A SYNTHESIS MAP OF GROUNDWATER VULNERABILITY IN THE CZECH REPUBLIC (CR)

SYNTETICKÁ MAPA ZRANITELNOSTI PODZEMNÍCH VOD ČR

Pavel Novák [1], Emil Michlíček [2], Josef Slavík [3], Eva Nováková [4], Ludmila Hartlová [5]

Abstract

This synthesis map is compiled as an overlay of three layers – a layer of hydropedological characteristics, a layer of rock environment vulnerability and a layer of the potential recharge of groundwater by precipitation water. The layer of hydropedological characteristics is based on an analysis of the codes of VSEU (Valuated Soil-Ecological Units). The map of rock environment vulnerability is made up of three input sub-layers: a sub-layer of the character of rock environment, a sub-layer of the character of groundwater circulation and a sub-layer of the transmissivity of an aquifer. In the last phase, a union of all the three layers is made, with a resulting categorization into 5 classes. Five categories of groundwater vulnerability are produced by multiplying the categories by coefficients of significance, with the maximum vulnerable category being 1 and the minimum vulnerable category being 5.

Abstrakt

Syntetická mapa je sestavena jako průnik tří dílčích vrstev – vrstvy hydropedologických charakteristik, vrstvy zranitelnosti horninového prostředí a vrstvy potenciální dotace podzemních vod srážkovou vodou. Vrstva hydropedologických charakteristik vychází z analýzy kódů BPEJ (bonitované půdně-ekologické jednotky). Mapa zranitelnosti horninového prostředí je sestavena ze tří vstupních vrstev, a to z vrstvy charakteru horninového prostředí, charakteru oběhu podzemních vod a transmitance kolektoru. V poslední fázi se vytvoří sjednocení všech tří dílčích vrstev s výslednou kategorizací do 5 tříd. Součinem kategorií a vah vznikne pět kategorií zranitelnosti podzemních vod, přičemž maximálně zranitelná je kategorie 1 a minimálně zranitelná pak kategorie 5.

Keywords

Groundwater vulnerability, infiltration capacity, water quality, GIS

Klíčová slova

Zranitelnost podzemních vod, infiltrační kapacita, jakost vody, GIS

1 Introduction

The term “vulnerability of a groundwater aquifer” was introduced by MARGAT, J. (1968), when within groundwater protection maps he defined an area in which contamination easily reaches groundwater from the surface. The term “vulnerability” thus relates to the construction of groundwater protection maps, to the definition of areas with natural protection of aquifers, and to the definition of areas without protection or with low protection where groundwater is very vulnerable.

The natural protection of groundwater aquifers is formed by overlying geological layers of rocks and soils called protective confining beds. According to the character of these confining beds in terms of permeability and physical-chemical and microbiological activity leading to the degradation of penetrated contamination, the underlying aquifer saturated by groundwater can be evaluated either as vulnerable, if a contaminant rapidly and without degradation penetrates into groundwater, or as low vulnerable, if a contaminant penetrates slowly and becomes naturally degraded. When evaluating vulnerability, it is the protective and cleaning property of confining beds which is assessed and indicated on maps.

Tab. 1 Parameters of the model DRASTIC

D	Depth to water – the depth to the groundwater table, i.e. the thickness of the unsaturated zone. The larger the thickness of the unsaturated zone, the greater the opportunity for attenuation (degradation) of the contaminant and vice versa.
R	Recharge – the amount of groundwater recharge through the infiltrated proportion of atmospheric precipitation. A contaminant seeps into the saturated zone of an aquifer by means of infiltrated water and thus it holds that the larger the recharge, the greater the vulnerability.
A	Aquifer media – the lithological characteristic of the water-saturated aquifer, its consolidation, the type of permeability, homogeneity, etc. A poorly porous aquifer (claystone) has a low rating (1 – 3), a highly porous aquifer (karst limestone, gravel sand) has a high rating (8 – 10).
S	Soil media – the character of soil, clayey soils holding water have low vulnerability (1 – 3), sandy and stony soil has high vulnerability (9 – 10).
T	Topography – the slope of the land in per cent, flat relief – high vulnerability, slopy relief (>18%) – low vulnerability (rating 1). Infiltration of a contaminant on slopes is low.
I	The impact of the vadose zone – the lithological characteristic of the unsaturated zone is similar to the characteristic of the aquifer; superficial deposits can dominate here lithologically.
C	Hydraulic conductivity – the permeability of an aquifer indicates the velocity of migration of contamination that has penetrated into a water-saturated aquifer; the higher the permeability, the greater the vulnerability.

Two summarizing publications are most often cited for the theoretical aspect of vulnerability:

- "Ground Water Vulnerability Assessment – Contamination Potential Under Conditions of Uncertainty", compiled by a scientific team of the US National Research Council, 1993; and
- "Guidebook on Mapping Groundwater Vulnerability", prepared by the Commission for Ground Water Protection of the International Association of Hydrogeologists (IAH) under the heads of J. Vrba and A. Zaporozec, 1994.

