GEOLOGICA BALCANICA, 38. 1–3, Sofia, Dec. 2009, p. 59–67.

Groundwater vulnerability map for the Ogosta River Basin, northwestern Bulgaria

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(Submitted: 27.07.2009; accepted for publication: 18.11.2009)

Abstract. The present paper deals with evaluation and mapping of the intrinsic vulnerability for the Ogosta River Basin in northwestern Bulgaria. The protective cover and infiltration conditions (PI) method is used developed within the scope of COST 620 Project. According to this method, PI factors are evaluated and groundwater vulnerability map is prepared. Groundwater in the karst basins is the most vulnerable to pollution. The alluvial deposits are classified as moderately vulnerable. The loess cover provides effective protection of groundwater against pollution and thus the respective areas are low vulnerable to pollution. The Neogene limestones, sands and sandstones are moderately vulnerable. Possible removing of the soil cover would result in high vulnerability of the respective aquifer. The prepared vulnerability map may be used for groundwater resource protection and land use planning in the Ogosta River Basin.

Orehova, T., Gerginov, P., Karimova, O. 2009. Groundwater vulnerability map for the Ogosta River Basin, northwestern Bulgaria. *Geologica Balcanica* 38(1–3), 59–67.

Key words: groundwater vulnerability, pollution, mapping, northwestern Bulgaria.

INTRODUCTION

Vulnerability maps are broadly applied for land use planning worldwide. They allow delimitation of areas with different degree of natural protection of groundwater against pollution. Vrba and Zaporozec (1994) defined groundwater vulnerability to pollution as an intrinsic property of a groundwater system that depends on the sensitivity of that system to human and/or natural impacts.

Lately, an increasing interest in groundwater vulnerability assessment and mapping is observed, together with intensive research in this field. Numerous methods and techniques to assess groundwater vulnerability were developed. Classification of the proposed methods and comparative studies were made by Gogu and Dassargues (2000), Civita and De Maio (2004), Lobo-Ferreira and Oliveira (2004), Neukum et al. (2008) and others.

The intrinsic vulnerability of groundwater to contamination is, by definition, independent of both the contaminant nature and the contamination scenario (Zwahlen, 2003). Amongst various methods of the intrinsic vulnerability assessment, the GLA and PI methods were found to be the most accurate (Neukum et al., 2008). This conclusion was based on validation of four different methods for a study area in Germany. The methods GLA and PI take into account the physical attenuation potential based on the thickness and permeability of overlaying strata, the PI method being developed especially for karst areas.

In Bulgaria, there are only few studies on groundwater vulnerability. Some of them are dated from 70–80s of the last century (Antonov and Raikova, 1978; Raikova et al., 1983) and other refers to application of the DRASTIC (Petkov and Petrov, 2005) and EPIK (Mihaylova et al., 2009) methods. The earliest research was based on European (mainly French) experience in this field, followed by practical application to a study area in central North Bulgaria and described by Benderev et al. (1992).

The present study aims at practical application of the PI method for evaluation and mapping of the intrinsic vulnerability for the Ogosta River Basin in northwestern Bulgaria where groundwater is widely used for rural water supply.

STUDY AREA DESCRIPTION AND HYDROGEOLOGICAL SETTING

The study area is located in northwestern Bulgaria (Fig. 1). The Ogosta River receives more than 40 tributaries with total catchment area of 3157 km^2, or 4231 km^2 including the watershed of the Skat River – the largest tributary flowing into the Ogosta River just before its mouth. The air temperature and precipitation values show clear zonality according to the altitude. The precipitation amount is below 500 mm for the lower part of the Ogosta River Basin, about 700 mm in the fore-mountain and up to 1200 mm in its mountain part (Koleva and Peneva, 1990).

All North Bulgaria belongs to the Danubian hilly plain developed on the Moesian Plate. In this lower part of the Ogosta River Basin, the relief is smooth, mantled by loess cover. The pre-Quaternary rock complex includes thick succession of Mesozoic and Cenozoic marine sediments within the Lom Depression (Dabovski et al., 2002). The Neogene formations dip in north-northwest direction and partly outcrop in erosion lows.

