Time-input, an innovative groundwater-vulnerability assessment scheme: application to an alpine test site

M. Kralik · T. Keimel

Abstract The time-input method provides a new approach to evaluating groundwater vulnerability especially in mountainous areas. Its main factors are: (1) the travel time from the surface to groundwater (about 60%) enhanced by (2) the amount of input as groundwater recharge (about 40%). In contrast to other assessment schemes comparable to this method, the vulnerability is expressed in real time and not classified by dimensionless numbers with the advantage that the credibility of results is easier to check and the evaluation process is more transparent. The Index-Method was applied in a well-studied forested dolomitic karst area in the front range of the Austrian Northern Calcareous Alps. The aspect and the dip of the bedding planes towards or away from the groundwater have been included in this method. These are additional to the traditionally chosen investigation layers such as vegetation, slope inclination, thickness of soil, unconsolidated sediment and unsaturated rock, and fault zones.

Keywords Groundwater vulnerability · Karst · Travel time · Groundwater recharge · Austria

Received: 14 October 2002 / Accepted: 10 March 2003
Published online: 17 June 2003

M. Kralik (✉) · T. Keimel
Federal Environment Agency,
Spittelauer Laende 5, 1090 Vienna, Austria
E-mail: kralik@ubavie.gv.at
Tel.: +43-131304-3530
Fax: +43-131304-3700

M. Kralik
Geol. Dept., University of Vienna,
Althanstr. 14, 1090 Vienna, Austria

Present address: T. Keimel
Promalis Ltd., Storchengasse 1, 1150 Vienna, Austria

Introduction

Vulnerability assessments and maps are important tools for the protection of the ecological integrity of groundwater and its use as a drinking water resource. Concepts are based on the simple assumption that some areas are more vulnerable to groundwater contamination than others (Gogu and Dassargues 2000). Some recharge areas with a more rapid transfer from the surface to the groundwater and a higher input (recharge) are regarded as more vulnerable than areas with longer travel-times of groundwater and less input (intrinsic vulnerability). In other cases, a high input may be regarded as less vulnerable due to a greater dilution of the contaminants. Specific interaction of different contaminants with the topsoil, subsoil (sediment) and the unsaturated zone (specific vulnerability) has not been considered in this study. Several groundwater vulnerability assessment techniques (Drastic, Sintacs, Epik, European Approach, UBA-Berlin etc.) have been introduced during the last 15 years (Aller and others 1987; Civita and De Maio 1997; Doerfliger and Zwahlen 1998; Daly and others 2002; Heinkele and others 2002). However, the practical application of these assessment schemes in mountainous areas and the need to evaluate results by obvious criteria require many modifications.

The time-input method, tested in this study, provides a new approach to assess groundwater vulnerability especially in mountainous areas based on the aforementioned schemes. Its main factors are: (1) the travel time (*TIME*) from the surface to groundwater (about 60%) enhanced by (2) the amount of precipitation input as groundwater recharge (*INPUT*; about 40%). This weighting is somewhat empirical giving the travel-time a slightly higher importance than the groundwater recharge. In contrast to other assessment schemes vulnerability is based on physical time and input values instead of dimensionless numbers. Even these time values are not the exact mean travel-time to groundwater, but its relative numbers have the advantage, so that the credibility of results is easier to check and the evaluation process is more transparent.

The Index Method was tested and evaluated in the well-studied but geologically challenging dolomite karst area in the densely forested front range of the Austrian Northern Calcareous Alps (Reichraminger Hintergebirge) 50 km south of Linz. The total area of 5 km^2 was split into a fine grid of 20×20 m cells. The Austrian Integrated Monitoring

