Geological Quarterly, 2017, **61** (1): 166–176
DOI: http://dx.doi.org/10.7306/gq.1331

Groundwater vulnerability based on four different assessment methods and their quantitative comparison in a typical North European Lowland river catchment (the Pliszka River catchment, western Poland)

Piotr HERMANOWSKI[1, *] and Tomasz IGNASZAK[2]

[1] Adam Mickiewicz University, Faculty of Geographical and Geological Sciences, Institute of Geology, Maków Polnych 16, 61-606 Poznań, Poland

[2] ul. Borówkowa 2, 62-002 Suchy Las, Poland

Hermanowski, P., Ignaszak, T., 2017. Groundwater vulnerability based on four different assessment methods and their quantitative comparison in a typical North European Lowland river catchment (the Pliszka River catchment, western Poland). Geological Quarterly, **61** (1): 166–176, doi: 10.7306/gq.1331

The assessment of groundwater vulnerability is a crucial part of planning and water management because it can identify areas where aquifers are more susceptible to contamination. Depending on the vulnerability assessment method, the results can differ significantly. Consequently, different methods can provide ambiguous information that could further influence decision-making processes in planning or water management. For the Pliszka River catchment, the intrinsic groundwater vulnerability of the uppermost aquifer was estimated using four different methods: DRASTIC, GOD, and two methods that are based on empirical formulas of water residence time in an unsaturated zone. The input data include a series of thematic maps supplemented by 1,322 shallow borehole profiles and laboratory tests of samples collected in the course of fieldwork. The collected data were processed in GIS software, and the results of each method were mapped in high resolution. The resulting maps of groundwater vulnerability were then quantitatively compared to validate their applicability for the assessment of groundwater vulnerability in a typical North European Lowland river catchment. The maps generated by the DRASTIC and GOD methods are dominated by areas with moderately high (54.6 and 48.4%, respectively) and moderate groundwater vulnerability (32.7 and 32.3%, respectively). No areas of high groundwater vulnerability are present. One of the water residence time methods provides results similar to the previous methods at the catchment scale, and one method yields high groundwater vulnerability values for the majority of area.

Key words: vulnerability mapping, groundwater protection, Pliszka River, Poland.

INTRODUCTION

Over the last 30 years, many methods have been proposed to determine intrinsic groundwater vulnerability. Certain methods, such as GOD (Foster, 1987), DRASTIC (Aller et al., 1987) and SINTACS (Civita, 1994), have simple structures and can be used in any hydrogeological conditions. Others are limited to unconsolidated sediments, e.g. AVI (Van Stempvoort et al., 1993), or karst aquifers, e.g. COP (Vías et al., 2006) and EPIK (Doerfliger and Zwahlen, 1997). Additionally, numerical hydrogeological modelling can be applied to assess groundwater vulnerability. Recently, numerous more sophisticated methods have been developed by modifying previous parametric methods (e.g., Lee, 2003; Dixon, 2005; Zuquette et al., 2009; Hernández-Espriú et al., 2014; Makonto and Dippenaar, 2014). The optimal method depends mainly on the data available and the specific conditions of the study area, so it requires very detailed geological surveying. The different methods take into account different physical properties in the soil and different hydrogeological parameters in the unsaturated and saturated zone (cf., Gogu and Dassargues, 2000; Civita, 2010). In general, the methods can be divided into index methods, which consider the most significant parameters for groundwater vulnerability assessment, and process methods, which estimate the travel time of contamination (Ligget and Talwar, 2009).

Groundwater vulnerability maps are used by Water Management Authorities in the planning process because they are important tools for groundwater protection. Therefore, the maps should be clear and also treated as initial information for decision makers (Foster et al., 2013). However, depending on the used method, different parameters will be taken into consideration and the resultant maps can provide different spatial distributions of vulnerability. Moreover, vulnerability maps present classes of groundwater vulnerability that refer to a numerical index or the travel time required for the pollution to enter the aquifer. Consequently, these maps may not be comparable and can be confusing for decision makers. The index methods provide a relative indication of the vulnerability (Ligget and Talwar, 2009), but they should also refer to the travel time of potential contamination through the unsaturated zone. Nevertheless, in certain

* Corresponding author, e-mail: piotr.hermanowski@amu.edu.pl

Received: March 11, 2016; accepted: April 28, 2016; first published online: December 1, 2016

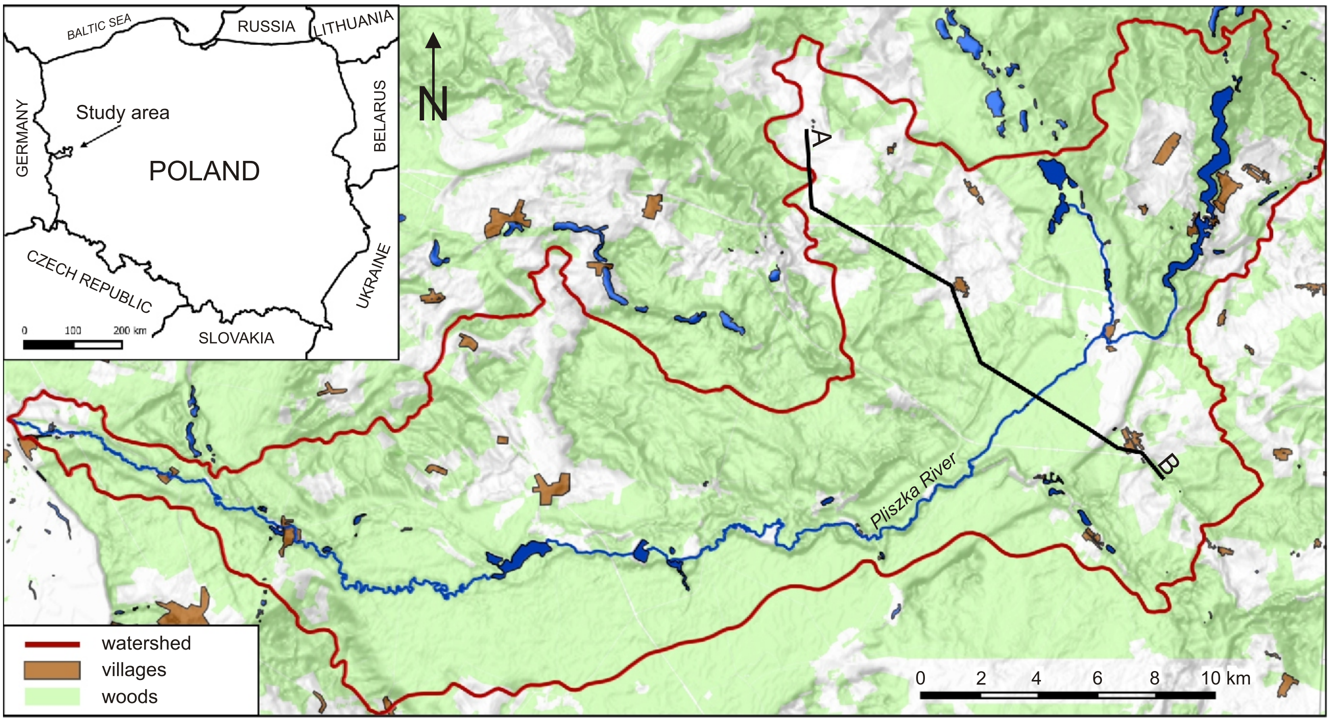

Fig. 1. Location of the Pliszka River catchment

The background presents the morphology of the study area; line A–B indicates location of the hydrogeological cross-section (Fig. 3)

cases, these methods can still be misleading because they do not analyse all physical processes in aquifers (Debernardi et al., 2008). Vulnerability maps reflect the sensitivity of aquifers to anthropogenic actions (Vrba and Zaporozec, 1994); this parameter could also be described as the natural ability of deposits in the unsaturated zone to purify water through the filtration process. Thus, a crucial role is played by factors that influence the duration of fluid percolation through the unsaturated zone, which in turn depends on different possible feedbacks or synergies between several hydrogeological parameters. Vias et al. (2005) compared results obtained from four index methods for diffuse flow in a carbonate aquifer and noticed that they generated maps that were different but shared generally similar spatial distributions of vulnerability. However, in certain areas, different methods may also provide thoroughly different results, rendering the results unreliable (Ravbar and Goldscheider, 2009).