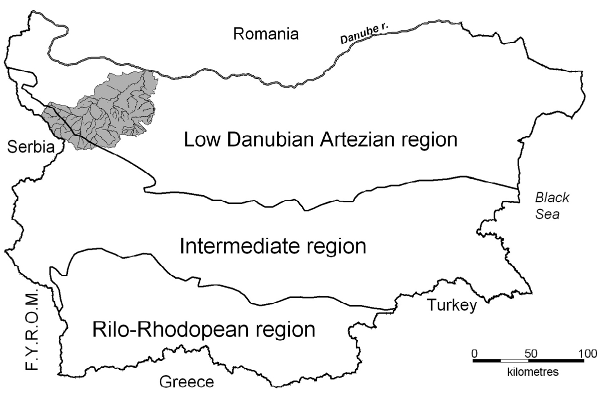

Fig. 1. Location of the Ogosta River Basin with respect to the hydrogeological regions of Bulgaria

The Ogosta River flows across large varieties of rocks from Precambrian to Quaternary age. A comprehensive review of the Quaternary deposits widespread in the northern part of the Ogosta River Basin is given by Angelova (2001, 2008a, b), along with several original maps for various formations.

From tectonic point of view, the upper mountain part of the river basin belongs to the West Balkan Unit and Fore-Balkan Unit, where mainly Paleozoic and Mesozoic igneous, sedimentary and metasedimentary rocks crop out. These basic tectonic structures are disrupted by faults and folds.

According to the Hydrogeological subdivision of this country, the upper mountainous part of the basin belongs to the West Fore-Balkan Subregion of the Intermediate Region (Fig. 1). Fissured groundwater is widespread here. In the lower part of the basin, within the Low-Danube Artesian Region, the porous aquifer media prevail. Within the Ogosta River Basin, groundwater both from porous and karst reservoirs is widely used for drinking water supply and industrial needs. Karst aquifers are the most important for groundwater supply in upland parts of the study area. Substantial porous aquifers in Neogene deposits are located in the plain part of the river basin where agriculture is the primary land use.

For the purposes of this study, the outcropping rocks are merged into nine groups according to the type of the groundwater reservoir (Table 1). The plain northern part of the study area is covered by the loess mantle (N 7 in Table 1) that is cut by river network with associated alluvial deposits (groundwater reservoir N 1). In the upper part of the basin, fissured reservoirs (N 2) and alternation of low permeable rocks and fissured reservoirs are usual.

The groundwater reservoir related to Neogene sands, sandstones and limestones (N 8 in Table 1) outcrops in the topographical lows along tributaries. General characteristics of the lithostratigraphy of the

Table 1
Description of the outcropping rocks and related groundwater reservoirs in the Ogosta River Basin

N	Type of groundwater reservoir	Lithological description	Geol. age
1	Porous reservoirs in alluvial and proluvial deposits	sand, gravel	Q
2	Fissured reservoirs in consolidated sedimentary, igneous and metamorphic rocks	sandstone, igneous and metamorphic rocks	Ptz, Pz, Mz, N
3	Karst reservoirs	limestone, marble	MZ
4	Low permeable rocks	marl, clay	P, J, K, N
5	Alternation of low permeable rocks and fissured reservoirs in consolidated sedimentary rocks	sandstone, siltstone, limestone	Pz, Mz
6	Low permeable eolian mantling sediments	clayey loess	Q
7	Porous reservoirs in mantling eolian sediments	loess	Q
8	Reservoirs in stratified porous media	sand, sandstone, limestone	N
9	Reservoirs in stratified porous media comprising low-permeable layers	sand, clay, sandstone, marl, limestone	N

