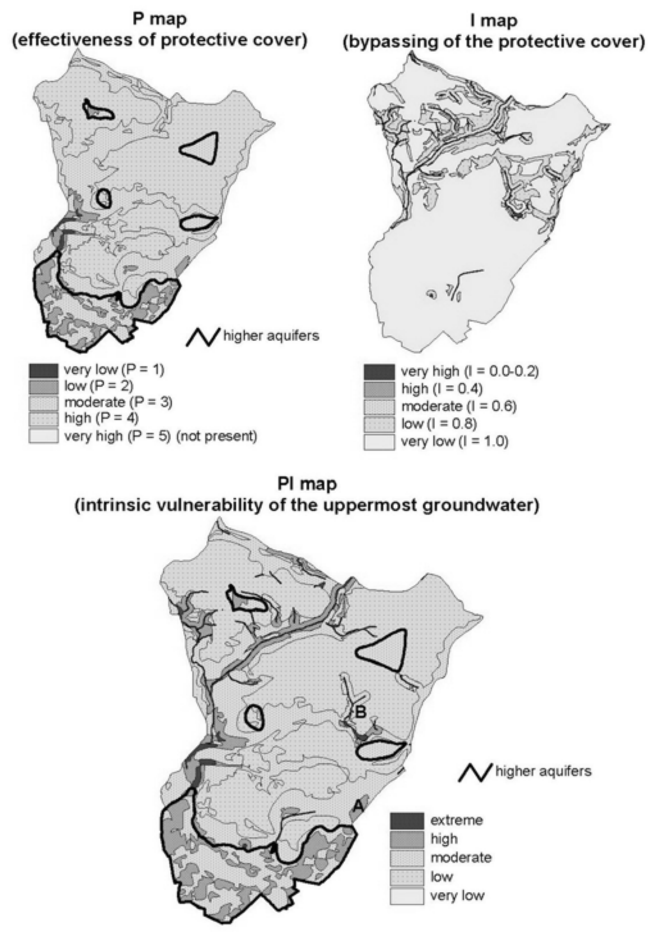


Fig. 9 The PI vulnerability map is made by overlying the P map and the I map. The vulnerability assessment at points *A* and *B* is discussed in the section Comparison of the Maps and compared with the results obtained using EPIK and the German method (see Fig. 8)

 DOI 10.1007/s10040-003-0291-3

as the target. Bold lines on the P map show the limits of the higher aquifers.

Determination of the I Factor

The I factor shows the degree to which the protective cover is bypassed by lateral surface and subsurface flow and subsequent concentrated recharge. The following three steps were carried out in order to determine the I factor and construct the I map, respectively:

- The topsoil properties decide on the dominant flow process. Surface flow predominates on low permeability soils ($K<10^{-6}$ m/s). Lateral subsurface flow takes place in permeable topsoils overlying low permeability layers. Infiltration and subsequent percolation predominates if low permeability layers are absent. A map (GIS coverage) showing the topsoil permeability was created. Another coverage shows the depth to low permeability layers inside or below the soil. The dominant flow process was determined by intersecting the two coverages using a GIS.
- Infiltration processes and runoff generation are also influenced by the slope gradient and vegetation. Gentle slopes and forests (natural forests and plantations) favour infiltration and percolation; steep slopes and agricultural land use favour runoff. The GIS coverage showing the dominant flow process was thus intersected with the coverages showing land use and vegetation. The resulting coverage is called I′ map. It shows the occurrence and intensity of lateral surface and subsurface flow.
- Lateral surface and subsurface flow may represent a risk to groundwater only if the water and possible contaminants enter the karst aquifer at another place in a concentrated way, e.g. via a sinking stream. Consequently, the I map (showing the degree to which the protective cover is bypassed) is obtained by intersecting the I′ map (showing the occurrence and intensity of lateral flow) with the so-called surface catchment map (showing the sinking streams and their catchments).

On the I map (Fig. 9), swallow holes, sinking streams and slopes that focus surface runoff towards these streams appear red (in this paper: dark grey), indicating that the protective cover, if present, will be completely bypassed in these zones. Areas that drain by diffuse infiltration and percolation appear blue (light grey), and also slopes that focus runoff towards a stream that leaves the area without sinking into the karst aquifer appear blue (light grey). In these areas, the protective cover is not bypassed.