The aim of this study is to assess the intrinsic groundwater vulnerability of a typical North European Lowland river catchment using four different assessment methods, including index methods and process methods. Moreover, this paper attempts to quantitatively compare the results of applied groundwater vulnerability methods in order to validate their applicability.

STUDY AREA

The Pliszka River is located in western Poland and is a second-rank tributary of the second-longest river in Poland, the Odra River. The river is approximately 59.5 km long and originates at Małcz Południowy Lake at an elevation of 101.3 m a.s.l. The difference between its source and mouth is approximately 78 m, which means that its average slope is relatively high in relation to other European rivers at this latitude. However, the final approximately 15 km features sections of braided river and sections where the river and the valley are wider and include adjacent swampy areas. The catchment area of the Pliszka River is approximately 441 km^2. About 85% of the catchment area is covered by woods. Additionally, only small villages surrounded by agricultural areas are located in the catchment (Fig. 1).

The study area is fully covered by Quaternary deposits that rest on Neogene clays and silts interbedded with lignite. The thickness of the Quaternary deposits is approximately 61 to 226 m, with an average thickness of ca. 123 m (Sztromwasser, 2005). These deposits are primarily glacial and fluvioglacial sediments deposited mainly during the Weichselian Glaciation but also in the Elsterian and Saalian glaciations. Consequently, the lithology of the Quaternary deposits is represented mainly by fine to coarse sands, tills and gravels. In certain locations, silts and clays are also observed. The uppermost Quaternary deposits are dominated by fluvioglacial (outwash) and glacial sands and gravels that cover approximately 80% of the area. In the northeastern part of the area, the surficial lithology is dominated by Weichselian till. Along the Pliszka River, the valley bed is composed of Holocene fluvial sands and local peats and lacustrine deposits (Fig. 2; Sztromwasser, 2005).

The Quaternary hydrogeological unit contains three aquifers that are separated by low-permeability tills and silts. The lowest Quaternary aquifer is composed of fluvioglacial sands and gravels of the Elsterian Glaciation and Holstenian interglacial period. This unit has discontinuous characteristics and is recognized only locally in erosional troughs and in sandy lenses. The intermediate Quaternary aquifer is composed of Eemian sands and gravels and has an average thickness of approximately 15 m. The highly permeable sediments of this layer are often interbedded with low-permeability silts and clays. The uppermost aquifer occurs along river valleys in fluvial and fluvioglacial deposits and in outwash sediments associated with the Weichselian Glaciation. The thickness of this aquifer is between 2 and 40 m (Fig. 3). The water table depth is from 0.5 m