Both works followed practical experience in compilation of vulnerability maps, which is evidenced by an ample set of references. It is interesting that Czech Hydrogeologists take very frequent places in the cited literature (Olmer, 1978, Vrána, 1984, Vrba, 1981).

The publication from the NATIONAL RESEARCH COUNCIL (1993) defines the term "groundwater vulnerability to contamination" as susceptibility to the penetration of a contaminant into a system of groundwater of the uppermost aquifer after it has been introduced at the ground surface. At the same time it notes that the basic principle is the rule given as the first law of groundwater vulnerability: All groundwater is vulnerable.

Although a contaminant can penetrate through confining beds into groundwater by various pathways, the evaluation of vulnerability can allow only for simple infiltration through homogeneous confining beds, without considering preferential pathways (bio-tunnels, fractures, joints, etc.). For this reason the determination of vulnerability strongly depends on the scale of compilation, the scale of available base maps and the scale of the output map. The determination of vulnerability is always somewhat inaccurate as it is given in the second law of vulnerability: Uncertainty is inherent in all vulnerability assessments. In contrast to the theoretical analysis of methods and techniques in the publication of the NATIONAL RESEARCH COUNCIL (1993), the publication by VRBA, J., ZAPOROZEC, A. [eds.] (1994) provides many more practical evaluations and instructions for compilation, including examples, and a recommended legend for vulnerability maps. The text evaluates a very wide range of works dealing with vulnerability; the list of references used is exhaustive, and thus it is not necessary to return to the literature of the year 1994. The tabular list of attributes and parameters influencing vulnerability is interesting. They consider these attributes as the principal ones: soil, unsaturated zone, saturated aquifer and recharge of aquifer. The subsidiary attributes are topography, the underlying layer of the aquifer and interaction between groundwater and surface water.

A method widely used for the determination of the relative vulnerability of a mapped area is the application of the model DRASTIC, which was developed by ALLER, L. et al. (1987) for the US EPA. Seven evaluated parameters of vulnerability (see Tab. 1) are assessed in categories from 1 to 10, while 10 means the highest vulnerability. In addition, each parameter has its weight in values from 1 to 5.

The compilation of the synthesis map of groundwater vulnerability is solved within the project remarked as NAZV No. QH 82096 "Creation of a Conceptual Model of Construction of Synthesis Maps of Groundwater Vulnerability and Its Comparison with the Model DRASTIC"; with the time for solution being 2008 – 2012. The aim of the project is to create a state-wide map at a scale of 1: 50 000.

2 Methodological Procedure

The synthesis map of relative vulnerability of groundwater for the conditions of the CR is constructed in the Arc GIS environment on the basis of a synthesis of three information layers: relative infiltration capacity of soil, relative vulnerability of rock environment, and groundwater recharge by precipitation resulting from the precipitation balance.

The relative infiltration capacity of soil – soil vulnerability – is categorized into five classes according to the following equation:

$$SV = F_1 \times V_1 + F_2 \times V_2 + F_3 \times V_3 + F_4 \times V_4 + F_5 \times V_5, \qquad (1)$$

where SV…the soil vulnerability,

F_i…the weight of one of five factors,

V_1…MSU – main soil unit – soil characteristic,

V_2…slope,

V_3…the skeleton character,

V_4…the depth of soil profile and

V_5…exposure.

The layer of rock environment vulnerability is constructed in the same procedure. It is created from three sub-layers: the character of rock environment, the character of groundwater circulation and the transmissivity of the aquifer. All three resulting layers are interconnected in a GIS into the synthesis map of relative vulnerability of groundwater. The map construction in its principles is similar to the model DRASTIC (Tab. 1), in which the weights of the individual factors, having a significant effect on the process of infiltration and vulnerability of soil and rock environment, are multiplied by the coefficients of importance, subsequently summed and linearly divided into 5 categories.

The decisive effect on the formation and recharge of groundwater reserves is exerted by infiltration of atmospheric precipitation into a hydrogeological aquifer. From the point of view of the contribution of precipitation to the amount of groundwater reserves, the distribution of atmospheric precipitation during the year is dominant. In the Czech Republic, most precipitation falls in the growing season when its contribution to infiltration, however, is reduced to the minimum by evaporation and the need of plants. A much higher contribution to the formation and recharge of reserves is made by atmospheric precipitation that falls in the non-growing season of the year, both in liquid and solid states (snow). The latter-mentioned precipitation, when the course of thaw is favourable (slow), is very significant for the recharge of reserves. In this period, it serves as the “carrying medium” for the mobility of contaminants into the groundwater circulation. Particularly at this stage, the proportion of inappropriate fertilizing takes an effect in autumn months. It is natural that the amount of infiltrated precipitation also depends on the elevation – the amount of infiltrated precipitation increases with the rising elevation.

When constructing maps, it is necessary to evaluate the individual layers and sub-layers in terms of general contamination. When assessing the effect (input) of contaminants on groundwater, it is always necessary when identifying a particular contamination to consider its character and behaviour in the unsaturated and saturated zones. If contamination spills onto the ground, the soil and rock environment above the groundwater table represents the unsaturated zone.

