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Characterization of groundwater vulnerability to fulfill requirements of the water framework directive of the European Union

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RESUMEN

La valoración de la vulnerabilidad acuífera es una base importante para satisfacer las demandas de la directiva marco agua de la Unión Europea. Para la determinación de la vulnerabilidad acuífera diferentes métodos han sido usados. En este trabajo la vulnerabilidad intrínseca de los recursos acuíferos es definida como el peor caso de contaminación en la zona no saturada sin interacción o decaimiento de la sustancia contaminante en su camino hacia el agua subterránea. Puede ser evaluada por el tiempo de transito del agua infiltrante desde la superficie hasta el nivel de saturación. Para evaluar la vulnerabilidad de acuerdo con esta definición, se presenta un método basado en un modelo analítico simple, el cual determina el tiempo de retención del agua infiltrante en la zona vadosa. El cálculo del tiempo de retención está basado en características litológicas de la zona vadosa y la recarga. El método tiene la ventaja que la cantidad de datos de entrada pueden ser derivados de mapas disponibles y puede ser manejado por un SIG.

PALABRAS CLAVE: Vulnerabilidad acuífera, Unión Europea.

ABSTRACT

Aquifer vulnerability assessment is an important basis in order to fulfill demands of the water framework directive of the European Union. For the determination of the groundwater vulnerability different methods can be used. In this paper, the intrinsic vulnerability of groundwater resources is defined as the worst case of a pollution input in the unsaturated zone without interaction or decay of the contamination substance on its way to groundwater table. It can be assessed by the transit time of the percolating water from surface to the groundwater table. To asses the groundwater vulnerability according to this definition, a method based on a simple analytic model which determines the retention time of the percolating water in the unsaturated zone is presented. The computation of the retention time is based on lithological characteristics of the vadose zone and on the groundwater recharge rate. The method has the advantage that the necessary input data can to be derived from available maps and can be handled by a GIS.

KEY WORDS: Groundwater vulnerability, European Union.

1. BACKGROUND AND DEFINITIONS

The Water Framework Directive of the European Union, EU, requires according to article 5 a characterization of the river catchment areas, in particular a description, in order to judge, "to what extent the groundwater bodies are used and the risk is as high that they do not fulfill the targets for each individual groundwater body in accordance with article 4 (environmental targets)". (E U, 2000, pp 10-11). In this context, the characterization of the groundwater vulnerability plays an important role.

In the water laws of the most European countries (for example the German Water Balance Law, WHG 1996) groundwater is considered to be a natural resource, which must be protected and activities endangering its quality are forbidden (Goldscheider 2002). Hötzl (1996) divided the subject into two sections, first the protection of the groundwater resource and second, the protection of the sources of groundwater use. Following this concept, the European COST Action 620 on "vulnerability and risk mapping for the protection of carbonate (karst) aquifers" suggested that the concepts for characterizing groundwater vulnerability should be based on an origin–pathway–target model (Figure 1) (Goldscheider *et al.*, 2000)

This suggests that the groundwater surface is the target in vulnerability assessments of groundwater resources and that the assessment should be based on the properties of first, the pathway from the surface to the groundwater level and second, the properties of the origin of the potential contamination. In the context of this concept, we propose that the vulnerability of groundwater resources can be defined as the probability that a certain proportion of a pollutant can reach the groundwater table within a particular time.

Vrba and Zaporozec (1994) first distinguished between intrinsic and specific vulnerability, where the intrinsic vul-