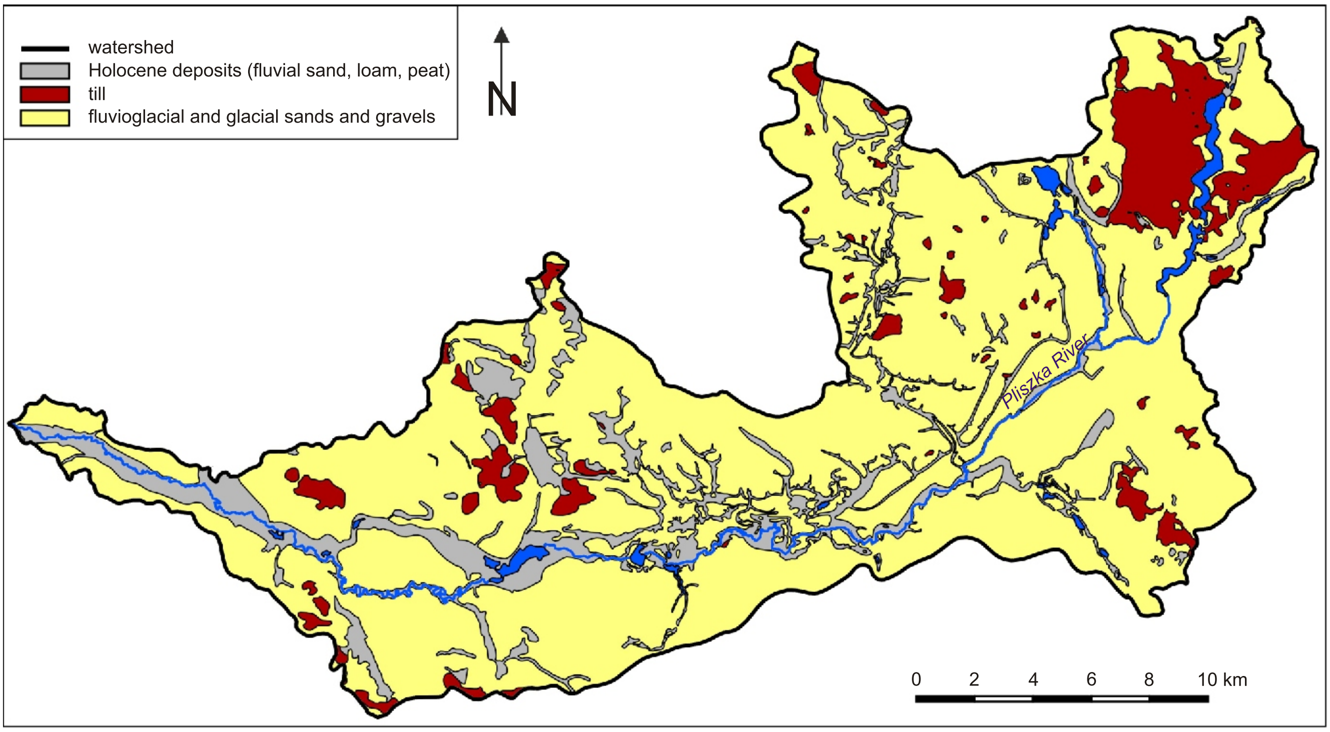

Fig. 2. A simplified geological map of the Pliszka River catchment

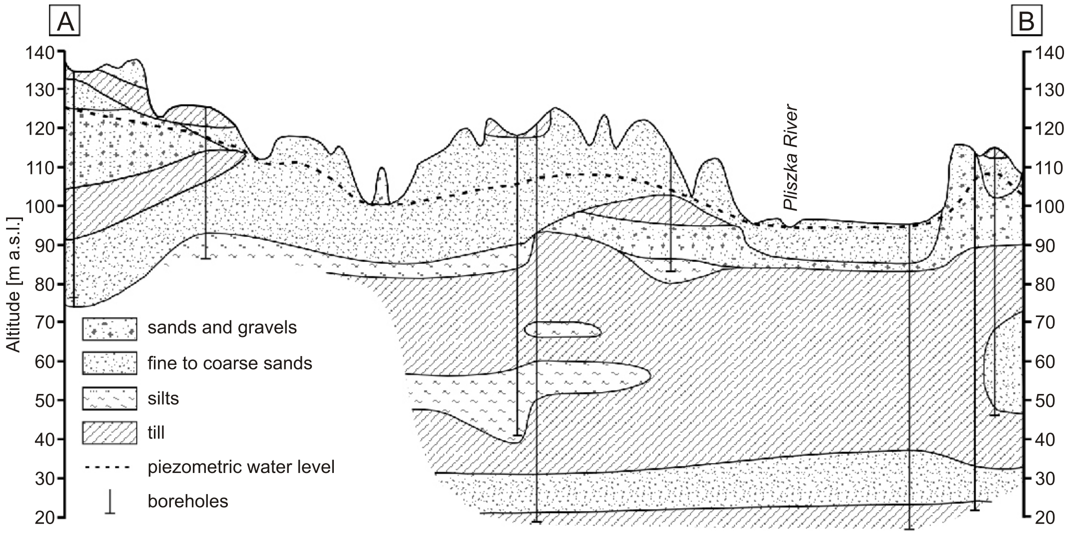

Fig. 3. Hydrogeological cross-section (for location see Fig. 1)

to several metres below surface level in areas where it is unconfined, and several tens of metres (to the top of aquifer) in areas where the aquifer is confined by low-permeability sediments (primarily Weichselian till). The aquifers are directly recharged by infiltration from the surface or through inter-aquifer flow.

METHODS

The most commonly used method developed for evaluation of groundwater vulnerability is DRASTIC (Aller et al., 1987), which has been applied to a number of groundwater basins throughout the world. This method is based on seven parameters of primary importance in terms of potential for groundwater pollution: depth to water (*D*), net recharge (*R*), aquifer media (*A*), soil media (*S*), topography (*T*), impact of the vadose zone (*I*), and hydraulic conductivity (*C*). Each parameter has an assigned weight (D_w, R_w, A_w, S_w, T_w, I_w and C_w, respectively) representing its importance, and each one is subdivided into ranges (D_r, R_r, A_r, S_r, T_r, I_r and C_r, respectively) which reflect the potential of contamination (Table 1; for details see Aller et al., 1987). With the required data, the vulnerability index (VI_{DR}), which differentiates areas of varying groundwater pollution potential, is expressed as follows:

$$VI_{DR} = D_rD_w + R_rR_w + A_rA_w + S_rS_w + T_rT_w + I_rI_w + C_rC_w \quad [1]$$

Table 1

Rating values of the vulnerability parameters for the DRASTIC method

Parameter	Weight		Rating
D	Depth to water	5	1–10
R	Net recharge	4	1–10
A	Aquifer media	3	1–10
S	Soil media	2	1–10
T	Topography	1	1–10
I	Impact of the vadose zone	5	1–10
C	Hydraulic conductivity	3	1–10

Another method used in this study to evaluate groundwater vulnerability is the GOD method (Foster, 1987). This model involves three main parameters: groundwater hydraulic confinement (*G*), lithology and consolidation of the overlying strata (*O*), and depth to water (*D*). For each parameter, the rating should be assessed based on the rating method (Fig. 4; for details see Foster, 1987). Then, the vulnerability index (VI_{GOD}) is calculated as follows:

$$VI_{GOD} = GOD \qquad [2]$$

The crucial issue in terms of intrinsic groundwater vulnerability is the time required for water to infiltrate from the surface through the unsaturated zone to the water table. If the intrinsic groundwater vulnerability is considered, the infiltration time reflects arrival of compound to the groundwater pollution potential. The infiltration time (*t*) can be calculated as follows:

$$t \quad \frac{m}{I_n} \qquad [3]$$

where: *m* – depth to the water table (thickness of unsaturated zone), – *moisture content, and* I_n – net infiltration (Bachmat and Collin, 1987; Schwartz, 2006).

Equation [3] provides a relatively fast and simple method for assessing intrinsic groundwater vulnerability. This formula assumes only a piston-flow model when calculating the mean fluid travel time. In the literature, other formulas that can determine the potential travel time of pollution from the surface to the groundwater-saturated zone exist, but they are often modifications of equation [3]. Furthermore, these formulas sometimes require more input data and yield a more complex approach.

Another formula for estimating the infiltration time through the unsaturated zone includes the thickness of unsaturated zone (*m*), moisture content ( ), net infiltration rate (I_n) and vertical hydraulic conductivity (*K'*), and is expressed as follows (Macioszczyk, 1999):

$$t \quad \frac{m}{\sqrt[3]{I_n^2 K'}} \qquad [4]$$

The DRASTIC and GOD methods represent index-based methods in which the considered parameters represent physical properties observed in the study area. The vulnerability index is calculated and then transformed into categories of vulnerability. The two methods that are based on empirical formulas [equations 3 and 4] are examples of process-based methods which use deterministic approaches to estimate infiltration times through the unsaturated zone (Liggett and Talwar, 2009). Consequently, a time instead of an index value is calculated, and the obtained values must be linked to a qualitative vulnerability index. To compare maps of intrinsic groundwater vulnerability, each vulnerability method was divided into 5 classes with prescribed relationships (Table 2). The infiltration travel-time classes are differently divided in literature: from 1 week to 1 year (Debernardi et al., 2008); from 0 years to >10,000 years (Anornu and Kabo-bah, 2013); from 0 years to >30 years (Krogulec, 2006); from <5 years to >100 years (Witczak et al., 2007); from <1 year to > 25 years (Schwartz, 2006). If real values are given in the text, such as years, results remain comparable.

Each of the equations described here represents a different method for assessing the intrinsic groundwater vulnerability. The evaluation of intrinsic groundwater vulnerability requires

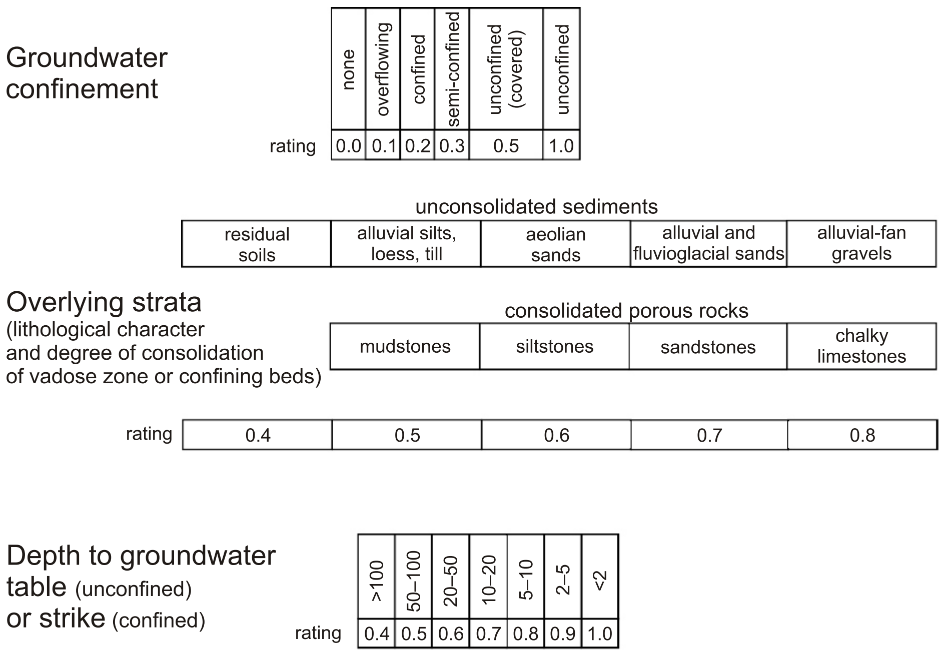

Fig. 4. Aquifer vulnerability components and rating values of the vulnerability parameters for the GOD method (Foster and Hirata, 1988 – modified, after Gogu and Dessargues, 2000)