In the event a contaminant spills onto the ground surface and infiltrates into the rock environment, the volume of the spilled contaminant can change already in the soil profile (for example, sorption processes or biodegradation have a significant effect). The reduction of the contaminant then continues also within the unsaturated zone. It holds in general that contaminants within the unsaturated zone move chiefly in vertical in relationship to the state of matter (liquid contaminants infiltrate directly) and then on the degree of solubility in water (the more soluble they are, the more rapid their movement is due to washout by infiltrating precipitation). The vertical movement of contaminants within the unsaturated zone can be influenced by impermeable beds, e.g. by intercalations of clay.

The processes impairing the movement of contamination through the rock environment depends both on the character of soils and rocks of the unsaturated and saturated zones (which will be the subject of the compiled maps), and on the type of the contaminant. Therefore, it is not possible to generalize the degree of reduction of the volume of the contaminant during its penetration through the unsaturated zone. The processes of movement of a contaminant in the saturated zone are collectively designated as natural attenuation. Natural attenuation is a sum of natural processes which are involved in the elimination of groundwater contamination. Both the abiotic and biotic processes (biodegradation) are responsible for the reduction of the content of contaminants in groundwater.

When assessing the significance of the individual layers of the compiled maps and the relating weights for these layers and sub-layers, it was considered that the environment is entered by substances having properties of conservative contaminants. In the case of conservative contaminants, these are substances which are not sorbed, are not degraded, and move unchanged (as a contamination plume, or a contamination "wave") through the soil and rock environment (the unsaturated zone) and then also through a water-saturated hydrogeological aquifer (the saturated zone). The main processes, thanks to which the substances of the type of the conservative contaminant migrate through the water-saturated environment, are advection and hydrodynamic dispersion, and the movement of the contaminant is not retarded by any other attenuation processes. The content of the contaminant in groundwater is then reduced by dilution. A typical example of these substances is chlorides or, in case of the oxygenic environment, nitrates.

3 Results

The synthesis map of groundwater vulnerability is constructed in the map sheets of the index diagram of the Base Map of the CR at a scale of 1: 50 000. The result is a set of analogue maps at a scale of 1:50 000 and a seamless layer of groundwater vulnerability in digital form in the format *.shp. The map of agricultural land vulnerability is compiled on the basis of a state-wide graphic and numerical database of valuated soil-ecological units (VSEU) (administered by the Research Institute of Soil and Water Conservation, v.v.i.; a public research institution), according to the above-given methodology that has general validity for the entire territory of the CR, at a corresponding scale of 1: 5 000. The map of rock environment vulnerability is compiled from three input sub-layers: the sub-layer of the character of the rock environment, the sub-layer of the character of groundwater circulation and the sub-layer of transmissivity. Each of these sub-layers has its weight relative to the process of infiltration of hazardous substances into groundwater. The resulting synthesis as the entire processing of the individual sub-layers takes places in the Arc GIS system of the American company ESRI. This system guarantees sufficiently good tools for spatial operations of graphic data, by means of which the synthesis map of groundwater vulnerability will be created.

Tab. 2 Categories of groundwater vulnerability

Category	Category of vulnerability
1.	Most vulnerable
2.	High vulnerable
3.	Medium vulnerable
4.	Low vulnerable
5.	Least vulnerable

The synthesis map of groundwater vulnerability is created by summing up the values of all the three basic information layers: the layer of soil vulnerability, the layer of rock environment vulnerability and the layer of the recharge of groundwater by precipitation.

$$GV = 0.4 \times K_1 + 0.5 \times K_2 + 0.1 \times K_3, \tag{2}$$

where GV…the groundwater vulnerability,

0.4…the coefficient of significance 40% for K_1,

K_1…soil vulnerability,

0.5…the coefficient of significance 50% for K_2,

K_2…rock environment vulnerability,

0.1…coefficient of significance 10% for K_3,

K_3…recharge by precipitation water.

For the overall vulnerability, a weighted average is calculated from the index of the infiltration capacity of soils with the weight 40%, from the index of rock environment with the weight 50% and from the index of the potential recharge of groundwater with the weight 10% (Fig. 4). As a consequence, a mosaic of areas in five categories of vulnerability will be created on the synthetic map of groundwater vulnerability (see Tab. 2).

