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Evaluation of intrinsic vulnerability of an Upper Jurassic karst-fissured aquifer in the Jura Krakowska (southern Poland) to anthropogenic pollution using the DRASTIC method

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This paper demonstrates the evaluation of intrinsic vulnerability of karst-fissured waters in an Upper Jurassic aquifer by applying modified DRASTIC method. The area investigated is the Jura Krakowska (South Poland) — an area of upland merokarst (or relict karst), where the Upper Jurassic aquifer is mainly unconfined. The method applied is a combination of a simulation model of the groundwater aquifer (factors: net recharge, hydraulic conductivity, groundwater flow velocity in the aquifer) and a geographical information system — *GIS* model (depth of groundwater table, lithology of vadose zone, thickness of Upper Jurassic aquifer), and additionally a soil factor was taken into account. In the area of the Jura Krakowska, 5 classes of intrinsic vulnerability to pollution were distinguished according to the values of vulnerability factors. These classes range from extremely high to low vulnerability (IP 200–50). Based on the synthetic map of vulnerability it emerges that high vulnerability indices cover 54% of the area studied while medium and low vulnerability indices cover 46% of this area. The modified DRASTIC method presented seems to be a useful tool to evaluate the intrinsic vulnerability of karst-fissured aquifers of "Torcal" type with a scattered system of recharge and discharge, and a thick vadose zone of variable permeability. This is consistent with the method developed with European programme COST ACTION 620. All rating methods recommended for karst have limitations, therefore the method applied is constantly updated. Many of them are particularly useful for areas of bare karst, mountain systems of "Aliou" type and in areas of complete karst development (holokarst).

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INTRODUCTION

The Jura Krakowska is situated in southern Poland within the Silesian-Cracow Monocline, which is a large regional unit built of Mesozoic deposits. Its southern part, from the Krzeszowice Graben, located along its southern margin, belongs to the Carpathian Foredeep (Figs. 1 and 2). It is underlain by Palaeozoic deposits of various age, which belong to Caledonian and Variscian structural stages (Buła, 2000; Żaba, 1999). The Alpine structural stage is represented by Triassic and Jurassic deposits. In the eastern part, they are covered by Cretaceous deposits (Bukowy, 1974; Fig. 1). Cenozoic deposits are represented mainly by Miocene clays which occur in tectonic grabens, and sandy-clayey deposits of Pleistocene and Holocene age. They occur in the form of thick sheets located in river valleys, and patches located in upland areas (Kaziuk and Lewandowski, 1980). The Jura Krakowska is a typical example of upland merokarst (or relict karst) and of variable internal structure. The Main Groundwater Reservoir Częstochowa E-326 which occurs in the Jura Krakowska is connected with Upper Jurassic limestones (Kleczkowski, 1990). This aquifer is mainly unconfined and it shows triple porosity and variable vulnerability to human impact. In hydrodynamic terms, it conforms to an aquifer of "Torcal" type, which shows the influence of the "capacity element" of the memory (Mangin, 1975). Regional investigations into the hydraulic structure of the Upper Jurassic limestone massif have shown its quasi-homogeneity on a regional scale with substantial variability of hydrogeological properties governed by facies development. The karstic character encompasses a complete profile of these carbonate rocks, as documented by observations of permeable karstic zones down to a depth of 200 m below ground level (borehole Trojanowice IG 1). Groundwater recharge and drainage show a scattered character (Różkowski, 2006). The hydrogeology of the area in ques-