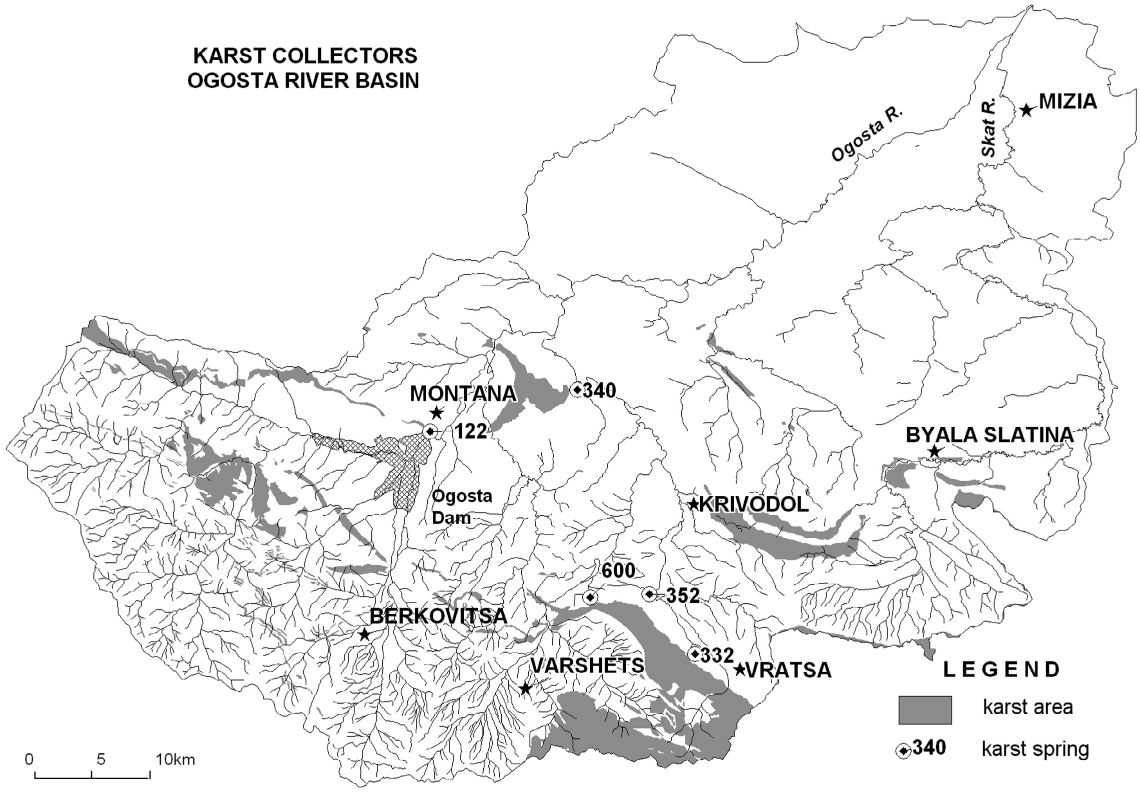

Fig. 2. Karst basins in the Ogosta River Basin and related major karst springs. The spring numbers are according to Hydrogeological network at National Institute of Meteorology and Hydrology

Neogene sediments in the study area are presented by Kojumdgieva and Popov (1988). The Neogene limestones are organogenic and primary porous and cavernous. Locally they show secondary karstification.

Several karst basins that refer to groundwater reservoir N 3 are located in the fore-mountain and mountain parts of the study area. They are built up from Mesozoic limestone and local Paleozoic marble bodies outcropping mainly in topographical highs as plateaus and are drained by springs (Fig. 2). Within the study area, the river network is denser in mountain areas and drains groundwater. Main features of the regional groundwater flow are evident from the map showing major equipotential lines in the study area (Vasileva et al., 2008).

Detailed description of the karst reservoirs including specific landforms and karst springs within the study area could be found in different publications (Troshanov et al., 1989; Spassov, 1998; Spassov et al., 1998; Benderev et al. 1999; Benderev, 2006). In local areas within the mountain part of the river basin, numerous caves and sinkholes are identified. Other areas, on the contrary, show low level of karstification. Some of the carbonate terrains are with continuous soil cover, and elsewhere bare karst is exposed.

The carbonate deposits of Mesozoic age outcropping within the fore-mountain part of the river basin are characterized with ascertained well-developed phreatic zone. Streams crossing such carbonate formations are susceptible to interact with groundwater and to be loosing upstream and gaining downstream. For several karst springs in the study area it was confirmed that they receive allogenic recharge and are fed additionally by river water (Antonov and Danchev, 1980; Spassov, 1998). The karst basins from Vratsa Mountain feed karst springs that refer both to Ogosta and Iskar River basins (Spassov et al., 1998).