3.1 Soil Vulnerability

The map of hydropedological properties was made by the union of two sub-layers – a sub-layer of agricultural soil vulnerability and a sub-layer of forest soil vulnerability. The sub-layer of agricultural soil vulnerability is based on the analysis of the material of VSEU (valuated soil-ecological units). For the evaluation of hydropedological properties, a group of parameters from the code of VSEU was selected, namely the main soil unit, slope, skeleton character, depth of soil and exposure (Mašát, K. et al., 2002) (equation 1). The individual parameters were divided into categories 1 – 5 (category 1 – the highest infiltration capacity, 5 – the lowest infiltration capacity). These parameters are assigned coefficients of significance so that their sum yielded 100. By multiplying the categories and the coefficient for the given parameter and by summing up the results of the five determined parameters, five categories of infiltration (vulnerability) will be formed. In the map of hydropedological properties, category 1 thus means the maximum capacity of the delineated area to infiltrate precipitation water and category 5 the minimum capacity. In map processing, the moduli of the Arc GIS CREATE REGION and REGIONQUERY systems were used. The methodology of map compilation was developed in the Research Institute of Soil and Water Conservation, v.v.i.

The input base is a vector polygon layer of VSEU of the system Arc GIS at a scale of 1: 5 000. The concept of creation of the layer of forest soil vulnerability is based on the quantification of the potential capabilities of the forest ecosystem of influencing groundwater vulnerability. The properties of the forest ecosystem were evaluated on the basis of the system of a forest typology at a scale of 1: 10 000 (1: 5 000). The map of soil vulnerability is in Figure 1.

3.2 Rock Environment Vulnerability

The rock environment is evaluated on the basis of three parameters (sub-layers): the character of rock environment, the character of groundwater circulation and, too, the transmissivity of the aquifer.

For the evaluation of the character of the uppermost geological layer cropping out according to the digital maps GeoČR50, similarly as in the case of soil genesis, all of the rock types in the legend of the geological map were assigned a value of 1 – 5 of the parameter (1 = porous rock types, 5 = intact plastic types); the weight of the parameter is 50%.

The character of the circulation of groundwater expresses the division of the flow system of the hydrogeological structure into the areas of groundwater formation (the infiltration area with the value 1 of the parameter, the transit area with the value 3 and the drainage area with the value 5); the weight of the parameter is 20%.