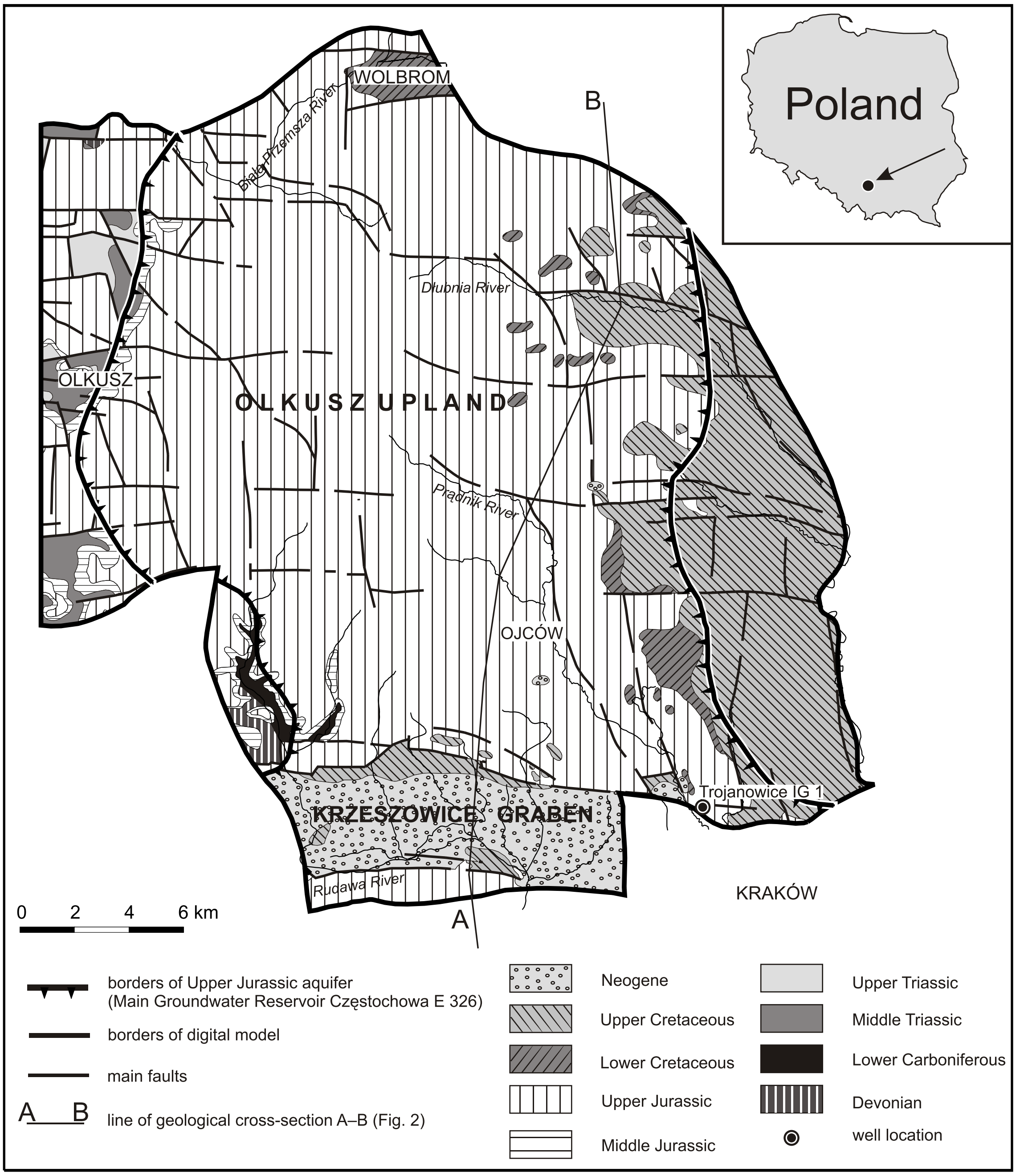


Fig. 1. Location and generalized geology of the study area (without Quaternary deposits; according to Kaziuk, 1978)

tion has been investigated by many authors, among them Tlałka (1970), Różkowski and Stachura (1971), Kleczkowski (1972), Dynowska (1983), Chełmicki (2001), Różkowski *et al*. (2001*a, b*, 2005), Zuber *et al*. (2004) and Różkowski (2006). In the last few years hydrogeological investigations of the Upper Jurassic limestones have been carried out by Motyka *et al*. (1999, 2002), Różkowski *et al*. (2005), Różkowski (2005, 2006).

To preserve natural environment and the groundwater resources, most of the area of Jura Krakowska is under protection. One of the useful tools for groundwater protection is a vulnerability map of the Upper Jurassic karst-fissure aquifer, discussed in this paper. Taking into consideration the specific character of this aquifer for its groundwater vulnerability assessment, a modification of the standard DRASTIC method (Aller *et al*., 1987) has been applied.

METHODS OF EVALUATION OF GROUNDWATER VULNERABILITY TO POLLUTION

Evaluation of groundwater to pollution generated by human impact (Warner, 1992) entails determination of its intrinsic vulnerability to pollution (Vrba and Zaporozec, 1994). Intrinsic vulnerability is understood as a natural property of a water-bearing system that determines the risk of migration of polluting substances from