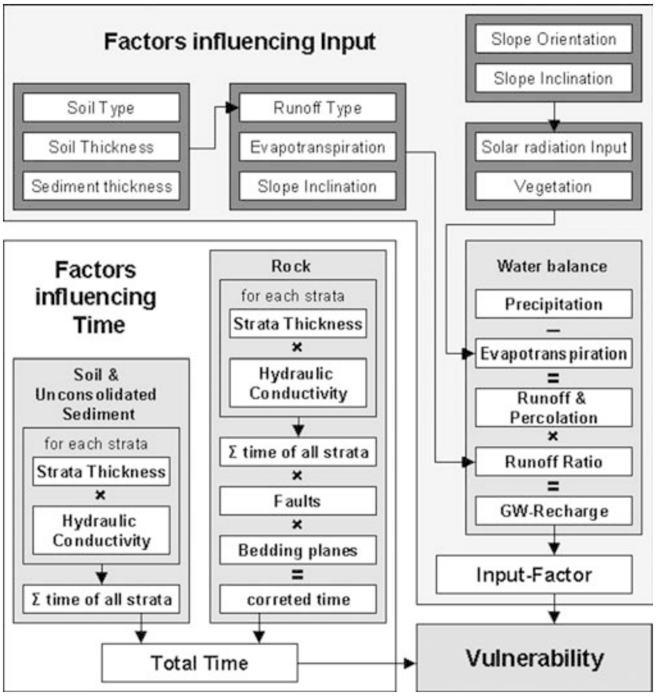


Fig. 1
Flow chart visualising the combination of vulnerability assessment data to the main assessment factors total travel time and input

test site (Zöbelboden ~1 km^2) is situated in the centre of this investigation area close to a small stream, where continuous input and output measurements are carried out.

Assessment scheme

The method is based on three main preconditions:

- For purely intrinsic vulnerability assessments, potential contaminants behave similarly to an ideal tracer and move more or less like the infiltrating water. Specific vulnerability assessments are based on intrinsic vulnerability data, but need further corrections for retardation and decay of specific contaminants. Specific vulnerability assessment is not discussed in this study.
- The main target of a vulnerability assessment is the surface of the uppermost groundwater body (resource protection). This includes a consistent investigation of the total recharge area. In contrast, for the protection of particular wells or springs (source protection), the distance to the source and the lateral movement in the saturated zone has to be considered.
- The "mean bad conditions" of a hydrological year are assessed preferentially. In this case, the mean hydrological conditions of periods with fairly rapid travel times and high inputs of water are investigated. Extreme events are not considered and would need a special assessment with little chance for actual evaluation in nature.

The fundamental data for groundwater vulnerability assessment are collected from existing geological, hydrogeological and soil maps, remote sensing data, aerial photographs, field measurements and field observations. All these data are usually stored in a computerised database.

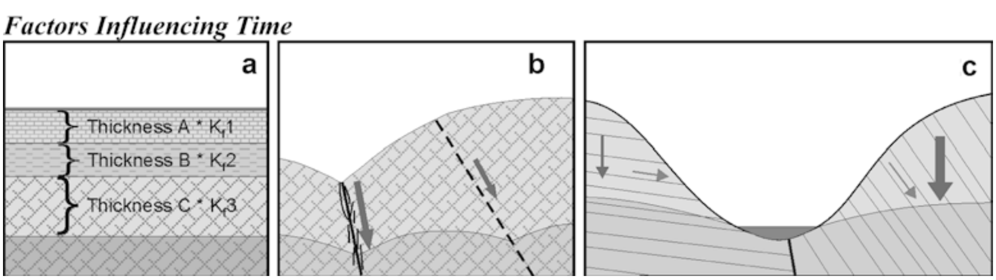
The two main factors, travel time and input, are combined by the simple equation:

$$Vulnerability = TIME[s] \times INPUT[f(mm)] \quad (1)$$

Vulnerability is mainly expressed as travel *time*-classes (measured in seconds [s]) modified by the *input* correction factor (f) based on groundwater recharge measured in millimetres per year [mm] (Fig. 1).