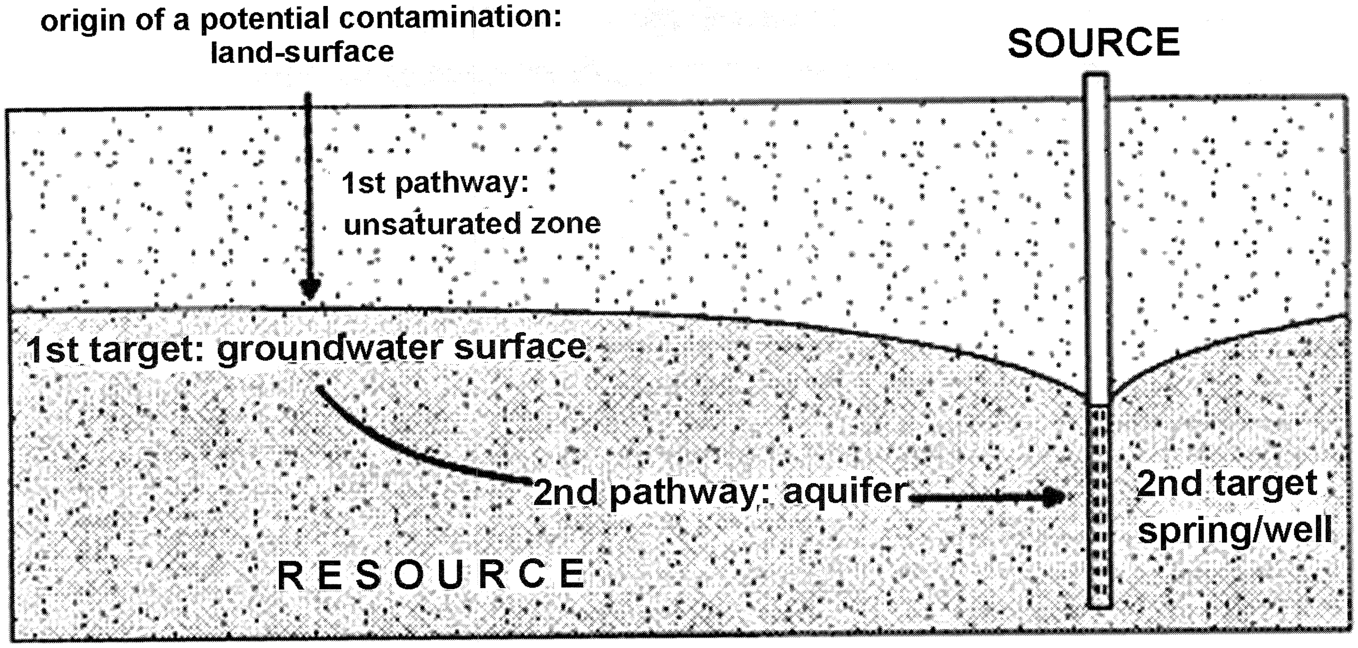

Fig. 1. The origin-pathway-target model for vulnerability assessment (Goldscheider *et al.,* 2000).

nerability characterizes a relative, non-measurable, dimensionless property of the groundwater cover, determined by its thickness, the lithologic properties of the vadose zone, the aquifer properties and the recharge. Specific vulnerability characterizes the vulnerability of groundwater to certain pollutants and takes into account land use practices. COST 620 suggests the following definitions (Goldscheider 2002):

- Intrinsic vulnerability of groundwater to contaminants takes into account the geological, hydrological and 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 in addition to the intrinsic vulnerability of the area.

The definitions of the COST working group do not include the possibility of a quantitative assessment of the two types of vulnerability and also do not discuss the "immeasurability" (Vrba and Zaporozec 1994) of groundwater vulnerability. Following our definition of the vulnerability of groundwater resources given above, we understand the intrinsic vulnerability of groundwater resources as the worst case of a pollution input in the unsaturated zone without interaction or decay of the contamination substance on its way to the groundwater table, which can be assessed by the transit time of the infiltration water from the surface to the groundwater table.

Accordingly, the specific vulnerability of groundwater resources can be assessed by the time of breakthrough of a certain contaminant or a group of contaminants to the groundwater table.

2. EXISTING METHODS OF MAPPING VULNERABILITY

The first vulnerability map at a scale of 1:1 million was prepared in France by Margat (1968). In Germany, Vierhuff *et al.* (1981) made a vulnerability map of the former Federal Republic of Germany before reunification in the same scale. For the whole territory of the former GDR, a complex of hydrogeological maps at scale 1:50000 (HK 50) was prepared from 1980 to 1985, which also included a map of groundwater endangerment (Voigt, 1987).