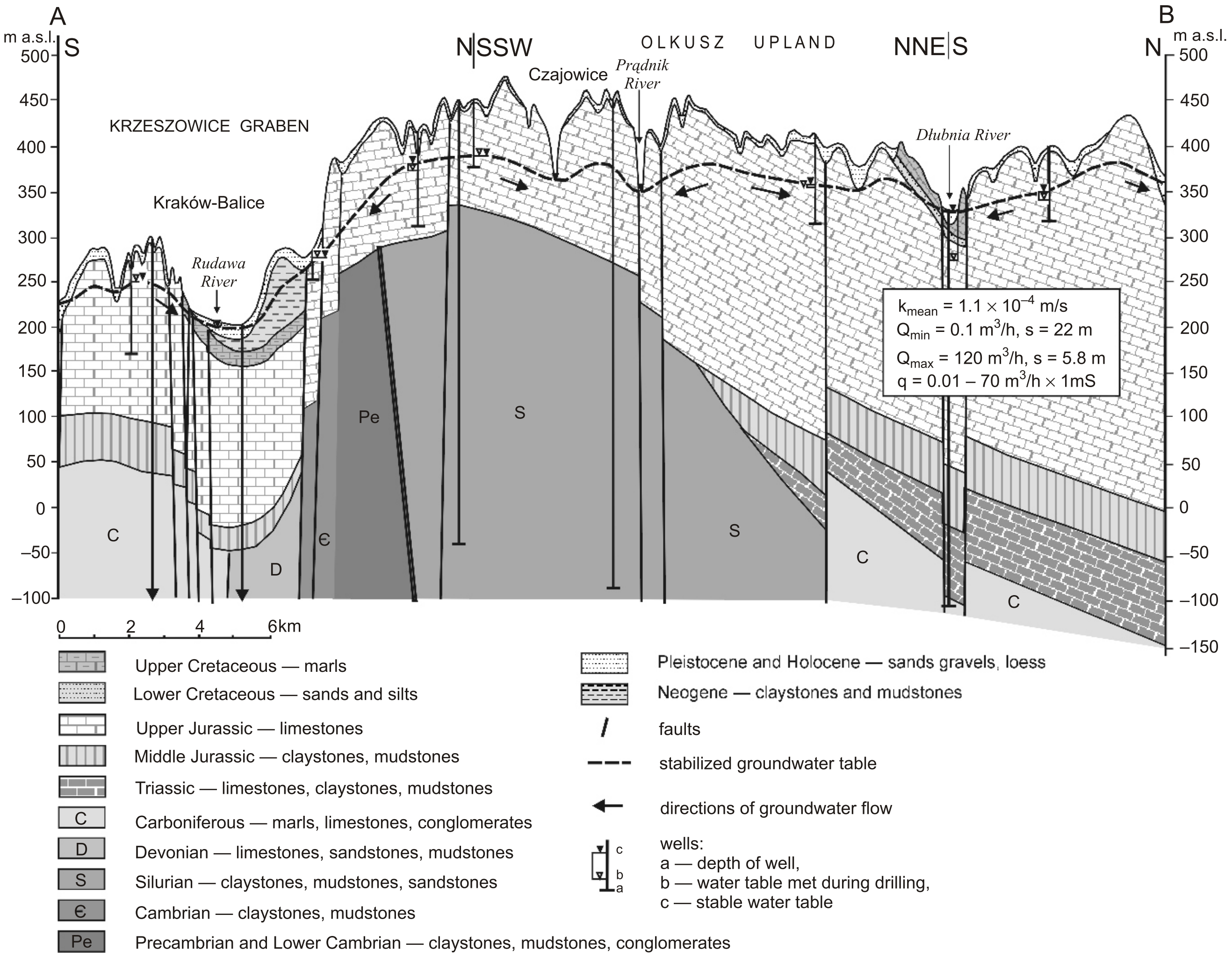


Fig. 2. Geological cross-section across the study area of the Jura Krakowska (according to Lewandowski, 2004)

See Figure 1 for a location

the ground surface to the groundwater aquifer. Intrinsic vulnerability results from geological conditions, land relief and hydrogeological conditions (conditions of recharge and discharge, properties of lithologies influencing confining character of groundwater and so on; Duijvenbooden and Waegeningh, 1987; Krogulec, 2004; Vrba and Zaporozec, 1994).

Among the methods of evaluation of groundwater vulnerability to pollution, the following groups may be distinguished: parametric methods, methods based on the characteristics of the groundwater aquifer, weight-rating methods, methods of mathematical and hydrogeochemical modelling, field indicator (marker) methods, hydrochemical methods, statistical and geostatistical methods (Krogulec, 2004).