Table 2

Groundwater vulnerability classes and their relationships to the indexes and water infiltration times

Vulnerability class	DRASTIC index (-)	GOD index (-)	Infiltration time (years)
High	>200	0.71–1.00	<5.0
Moderately high	161–200	0.51–0.70	5.0–25.0
Moderate	131–160	0.31–0.50	25.1–50.0
Moderately low	101–130	0.11–0.30	50.0–100.0
Low	<100	0.0–0.10	>100.0

the collection of significant amounts of data which are used directly or processed further depending on the assessment method. This study decided to compare four different assessment methods. Therefore, numerous map sheets were collected: 4 geological maps; 7 general hydrogeological maps; 4 hydrogeological maps of the uppermost aquifer; 6 hydrographic maps (all at a scale of 1:50,000); 2 soil maps at a scale of 1:100,000; a map of land development, and a digital terrain model. The data obtained from these maps were supplemented by 1,322 borehole profiles provided by the Polish Geological Institute. Moreover, in the field, 40 hand auger borings up to 2 m deep were made (Fig. 5), and 80 samples of soils and sediments from the unsaturated zone were collected. The samples were tested in the laboratory to determine the grain-size distribution, hydraulic conductivity and moisture content. The data were interpolated on a grid of rectangles, in which each cell is 50 50 m, and the final grid contains 175,801 nodes. GIS software was used to process the collected data to perform overlay analyses, which are very useful in examining spatial patterns (e.g., Wang et al., 2007; Khan et al., 2014).

RESULTS

The spatial distribution of each parameter used for the DRASTIC and GOD methods were mapped in order to show the variability in the parameters. Additionally, when compared with the vulnerability maps, the parameter maps provide information about the significance of the presented factors.

DRASTIC METHOD

The DRASTIC method requires information on the seven primary parameters that affect the groundwater pollution potential (Table 1). The results of the parameters mapping are discussed below.

The map of the depth to water table (Fig. 6A) shows that almost a quarter (24.7%) of the catchment area's water table is at a depth between 1.5 and 4.5 m. Moreover, in 35.9% of the study area, the water table is at a depth of 4.5 m. Such shallow water table depths occur along the Pliszka River valley and its tributar-