The current international practices in mapping groundwater vulnerability have been reviewed by Vrba and Zaprozec (1994), Magiera (2000), Goldscheider (2002), Heinkele *et al.* (2002) and others. Goldscheider (2002) identified and characterized them according to five groups of methods: 1-Hydrogeologic complex and setting methods, 2-Index methods and analogical relations, 3-Parametric system methods, 4-Mathematical methods and 5-Statistical methods.

Vrba and Zaprozec (1994) and Magiera (2000) have reviewed the use of the different groups of methods, and based on their compiliation we can conclude that the parametric system methods are most common today. Examples of this group of methods are the point count system DRASTIC (Aller *et al.*, 1987), the rating system GOD (Foster, 1987) and the EPIK method (Dörflieger 1996). In Germany, the State Geological Survey of the Federal States developed a point count rating system referred named "SGD-method" (Hölting *et al.*, 1995) which compares well with the DRASTIC method. To assess the overall protective effectiveness, values for the following parameters are required:

S - Available Water Capacity (AWC) of the soil (each AWC class assigned a different rating down to 1 m depth, the average plant root depth),
W - Percolation rate factor,
R - Rock type factor,
T - Thickness of rock cover above the groundwater table,
Q - Bonus points for perched aquifer systems (500 points),
HP- Bonus points for hydraulic (artesian) pressure conditions (1500 points).

The parameterization of points and factors according to soil properties, percolation rate and rock type structure is given in Tables 1 – 3.

The available water capacity (AWC) is the amount of water retained in the soil reservoir that can be used by plants. It is the difference in the soil water content between field capacity (FC) and permanent wilting point (PWP, water content at 1500 kpa pressure). The available water capacity [mm/dm] is determined for each individual soil horizon or is derived from the soil textural class. The AWC is then multiplied by the thickness of the horizon in decimeters [dm]. The rooting depth is assumed to be at 10 dm. The total available water capacity of a soil (ΣAWC) is obtained by addition of the available water capacity values calculated for each horizon down to 1 m depth.

The assessment of points according to the rock type in case of unconsolidated materials is mainly based on the grain size distribution. Examples are given in Table 3.

The **overall protective effectiveness** (P_T) is calculated using the following formula:

$$P_T = P_1 + P_2 + Q + HP$$

with $P_1 = S * W$ and $P_2 = W * (R_1 * T_1 + R_2 * T_2 + \ldots +$, where P_1 is the protective effectiveness of the soil cover to a 1m depth and P_2 is the protective effectiveness of the rock cover in the unsaturated zone without the soil cover.

The points are summarized into five classes of "overall protective effectiveness" of the soil and rock cover. These classes are correlated to approximate retention time ranges (Table 4).

Table 1

Assessment of soils on the basis of Available Water Capacity (AWC)

Σ AWC(mm/dm)	S (number of points)
< 50	10
> 50 - 90	50
> 90 – 140	125
> 140 – 200	250
> 200 - 250	500
> 250	750

Table 2

Percolation rates and the corresponding factor (W), based on the actual groundwater recharge (GWR)

Groundwater Recharge (GWR) (mm/a)	factor W
< 100	1.75
> 100 – 200	1.50
> 200 – 300	1.25
> 300 – 400	1.00
> 400	0.75

Table 3

Assessment of unconsolidated rocks (examples)

Grain size class	R = No. of points per meter thickness
clay	500
clay loam	300
clayey silt loam	240
sandy loam	180
sandy silt	120
loamy sand	90
slightly loamy sand	60
sand	25
gravel, gravel and breccia	5

3. THE BTU–METHOD TO ASSESS INTRINSIC VULNERABILITY OF GROUNDWATER RESOURCES

In order to characterize the intrinsic vulnerability of a groundwater resource according the definition given in sec-

Table 4

Classes of overall protective effectiveness of the soil and rock cover and corresponding residence time of percolating water in the unsaturated zone (Hölting *et al.,* 1995).