The basic data required to obtain the first main factor travel *TIME* (see Figs. 1 and 2a) are the thickness of each layer of the overlying unconsolidated deposits and the different bedrock strata. The unconsolidated deposits, often regarded as protective cover, include soil and subsoil, while the bedrock comprises non-carbonate rocks and the unsaturated zone in one or more carbonate formations (Daly and others 2002; Fig. 2a). The thickness of soils can be obtained from direct measurements, soil maps and interpolation from measurements of characteristic rounded hilltops, slopes and troughs. The thickness of the rocks and the overlying sediments is evaluated most accurately by boreholes and geophysical measurements, but usually must be estimated from geological maps. Information on faults and karstification has to be obtained by structural and karst morphology mapping (Fig. 2b). This can be significantly augmented by use of remote sensing and aerial photographs. For each stratum the mean hydraulic conductivity has to be estimated with sufficient resolution. In rock strata and particularly in

Fig. 2
a The sum of the hydraulic conductivity multiplied by the thickness of each strata results in the basic travel time. **b** Faults are often the most important factor influencing travel time. Different correction factors should be used for different types and sizes of faults. **c** In layered rock, the travel time is often influenced by bedding planes. Its significance depends on degree and type of inclination (towards runoff or towards groundwater)



bedded formations, the hydraulic conductivity will be much enhanced by faults, the inclination of bedding planes towards the groundwater and karstification features like swallow holes, karrenfields, etc. (Figs. 2b, c and 3d).
The main factor *INPUT* (groundwater recharge) is classified as a correction factor similar to factor W in the German vulnerability assessment scheme (Hölting and others 1995). Low recharge quantities have high correction factors thus increasing time, whereas high recharge quantities reduce time and therefore increase vulnerability. This main *INPUT* factor depends on the amount of precipitation, the solar radiation input, the slope inclination and aspect, the vegetation, the type and thickness of the soil as well as the catchment area (Fig. 3a–d). Correction factors need to be modified according to the climatic zone. The vulnerability is shown in modified time classes. The main factor travel *TIME* is corrected by the main *INPUT* factor (groundwater recharge). This has the advantage that the physical parameters *TIME* and *INPUT* can be evaluated separately.

Acquisition of assessment data

Geographical map and digital elevation model: The official Austrian geographical map 1:25,000 was enlarged to a scale of 1:5,000 and the investigation area of 5 km^2 provided with a grid of 20×20 m. This allows a reasonable resolution and is close to the limit of locating a position in an area, which is partly rugged mountainous terrain. The investigated area thus has about 13,700 cell units, a number, that can be easily handled with basic computer programs. The slope inclination and aspect of each cell unit were calculated from the Austrian digital elevation model with a resolution of 50×50 m.
Geological map: The geological 1:50,000 map of the Austrian Geological Survey and a detailed 1:10,000 (Leithner 1997; Keimel 1999) hydrogeological map of this area were used as geological background information. These also provided the basis to estimate the thickness of the layers and to delineate areas with the dip of bedding planes towards and away from the groundwater.
Aerial photographs: Digital coloured ortho-photographs (Amt der OÖ Landesregierung 1999) and older black and white aerial photographs were used for the distribution of vegetation and soil, and the location and direction of tectonic faults.
Field measurements: In addition to the aforementioned interpretation, six days of fieldwork were undertaken to obtain the necessary additional data. The soil types were identified and measurements were made of their thickness and the inclination and aspect of slopes were checked. Estimates also were made of the thickness of talus or scree from erosion trenches and checks were made of critical points in the geological mapping. Finally, additional structural observations and measurements were made. The soil type and thickness was obtained from the mean value of 8–10 penetration tests with a 3 cm diameter soil auger in each basic cell of 20×20 m. Usually, soil information was obtained by assigning typical morphologies such as, hilltops, plateaux, depressions, trenches, steep and gentle slopes and soil assemblages. This information was obtained from aerial photographs.
Morphological features such as slope inclination and aspect as well as structural parameters were checked and occasionally corrected by simple geological compass-measurements.

QA/QC of each step

The quality control of each step of data acquisition has to be carried out by standard procedures and field documentation (Csuros 1994). The source of the data: existing data and maps, data obtained from aerial photographs or model interpolation, as well as field and laboratory measurements require documentation in the vulnerability database. Similarly, all correction factors and vulnerability calculations must be transparent and reproducible by hydrogeologists and officials using the vulnerability assessment.