In the uppermost mountain part of the river basin, a few carbonate bodies are identified in the southern part of the river basin with classical mountain karst where hundreds of caves are registered (Benderev, 2006) and groundwater flows through a conduit system. Bare karst with shallow soils contributes to intensive infiltration and direct inflow of surface waters. Generally such carbonate bodies are completely drained.

Forests and shrubs are widespread in the upper part of the basin. Post-mining sites in the mountain part may contribute to contamination of waters. In the lower plain part of the river basin, agricultural land use predominates. The threats to groundwater quality come from over-fertilizing of crops in past time. Another serious problem is related to contamination of waters from livestock manure (lagoons) which is usually preserved incorrectly. In addition, many settlements are without wastewater treatment plants. Nitrate is the most widespread contaminant (Vasileva et al., 2008).

METHODOLOGY

In choosing among available techniques for groundwater vulnerability mapping, the priority is given to recently developed and widely used in practice methods which are applicable to all kinds of aquifers including karst. The appropriate method has to consider the specific nature of karst aquifers and to rely on physical basis.

At the end of the 20th century, EPIK was the only existing karst-specific methodology (Zwahlen, 2003). The PI method developed by N. Goldscheider marked a further advance in assessing the degree of vulnerability of karst aquifers. This method requiring large amount of input data is here selected to evaluate intrinsic vulnerability for the Ogosta River Basin. The PI method was developed within the scope of COST Action 620 Project "Vulnerability and Risk Mapping for the Protection of Carbonate (Karst) Aquifers" (Goldscheider, 2003). It is based on the hazard – pathway – target model and is applicable for resource vulnerability mapping. The PI method served as a basis for further development of the conceptual model of the European Approach (Daly et al., 2002).

The choice of the PI method is based on good references from its users (for example, Neukum et al., 2008; Ravbar et al., 2009) and commonly available input data. The acronym stands for the two factors: protective cover (P) and infiltration conditions (I). The second factor expresses the degree to which the protective cover is bypassed as a result of lateral concentration of flow which is usual for sinking streams. The P factor indicates the effectiveness of the protective cover. It is calculated using a modified German (or the so-called GLA) method proposed by the German State Geological Survey (Hölting et al., 1995). The GLA method takes into account the fact that different sediments have specific natural attenuation capacity and requires commonly available information. The main idea is based on lithological description of each layer to use the respective proposed values of the factor and to multiply it by the thickness of the layer. This action is repeated up to the groundwater level. There is a special factor responsible for groundwater recharge value.

After the summation, the total score is found. Large scores refer to high protective effectiveness of the cover. The total protective function P_{TS} is calculated under the modified GLA method, using the following formula (Goldscheider, 2003):

$$P_{TS} = \left[T + \left(\sum_{i=1}^{m} S_i M_i + \sum_{j=1}^{n} B_j M_j \right) \right] R + A \qquad (1)$$

where T refers to topsoil (up to 1 m), S – to subsoil, B – to bedrock, M is the thickness of each layer in meters, R is the recharge factor, A is the artesian pressure factor, m is number of subsoil layers, and n – of the bedrock layers. The factor B presents a product $B = LF$, where L depends on the type of the bedrock and F – on the degree of its fracturing and/or karstification. The proposed values for the factors cover wide range of rocks (Goldscheider, 2003). The values presented in Table 2 encompass only rocks outcropping in the study area.

The input parameters are as follows:

- effective field capacity (eFC) of the topsoil up to 1 m depth;
- groundwater recharge;
- type of the subsoil;
- type of the bedrock and degree of its fracturing (and/or karstification);
- thickness of each layer above the groundwater level;
- presence or lack of permanent artesian conditions (1500 points are given for artesian pressure).

The factor R is assessed based on the value of the groundwater recharge. For the recharge rates <100 mm/y and 100–200 mm/y, it is equal to 1.75 and 1.50, respectively (Hölting et al., 1995, Margane et al., 1999).

The final value P_{TS} is called "total protective function". The total score values are classified into five classes of the P-factor (Table 3).

