KARST GROUNDWATERS VULNERABILITY ASSESSMENT METHODS

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Abstract. A major socio-economic and scientific issue is represented by karst hydrostructures vulnerability mapping, which qualitatively and quantitatively highlights their exposure degree. Two research trends have been developed, one taking into account the environment features exclusively – the aquifer and protective cover type, permeability, aquifer depth, recharge rate, etc. (*intrinsic vulnerability*), the other focused on the types and quantities of pollutants (*specific vulnerability*). MAGIERA (2000) described and compared 69 methods, grouped in 5 types: hydrogeological complex and setting methods, index models and analogical relations (AF, AVI, Ekv, ΔhT'), parametric system models (DRASTIC, DWSAP, SINTACS, EPPNA, GOD, EPIK, REKS, PI, GSI, GLA), mathematical models (VULK, FAVA) and statistical methods (CALVUL). However, it is also possible to classify the methods on the basis of other criteria, such as scale (local, regional, national), aim (land use planning, protection zoning, site assessment) and target (source or resource vulnerability).

Key words: karst groundwaters, vulnerability, assessment methods.

1. INTRODUCTION

The carbonate rocks cover up to 12% of the continental surface, outcroping widely in the Northern Hemisphere (on about 35% of the European area). Hence, a large number of people live and work in karst regions, 25% of the whole population exploiting their groundwater resources (FORD & WILLIAMS, 1989).

The term „vulnerability", used to describe the sensitivity of any environmental factors to different types of stress (such as the global climate vulnerability to human impact), was mentioned by MARGAT (1968), to show the aquifers exposure degree to contamination.

Defining hazards and risks is a difficult task, due to the recent terminology, the concepts being usually analysed from the human health and safety perspective. Today, in Romania, **a hazard** is acknowledged as *a potentially dangerous phenomenon, harmful for people, assets and environment*, while **the risk** represents *its occurrence probability*.

The conceptual model *origin-pathway-target* (Fig. 1) clearly points out the influence of the 3 control factors of aquifers vulnerability: the potential pollution, the transport way and the contaminated resources.

The effective management of karst terrains implies hazards identification, potential impact analysis, vulnerability assessment and mapping. Lithological, tectono-structural and hydrogeological data acquisition is strictly necessary, along with the implementation of adequate protection norms and methodologies, in accordance with the current legislation. The study of karst areas appeals to field observations, laboratory screening and inventory records (files, databases, major hazards and risks maps, airborne and satellite images).

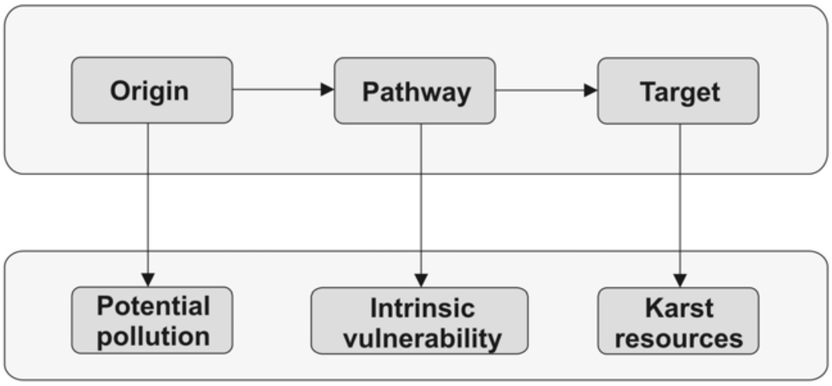

Fig. 1. – The conceptual model *origin-pathway-target*.

The maps utility should be qualitatively and quantitatively emphasized. MAGIERA (2000) described and compared 69 methods, grouped in 5 types: hydrogeological complex and setting methods, index models and analogical relations, parametric system models, mathematical models and statistical methods, which could be also classified on the basis of other criteria, such as scale (local, regional, national), aim (land use planning, protection zoning, site assessment) and target (source or resource vulnerability).

The DRASTIC method (ALLER *et al.*, 1987) is used for qualitative assessments of the incidence of agricultural pollutants (pesticides and fertilizers) on groundwater, assigning indices (1–10) to the next parameters: **D – aquifer depth**, **R – recharge rate**, **A – aquifer lithology**, **S – soil type**, **T – topography, I – impact** (unsaturated zone lithology), **C – aquifer hydraulic conductivity**.