Calculating the intrinsic vulnerability

Travel *TIME*

The basic data to calculate the main factor travel *TIME* (see Fig. 1) are the thickness of each stratum of the unsaturated zone (Fig. 2a). The mean travel time by vertical infiltration in more or less homogeneous substrata can be calculated by dividing the thickness of the layers by their hydraulic conductivity (Table 1).
The soil thickness was obtained by direct measurements from characteristic rounded hilltops, slopes and troughs

Table 1
Assumed hydraulic conductivity of layers in the investigation area

	Layers	k-Values (m/s)
Soil	Rendzina	10^{-4}
	Cambisol	10^{-6}
Subsoil; sediment	Fine and medium gravel (talus, scree)	10^{-3}
Rock	Jurassic marls	10^{-6}
	Platten-Limestone	10^{-4}
	Haupt-Dolomite	5×10^{-5}

Table 2
Correction factors for tectonics

Classes	Structures	Correction factors
1	Major fault and deformation zones	20
2	Small fault zones	10

Table 3
Correction factors for bedding inclination

Classes	Inclination of bedding planes	Correction factors
1	0–5°	1
2	5–45° off the groundwater	0.5
3	5–45° towards groundwater	3
4	46–90°	4

and interpolation from aerial photographs. The K-values for the soil and the sediment (Table 1) are based on grain-size measurements. The thickness of the overlying sediments and the bedrock is estimated from geological maps with limited point data from boreholes and trenches. Information on faults and karstification was obtained by structural and karst morphology mapping. This has been considerably augmented by interpretation of structural elements from aerial photographs. For each stratum the mean hydraulic conductivity has to be estimated with sufficient resolution. In bedrock the hydraulic conductivity will be significantly enhanced by faults (Fig. 2b; Table 2), inclination of bedding planes towards the groundwater (Fig. 2c; Table 3) and karst features like swallow holes, karrenfelds, etc. (Fig. 3d). In these locations the mean hydraulic conductivity has to be adapted by an acceleration factor (Tables 2 and 3).

INPUT (groundwater recharge)

The quantitative input to the groundwater is expressed as groundwater recharge in mm/year. It is calculated by the simple water balance:

$$\begin{aligned} \textit{Ground water recharge} = \textit{Precipitation} &- \textit{Surface flow} \\ &- \textit{Inter flow} \\ &- \textit{Evapotranspiration} \end{aligned} \tag{2}$$

(Chow and others 1988).

Precipitation: In this investigation area of about 5 km^2 with a single rain-gauge, the mean precipitation value of recent years (1,700 mm/year) was assigned to each cell unit.

Runoff ratio: A differentiation has to be made between infiltration to the groundwater and the surface runoff or the surface near interflow, which leaves the investigation area via streams and rivers (Fig. 3d).

Soil type, soil thickness and slope inclination are the most important factors influencing the runoff ratio (Figs. 1 and 3c). The classification scheme using the hydraulic conductivity of soil and the depth to the uppermost impervious layer (Goldscheider and others 2000) offers a pragmatic solution (Table 4). To integrate this complex