The weight-rating (parameters' indexation) method consists of a choice of the group of parameters which show the largest influence on the hazard of groundwater contamination. Among weight-rating methods applied in the evaluation of vulnerability of karst-fissured groundwater aquifers, the most useful include: DIVERSITY (Dispersion Velocity, Rated Sensitivity; Ray and O`Dell, 1993), EPIK (Epikarst, Protective cover, Infiltration conditions, Karst network development; Doerfliger *et al*., 1999), KARSTIC (Karst sinkholes with surface recharge, Aquifer medium, Recharge rate, Soil medium, Topography, Impact of the unsaturated zone, Conductivity — hydraulic — of the aquifer; Davis *et al*., 2002), REKS (Rocks, Epikarst, Karstification, Soil cover; Malik and Svasta, 1999) and RISKE (the Rock characteristic, Infiltration, Soil, the Karst development, Epikarst; Petelet-Giraud *et al*., 2000).

The DRASTIC (Depth to water, Recharge, Aquifer media, Soil, Topography, Impact of vadose zone, Conductivity) method is recommended by the EPA and is applied in many countries including Poland (Krogulec, 2002; Żurek *et al*., 2002; Witkowski *et al*., 2003). The vulnerability evaluation takes into account the following criteria: depth to groundwater table, net recharge, lithology of water-bearing horizon, type of soil, topography, influence of vadose zone, hydraulic conductivity of aquifer. Taking into account the role of each factor in the process of migration of potential pollution, weightings ranging from 1 to 5 were assigned. Next, for each criterion, the classes of values for each factor were distinguished and a suitable rating according to a general scale from 1 (least vulnerable to pollution) to 10 (most vulnerable to pollution) was assigned to each class. The final evaluation of groundwater vulnerability to pollution using the DRASTIC method is based on the vulnerability index IPZ, which is the sum of the multiplied weightings and factor ratings, IPZ = Σ (weight *x* factor rates). The vulnerability index is a relative value and makes it possible, within the area studied and assuming certain intervals of the index values, to distinguish areas that are more or less vulnerable to pollution. The DRASTIC method is suitable for regional evaluations and requires the use of generalised data. The final evaluation consists of summing up rating points from individual maps that illustrate variation in the seven parameters applied in this method.

The proposed "European approach" in the methods of preparation of vulnerability and hazard maps aimed at protecting groundwater aquifers in carbonate strata, developed by the working group of COST 620 (Zwahlen, 2003), considers four factors: overlying layers (*O*), concentration of flow (*O*), precipitation regime (*P*) and karst network development (*K*).

THE RESULTS OF VULNERABILITY EVALUATION USING THE MODIFIED **DRASTIC** METHOD

I have applied the modified DRASTIC method (Witkowski *et al*., 2003) adopting it to the specific hydrogeological environment of the karstified carbonate Upper Jurassic massif (Różkowski, 2005). This method uses a simulation model of the water-bearing horizon (according to *MODFLOW* software) and a geographical information system, additionally taking into account a soil factor, and the specificity of karst-fissured carbonate massif of Upper Jurassic age. The last one of the indices should be taken into account especially for areas of carbonate rock outcrops or under minimally thick overburden of Pleistocene and Holocene deposits. Such areas occupy about 50% of the total surface investigated. The production of the synthetic vulnerability map was possible due to detailed recognition of land topography, geology and hydrogeological conditions of the area studied.

The construction of the final vulnerability map was based on seven geological and hydrogeological factors that determine the potential contamination of the karst-fissured aquifer. Three factors: net recharge, hydraulic conductivity in the Upper Jurassic aquifer and groundwater flow velocity in the Upper Jurassic aquifer were obtained from the calibration of the digital model. The area of the model projecting the Upper Jurassic aquifer was 652 km^2. A set of basic information was assigned to blocks of dimensions 500 m × 500 m (Różkowski *et al*., 2001*a*). Three further factor maps — a map of groundwater table depth, a map of the lithology of the vadose zone and a map of the Upper Jurassic aquifer thickness — were digitised from the sheets of raster maps and transformed into a grid model. The methodology of the preparation of factor soil map was derived from Witczak and Żurek (1994) and Żurek *et al*. (1999). Each of the vulnerability factors was assigned a weighting (from 1 to 5) showing its relative importance (Table 1). For comparison of the vulnerability of karst-fissured aquifers to pollution within the area of the Silesia-Cracow Monocline I have taken, after Witkowski *et al*. (2003), weighting values of vulnerability indices applied by these authors to the Triassic aquifer situated in this area. For soil index, additionally taken because of the uncovered character of the Upper Jurassic aquifer, the weighting recommended by the DRASTIC method is 2.