To be relevant regarding the significance for the total vulnerability, the resulting values are weighted with coefficients, selected from the 1 (**T**) – 5 (**D**; **I**) range. After the multiplication and addition of all data, the vulnerability index (23–230; in current work: 50–200), may be inferred, defining its degree („very low" – „high") and favouring intra- or interregional comparisons.

The DWSAP method – Drinking Water Source Assessment and Protection (BLODGETT, 1993), requires a similar algorithm, taking into account the potential contaminant activities, the effectiveness of the natural barrier protection to pollution events and the travel time of chemical compounds or microorganisms.

The SINTACS method (CIVITA *et al.*, 1990) assesses the same 7 parameters: **S – soggiacenza** (aquifer depth), **I – infiltrazione** (seepage water input), **N – non saturo** (unsaturated zone features: grain size, texture, mineral composition, faulting and karstification), **T – tipologia della copertura** (soil type), **A – acquifero** (hydrogeological characteristics of aquifer), conditioning molecular and kinematic dispersion, contaminants adsorption and dilution, and even the chemical reactions between them and reservoirs, **C – conducibilità** (aquifer hydraulic conductivity), **S – superficie topografica** (roughness of land surface).

The method has a complex structure, data processing being mediated by a software. In order to describe the total vulnerability, it is possible to add some other variables to those already mentioned, estimated by indices (1–10). The weighting coefficients will be chosen from the 8% (**I**) – 22% (**S**) interval, while the vulnerability degrees assigned to various regions oscillate between "very low" and "extremely high".

The SI method, focused on **susceptibility index**, and that adopted in Portugal, by **EPPNA – Equipa de Projecto do Plano Nacional da Água** (INAG, 1998), belong to the same group of vulnerability assessment methods.

By **the GOD method** (FOSTER, 1987), 3 parameters are studied: **G – groundwater occurrence** (aquifer type), **O – overall aquifer class** (protective cover lithology) and **D – aquifer depth**; afterwards, indices selected from the 0–1 range will be assigned to the resulting values, the graphical processing of the 3 charts allowing vulnerability assessment, between "the minimum degree" (0) and "the maximum degree" (1).

The EPIK method (DOERFLIGER & ZWAHLEN, 1997) is highly useful for the land use planning, especially for the catchments protection.

By analysing the hydrodynamical behaviour of the Swiss karst aquifers, it has been shown the fact that vulnerability is controlled by 4 main factors, which will be mapped: **E – epikarst** (thickness of subcutaneous, high permeability zone), **P – protective cover** (soil and/or low permeability formations), **I – infiltration conditions** (diffuse or concentrated seepage water input) and **K – karst network development**.

The semiquantitative evaluation is carried out with the help of the classification indices: E_1 – sinkholes, karren fields, ruin-like relief, intensely fractured outcrops, E_2 – intermediate zones in doline fields, dry valleys, E_3 – epikarst absent; on top of carbonate rocks or coarse, very permeable detrital deposits: P_1 – 0–0.2 m of soil, P_2 – 0.2–1 m of soil, P_3 – >1 m of soil; overlaying low permeability formations: P_1 – omitted for deposits that are less than 0.2 m thick, since the units provide a limited protection; P_2 – 0.2–1 m (the whole sequence); P_3 – >1 m (total thickness of the column); P_4 – >8 m of low permeability formations or >1 m of soil on >6 m of silts or clays; inside the catchment: I_1 – permanent or temporary sinkholes, banks and beds of the streams recharging them, artificially drained sectors; I_2 – naturally drained regions, with a high runoff coefficient, imposed by a slope steeper than 10% for arable areas and steeper than 25% for meadows and pastures, I_3 – naturally drained terrains, with a low runoff coefficient, the slope being less than 10% for arable areas and less than 25% for meadows and pastures; outside the catchment: I_3 – slopes with a high runoff coefficient, steeper than 10% for arable areas and steeper than 25% for meadows and pastures, taken into account along with their foot zones; I_4 – the rest of the basin; K_1 – moderate or well-developed karst network (dm-m wide interconnected conduits), K_2 – clogged or less-developed karst network, K_3 – fissured or porous media.

The protection index, rated by adding the weighted resulting data: $F = 3 \cdot E + P + 3 \cdot I + 2 \cdot K$, delineates 4 vulnerability classes from "very high" to "low".