The PI Vulnerability Map

The PI vulnerability map is obtained by overlying the P and the I map, and the protection factor π is calculated by multiplying the P and the I factor (Fig. 9). The range of possible values for π is subdivided in five classes of natural protection and vulnerability, respectively.

On the PI vulnerability map for the Engen area, most areas range between high and low vulnerability. Only the swallow holes, sinking streams and small parts of their catchments turn out to be extremely vulnerable. A high to moderate vulnerability was assigned to large parts of the valleys, the perched aquifers and the granular aquifer in the south. The elevated areas, which are covered by glacial deposits and Tertiary sediments, are characterised by low vulnerability. The class “very low vulnerability” is not present in the area.

Comparison of the Maps

Comparing the vulnerability maps that were created using the three different methods, it is noticeable that the valleys are always assessed to be more vulnerable than the adjacent hills and plateaus. However, there are different reasons for that common result: on the EPIK map, the valleys are vulnerable because they are classified as epikarst features and catchments of sinking streams. According to the German method, the valleys are vulnerable due to the reduced thickness of the protective cover. On the PI map, both the reduced thickness (P) and the concentrated infiltration (I) are considered.

In detail, there are significant differences between the three maps. On the EPIK map, areas outside the catchments of sinking streams and without visible karst features are always evaluated to be moderately vulnerable, even when the karst rock is only covered by shallow soils. According to the German method, the vulnerability of the same areas appears to be very high, as this method takes into account the thickness and properties of all layers. On the PI map, these areas are classified as highly vulnerable due to the modified assessment scheme for the P factor (compare point A in Figs. 8 and 9). The catchments of sinking streams, which are often formed by marl or clayey moraine, are classified as areas of high to extreme vulnerability according to the EPIK and PI method. The German method often classifies these catchments as zones of low vulnerability because this method does not consider the effect of lateral flow and point recharge (compare point B in Figs. 8 and 9).

Comparing the maps produced with the German and the PI method, there are two noticeable differences regarding the relative proportion of the vulnerability classes, mainly as a result of the different classification schemes for the protective cover: First, there are no areas of “very low vulnerability” on the PI map, which appears sensible for a karst system. Second, only small areas are classified to be extremely vulnerable, which makes it easier for the decision makers to delineate zones where maximum protection is required. Another difference between the two maps is that the PI map always shows the vulnerability of the uppermost aquifer, while the map produced with the German method always shows the vulnerability of the main karst aquifer. As a consequence, the southern lowlands are a zone of high to moderate groundwater vulnerability according to the PI method

 DOI 10.1007/s10040-003-0291-3

because the porous aquifer in that area is very slightly protected there.

Conclusions and Outlook

The PI method was first applied in the Engen area and later tested by various European research groups in many other sites. COST Action 620 proposes this method as a possibility to intrinsic vulnerability mapping of karst groundwater resources, particularly in areas where detailed data are available (Zwahlen 2003).

However, a vulnerability map is not a stand-alone element, but should be integrated into a comprehensive groundwater-protection scheme. COST Action 620 proposes such a scheme, comprising intrinsic and specific vulnerability mapping for both resource and source protection, validation techniques, and hazard and risk assessment (Zwahlen 2003).

For source vulnerability mapping, the horizontal groundwater flow in the aquifer has to be considered as an additional factor. A source vulnerability map can be obtained by putting together a resource vulnerability map and a map showing the flow towards a drinking water source. This approach is used in Ireland (DoELG/EPA/GSI 1999).

Intrinsic vulnerability maps do not take into account the specific properties of particular contaminants. However, if one group of contaminants is known to present the main risk for a given groundwater body, specific vulnerability maps should be produced and used, for example for pesticides, nitrates, bacteria or chlorinated organic hydrocarbons. Examples can be found in Zwahlen (2003).

COST Action 620 also stated the need to validate vulnerability maps and proposes different methods of how this could be done. Goldscheider et al. (2001) validated a source vulnerability map (EPIK) by spreading different tracers at the land surface (origin) and observing their breakthrough at a spring (target). The travel time, concentration and recovery rate of the tracers were used to validate the vulnerability map.