The I-factor is responsible to infiltration conditions and ranges between 0.0 and 1.0. The lowest values are assigned to swallow holes, its 10-m and 100-m buffer zones, followed by catchment of sinking streams and areas discharging inside karst area. To define the value of this factor, a three-step procedure is used (Goldscheider, 2003): (i) determination of the dominant flow process; (ii) determination of the I'-factor; (iii) determination of the I-factor. For any area discharging out of the karst area, the I-factor is equal to 1.0.

Table 2
Values of the factors T, S, L and F (Goldscheider, 2003)

eFC [mm] up to 1 m depth	T
>250	750
>200-250	500
>140-200	250
>90-140	125
>50-90	50
<50	0
Type of subsoil	**S**
Clay	500
Clay loam	300
Silt loam	220
Sandy loam	180
Sand	25
Lithology	**L**
Marl, siltstone	20
Sandstone, plutonite, metamorphite	15
Porous sandstone	10
Limestone	5
Fracturing	**F**
Non joined	25
Slightly joined	4
Slightly karstified	1
Moderately karstic	0.5
Strongly fractured or strongly karstified	0.3
Not known	1

Table 3
Determination of the P-factor (according to Goldscheider, 2003)

Score P_{TS}	Effectiveness of protective cover	**P-factor**	Example
0–10	very low	**1**	0–2 m gravel
>10–100	low	**2**	1–10 m sand with gravel
>100–1000	medium	**3**	2–20 m slightly silty sand
>1000–10 000	high	**4**	2–20 m clay
>10 000	very high	**5**	>20 m clay

The vulnerability map is prepared for the π-factor, which is a product of P and I factors (Goldscheider, 2003):

$$\pi = P \cdot I \quad (2)$$

RESULTS AND DISCUSSION

For the Ogosta River Basin, the protective efficiency of the cover for each groundwater reservoir from Table 1 has been evaluated using Eq. 1. For consolidated rocks, both their lithology and fracturing degree determine their protective effectiveness, and for unconsolidated rock – the type of the subsoil. The values of the factors used in this study are presented in Table 2 following the PI method.

According to the PI method, evaluation of the factor T is based on the effective field capacity of the topsoil (Table 2). An estimate of the eFC is available water capacity of the topsoil.

Available water capacity (AWC) is defined as the maximum amount of plant available water a soil can provide. It is an indicator of a soil's ability to retain water and make it sufficiently available for plant use. Available water capacity is the water held in soil between its field capacity and permanent wilting point.

Amongst Bulgarian soils, the highest values of the AWC are usual for Chernozems and Fluvisols (from 160 to 180 mm for the 1-m topsoil); the AWC is less for other thick soils with higher clay fractions (130–150 mm/m). Sandy soils in hilly regions of the country are characterized with AWC in the range 80–120 mm for the topsoil. In general, thick soils are characterized with higher available water capacity. In mountain regions, the topsoils are commonly thin with the least values of the AWC (Hershkovitch, 1968).

Fluvisols are common for alluvial deposits (groundwater reservoir N1 from Table 1). Typical, Calcareous and Leached Chernozems are developed on loess and loess-like sediments (N 6 and 7 from Table 1) in the plain part of the study area. This renders the value of the topsoil factor equal to 250 points for these soils (Table 2). The soils developed in mountain areas and particularly formed on limestone plateaus are thin (Koinov et al., 1998), and as a result would have lower values of the AWC and eFC.

For each groundwater reservoir, typical values of the factors and the resulting value of the total protective function P_{TS} are presented (Table 4). The last column in Table 4 refers to the class of the P-factor according to Table 3.

According to the results presented in Table 4, the effectiveness of the protective cover in the study area varies from high to low. Low permeable rocks (N 4) are characterised by high protective function. The loess cover (N 6 and 7) provides high protectiveness due to the presence of fine fractions and enhanced thickness. A moderate protective efficiency is assigned to the alluvial deposits along rivers (N 1) and some others including fissured and stratified media.

The Neogene limestones and sandstones (N 8) that outcrop in erosion lows are assigned to medium effectiveness of the protective cover. Removing of the soil cover (for example, in quarries) would result in change of the effectiveness of the protective cover for groundwater from medium to low.