Overall protective effectiveness	Total number of points	Approximate retention time in the unsaturated zone
very high	> 4000	> 25 years
high	> 2000 – 4000	10- 25 years
moderate	> 1000 – 2000	3–10 years
low	> 500 – 1000	several months to about 3 years
very low	≤ 500	few days to about one year, in karstic rock often less

tion 1, a method for the assessment of vulnerability of porous media aquifers was developed in a joint project of the German Federal Environmental Agency (UBA) and the Chair of Environmental Geology of Brandenburg University of Technology (BTU). This method fulfils the following two conditions:

- Duties of reporting to the European Union must be guaranteed,
- Different hydrogeological databases in the various States of Germany must be considered.

Initially, the availability of geoscientific data needed to assess the groundwater vulnerability was analyzed in the different Federal States of Germany. We found that the completeness of the data base available to assess groundwater vulnerability in the Federal States of Germany is quite variable. Only the soil and geological maps (both at a scale of 1.200,000) of the Federal Institute for Geosciences and Natural Resources (BGR) give a common data base and comparable information which could be used to assess the vulnerability over all of Germany. Both maps are at least partly availably digitally.

Following our definition of the intrinsic vulnerability of groundwater resources given above, the vulnerability has to be characterized by the transit (retention) time of the infiltration water through the vadose zone based on an analytical model. This approach differs from the point count rating system of the "SGD"-method as it does not calculate retention times, but instead correlates five classes of "overall protective effectiveness" to approximate retention time ranges (see Table 4).

The assessment of the retention time using the BTU method takes into consideration the German Standard "DIN19732"–Bestimmung des standörtlichen Verlagerungspotentials von nicht sorbierbaren Stoffen (1997) ("Soil quality – Determination of the site specific potential for infiltration of not sorbable substances"). The retention time of infiltration water is calculated by the following formula:

$t_s = T / v_s$, or
$t_s = \Sigma T_i * FC_i / GWR = (T_1*FC_1+T_2 2*FC_2+\ldots+T_n*FC_n) / GWR$,

where

v_s=GWR/FC-transport velocity of infiltration water ($dm*a^{-1}$)
GWR – rate of groundwater recharge, ($mm*a^{-1}$)
FC_i - field capacity of the n-th soil- or substrate-layer of the aeration zone ($mm*dm^{-1}$)
T, T_i - thickness of entire unsaturated zone or of the n-th layer of it (dm).

Qualitative statements are met to the vulnerability of groundwater bodies in a catchment area, before assessing the intrinsic vulnerability by calculating the retention time of the percolating water in the unsaturated zone. These are based on the so-called "geohydraulic structure position". We distinguish three geohydraulic structure positions, 1:

- discharge areas, 2:
- areas with reduced groundwater recharge and 3:
- areas without usable groundwater supply.

Discharge areas are distinguished according to the occurrence of hydromorphic (gleyic) soil types which display a groundwater table at less than 2 m. Areas without usable groundwater supply are defined on the basis of hydrogeological maps. The remaining areas are separated according to the occurrence of sandy or loamy surface layers into areas of groundwater recharge (sandy surface layers) or into areas with reduced groundwater recharge or transition areas (loamy surface layers).

Discharge areas are generally characterized by very shallow groundwater tables. The unsaturated zone in discharge areas is generally less than 2 m thick. With regard to protection of groundwater from the input of contaminants into the groundwater, the thin unsaturated zone of less than 2 m thickness has a very limited protective function. Due to the facts that groundwater discharge areas are commonly hydraulically connected to surface waters with dominant upward and limited lateral flow, the effects of contaminant input can be quite limited. Discharge areas represent groundwater bodies which can directly be connected to surface water ecosystems and therefore are considered as particularly sensitive to interaction processes between surface waters and groundwater. Areas without usable groundwater supply do not need to be evaluated with regard to groundwater vulnerability in detail, since they do not indicate relevant groundwater supply due to the hydrogeological rock characteristics of the groundwater body.

Areas of groundwater recharge and of reduced groundwater recharge are to be indicated basically as vulnerable because in these areas the transport of contaminants with the infiltrating water into the groundwater can take place. In these areas, the German Standard "DIN 19732" is applied to assess the retention time of the infiltrating water in the vadose zone.