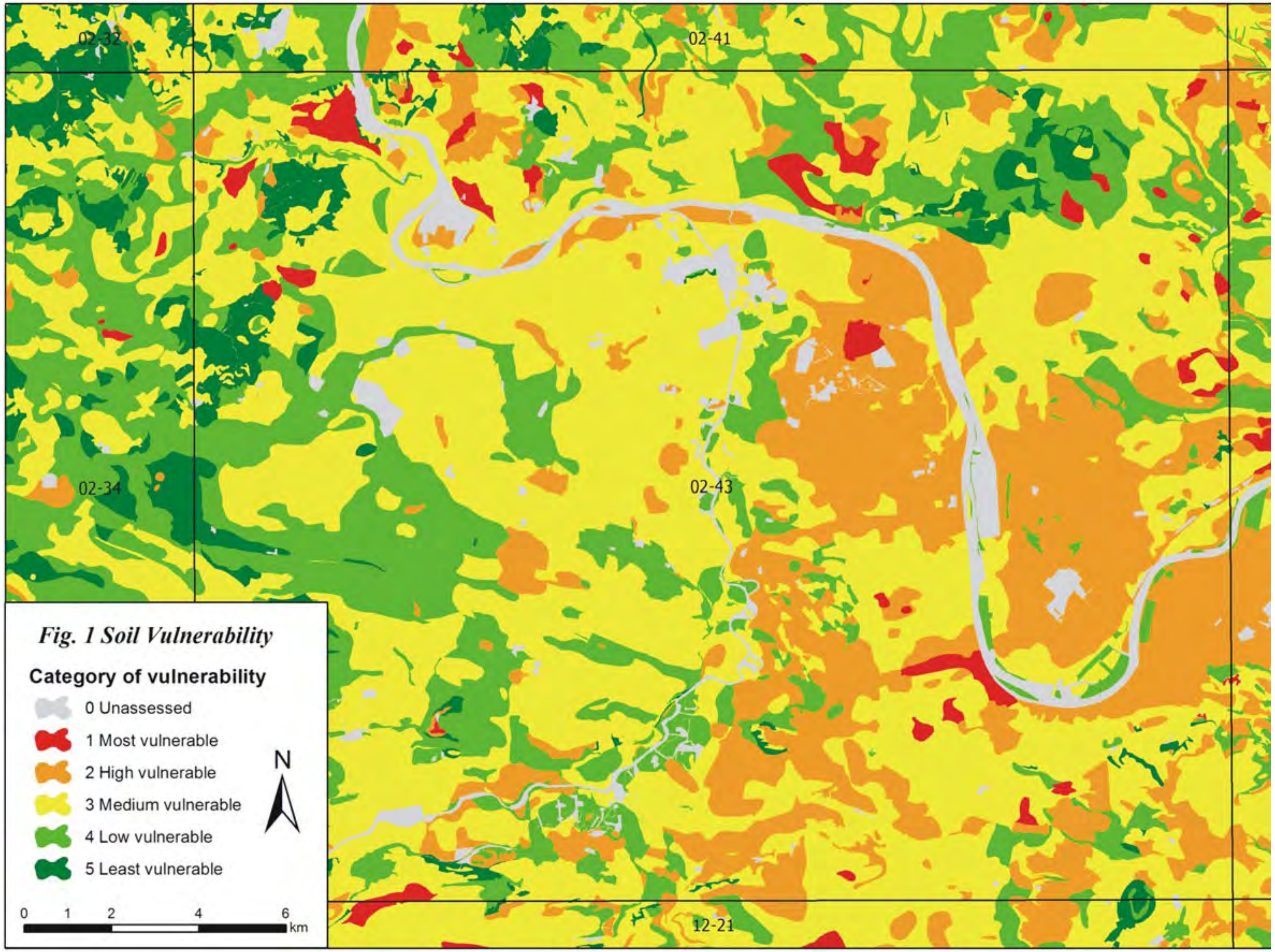

Fig. 1 Map of soil vulnerability

The transmissivity of the aquifer, i.e. the hydraulic parameter of transmissivity, is not only the parameter expressing the velocity of possible horizontal propagation of contamination in a water-saturated aquifer, but also a very important parameter of the water-management use of a site (Krásný, J., 1986), because the high transmissivity of an aquifer also means the high yield of wells and abstraction boreholes (500 [$m^2.day^{-1}$] and more = a value of 1, less than 1 [$m^2.day^{-1}$] = a value of 5). The weight of the parameter is 30%. The resulting map of rock environment vulnerability is produced on the basis of a synthesis of three above-given sub-layers and vulnerability is again divided into 5 categories (Fig. 2)

3.3 Groundwater Vulnerability in the Form of Recharge by Precipitation Water

The basic data of the precipitation balance were provided by the Czech Hydro-meteorological Institute (CHMI). These data were in raster form in a grid of 500 x 500 m recording the precipitation balance of the CR on the basis of the difference between the average sum of precipitation (P) over a cold season of the year (October to March) and the average sum of potential evapotranspiration (ETo) over a cold season of the year (October to March) for the period 1961 – 2008. The rating scale contained 11 classes.