The effectiveness of the protective cover for karst basins (N 3) may be low or medium (Table 4). It depends mainly on the level of karstification and the

Table 4
Typical values of the input factors and resulting values for the study area

N	**T**	**S**	**L**	**F**	**M**	**R**	P_{TS}	**P-factor**
1	125–250	180–220	–	–	1–2	1.75	500–950	**3**
2	50–125	–	15	1	3–10	1.75	170–480	**3**
3	0–125	–	5	0.3–1	5–10	1.50	12–90	**2**
				1	20–50–100	1.50	150–900	**3**
4	125	500	20	4–25	1–4	1.75	1300–3700	**4**
5	125	–	15; 20; 5	1–4	2–5	1.75	300–500	**3**
6	250	220–300	–	–	3–5–10	1.75	1600–5600	**4**
7	125–250	180–220	–	–	4–10–20	1.75	1500–8000	**4**
8	50–125	–	5; 10	1	1–5	1.50	100–260	**3**
9	50–125	25; 500	5; 20	1–4	1–5	1.75	100–900	**3**

Table 5
Legend for the vulnerability map and supporting maps (Goldscheider, 2003)

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

topsoil properties. Usually, shallow intrazonal soils are developed in karst terrains (Koinov et al., 1998). In this study, all this area is assigned to low effectiveness of the protective cover, with some underestimation. In karst areas autogenic recharge prevails for both groundwater reservoirs – N 3 and N 8. The first one is related to Mesozoic carbonate rocks that are located mainly at high topographic position in karst plateaus, where the dominant flow process is infiltration. The second one refers to Neogene formations that outcrop in erosion lows in valleys along tributaries. Here infiltration prevails as well, and the related streams are perennial. Allogenic recharge with sinking streams is not typical for the region.

According to the PI method, the I-factor responsible to the infiltration conditions is maximal both for areas discharging out of the karst area and for flat topographic catchments where infiltration predominates (Goldscheider, 2003). This means that no flow concentration and bypassing of the protective cover occurs in such areas irrespectively of the presence of karst terrains. The main type of the groundwater recharge is autogenic. Nevertheless, interaction of karst waters and streams occurs locally (for example, Spassov, 1998).

Thus, the I-factor is equal to 1.0 for almost all the study area. The only exception is found south to the two sub-parallel strips in the southeastern part of the study area (Mramoren karst basin). The surface runoff generated within this small catchment area is lost on entering the carbonate terrains. According to the PI-method, this area is characterized with I-factor <1.0. For this area with agricultural land use and the slope 7–14%, the I'-factor is about 0.4–0.6 that leads to the value of the I-factor in the range 0.8–1.0 for the area discharging inside karst area. This means a low or very low degree of bypassing (Table 5). Indeed, for P-factor equal to 3 (moderate protective function) and I-factor equal to 0.8, their product according to Eq. 2 lies in the same range of the vulnerability class compared to the case of the bypass lacking (I=1.0). The adopted scale does not allow delineation of the swallow holes and its 10-m and 100-m buffer zones, where substantial bypass of the protective cover occurs. Thus, irrespectively of the karst terrains in the study area, the I-factor is not important taking into account the used spatial scale of the study.

Table 6
Values of the factors and groundwater vulnerability in the Ogosta River Basin

N	**P-factor**	**I-factor**	**π-factor**	**Groundwater vulnerability**
1	3	1	3	moderate
2	3	1	3	moderate
3	2	1	2	high
4	4	1	4	low
5	3	1	3	moderate
6	4	1	4	low
7	4	1	4	low
8	3	1	3	moderate
9	3	1	3	moderate

The π-factor was evaluated based on Eq. 2. Low protective function of overlying layers results in high vulnerability of groundwater, and *vice versa* (Tables 5 and 6). Thereby the outcropping carbonate formations in karst basins (N 3) are classified as zones of high vulnerable groundwater. The areas covered by the loess formation and low permeable rocks refer to low vulnerable class. Alluvial and proluvial aquifers refer to moderately vulnerable class, along with others including Neogene sediments (limestones, sands and sandstones) that outcrop in erosion lows along rivers. The last may become highly vulnerable after removing of the soil cover.