Hazards are potential sources of groundwater contamination, comprising point (e.g. septic tank), linear (roads, pipelines) and diffuse hazards (spreading of fertiliser and pesticides). COST 620 proposes to create risk maps by overlying vulnerability and hazard maps. The economic, social or ecological value of the groundwater body could be used as an additional criterion for risk assessment. A Committee on Valuing Ground Water (1997) worked out guidelines of how this could be done. The highest risk is present when a dangerous hazard is located in a highly vulnerable zone of a highly valuable groundwater resource that is used for drinking water supply. A risk map consequently shows the need for action.

Acknowledgement First of all, I want to thank Sebastian Sturm and Markus Klute for the very good cooperation; they contributed to vulnerability mapping with their excellent diploma works. I'm also grateful to the German Federal Institute of Geosciences and Natural Resources (BGR) for funding; the LGRB Freiburg for providing data and information; D. Daly, Prof. Dr D. Drew, Prof. Dr H. Hötzl, Dr M. von Hoyer, Dr B. Söfner, Prof. Dr F. Zwahlen and all other colleagues from COST Action 620 for valuable and inspiring discussions.

References

Aller L, Bennett T, Lehr JH, Petty RJ (1987) DRASTIC: a standardized system for evaluating ground water pollution potential using hydrogeological settings. US Environmental Protection Agency, Oklahoma

Batsche H, Bauer F, Behrens H, Buchtela K, Dombrowski HJ, Geisler R, Geyh MA, Hötzl H, Hribar F, Käss W, Mairhofer J, Maurin V, Moser H, Neumaier F, Schmitz J, Schnitzer WA, Schreiner A, Vogg H, Zötl J (1970) Kombinierte Karstwasseruntersuchungen im Gebiet der Donauversickerung (Baden-Württemberg) in den Jahren 1967–1969 [Combined karst water investigations in the area of the sinking Danube River (Baden–Württemberg) in the years 1967–1969]. Steir Beitr Hydrogeol 22:1–165

Civita M, De Maio M (2000) Valutazione e cartografia automatica della vulnerabilità degli acquiferi all'inquinamento con il systema parametrico SINTACS R5 [Evaluation and automatic cartography of aquifer vulnerability using the parametric system SINTACS R5]. Pitagora Editrice, Bologna

Committee on Valuing Ground Water (1997) Valuing ground water. economic concepts and approaches. National Academic Press, Washington, DC

COST 65 (1995) Hydrogeological aspects of groundwater protection in karstic areas, Final report (COST action 65). European Commission, Directorate-General XII Science, Research and Development, Report EUR 16547 EN, Brussels, 446 pp

Daly D, Dassargues A, Drew D, Dunne S, Goldscheider N, Neale S, Popescu IC, Zwahlen F (2002) Main concepts of the European approach for (karst) groundwater vulnerability assessment and mapping. Hydrogeol J 10:340–345

DoELG/EPA/GSI (1999) Groundwater protection schemes. Department of Environment and Local Government, Environmental Protection Agency and Geological Survey of Ireland, Dublin, 24 pp

Doerfliger N, Zwahlen F (1998) Practical guide, groundwater vulnerability mapping in karstic regions (EPIK). Swiss Agency for the Environment, Forests and Landscape (SAEFL), Bern, 56 pp

Drew D, Hötzl H (eds) (1999) Karst hydrogeology and human activities. Impacts, consequences and implications. Int Contrib Hydrogeol 20:322

DVGW (1995) Richtlinien für Trinkwasserschutzgebiete, I. Teil: Schutzgebiete für Grundwasser [Guidelines for drinking water protection zones, part I: protection zones for groundwater]. Deutscher Verein des Gas und Wasserfaches e.V., DVGW-Regelwerk, Arbeitsblatt W101:23

European Water Directive (2000) Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for community action in the field of water policy. European Commission, Brussels

Ford D, Williams DW (1989) Karst geomorphology and hydrology. Unwin Hyman, Boston, 601 pp

Foster SSD (1987) Fundamental concepts in aquifer vulnerability, pollution risk and protection strategy. In: Van Duijevenboden W, Van Waegeningh HG (eds) Vulnerability of soil and groundwater to pollutants, vol 38. TNO Committee on Hydrogeological Research, Proceedings and Information, The Hague, pp 69–86