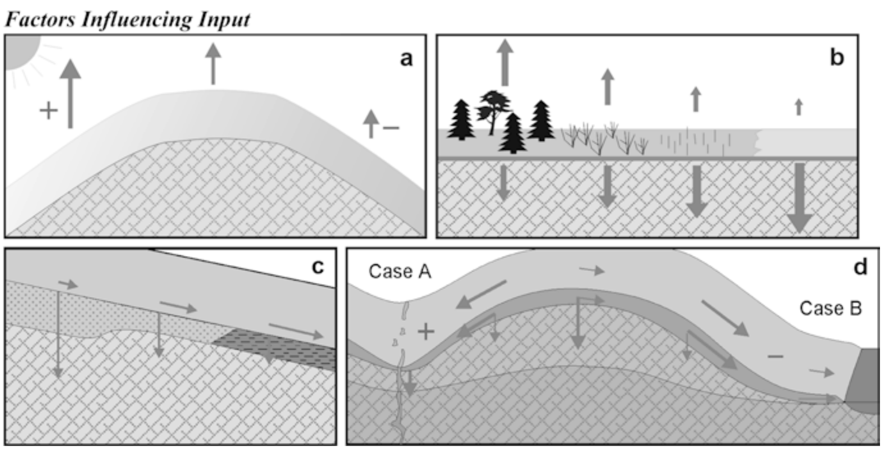


Fig. 3
a Influence of solar radiation-input (determined by slope inclination and slope orientation) on evapotranspiration. **b** Influence of vegetation type on evapotranspiration. **c** Soil thickness and soil type and influencing the ratio between runoff and infiltration. **d** Dependence of slope inclination and catchment area on runoff ratio (surface runoff and interflow vs. infiltration): *case A* sinking stream—accumulation of runoff to groundwater recharge; *case B* surface water—no accumulation of runoff to groundwater recharge

Table 4
Predominant flow processes as function of saturated hydraulic conductivity and soil properties (modified according Goldscheider and others 2000)

Hydraulic conductivity (m/s)	$>10^{-4}$	Type D: frequently saturated overland flow		Type C: very fast subsurface storm flow	Type A: infiltration and subsequent percolation
	10^{-4}–10^{-5}			Type B: fast subsurface storm flow	
	10^{-5}–10^{-6}	Type E: Hortonian surface flow rarely (during heavy rainfall only)			
	$<10^{-6}$	Type F: Hortonian surface flow frequently (also during low intensity precipitation)			
		<30 cm	30–100 cm Depth to low permeable layer (cm)		>100 cm

Table 5
Correction factors for obtaining the amount of infiltration caused by the dominant flow process, the vegetation and the slope inclination (modified after Goldscheider and others 2000)

Dominant flow process	<5° Slope inclination		5–30° Slope inclination		>30° slope inclination	
	Forest	Other vegetation	Forest	Other vegetation	Forest	Other vegetation
Type A	1.0	1.0	1.0	1.0	1.0	0.8
Type B	1.0	1.0	0.8	0.6	0.6	0.4
Type C	1.0	1.0	0.6	0.4	0.4	0.2
Type D	0.8	0.6	0.6	0.4	0.4	0.2
Type E	1.0	0.8	0.6	0.4	0.4	0.2
Type F	0.8	0.6	0.4	0.2	0.2	0

relationship a table of runoff correction-factors linked to infiltration type (A–F: Goldscheider and others 2000), slope inclination (<5°, 5–30°, >30°) and the three vegetation types (see evapotranspiration) has to be prepared (Table 5).
Evapotranspiration depends on slope aspect as well as inclination due to the time and angle of solar radiation (Figs. 1 and 3a). Dyck and Peschke (1995) demonstrated that in mountainous areas evapotranspiration rate can vary up to 100% depending on a sunny or shaded aspect (Fig. 3a and Table 6).
Vegetation types (forest, scrub and grassland, bare rock) investigated in an area close to the test site (Katzensteiner 1999) showed a significant impact on the evapotranspiration rate, which are reflected by the use of adequate correction factors (Figs.1 and 3b). The percentage of mean evapotranspiration decreases from 35% and 23% to 7% (Table 7). Therefore, vegetation can be simplified into three classes as forest, scrub and grassland, as well as bare rock. The two main factors travel time and input are combined by the previously mentioned Eq. (1).
An example of this intrinsic vulnerability assessment scheme in a forested mountain area is shown in Fig. 4. It indicates that fault zones and the lowest parts of slopes closest to the groundwater are the most sensitive areas for groundwater contamination. Most springs emerge in the latter area.