Some parts of the areas designated here as highly vulnerable might be related to other categories based on detailed studies on the level of fissuring and karstification of carbonate rocks, soil cover properties, etc. Such refining is out of the scope of this paper.

A geological (scale 1:100 000) and a topographic map (scale 1:50 000) served as a basis for the vulnerability mapping. The respective map (Fig. 3) was prepared in GIS using MapInfo 7.0. The legend for the vulnerability map is presented on Table 5 for the π-factor. Most of the upper and middle parts of the Ogosta River Rasin are characterised with moderate vulnerability to pollution, and in the plain part of the study area low vulnerable class prevails. Large area referred to highly vulnerable class is located within the National park and the reserve "Vratsa karst". In general, 6.4 % of the study area is characterized with high vulnerability of groundwater to

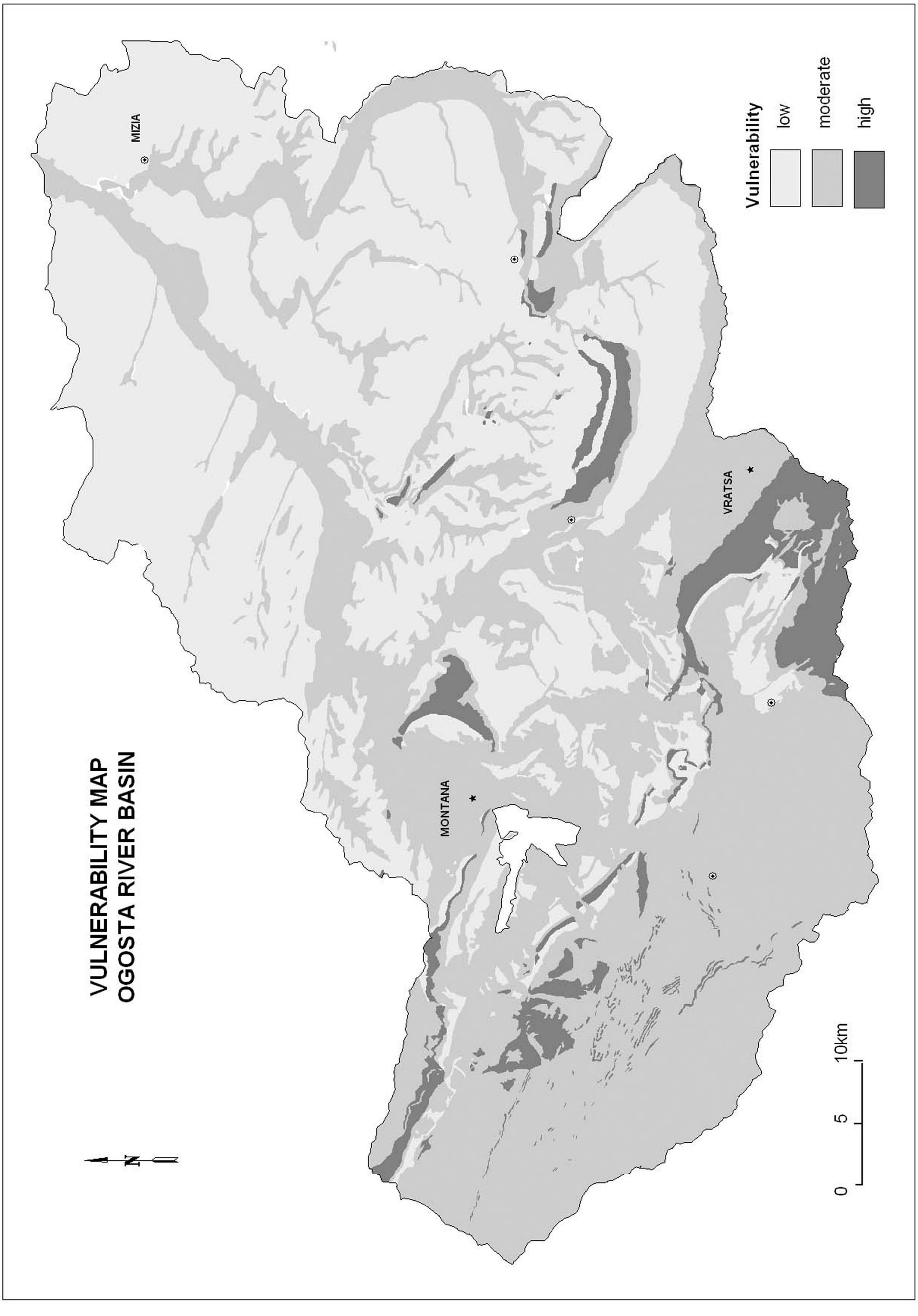

Fig. 3. Vulnerability map for the Ogosta River Basin

pollution. Moderate and low vulnerable classes cover 48.0 % and 45.6 % respectively. The groundwater vulnerability map refers to the shallowest aquifer. Yet, there are important deeper aquifers, mainly in the northern part of the study area. These Neogene aquifers are well protected from pollution by the loess formation.

Human activities and hazards are unevenly distributed over the study area. They are concentrated in the vicinity of towns and villages. Many settlements are located along the river courses; most of them are without wastewater treatment plants. As a result, alluvial aquifers are exhibited to enhanced hazard, and consequently, the risk of contaminations for alluvial groundwater is high, irrespectively of its moderate vulnerability.

The "European approach" requires the quality assurance or validation assessment based on data not used in the groundwater-vulnerability-assessment method, for example, hydrograph, graphs of chemical properties, bacteriology, tracer techniques, or other (Daly et al., 2002). The validation of the vulnerability map is based using data on groundwater quality, especially pollution with nitrate, nitrite and ammonium. The respective data are stored in the reports from previous groundwater studies. Most of the water samples are from alluvial aquifers with usual signs of pollution. Another useful information is related to spring flow variation, chemical composition and turbidity of karst waters. Karst springs show high variation of the discharge, pollution by nitrate and other contaminants and sometimes turbidity of karst waters which are signs of groundwater highly vulnerable to pollution. Thus, the vulnerability to pollution is confirmed by the periodic contamination of the groundwater.