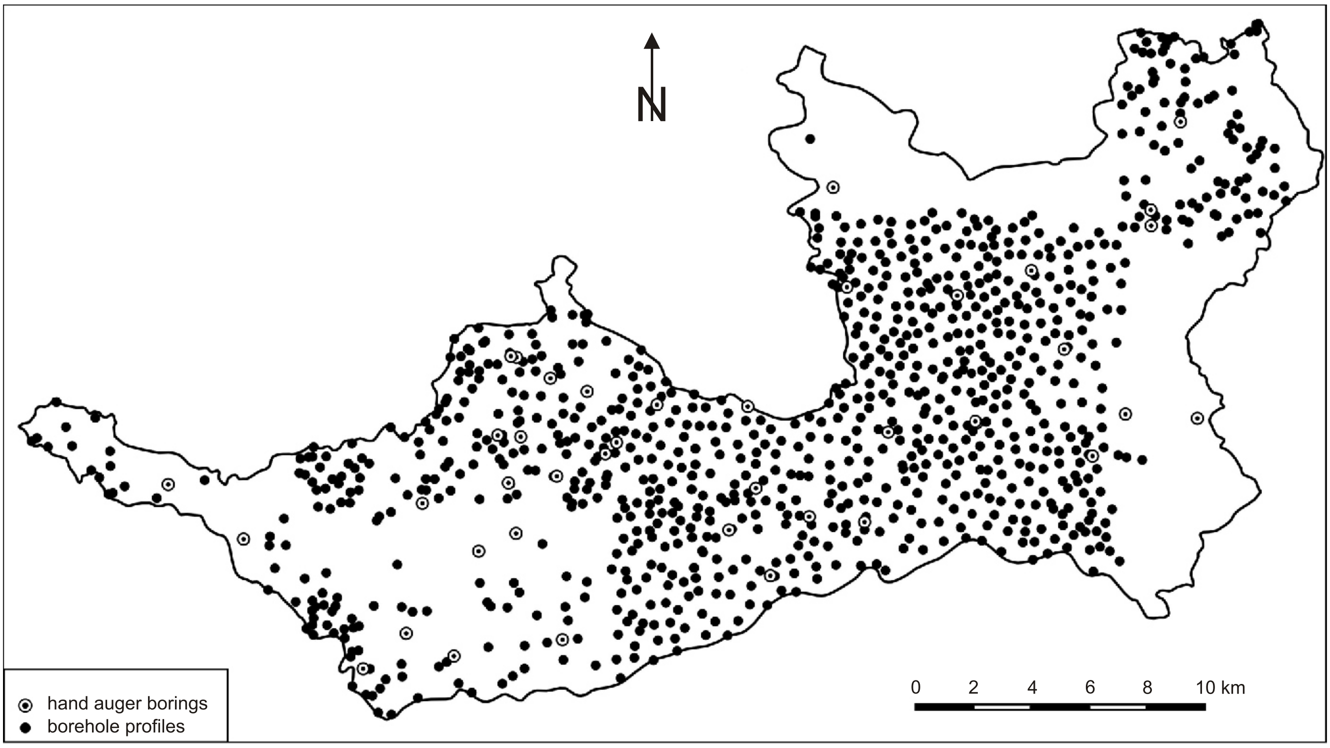

Fig. 5. Spatial distribution of the boreholes used in this study

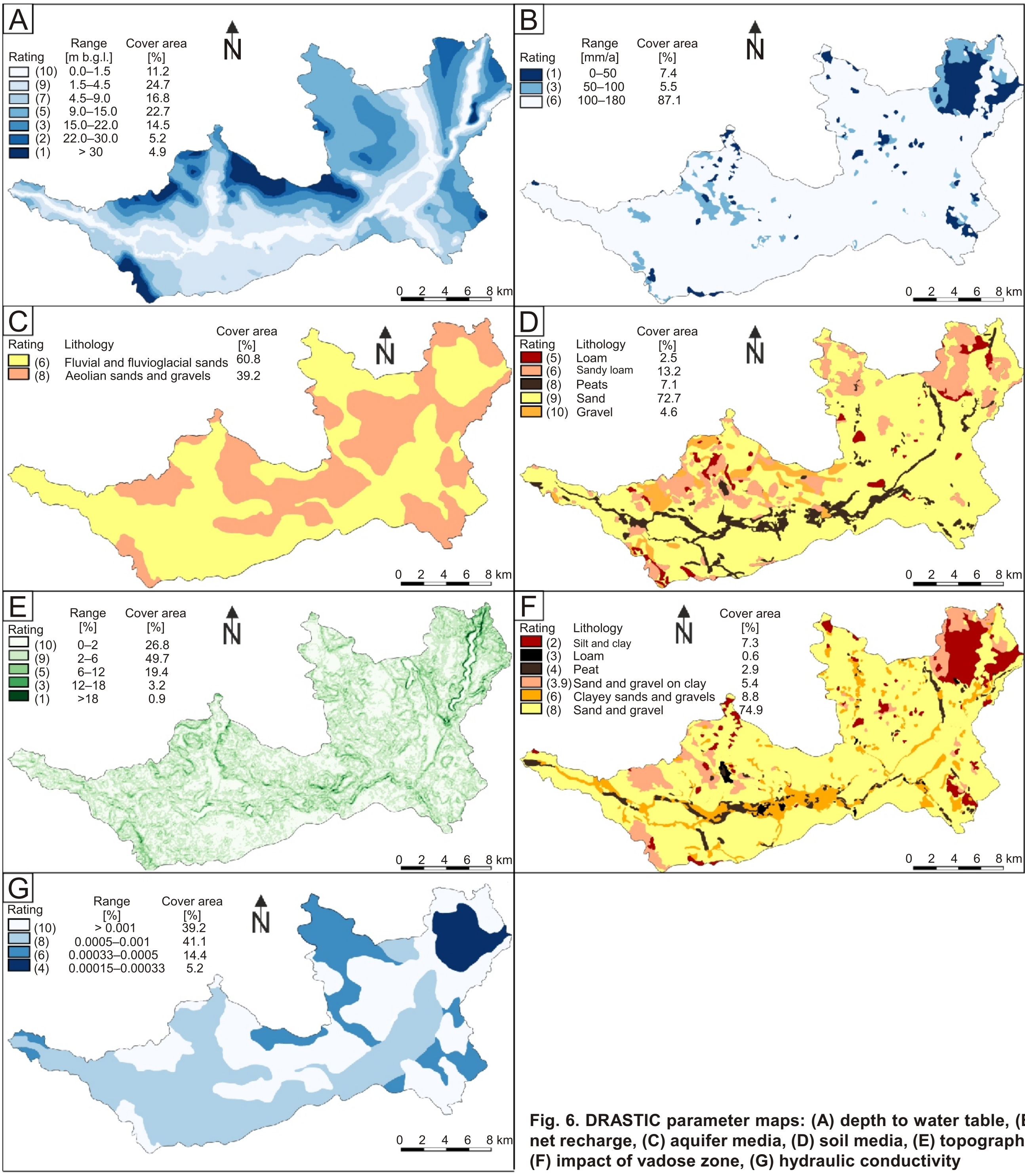

Fig. 6. DRASTIC parameter maps: (A) depth to water table, (B) net recharge, (C) aquifer media, (D) soil media, (E) topography, (F) impact of vadose zone, (G) hydraulic conductivity

ies, reflecting the general morphology of the study area. In almost 5% of the area, the depth to water is >30 m. These conditions indicate longer travel times of potential pollution from the ground surface and, consequently, lower groundwater vulnerability. The net recharge values were obtained multiplying the mean annual precipitation value for the study area and effective infiltration coefficient depending on types of sediments in the unsaturated zone (Witczak et al., 2007). For the majority of the area (87.1%), the net recharge is estimated to be between 100 and 180 mm/a (Fig. 6B), and these values correspond to the areas with highly permeable sands and gravels. Lower net recharge values occur primarily in areas where the aquifer is confined by a low-permeability till. In the study area, only unconsolidated sediments act as aquifers. These sediments were divided into fluvial and fluvioglacial sands and gravels and aeolian sands and gravels. This division allowed us to distinguish two types of aquifer media (Fig. 6C). The catchment area is dominated by aquifers consisting of fluvial and fluvioglacial sediments (60.8%). Five different types of soil media were distinguished in the study area (Fig. 6D). The predominant type is sandy soil which covers >72% of the area. The predominance of this soil media indicates a potentially rapid vertical movement of contamination. Topography determines the surface runoff potential and has the lowest weight among the DRASTIC pa-

Table 3

Percentages of the study area represented by different vulnerability classes based on the different methods

Vulnerability class	Percentage of the study area			
	DRASTIC	GOD	Bachmat and Collin (1987; eq. 3)	Macioszczyk (1999; eq. 4)
High	0.0	0.0	49.4	95.2
Moderately high	54.6	48.4	37.3	4.7
Moderate	32.7	32.3	3.9	0.1
Moderately low	8.1	7.5	4.6	0.0
Low	4.5	11.9	4.8	0.0

rameters. In this case, approximately 50% of the study area is dominated by slopes between 2 and 6% (Fig. 6E). The characteristics of the vadose zone have a significant influence on the infiltration of meteoric water, and the lithology of the vadose zone in the study area shows great potential for water infiltration. Approximately 75% of the area is composed of sands and gravels (Fig. 6F). Another parameter that emphasizes the widespread occurrence of highly permeable sediments is hydraulic conductivity (Fig. 6G). More than 80% (approximately 353 km^2) of the study area features an estimated hydraulic conductivity greater than 5 10^{-4} m/s, and almost half of this area features values greater than 1 10^{3} m/s.

The final vulnerability index values calculated using the DRASTIC method for the grid of rectangles (50 50 m) range from 66 to 196. No areas are illustrated where the index value indicates a high vulnerability of the uppermost aquifer (index value >200). The final map shows that the moderately high vulnerability zone occurs principally along the Pliszka River and its tributaries. This region covers approximately 54.6% of the area (approximately 241 km^2; Table 3). The moderate groundwater vulnerability zone occurs in the northern and eastern parts of the study area. This zone covers almost 33% of the area (approximately 144 km^2; Table 3). The moderately low and low vulnerability zones were together estimated to cover approximately 56 km^2 (approximately 36 and 20 km^2, respectively) and are localized mainly in the northeastern portion of the catchment, although the moderately low class is also observed in the western part. The low vulnerability class is almost completely absent.

GOD METHOD

In the GOD method, three parameters with prescribed ratings are taken into consideration (Fig. 4), and they are multiplied to yield groundwater vulnerability values.

The uppermost aquifer is unconfined across >76% of the study area (approximately 336 km^2). In greater than 15% of the area, the aquifer is confined or semi-confined (Fig. 7A); these areas are usually associated with the locations of till (Fig. 2). The degree of confinement is strictly linked to the hydraulic conductivity of the till, which can vary by several orders of magnitude depending on the sand and gravel contents and the presence of fractures (e.g., Allred, 2000). These factors significantly influence the amount of effective recharge (Fitzsimons and Misstear, 2006). The lithological characteristics of the aquifer's overlying strata (Fig. 7B) are similar to the map that illustrates the impact of the vadose zone in the DRASTIC method (Fig. 6F). However, in this case, fewer types of lithologies are considered. Nevertheless, this map again shows that the over-