The necessary input data of the field capacity (FC) and the thickness of the vadose zone can be taken over or derived from the above mentioned geoscientific maps by GIS operations. Some examples of the FC values according to the parameters of grain size class for soils or lithologic units of the unsaturated zone according to the German Soil Survey Manual (Ad hoc-Arbeitsgruppe Boden, 1994) are given in Table 5. The FC is defined as the quantity of water, which a soil can hold back against the force of gravity.

The thickness of the groundwater cover under unconfined conditions is the difference between the land surface and the groundwater table and under confined conditions is the difference between the land surface and the bottom of the aquifer's overlying aquiclude or aquitard.

FC data are derived from soil maps for the upper 2 m of the vadose zone and from lithological information given by geological maps for the deeper unsaturated zone. In areas of thin groundwater cover which does not exceed 2 or 3 meters, FC data derived from soil and geological maps are reliable. With increasing thickness of the unsaturated zone, FC data derived from geological maps are less reliable. Lithologic information from geological maps in most cases does not consider the vertical heterogeneity in the vadose zone lithology. In order to get more specific information of the lithology of the deeper unsaturated zone, e.g. vertical homogeneity or heterogeneity, borehole information has to be assessed. An example is given in Figure 2. This example displays a typical situation which was found in the state of Hamburg. Till of the second last glacial period extends considerably over this state. According to the soil and the geological maps, the grain size class of this glacial till is silt loam. According to Table 2, silt loam's field capacity is 33 mm*dm^{-1}. Groundwater cover field capacity is calculated by multiplying the silt loam FC by the thickness of the groundwater cover, In the case of a 20 to 25 m deep groundwater table, the total FC of the unsaturated zone as derived from the information of soil maps and geological maps is about 8000 mm. (see Figure 2). In order to validate the data derived from maps, the borehole data, which identify the vertical heterogeneity of the lithologic classes within the groundwater cover, were assessed. About 1500 boreholes were investigated over the area where the geological unit "glacial till, silt loam" occurs. The FC capacity of the layers in each borehole was calculated according to thickness and particle size class. Finally,

Table 5

Examples of the assessment of field capacity of selected grain size classes
(German Soil Survey Manual, 4th edition, 1994)

Sand grain size class	Field capacity (FC mm*dm-1)	Sand-silt-clay-mixtures grain size class	Field capacity (FC mm*dm-1)
coarse-medium	11	loamy sand	24
fine-medium	16	sandy silt loam	29
medium-fine	19,5	silt loam	33
fine	24	clay silt loam	36
		sandy clay loam	42
		silty clay	49
		clay	56

the total FC of each borehole was calculated by summing up the FC of each layer up to the groundwater table. The results of this approach is summarized in Figure 2 and compared to the FC derived from maps. Borehole FCs are displayed by box plots which show the 50th percentile, the median and the overall range of results. Within the 20 to 25 meter depth to groundwater table class, the FC median derived from boreholes is about 6300 mm, 50% of the boreholes have an FC ranging from about 5700 to 7000 mm whereas the map-derived FC for this depth to groundwater table class is 8000 mm (see above). Within the "glacial till, silt loam" unit, the map-derived FCs is overestimated as compared borehole-derived FC in all depths to groundwater table classes (see Figure 2). In order to achieve reliable data, the field capacity derived from maps should be adjusted according to the field capacities which are derived from borehole data for each geological unit.

In addition to the information collected for the determination of the groundwater cover the groundwater recharge rates must be determined as exactly as possible. The method used to calculate retention time of the infiltrating water is most sensitive to groundwater recharge rates. For calculating groundwater recharge rates, suitable models can be coupled to GIS for processing information about land use, precipitation, evapotranspiration, the drainage network and if it possible, the overland runoff and the interflow. In our studies of the catchment area of the "Große Aue" and for the city of Hamburg, we also show that the "SGD-method" (Hölting *et al.*, 1995) does not take adequately into consideration the rate of groundwater recharge. An example (Table 6) shows the FC according to the "BTU-method" and the points according to the "SGD-method" of a typical profile of unconsolidated rocks of the unsaturated zone in the north part of Germany.