The REKS method (MALÍK & ŠVASTA), a similar one, is best suited for the Slovak karst peculiarities, while **the PI method** (GOLDSCHEIDER *et al.*, 2000), describes the **protective index**, mainly following the EPIK method principles.

The GSI method – Geological Survey of Ireland (DALY & DREW, 1998) integrates the aquifer map with the importance of the resources, the hydrogeological features and the vulnerability map, highlighting the soil thickness and hydraulic conductivity, internal and external protection zones of the catchments and the hydrostructure response to land use.

The GLA method – Geologisches Landesamt (HÖLTING *et al.*, 1995) is designed to thoroughly investigate the protective cover of the karst regions, trying to explain the relationship between the effectiveness of the natural attenuation processes and the contaminants travel time.

The AF method (RAO *et al.*, 1985) presents **the pollutants impact attenuation factor** and is conceptually similar to **the AVI method – aquifer vulnerability index** (VAN STEMPVOORT *et al.*, 1992) and to the **EKv** method (AUGE, 1995).

The latter checks over 2 factors: **unconfined aquifer depth (E)** and **unsaturated zone vertical permeability (Kv)**, assigning them indices selected from the 1–5 range, depending on their significance for the groundwater vulnerability degree. After adding the data, the final index defines the vulnerability classes: low (2–4), medium (5–7) and high (8–10).

The ΔhT' method (AUGE, 1986) may be applied for the semiconfined aquifers, **the hydraulic potential gradient (Δh)** and **the vertical transmisivity (T')** marking 3 major vulnerability categories.

The VULK mathematical model – vulnerability and karst (JEANNIN *et al.*, 2001) has been developed for the specific vulnerability appraisal, in the framework of the European Union COST Action 620. Thereafter, in the USA, **the**

FAVA model – Florida aquifer vulnerability assessment (BAKER *et al.*, 2002), also built on a GIS platform, was considered more appropriate for the local case.

The statistical methods, including **CALVUL – California vulnerability** (TROIANO *et al.*, 1999), are accurate and reliable on a small or medium scale. The geostatistical analysis of groundwater vulnerability requires: the mapping of specific parameters – aquifer depth and recharge rate, protective cover type and permeability; the graphical representation of pollutants distribution within the hydrostructure; the identification of some correlations with the environmental factors, difficult in karst areas, due to a quick lateral transfer of contaminants.

2. VULNERABILITY TYPES

The intrinsic vulnerability is a worldwide notion, used to determine the karst sensitivity to human activities, by mapping geological, geomorphological, hydrogeological, climate, vegetation and land use features.

By definition, **the specific vulnerability** depends on 3 essential variables, joined in a three-dimensional chart (a cube): the contaminant travel time, the pollution duration and the contaminant maximum concentration.

The direct release of pollutants in streams, their transport intermediated by runoff or air currents, the volatilization and airborne subsequent deposition, as well as their uptake in the trophic cycles, trigger the aquifers contamination. During the droughts, the pollutants are stored in soil and epikarst; when humidity rises, they are washed-out and detected at springs and monitoring drillings. The advective transport of noxious compounds (nitrates and nitrites, chlorides, hydrocarbons, heavy metals), bacteria and viri through karst systems, is controlled by the environmental features (permeability, effective porosity, hydraulic gradient) and also by the distance between origin and target. A long travel time offers to the human population an opportunity to react to a contamination event. Meanwhile, the natural attenuation processes (by diffusion or dispersion) may significantly decrease the pollutants concentrations. Unfortunately, the discharge is often very fast, affecting large areas.

3. THE PI METHOD

The conceptual model shown in Fig. 2 presents 4 factors – O, C and K illustrate the system internal features, as opposed to P, which marks an external stress.

In order to map *the vulnerability resources*, only O, C and P parameters are considered, K factor being assessed as *a vulnerability source*.