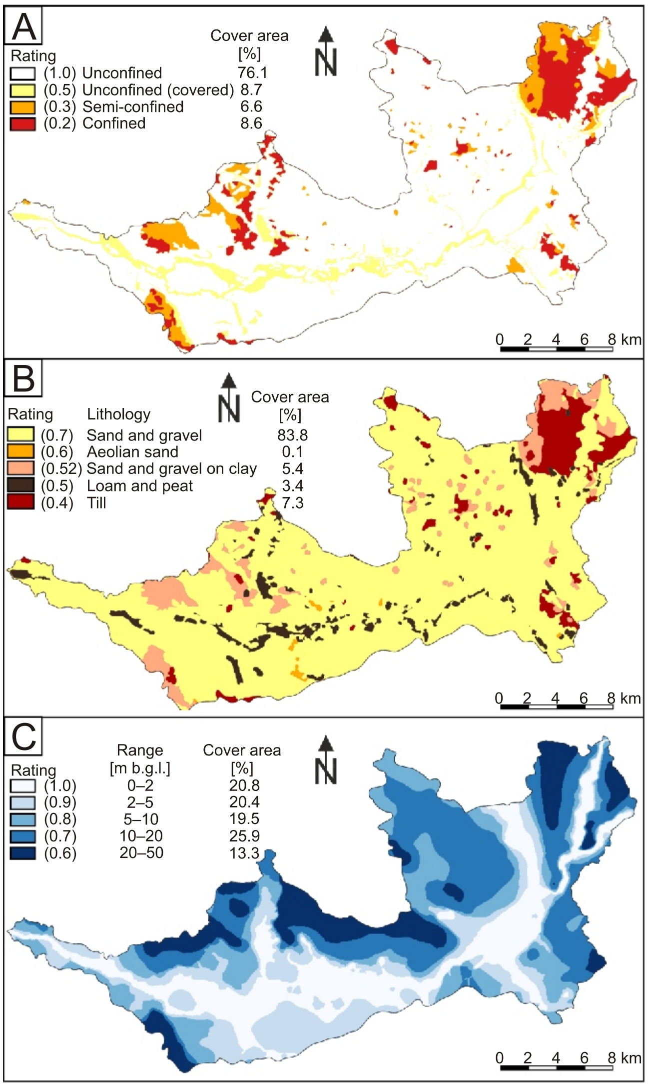

Fig. 7. GOD parameter maps: (A) groundwater hydraulic confinement, (B) lithology and consolidation of overlying strata, (C) depth to water

lying strata are dominated by fluvioglacial sands and gravels. The depth to groundwater is also one of the parameters used in the DRASTIC method, but the distinguished ranges differ slightly; consequently, the obtained map of this parameter also differs slightly (Fig. 7C).

The final vulnerability map derived using the GOD method (Fig. 8B) shows intrinsic groundwater vulnerability conditions that are similar to those shown in the map produced using the DRASTIC method. The moderately high vulnerability zone covers approximately 48% (213 km^2) of the study area (Table 3). The moderate and moderately low vulnerability zones were estimated to cover approximately 32% (142 km^2) and 7% (33 km^2) of the area, respectively. Almost identical values were estimated using the DRASTIC method (Table 3). The low groundwater vulnerability zone covers approximately 52 km^2 and is localized in the eastern and western portions of the catchment.

PROCESS-BASED METHODS

Calculated using equations [3] and [4], the infiltration times through the unsaturated zone were also classified into five groundwater vulnerability classes according to Table 2.

Using equation [3], approximately 49% of the area features infiltration times of <5 years; thus, the groundwater vulnerability is described as high (Fig. 8C). The moderately high class covers approximately 37% of the area. These values suggest that relatively high groundwater vulnerability zones (i.e., the high and moderately high classes) dominate the Pliszka River catchment. The moderate, moderately low, and low vulnerability classes cover only approximately 3.9, 4.6 and 4.8%, respectively (Table 3). In this case, the location of the high groundwater vulnerability zone corresponds to the location of the moderately high vulnerability zone obtained using the DRASTIC method.

The results of equation [4] suggest that the infiltration time for any given point in the study area is <28 years. The infiltration times for the entire area range between 18 days and 28 years. Moreover, >95% of the area features infiltration times of <5 years. Therefore, the groundwater vulnerability map is dominated by high-vulnerability areas (Fig. 8D). In the remaining areas, the vulnerability is estimated to be moderately high (4.7%) and moderate (0.1%). No areas with moderately low or low vulnerability classes were observed (Table 3).

DISCUSSION

Evaluation of groundwater vulnerability has been done based on four different methods. Moreover, these methods are based on different parameters that can be used to calculate a vulnerability index or a fluid travel time through the unsaturated zone, both of which aim to assess groundwater vulnerability. These parameters variously influence the final result, and one parameter can dominate over the others in certain cases, leading to particular results.

The obtained maps of groundwater vulnerability differ from each other, but general similarities also exist. These similarities are especially noticeable in the maps generated by the DRASTIC and GOD methods (Fig. 8A, B). The spatial distribution of vulnerability classes is also similar in the map produced by the process method based on equation [3], which was proposed by Bachmat and Collin (1987; Fig. 8C). Similar observations, i.e. the same distribution of spatial variability of vulnerability, were reported by Vías et al. (2005), but that study compared only index methods.

A thoroughly different map was obtained using equation [4] (Macioszczyk, 1999). This map shows the high groundwater vulnerability class covering the majority of the study area (Fig. 8D). According to this map, even in the northeastern part of the area where the aquifer is confined by at least 15 m of till, the water travel time from the surface to the confined water table is <25 years, resulting in an assignment of moderately high vulnerability. This travel-time value is rather unrealistic, even considering the wide range of hydraulic conductivity values for till, which vary in the range of 10^{-12}–10^{-6} m/s (e.g., Davis, 1969; Domenico and Schwartz, 1998) depending on the sand content. Other unrealistic values are also observed throughout the area, which suggests that this method yields misleading information. However, we do not discredit this method because it may be applicable in certain specific areas or conditions which were not analysed in this study. In this case though, it is unreliable and is excluded from further discussion.

Although the obtained maps are generally similar in their spatial distribution, the actual spatial correlation of the assessed vulnerability classes were analysed between the maps (Table 4). The analysis assumed perfect correlation if, at the particular point of the study area, groundwater has the same class or corresponding class of vulnerability (i.e., the highest estimated class in GOD corresponds to the highest class in process-based methods). The obtained values show relatively good correlation (0.8) between the DRASTIC and GOD methods. The correlation coefficients are also satisfactory between the Bachmat and Collin (1987) method [equation 3] and the DRASTIC and GOD methods (0.7 and 0.8, respectively). The difference between these three methods is due to the prescribed vulnerability classes but not their spatial variability. The locations of the moderately high vulnerability class in the index method maps (Fig. 8A, B) correspond to the high vulnerability class in the process method map (Fig. 8C). The other vulnerability classes also coincide in these maps. The correlation values would change if the travel time prescribed to the high vulnerability class was changed from 2 years to 5 years. Thus, these results emphasize the indicative nature of groundwater vulnerability maps and their ability to identify areas where further investigations are needed at the stage of decision making. These findings agree with Foster's et al. (2013) remarks.

The strongest influence on the final results in the index methods is the lithology of the sediments overlying the aquifer. This pattern is particularly well noticeable in the northeastern part of the study area (Fig. 8A, B). The second most important parameter is the depth to the water table. These two parameters are most important in terms of the fluid travel time from the surface to the water table because they are responsible for the retention capacity of the unsaturated zone, and increase time for remedial actions (Maxe and Johansson, 1998; Healy, 2010). Similarly, the Bachmat and Collin (1987) formula employs thickness of the unsaturated zone as well as moisture content [eq. 3], important factors in the process of water movement in the unsaturated zone (e.g., Hiscock and Bense, 2014) and the fate of contaminants (Bakesi and McConchie, 2000). These parameters are also crucial in terms of the recharge coefficient, which can be used to calculate the recharge and is of primary importance for groundwater vulnerability (Misstear et al., 2009). This discussion suggests that a very simplified but applicable method could use only the thickness of the unsaturated zone and its hydrogeological properties, which reflect the rate at which fluids move downward through the medium.