Gogu RC, Dassargues A (2000) Current trends and future challenges in groundwater vulnerability assessment using overly and index methods. Environ Geol 39(6):549–559

Goldscheider N (2002) Hydrogeology and vulnerability of karst systems: examples from the Northern Alps and Swabian Alb. PhD Thesis, Schr Angew Geol Karlsruhe, Karlsruhe, 236 pp

 DOI 10.1007/s10040-003-0291-3

Goldscheider N, Klute M, Sturm S, Hötzl H (2000) The PI method: a GIS-based approach to mapping groundwater vulnerability with special consideration of karst aquifers. Z Angew Geol 463:157–166

Goldscheider N, Hötzl H, Fries W, Jordan P (2001) Validation of a vulnerability map (EPIK) with tracer tests. 7th Conference on Limestone Hydrology and Fissured Media, Besançon 20–22 September 2001. Sci Tech Environ Mém 13:167–170

GSchV (1998) Gewässerschutzverordnung vom 28. Oktober 1998 (GSchV, SR 814.201) [Swiss Water Protection Ordinance]. Swiss Federal Law, Bern

Hölting B, Haertle T, Hohberger KH, Nachtigall KH, Villinger E, Weinzierl W, Wrobel JP (1995) Konzept zur Ermittlung der Schutzfunktion der Grundwasserüberdeckung [Concept for the evaluation of the protective function of the layers overlying groundwater]. Geol Jahrb C63:5-24

Hötzl H (1973) Die Hydrogeologie und Hydrochemie des Einzugsgebietes der oberen Donau [Hydrogeology and hydrochemistry of the catchment area of the upper Danube River]. Steir Beitr Hydrogeol 25:5-102

Klimchouk AB, Ford DC, Palmer AN, Dreybrodt W (eds) (2000) Speleogenesis, evolution of karst aquifers. National Speleological Society, Inc., Huntsville, Alabama, 527 pp

Magiera P (2000) Methoden zur Abschätzung der Verschmutzungsempfindlichkeit des Grundwassers [Methods of assessing groundwater vulnerability]. Grundwasser 3:103–114

Margat J (1968) Vulnérabilité des nappes d'eau souterraine à la pollution {Vulnerability of groundwater to pollution]. BRGM-Publication 68 SGL 198 HYD, Orléans

ÖVGW (1995) Richtlinie W72: Schutz- und Schongebiete (Guideline W72: protection zones). Österreichische Vereinigung für das Gas- und Wasserfach, Wien, 45 pp

Schreiner A (1992) Erläuterungen zu Blatt Hegau und westlicher Bodensee. Geol Karte 1:50,000 Baden-Württemberg [Explanations to the geological map of the Hegau region and the Western Lake Constance]. Freiburg, Stuttgart, 290 pp

Schreiner A (1997) Erläuterungen zu Blatt 8118 Engen. Geol Karte 1:25,000 Baden-Württemberg [Explanations to the geological map of Engen]. Freiburg, 184 pp

Villinger E (1977) Über Potentialverteilung und Störungssysteme im Karstwasser der Schwäbischen Alb (Oberer Jura, SW-Deutschland) [Potentiometric distribution and fracture systems in the karst water of the Swabian Alb, Upper Jurassic, SW Germany]. Geol Jahrb C18:3–93

Vogelsang D, Villinger E (1987) Elektromagnetische und hydrogeologische Erkundung des Donau–Aach-Karstsystems (Schwäbische Alb) [Electromagnetic and hydrogeological investigation of the Danube–Aach karst system, Swabian Alb]. Geol Jahrb C49:3–33

Vrba J, Zaporozec A (eds) (1994) Guidebook on mapping groundwater vulnerability, vol 16. Int Contrib Hydrogeol, Hannover, 131 pp

Zwahlen F (ed) (2003) Vulnerability and risk mapping for the protection of carbonate (karst) aquifers, final report (COST action 620). European Commission, Directorate-General XII Science, Research and Development, Brussels 297 pp (in press)

 DOI 10.1007/s10040-003-0291-3