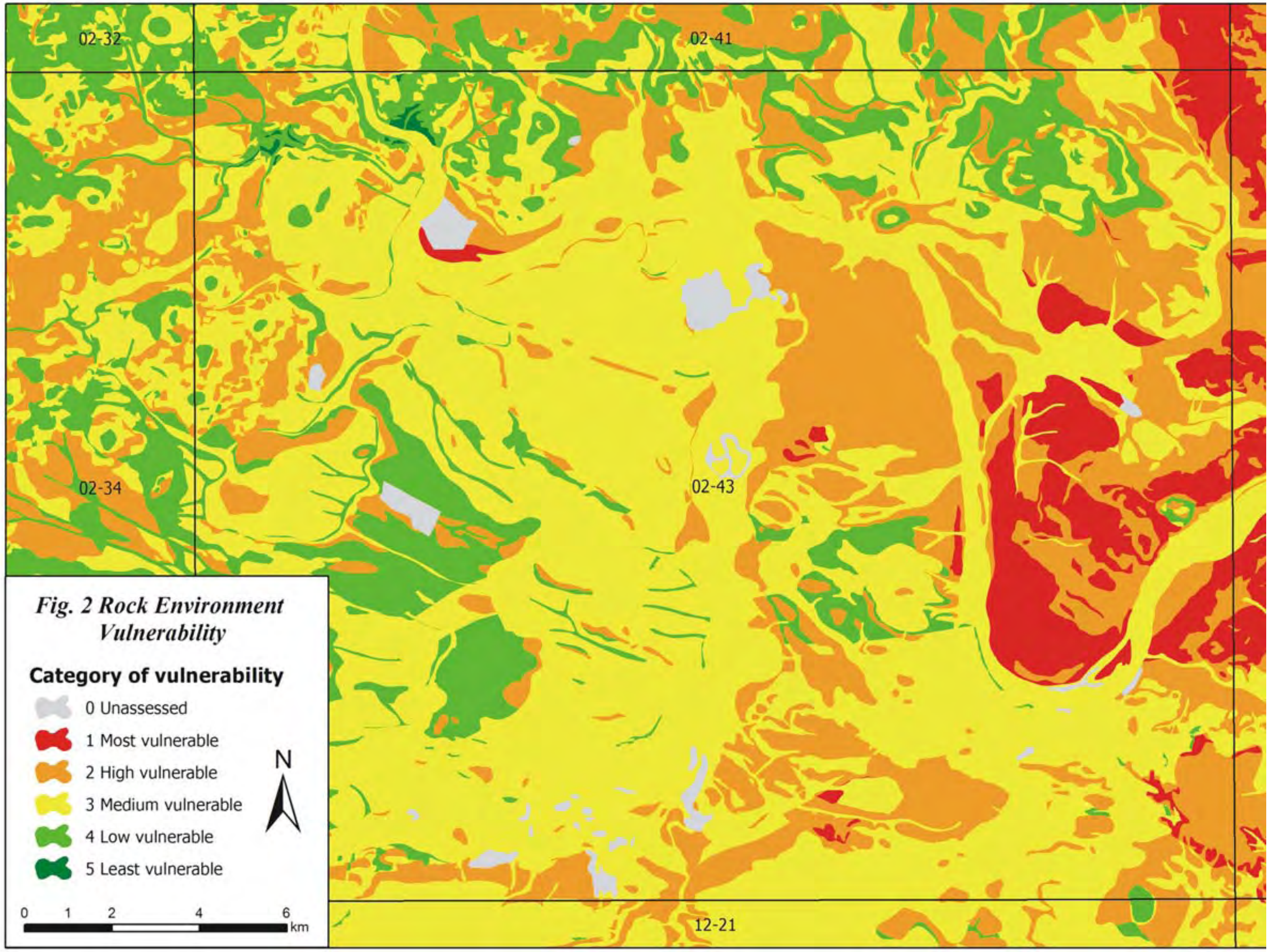

Fig. 2 Map of rock environment vulnerability

For the processing of the layer of the precipitation balance, it was necessary to convert the raster into a vector format and to carry out a change in the rating of the individual classes, i.e. to create a layer with five-grade rating scale (Fig. 3). The rating scale was changed on the basis of an analysis of the proportion of the newly proposed rating classes relative to their percentage of the whole area of the territory of the Czech Republic. In relation to the uniform distribution of the rating classes on the territory of the CR, a non-linear rating scale was chosen.