Even though the groundwater vulnerability maps were assessed using a large quantity of data and mapped at high resolutions, the scale of this study prohibits detailed investigations. For example, the heterogeneity of the geological strata was not

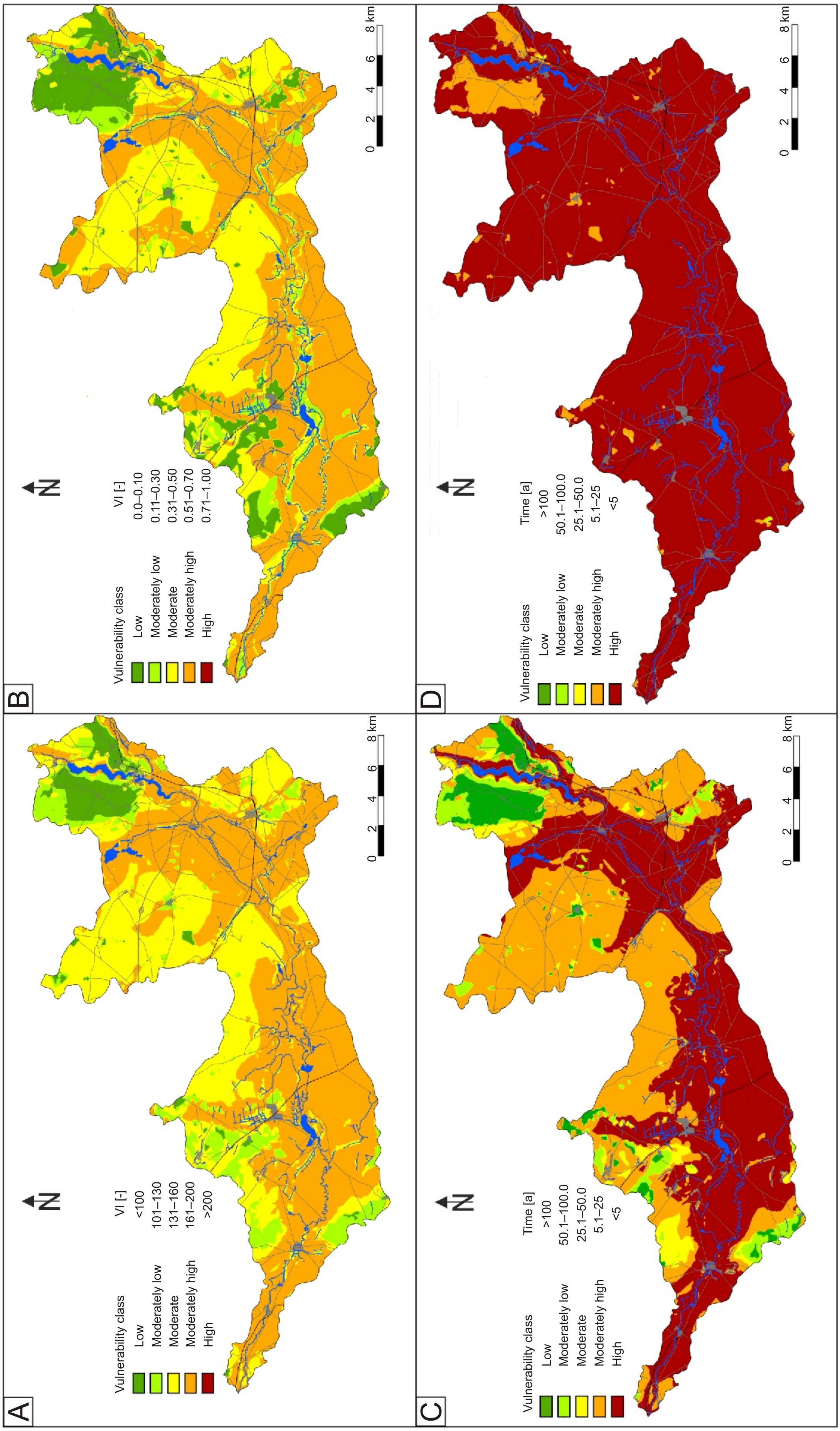

Fig. 8. Vulnerability classes of the uppermost aquifer in the Pliszka River catchment with the (A) DRASTIC, (B) GOD, (C) Bachmat and Collin (1987), (D) Macioszczyk (1999) methods

Table 4

Correlation coefficients between vulnerability classes based on different assessment methods

Groundwater vulnerability assessment method	DRASTIC	GOD	Bachmat and Collin (1987)	Macioszczyk (1999)
DRASTIC	1	–	–	–
GOD	0.8	1	–	–
Bachmat and Collin (1987)	0.7	0.8	1	–
Macioszczyk (1999)	0.4	0.3	0.4	1

taken into consideration. This matter is especially important in areas where the geology features Quaternary glacial sediments (Klint et al., 2013), such as in the Pliszka River catchment. In certain locations, the aquifer is covered by the till that is likely fractured in its uppermost part. This till undoubtedly causes spatial variations in the recharge and geochemical conditions (Jørgensen et al., 2004).

CONCLUSIONS

The intrinsic groundwater vulnerability of a typical European Lowland river catchment, the Pliszka River catchment, was assessed using the DRASTIC and GOD methods. These methods primarily identified areas of moderately high (54.5 and 48.4%, respectively) and moderate vulnerability (32.7 and 32.3%, respectively), with no areas of high groundwater vulnerability. In the same area, the process method based on Bachmat and Collin's (1987) formula identified chiefly high (49.4%) and moderately high (37.3%) groundwater vulnerability areas. The infiltration travel time through the unsaturated zone estimated on the basis of Macioszczyk's (1999) formula indicated high groundwater vulnerability for the majority of the area, which appears to be unrealistic. Therefore, the latter method's applicability is questionable.

Correlation coefficients calculated based on the spatial representation of the assessed groundwater vulnerability indicate that relatively strong correlations exist between three out of the four applied methods. Although the resultant maps obtained by the DRASTIC, GOD, and Bachmat and Collin's (1987) formula show different vulnerability classes for certain areas, the applicability of these methods is unquestionable for water management at the catchment scale, but may be misleading at more detailed scales. This finding emphasizes the indicative nature of the vulnerability maps, and they should be thoroughly analysed and validated in each application before decisions are made.

Acknowledgements. We would like to thank Prof. S. Staśko and an anonymous reviewer for the critical and constructive comments on the first version of the manuscript.

REFERENCES

Aller, L., Bennett, T., Lehr, J.H., Petty, R.J., Hackett, G., 1987. DRASTIC: A Standardized System for Evaluating Ground Water Pollution Potential Using Hydrogeologic Settings. United States Environmental Protection Agency, Robert S. Kerr Environmental Research Laboratory, Ada, Oklahoma.

Allred, B.J., 2000. Survey of fractured glacial till geotechnical characteristics: hydraulic conductivity, consolidation, and shear strength. The Ohio Journal of Science, **100**: 63–72.

Anornu, G.K., Kabo-bah, A.T., 2013. Evaluation of AVI and DRASTIC methods for groundwater vulnerability mapping. Journal of Environment and Ecology, **4**: 126–135.

Bachmat, Y., Collin, M., 1987. Mapping to assess groundwater vulnerability to pollution. In: Vulnerability of Soil and Groundwater to Pollutants, Proceedings and Information (eds. W. van Duijvenbooden and H.G. van Waegeningh): 297–307. TNO Committee on Hydrological Research, Hague.

Bakesi, G., McConchie, J., 2000. Empirical assessment of the influence of the unsaturated zone on aquifer vulnerability, Manawatu region, New Zealand. Ground Water, **38**: 193–199.