Table 6
Assessment of actual evapotranspiration (ET) according to vegetation in % of the annual precipitation (modified from Katzensteiner 1999)

No.	Vegetation	ET (%)
1	Forests (3.1)*	35
2	Scrub and grassland (3.2)[a]	23
3	Bare rock (3.3.2)*	7

[a]Land-use classes according to Corin Landcover (European Communities 1989)

Evaluation of main factors

The main advantage of this vulnerability assessment scheme with real physical values of time and input is that the evaluation of its main factors can be undertaken using different techniques. Such techniques include investigations of the discharge and dynamics (hydrographs) of springs or wells, analysis of isotope or natural tracers, water balance calculations, tracer experiments and model calculations. The simple basic concept of the Time-Input Method makes it very flexible for use in areas with different hydrogeological settings, data sources and scales.
Discharge and chemograph analysis of springs: discharge, temperature, electrical conductivity, pH and major ions were measured periodically at twenty springs and surface waters (small sub-catchments). These data were combined with measurements of a main on-line station with a weekly sampling for chemistry. This allows the identification of sub-catchments with an excess or a deficit of the nominal discharge. Likewise, those sub-catchments may be identified with highly variable water composition and rapid travel-times of at least part of the water input (Pinault and others 2001; Kralik 2001).
The significant lower surface runoff of the southern sub-catchments reflects the importance of the higher evapotranspiration due to greater solar radiation input. Excess discharge from the southeastern and eastern springs and surface runoff from their sub-catchments indicate rapid groundwater transport from the plateau area and the north-facing catchment areas along tectonic fault zones. Springs at higher altitudes (700–800 m) are very dynamic (high relative standard deviations) in water temperature and conductivity. These southeastern and eastern springs show a medium response after storms, whereas the northern springs close to the receiving stream are very constant.

Table 7
Correction factors of sun radiation input (α) derived from catchment slope inclination and orientation (modified according Dyck and Peschke 1995)

Slope inclination	Slope orientation				
	N	NE and NW	E and W	SE and SW	S
0–5°	0.97	0.98	1	1.01	1.02
6–10°	0.92	0.94	1.01	1.04	1.08
11–20°	0.85	0.89	1.03	1.12	1.19
21–30°	0.77	0.83	1.08	1.25	1.35
31–45°	0.7	0.8	1.17	1.43	1.58
>45°	0.65	0.78	1.25	1.55	1.75