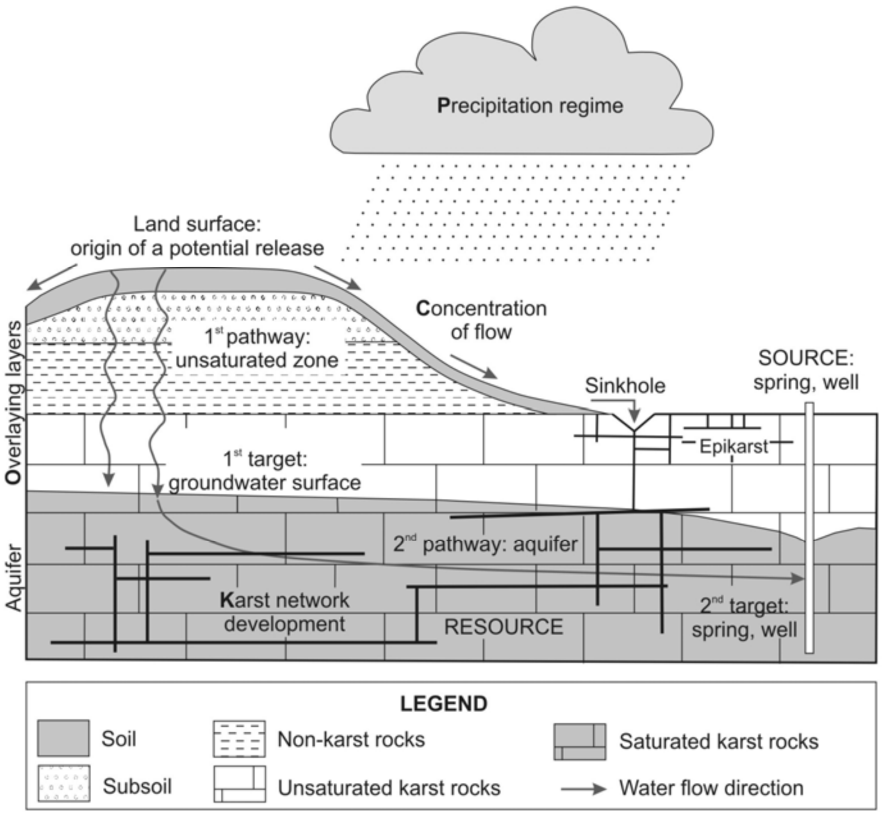

Fig. 2. – The PI method (after COST Action 620, 2003, slightly modified).

3.1. THE O FACTOR (OVERLAYING LAYERS)

The protective cover, located between the land surface and the aquifer level, comprises 4 layers: soil, subsoil, non-karst rocks and unsaturated karst rocks. Some of these units may be divided into several sublayers. Not all layers always outcrop, the most karst areas consisting of soil and unsaturated carbonate rocks.

The external surface, ideal for ions exchange and adsorption, also available to be abundantly colonized by microorganisms, has a lesser extent when it overlays intensely faulted carbonate rocks, protected by a thin cover, than in the case of some porous, elastic sediments, burried under a thick soil.

The soil, which includes minerals, organic compounds, air and water, is the biologically active zone, directly affected by the climate factors, and decisively controls the specific pollution mitigation.

The layer is less significant for the intrinsic vulnerability assessment. Its main features, which should be mapped, are thickness, porosity and permeability; the latter two mainly depend on the grain size distribution, an effective mean for the evaluation of soil protective function. The soil type, vegetation and drainage density provide supplementary indirect information.

The subsoil is the granular, non-lithified material below the soil cover (for example Quaternary deposits, such as gravels, sands, silts or clays). The essential factors mentioned above should be investigated for this layer also. Preferential flowpaths (which follow the macropores network) are less likely to occur than in the soil. Sometimes, the low permeability of these layers may be avoided, if they are not laterally extensive, forming only lenses. A certain minimum thickness of them may be used as a selection criterion.

The non-karst rocks consist of sandstones, marls, shales etc.; the same parameters will be studied. In order to estimate them, one may appeal to some geological (lithological and tectonical), as well as geomorphological data (density, width, continuity, spatial distribution and roughness).

The unsaturated karst rocks are located in the vadose zone. The epikarst is a part of the aquifer unsaturated zone, and it influences its protective function by controlling the infiltration-percolation processes. There are two extreme cases – either the epikarst allows water storage and a diffuse percolation, meeting the demands of protection for the unsaturated karst rocks, or the concentrate flow is dominant in the epikarst zone, which loses its protection capacity (like in the case of the karren fields drained by potholes).

The protective function of the 4th layer depends on its thickness and permeability and also on the karstification degree and spatial distribution. Indirectly, the parameters impose an analysis of all karst features, focused on lithology, structure, texture and paleolandscape reconstruction, but also a certain number of hydrogeochemical and biopedological researches. The O factor will be considered satisfactory for the karst aquifer vulnerability assessment, if all rainfall input diffusely infiltrates through soil or low permeability formations and goes over the vadose zone, before it reaches the saturated one. The runoff may be significant on these terrains and the free access to underground, provided by sinkholes, denies the protective function of the overlaying layers. On the other hand, the runoff directed outside the karst system offers an effective natural protection to contamination.