Civita, M.V., 1994. Le carte della vulnerabilità degli acquiferi all'inquinamento: teoria & pratica (in Italian). Pitagora Editrice, Bologna.

Civita, M.V., 2010. The combined approach when assessing and mapping groundwater vulnerability to contamination. Journal of Water Resource Protection, **2**: 14–28.

Davis, S.N., 1969. Porosity and permeability of natural materials. In: Flow through Porous Media (ed. R.J.M. De Wiest): 54–89. Academic Press, New York.

Debernardi, L., De Luca, D.A., Lasagna, M., 2008. Correlation between nitrate concentration in groundwater and parameters affecting aquifer intrinsic vulnerability. Environmental Geology, **55**: 539–558.

Dixon, B., 2005. Groundwater vulnerability mapping: a GIS and fuzzy rule based integrated tool. Applied Geography, **25**: 327–347.

Doerfliger, N., Zwahlen, F., 1997. EPIK: a new method for outlining of protection areas in karstic environment. In: International Symposium and Field Seminar on "Karst waters and environmental impacts", Antalya, Turkey (eds. G. Günay and A.I. Jonshon): 117–123. Balkema, Rotterdam.

Domenico, P.A., Schwartz, F.W., 1998. Physical and Chemical Hydrogeology, 2nd ed. John Wiley & Sons, New York.

Fitzsimons, V.P., Misstear, B.D.R., 2006. Estimating groundwater recharge through tills: a sensitivity analysis of soil moisture budgets and till properties in Ireland. Hydrogeology Journal, **14**: 548–561.

Foster, S., 1987. Fundamental concepts in aquifer vulnerability pollution risk and protection strategy. In: Vulnerability of Soil and Groundwater to Pollutants, Proceedings and Information (eds. W. van Duijvenbooden and H.G. van Waegeningh): 69–86. TNO Committee on Hydrological Research, Hague.

Foster, S., Hirata, R., 1988. Groundwater pollution risk assessment: a methodology using available data. WHO-PAHO/HPE-CEPIS Technical Manual. Lima, Peru.

Foster, S., Hirata, R., Andreo, B., 2013. The aquifer pollution vulnerability concept: aid or impediment in promoting groundwater protection? Hydrogeology Journal, **21**: 1389–1392.

Gogu, R.C., Dassargues, A., 2000. Current trends and future challenges in groundwater vulnerability assessment using overlay and index methods. Environmental Geology, **39**: 549–559.

Healy, R.W., 2010. Estimating Groundwater Recharge. Cambridge University Press.

Hernández-Espriú, A., Reyna-Gutiérrez, A., Sánchez-León, E., Cabral-Cano, E., Carrera-Hernández, J., Martínez-Santos, P., Macías-Medrano, S., Falorni, G., Colombo, D., 2014. The DRASTIC-Sg model: an extension to the DRASTIC approach for mapping groundwater vulnerability in aquifers subject to differential land subsidence, with application to Mexico City. Hydrogeology Journal, **22**: 1469–1485.

Hiscock, K.M., Bense, V.F., 2014. Hydrogeology: Principles and Practice, 2nd ed. Wiley Blackwell, Oxford.

Jørgensen, P.R., McKay, L.D., Kistrup, J.P., 2004. Aquifer vulnerability to pesticide migration through till aquitards. Ground Water, **42**: 841–855.

Khan, A., Khan, H.H., Umar, R., Khan, M.H., 2014. An integrated approach for aquifer vulnerability mapping using GIS and rough sets: study from an alluvial aquifer in North India. Hydrogeology Journal, **22**: 1561–1572.

Klint, K.E.S., Nilsson, B., Troldberg, L., Jakobsen, P.R., 2013. A poly morphological landform approach for hydrogeological applications in heterogeneous glacial sediments. Hydrogeology Journal, **21**: 1247–1264.

Krogulec, E., 2006. Methods and results of groundwater vulnerability evaluation to contamination in the Kampinoski National Park, central Poland. Acta Geological Polonica, **56**: 349–359.

Lee, S., 2003. Evaluation of waste disposal site using the DRASTIC system in Southern Korea. Environmental Geology, **44**: 654–664.

Ligget, J.E., Talwar, S., 2009. Groundwater vulnerability assessments and integrated water resource management. Streamline Watershed Management Bulletin, **13**: 18–29.

Macioszczyk, T., 1999. Time of the vertical seepage as an indicator of the aquifers' vulnerability (in Polish with English summary). Przegląd Geologiczny, **47**: 731–736.

Makonto, O.T., Dippenaar, M.A., 2014. Aquifer vulnerability using recharge, depth to groundwater, soil type and slope to classify the vadose zone (Molototsi and Middle Letaba quaternary catchment, Limpopo Province, South Africa). Environmental Earth Sciences, **72**: 1615–1623.

Maxe, L., Johansson, P.-O., 1998. Assessing groundwater vulnerability using travel time and specific surface area as indicators. Hydrogeology Journal, **6**: 441–449.

Misstear, B.D.R., Brown, L., Daly, D., 2009. A methodology for making initial estimates of groundwater recharge from groundwater vulnerability mapping. Hydrogeology Journal, **17**: 275–285.

Ravbar, N., Goldscheider, N., 2009. Comparative application of four methods of groundwater vulnerability mapping in a Slovene karst catchment. Hydrogeology Journal, **17**: 725–733.

Schwartz, M.O., 2006. Numerical modelling of groundwater vulnerability: the example Namibia. Environmental Geology, **50**: 237–249.

Sztromwasser, E., 2005. Objaśnienia do Szczegółowej Mapy Geologicznej Polski w skali 1:50 000, ark. Torzym (in Polish). Ministerstwo Środowiska, Warszawa.

Van Stempvoort, D., Evert, L., Wassenaar, L., 1993. Aquifer vulnerability index: a GIS compatible method for groundwater vulnerability mapping. Canadian Water Resources Journal, **18**: 25–37.

Vías, J.M., Andreo, B., Perles, M.J., Carrasco, F., 2005. A comparative study of four schemes for groundwater vulnerability mapping in a diffuse flow carbonate aquifer under Mediterranean climatic conditions. Environmental Geology, **47**: 586–595.

Vías, J.M., Andreo, B., Perles, M.J., Carrasco, F., Vadillo, I., Jiménez, P., 2006. Proposed method for groundwater vulnerability mapping in carbonate (karstic) aquifers: the COP method. Application in two pilot sites in Southern Spain. Hydrogeology Journal, **14**: 912–925.

Vrba, J., Zaporozec, A., 1994. Guidebook on mapping groundwater vulnerability. IAH – International Contribution to Hydrogeology 16, Heise, Hannower, Germany.

Witczak, S., Duda, R., Zurek, A., 2007. The Polish concept of groundwater vulnerability mapping. In: Groundwater Vulnerability Assessment and Mapping. (eds. A.J. Witkowski, A. Kowalczyk and J. Vrba): 45–59. Selected papers from the Groundwater Vulnerability Assessment and Mapping International Conference, Ustron, Poland, 2004.

Wang, Y., Merkel, B.J., Li, Y., Ye, H., Fu, S., Ihm, D., 2007. Vulnerability of groundwater in Quaternary aquifers to organic contaminants: a case study in Wuhan City, China. Environmental Geology, **53**: 479–484.

Zuquette, L.V., Palma, J.B., Pejon, O.J., 2009. Methodology to assess groundwater pollution conditions (current and pre-disposition) in the São Carlos and Ribeirão Preto regions, Brazil. Bulletin of Engineering Geology and the Environment, **68**: 117–136.