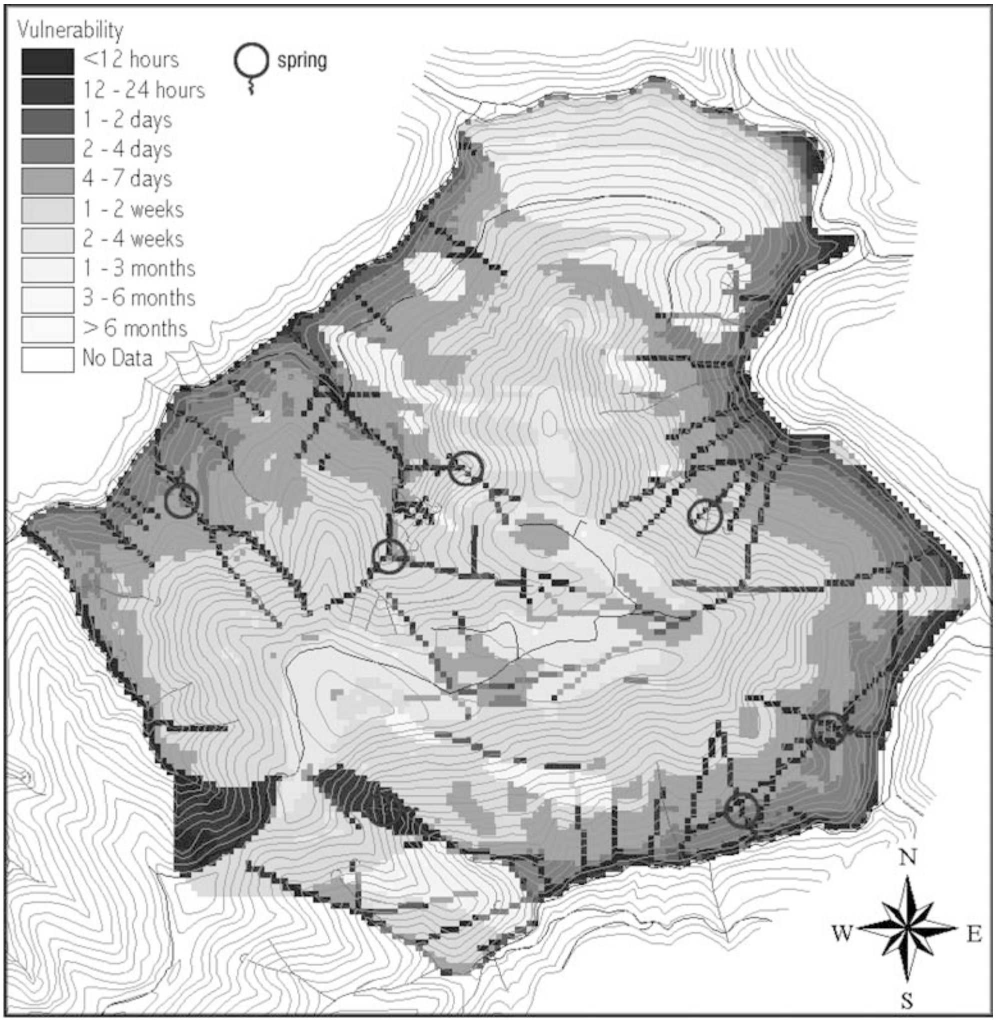


Fig. 4
Example of an intrinsic vulnerability assessment map in a forested dolomite karst area in the front range of the Austrian Northern Calcareous Alps (Reichraminger Hintergebirge) 50 km south of Linz. The total area of 5 km^2 was split into a fine grid of 20×20 m cells .The results indicate the high vulnerability of fault zones and the area close to the creeks

O-18, Deuterium and Tritium model evaluation: Oxygen-18, deuterium and tritium model calculations indicate mean residence times of some weeks in agreement with the vulnerability assessment. Only the northern spring waters have ages of several months.

Natural tracers and tracer experiments: Four tracer experiments on top of the plateau close to the fault zones and karstification structures (removed soil covers) indicate a short residence time of 1–2 days as determined by the time-input-method during and after heavy rainfall (Haseke 2000).

Model calculation: Up to now, only basic balance models have been used. However, more sophisticated models could help to validate and improve the vulnerability assessment.

Discussion

The time-input-method presented in this study is intended for use as a quick and practical procedure at different scales. It can be used for detailed studies in small areas like environmental impact assessments or larger areas or groundwater bodies as required in the European Water Framework Directive (Directive 2000/60/EC). The limiting factor is the availability of basic data. A minimum amount of basic information is necessary to warrant confidence in the vulnerability assessment. The method has been tested in a relatively complicated mountainous dolomite karst area, but can also be applied with minor modifications to porous aquifers. Several critical aspects have to be considered to obtain good quality controlled data in a relatively short time:

Factors influencing travel time (retention time of the infiltrating water): The main uncertainties are related to the estimation of the thickness and the assigned hydraulic conductivities of the unsaturated zones due to a lack of boreholes (only a single site). However, due to spring discharges at different altitudes, the thickness of the unsaturated zone can be estimated with acceptable levels of error.

In this strongly tectonized bedded dolomite formation some fault zones seem to be responsible for rapid travel-time to groundwater as demonstrated by tracer tests. Only detailed hydrogeological field observations and structural analysis supported by aerial photographs make it possible to analyze these important fault zones. The correction

Table 8
Attribution of total bulk infiltration (travel times) to time classes

Time classes	Time intervals	Bulk infiltration times (s)
1	<12 h	<43,200
2	12–24 h	43,200–86,400
3	1–2 days	86,400–172,800
4	2–4 days	172,800–345,600
5	4–7 days	345,600–604,800
6	1–2 weeks	604,800–1,209,600
7	2 weeks–1 month	1,209,600–2,592,000
8	1–3 month	2,592,000–7,776,000
9	3–6 month	7,776,000–15,552,000
10	>6 month	>15,552,000

factors chosen for faults (Table 2) and inclination of bedding planes (Table 3) expressing the acceleration of travel time and the efficiency of transport to the groundwater are at the present stage somewhat arbitrarily, but future research on this topic at different geological environments will improve these factors.