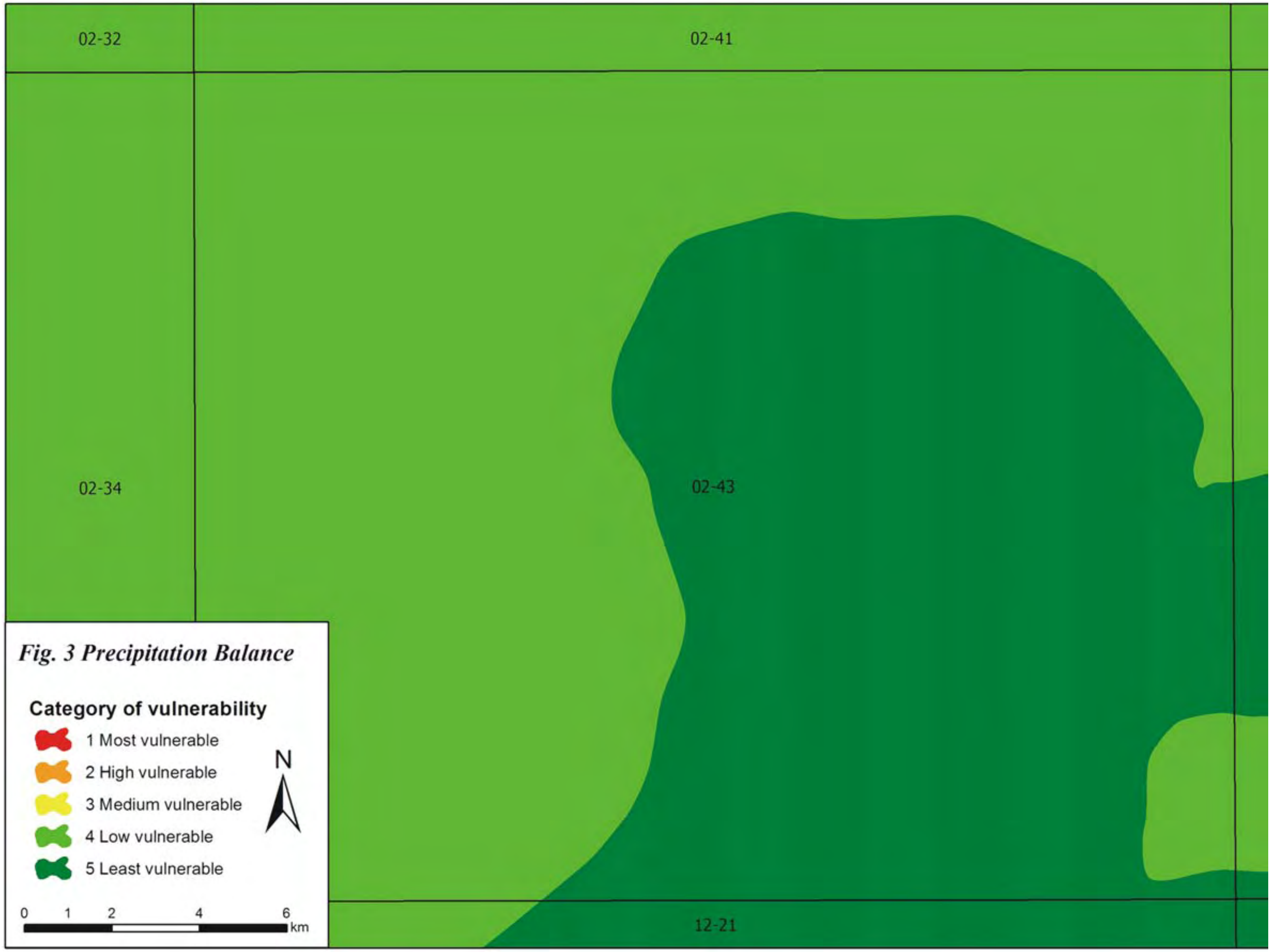

Fig. 3 Map of precipitation balance

3.4 Comparison of the Method DRASTIC with the Method of the Synthesis Map of Groundwater Vulnerability

If both the methodologies are compared, a basic agreement in the concept of indices and in the method of calculation can be identified. An absolutely fundamental difference is in the rating of parameters, in which both the methods differ from one another. DRASTIC uses an ascending rating – the higher the value of parameter, the greater the vulnerability. The methodology of the synthesis map of relative soil and rock environment vulnerability uses a reverse, descending rating, in which the value 1 means high vulnerability and, conversely, the value 5 means low vulnerability. This reverse character of evaluation is also shown in the calculation procedures, in which DRASTIC uses a simple summation of the values of parameters multiplied by the coefficient of weight. For calculating the overall index, the method of groundwater vulnerability uses a value when parameters have a different weight in per cent.

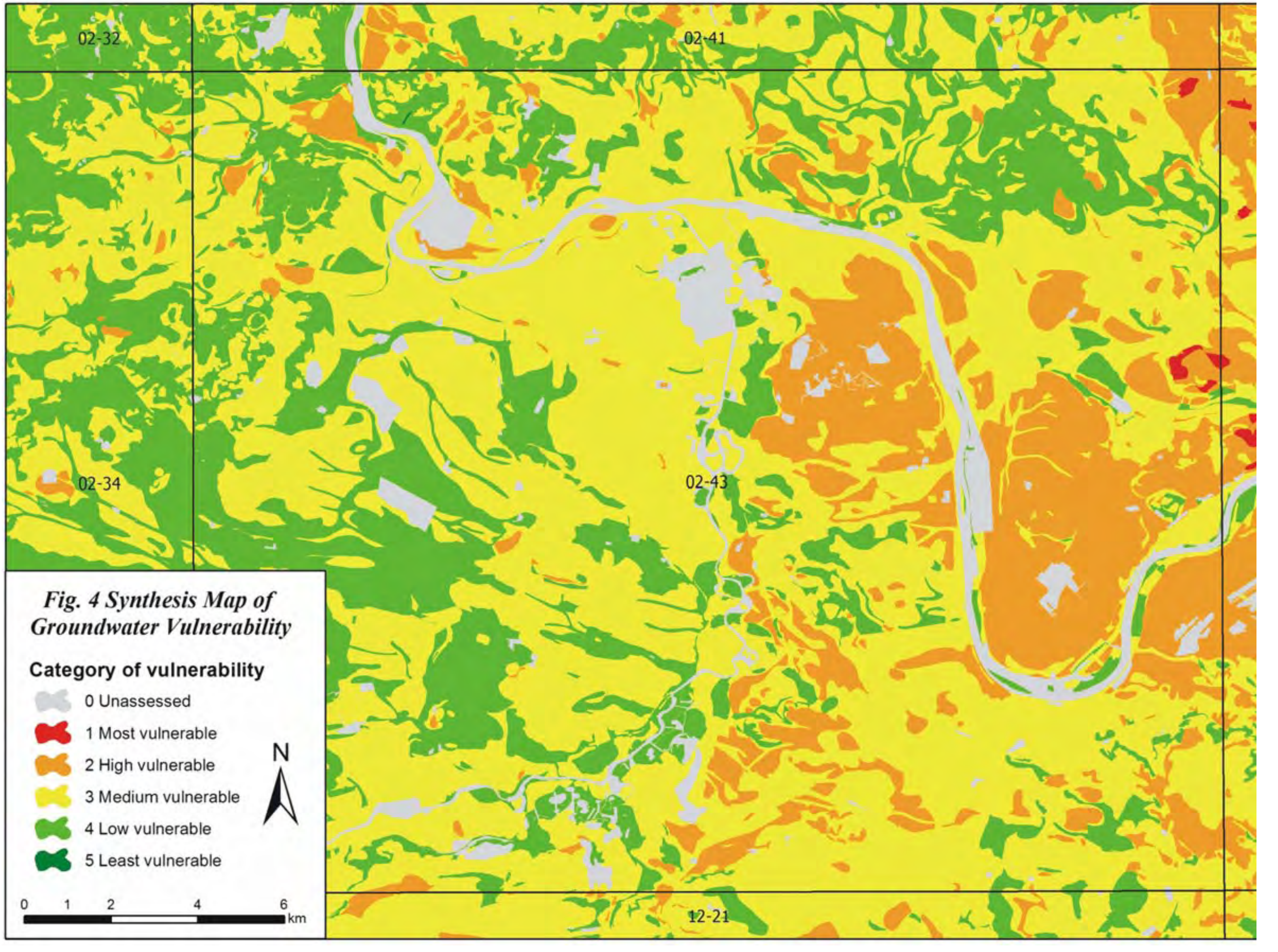

Fig. 4 Synthesis map of groundwater vulnerability

Naturally, the generally philosophical approach is similar, led by the effort to obtain and evaluate both the objective values of parameters (transmissivity, slope, infiltration intensity) and subjectively assessed parameters (type of rock, type of soil). Both the methodologies apply available national databases to the evaluation of the intensity of groundwater circulation and to the evaluation of the soil cap that is significantly involved in the reduction of contamination penetration.