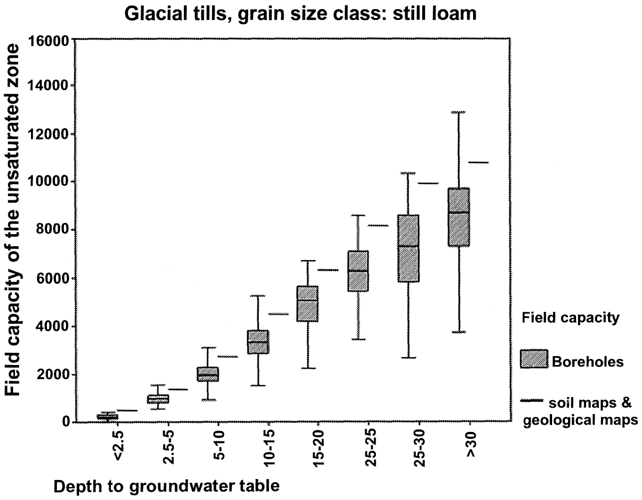

Fig. 2. Relation between field capacities (FC) of silt loam unit derived by maps and by boreholes.

The protective effectiveness of the soil cover (0-100 cm) is $P_1 = 500$, the protective effectiveness of the rock cover - $P_2 = 550$. Having a groundwater recharge rate of 300 mm, the percolation factor W, according to the "SGD-method", is 1.25 so the overall protective effectiveness $P_T = 1313$ points which corresponds to a range of retention time (Table 4) of 3 to 10 years. Having a groundwater recharge rate of 50 mm/a, which is typical for middle-east Germany, the W-factor according to the "SGD-method" is = 1.75, P_1 and P_2 are not changed, and therefore PT = 1838 which corresponds to the same range of retention time of 3 – 10 years (Table 4). This suggests that the SGD-method is quite insensitive with regard to groundwater recharge rates. In both cases, the protective effectiveness of the groundwater cover is estimated as "moderate" according to Table 4. This is not satisfactory. Applying the BTU-method, the evaluation of ground water vulnerability for these examples differs significantly. The field capacity of the profile shown in Table 6 is 1500 mm. Having a groundwater recharge rate of 300 mm, the retention time of the percolating water in the groundwater cover is calculated as 5 years and thus the protective effectiveness is assessed as "moderate". Having a groundwater recharge rate of 50 mm, the retention time is calculated as 30 years and the protective effectiveness is assessed as "very high". Therefore, the BTU method is more sensitive with regard to groundwater recharge rates. To achieve reliable retention times, precise data for groundwater recharge rates are critical.

CONCLUSIONS

The BTU-method is well adapted to the working steps of the EU Water Framework Directive. On the basis of the documents and data, which are used for the general description of groundwater bodies according to the appendix II of the Water Framework Directive, general and qualitative statements can be met for the characterization of the vulnerability of groundwater resources. This method enables to differentiate between different geohydraulic area types and thus to characterize discharge areas, which are most sensitive for interaction processes between surface waters and ground water.

In recharge areas, the intrinsic vulnerability is assessed by calculating the retention time of the percolating water in the unsaturated zone. This operation is based on a simple analytical model that considers the most important interactions between the physical characteristics of the unsaturated zone and hydrologic conditions, e.g. the groundwater recharge rate. In comparison to the point count rating system of the "SGD"-method the BTU-method allows more precise conclusions, as the SGD method is too insensitive with regard to computation of groundwater recharge rates.

Table 6

Field capacity and points according to the SGD-Method of a soil and rock cover ın the northern part of Germany

Depth (cm)	Thickness (dm)	Grain Size Class	Field capacity (%)	Field capacity (mm)	Points (according to Hölting *et al.*, 1995)
0 – 25	2.55	loamy sand	24	60	
25 –50	2.55	silt loam	36	90	
50 – 100	5.0	silt loam	36	180	500
100 – 200	10.0	sandy loam	26	260	90
200 - 300	10.0	loamy sand	24	240	60
300 - 500	20.0	loam	33,5	670	400
sum	**50.0**			**1500**	**1050**

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