3.2. THE C FACTOR (CONCENTRATION OF FLOW)

The driven of rainfall water towards fast infiltration points is illustrated by the C factor. If the infiltration is diffuse, the protective function of the overlaying layers may be important.

In the case of a concentrated flow, the aquifer is directly polluted by the mediation of sinkholes. The concentration of flow depends on the slope gradient, surface features (soil thickness and permeability), vegetation and the presence of sinkholes. The C factor has been adopted after the I factor (infiltration conditions) of the EPIK method (DOERFLIGER & ZWAHLEN, 1998).

3.3. THE K FACTOR (KARST NETWORK DEVELOPMENT)

The horizontal flowpaths of the saturated zone are often surveyed for the vulnerability source assessment. Therefore, the K factor, similar to that of the EPIK method (DOERFLIGER & ZWAHLEN, 1998), has been set up, denoting the karst network development degree.

It must be analysed along with the distance and the contaminants travel time. The K factor evaluation is based on geological, geomorphological and geophysical data, karst maps, bedrock sampling, dye tracing experiments, pumping tests, spring hydrographs and chemographs. The drainage density, soil type and vegetation are also examined.

3.4. THE P FACTOR (PRECIPITATION REGIME)

The P factor considers not only the annual rainfall input, but also the frequency, intensity and duration of the extreme events, which may have a major influence on the infiltration type and volume and, consequently, on the vulnerability.

A large rainfall input, some favourable infiltration conditions and a limited evapotranspiration cause a high recharge rate and a quick transport of contaminants. As a result, the P factor may be considered an external stress, affecting O, C and K parameters. In many cases, there is no clear variation of the rainfall regime within one catchment, but obvious differences may be established between various climate zones. Thus, the P factor is not significant on a local scale, while on a national or continental one it may be relevant.

4. KARST VULNERABILITY ASSESSMENT IN ROMANIA

Although the Cerna-Jiu area, the Mehedinți Plateau, the Piatra Craiului Mountains and the Southern Dobrogea Plateau have been repeatedly investigated from the hydrogeological point of view, up to the present only 2 methods have been applied in Romania – EPIK, in the northern unit of the Banat Mountains (IURKIEWICZ *et al*., 2005) and PI – in the Bihor Mountains (ORĂȘEANU *et al.*, 2005).

The first study aimed to highlight the vulnerability of the karst included in the Semenic-Caraş Gorges National Park, developed on the Middle Jurassic-Early Cretaceous limestones, widespread in the north of the Reşiţa-Moldova Nouă Synclinorium. The zone has been divided in 3 major karst areas: Caraşova-Prolaz, Ponicova-Comarnic and Sodol-Baciului, marked by many caves, sinkholes and springs.

Besides the field activity, comprising the epikarst mapping and the hydrogeological data acquisition, the analysis of the satellite images and maps (topographical – 1:10.000 and geological – 1:50.000) was an important stage of the study.

Intensely karstified, the region is dominated by high vulnerability degree terrains, mainly located on the Iabalcea Plateau and nearby the Comarnic Cave, imposing the change of the Semenic-Caraş Gorges National Park limit and the designation of an adequate buffer zone (IURKIEWICZ *et al*., 2005).