The classification of the travel-time of infiltration from the land surface to the groundwater surface into ten classes certainly indicates tendencies rather than accurate estimates. It could also be grouped into three vulnerability classes: high (travel times 1–4 days), medium (1–4 weeks) and low vulnerability (>months) during or after a series of major rainfall events (Fig. 4; Table 8).

Factors influencing input (groundwater recharge): The 50×50 m resolution of the Austrian digital elevation model can smooth out morphological structures. Therefore, in areas of steep rock slopes and steep trenches based on aerial photographs, iso-lines of topographical maps and control measurements should be used to correct the slope inclinations. Water accumulating morphological structures like trenches and small depressions are important for vulnerability assessments, and are obtained with the aid of aerial photographs and field observations. In karst areas, karst-morphological mapping is essential.

Seasonal variation of the water saturation of soils or desiccation cracks in clay-rich soils cannot be considered. Only the mean infiltration conditions based on one hydrological year can be assessed in a seasonally independent vulnerability map.

Dyck and Peschke (1995) showed that in mountainous areas with the same vegetation type, the evapotranspiration rate can vary up to 100% depending on a sunny or shaded aspect. This is confirmed by considerably lower discharge in all springs and surface runoff on the southern slope of the dolomite massif.

Particular attention needs to be given to the common situation where runoff or interflow (runoff close to the surface) contributes nearly quantitatively to the groundwater through swallow holes or faults bypassing overlying protective layers or leaves the recharge area mainly by surface flow through rivers and tributaries (Fig. 3d). Because extensive karst features are absent in this dolomitic test area, a bypassing factor as in the European Method (Daly and others 2002) is not used in this study (Fig. 1), but the time-input scheme can be easily adapted to this case.

Table 9
Correction factors for the Input (groundwater recharge by the amount of infiltrating waters)

GW-recharge by infiltrating waters	Correction factor Q
0–200 mm	1.5
200–400 mm	1.25
400–600 mm	1.0
600–800 mm	0.75
800–1,000 mm	0.5
>1,000 mm	0.25

The assumption that high input is more vulnerable than low input is based on the premise that higher recharge will more likely wash down larger quantities of contaminants to the groundwater (Table 9). In other cases the correction factors must also be modified but in the opposite direction, for example, when high input significantly dilutes a quantitatively limited contaminant below the regulatory limit or toxicity values.

To extend these intrinsic vulnerability investigations to *specific vulnerability,* often clay minerals, organic matter and carbonate content have to be estimated in the field or measured in the laboratory for each stratum.

As a second step after the groundwater recharge assessment, a minimum evaluation of the two physical key factors of (1) travel *TIME* as well as (2) *INPUT* (recharge) has to be performed. They can be very basic or include very time-consuming investigations. Like in an iterative process they will modify and improve the correction factors. Hydrology and hydrogeology offer various methods to verify these physical parameters independently.

Conclusions

Even the modified time classes for expressing the degree of vulnerability and the input (groundwater recharge) classes, need some adaptation for different hydrogeological environments. The method has universal practical application in porous as well as in complicated fractured and karstified groundwater bodies. The method can be widely applied, is quality assured and transparent. It can be used for an initial and further characterisation of groundwater bodies in the sense of the European Water Framework Directive. The initial characterisation will be based mainly on available digital land use data (Corine landcover; European Communities 1989), soil and hydrogeological maps. Further characterisation of groundwater bodies and detailed studies (e.g. environmental impact assessments) will need a much higher quality and amount of basic data. The scheme will stimulate further research in evaluation tools in intrinsic vulnerability and even more so in specific vulnerability (not discussed in this study).

Acknowledgements The authors are grateful to all colleagues, participants of the COST 620 Action on "vulnerability and risk mapping for the protection of carbonate (karst) aquifers" for the useful discussion they had around a draft version of this paper.

Particular thanks to Dr. Robert Aldwell, Irish Geological Survey for English language corrections. We would like to thank the Environment Agency for financial support and M. Mirtl for providing background data of the investigation area.

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