We recommend checking the actual land use practice in areas designated as vulnerable. To avoid entering of pollutants in karst waters, inappropriate land uses should be stopped. Karst groundwater presents a precious resource and is used for rural water supply. In response to enhanced water needs, there are plans for better utilization of the karst groundwater in the region (Spassov et al., 1998). This resource should be efficiently safeguarded.

CONCLUSIONS

For the Ogosta River Basin, intrinsic vulnerability of groundwater is evaluated and mapped. The PI method is chosen due to presence of the specific karst features in the landscape within the study area. The results show that the level of vulnerability varies from high to low. The natural protection of groundwater against contamination is the most effective in the loess plateaus between river valleys and for outcropping low permeable rocks. Important groundwater resources related to alluvial sediments are found to be moderately vulnerable to pollution. Locally they show evident signs of contamination as a result of high human pressure.

The groundwater related to mainly Mesozoic karst basins is highly vulnerable to pollution. Despite the presence of karst terrains, they do not contribute considerably to bypassing of the protective cover, as the dominant flow process there is infiltration. The areas with highly vulnerable groundwater are located in topographical highs and partly enter in protected areas.

The Neogene sediments (limestones, sands, sandstones) that outcrop in erosion lows along rivers are classified as zones of moderate vulnerability. Removing of soil cover would result in high vulnerability of groundwater to pollution in the respective areas.

The prepared vulnerability map is related to the uppermost aquifer. It may be used for groundwater resource protection and land use planning in the Ogosta River Basin. The map provides a general overview for the study area and could not replace detailed studies. The groundwater protection especially in karst areas is in close relation to land use. It is recommended to pay attention to actual land use within vulnerable areas and to stop inappropriate activities. These areas make a reserve for future water supply.

Acknowledgements

The study is made within the frame of the scientific cooperation between Bulgarian and Russian Academies of Sciences (bilateral agreement of the BAS). We acknowledge both the reviewers and the editors for their important contributions in improving the quality of the manuscript.

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