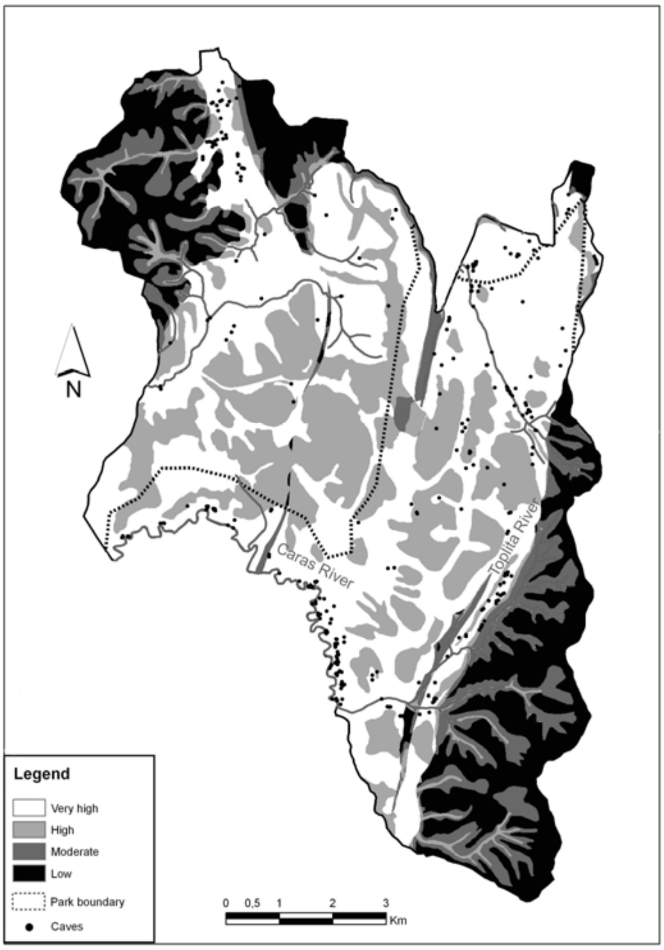

Fig. 3. – Vulnerability map of the karst areas included in the northern unit of the Banat Mountains (after IURKIEWICZ *et al.*, 2005).

The second article brings forward the results of the Apuseni Project, deployed on the Gârda Seacă-Ordâncuşa Watershead, aiming to evaluate the impact of agrotourism on the karst system drained by the Coteţul Dobreştilor Spring.

The karstified sedimentary sequences (ascribed to the Bihor Unit – Anisian dolomites, Ladinian-Early Carnian and Jurassic limestones) form a homoclinal structure, deeply faulted, which generally strikes NE-SE and dips NE-SW (in the northern half of it) and E-W (in the southern one).

The aquifer intrinsic vulnerability was appraised within the internal drainage area and the mountainside karst catchment, by the means of geological, hydrogeological and pedological research.

The shallow soil enables the superficial flow to easily pass through it, providing a weak protection to pollution, while the karst network is very well developed. The PI map (Fig. 4) displays many perimeters with high or extreme vulnerability degree (ORĂȘEANU *et al.*, 2005).

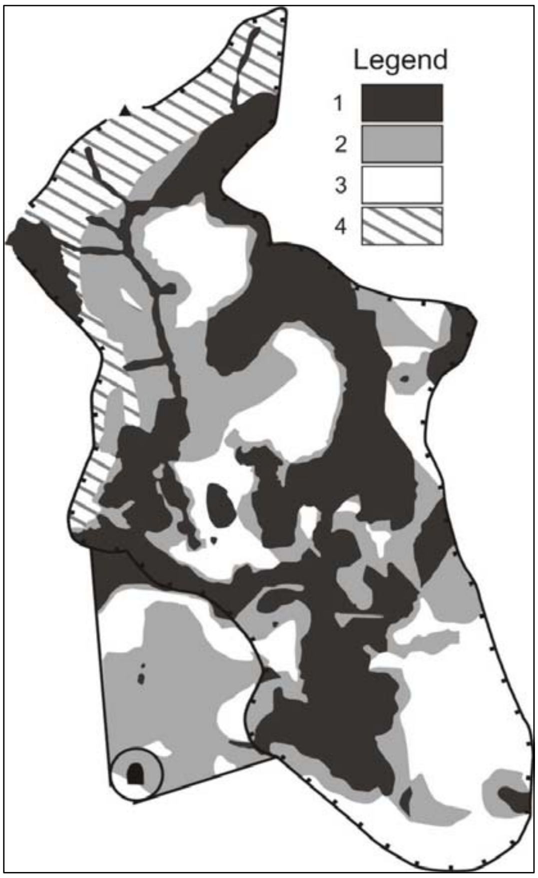

Fig. 4. – Vulnerability map of the Ghețar-Ocoale Plateau (Bihor Mountains): 1 – very high; 2 – high; 3 – moderate; 4 – low (after ORĂȘEANU *et al.*, 2005).

5. CONCLUSIONS

The karst groundwater vulnerability assessment is focused both on the karst systems features and on the pollutants physico-chemical properties.

The natural attenuation processes run when the overlaying layers allow filtration, adsorption and elimination of contaminants or at least the decrease of their travel speed. If these requirements are not fulfilled, the human impact may be catastrophic; therefore, the vulnerability maps represent useful management tools, granting to the authorities the chance of an operative and effective intervention in the affected areas, and also the possibility to delineate some special protection zones for the catchments.

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