However, neither the first law of vulnerability “All groundwater is vulnerable” nor the second law of vulnerability “Uncertainty is inherent in all vulnerability assessments” (National Research Council, 1993) must be forgotten.

4 Conclusion

The synthesis maps of groundwater vulnerability are constructed from the layer of soil vulnerability, the layer of rock environment vulnerability and the layer of the potential recharge of groundwater by precipitation water. These maps very well convey the issue of the degree of the potential risk of relative groundwater vulnerability particularly to contaminants originating from agricultural practices. From this point of view, it is possible to consider their application wherever there is a conflict between water protection and negative effects of farming and other activities in a landscape.

Other possibilities of using these maps are in the cases in which the extents of protection zones of water resources are proposed or revised within protective preventive measures, including proposed measures (a change in land use, planting with grass, erosion-control measures, etc.).

It will also be possible to use the compiled synthesis maps of vulnerability for verifying the validity of the extent of vulnerable areas of the CR, determined on the basis of the Nitrates Directive, also in planning in the area of water protection and in land-use planning.

Acknowledgements

This paper has been prepared with the support of the projects NAZV QH 82096 and VZ MZE 0002704902.

References

ALLER, L. et al. *DRASTIC: A Standardized System for Evaluating Ground Water Pollution Potential Using Hydrogeological Settings*. Environmental Research Laboratory, US Environmental Protection Agency, Ada, Oklahoma, 1985, EPA/600/2–85/018.

KRÁSNÝ, J. Klasifikace transmisivity a její použití (Rating of transmissivity and its use). *Geologický průzkum* 6/1986, Praha, 1986, p. 177 – 179.

MARGAT, J. *Vulnérabilité des nappes d‘eau souterraine a la pollution (Groundwater vulnerability to contamination).* Bases de la cartographie, (Doc.) BRGM, 1968, SGL 198 HYD, Orléans, France.

MAŠÁT, K. et al. *Metodika vymezování a mapování bonitovaných půdně ekologických jednotek (The methodology of defining and mapping valuated soil-ecological units)*. VUMOP Praha, 2002, 113 p., ISBN 80-238-9095-6.

NATIONAL RESEARCH COUNCIL (NRC) *Ground water vulnerability assessment: contamination potential under conditions of uncertainty*. Committee on Techniques for Assessing Ground Water Vulnerability, 1993, Water Science and Technology Board.

NOVÁK, P., FUČÍK, P., NOVOTNÝ, I., HEJDUK, T., ŽÍŽALA, D. An integrated approach for management of agricultural non-point pollution sources in the Czech Republic. *AUC Geographica*, 2/2012, Prague, 2012, p. 33 – 43.

OLMER, M. et al. *Map for protection of ground water - example map 1: 200 000.* Memoires Int Symp. on Ground Water Pollution by Oil Hydrocarbons, IAH, Praha, 1978.

VRÁNA, M. Methodology for construction of groundwater protection maps. (Lecture for UNESCO/UNEP Project PLCE-3/29, Moscow, 1981) In KOZLOVSKY, E. A. [ed.] *Hydrogeological Principles of Groundwater Protection*, UNESCO/UNEP, Moscow, 1984, p. 147 – 149.

VRBA, J. General aspects of ground water non-point pollution. *Studies in Env. Sci. Elsevier*, Amsterdam, 1981, 17, p. 41 – 53, ISBN: 9780444420220.

VRBA, J., ZAPOROZEC, A. [eds.] Guidebook on mapping groundwater vulnerability. *In International Contributions to Hydrogeology*, vol. 16, Heise, Hannover 1994, 131 p.

Authors

[1] RNDr. Pavel Novák, Výzkumný ústav meliorací a ochrany půdy, v.v.i., Žabovřeská 250, 156 27 Praha 5 – novak.pavel@vumop.cz, tel. 728184577

[2] RNDr. Emil Michlíček, GEOtest, a.s., Šmahova 112, 659 01 Brno – michlicek@geotest.cz, tel. 548125272

[3] RNDr. Josef Slavík, GEOtest, a.s., Šmahova 112, 659 01 Brno – slavik@geotest.cz, tel. 548125264

[4] Mgr. Eva Nováková, Výzkumný ústav meliorací a ochrany půdy, v.v.i., Žabovřeská 250, 156 27 Praha 5 – novakova.eva@vumop.cz, tel. 541126273

[5] Ing. Ludmila Hartlová, GEOtest, a.s., Šmahova 112, 659 01 Brno – hartlova@geotest.cz, tel. 548125273