The depth of the groundwater table shows a relationship with topography and also with the occurrence of Neogene deposits of considerable thickness overlying clayey lithologies in tectonic grabens (Fig. 2). In karst gorges cut into the plateau, the depth of the groundwater table changes from several to 30 m. In the area of the plateau and tectonic horsts, the depth of the groundwater table increases to 30–70 m and in Krzeszowice Graben it reaches 90 m (Fig. 3A).

The lithological description of the vadose zone was prepared based on the *Geological Map of Poland 1 : 200 000 Cracow sheet* (Kaziuk, 1978), *Geological Maps of Poland 1 : 50 000* (Bukowy, 1963; Płonczyński and Łopusiński, 1988; Rutkowski, 1989; Kurek and Preidl, 1990) and geological profiles of about 230 wells and investigation boreholes. Taking into account the protective role of the vadose zone with respect to the phreatic zone, 6 lithological classes have been distinguished. A considerable hazard affects the areas of carbonate rock outcrops. A moderate hazard affects the outcrops of Cretaceous marls and Quaternary loess and also deluvium deposits that cover Mesosoic rocks. A minor hazard is present in the area of the Krzeszowice Graben, where thick clayey deposits are present in the overburden (Fig. 3B).

The size of recharge of the Upper Jurassic aquifer from the percolation infiltration from a multi-annual period is in the range from 10 to 273 mm/year. High values (>150 mm/year) are located in the area of plateaux and tectonic horsts. Low values (<100 mm/year) are located in the Dłubnia valley and in the Krzeszowice Graben (Fig. 3C).

In the distribution of hydraulic conductivity, a spatial differentiation in the permeability of the carbonate massif and a tectonic influence within the rock medium are shown. The lowest permeability (0.01–1.0 m/day) is present in the upland areas (Olkusz Plateau and tectonic horsts). The highest values (5–10 m/day) are present in valley areas (Fig. 3D).

The groundwater flow velocity determines the velocity of migration of potential pollution in the aquifer. The flow velocities obtained from modelling investigations are in the range

Table 1

Criteria of rating evaluation of vulnerability and their weighting used here to evaluate the vulnerability of groundwater to pollution in the area of the Jura Krakowska

	Factor	Weight (W)
A	Depth to the Upper Jurassic aquifer	5
B	Lithology of vadose zone	5
C	Net recharge from numerical modelling [mm/year]	4
D	Hydraulic conductivity of the Jurassic aquifer from numerical modelling [m/day]	2
E	Groundwater flow velocity within the Jurassic aquifer derived by numerical modelling [m/day]	3
F	Thickness of the Jurassic aquifer [m]	1
G	Type of soil cover	2

Table 2

The ratings of individual criteria in the DRASTIC rating method

No.	**A**. Depth to the aquifer [m]	Rating (R)	W × R
1	0–10	10	50
2	10–20	7	35
3	20–50	5	25
4	50–100	2	10
	B. Lithology	Rating (R)	W × R
1	Limestone — outcrops [J_3]	10	50
2	Sand and loam in river valleys/limestone [Q/J_3]	8	40
3	Loess, diluvium or local marls/limestone [$Q/Cr_3/J_3$]	6	30
4	Sand and loam in river valleys/marls/limestone [$Q/Cr_3/J_3$]	5	25
5	Loess/marls/limestone [$Q/Cr_3/J_3$]	4	20
6	Sand, loess, clay/limestone [$Q/Tr/J_3$]	1	5
	C. Net recharge [mm/year]	Rating (R)	W × R
1	< 100	2	8
2	100–150	5	20
3	150–200	7	28
4	> 200	9	36
	D. Hydraulic conductivity [m/day]	Rating (R)	W × R
1	< 0.4	2	4
2	0.4–0.8	4	8
3	0.8–1.0	5	10
4	1,0–5,0	6	12
5	5.0–10.0	7	14
	E. Flow velocity [m/day]	Rating (R)	W × R
1	< 0.0001–0.001	1	3
2	0.001–0.01	2	6
3	0.01–0.05	3	9
4	0,05–0,10	4	12
5	0.10–0.15	6	18
	F. Thickness of the aquifer [m]	Rating (R)	W × R
1	0–50	8	8
2	50–100	5	5
3	100–150	4	4
4	150–200	3	3
5	200–250	2	2
6	250–300	1	1
	G. Type of soil cover	Rating (R)	W × R
1	Skeletal soil	10	20
2	Jurassic rendzina	7	14
3	Loess and loess–like soils	4	8

Weights for particular factors A–G are given in Table 1

from 2.9×10^{-4} to 1.5×10^{-1} m/day (Fig. 3E). The variation in groundwater flow velocity demonstrates the heterogeneity of the karst-fissure massif. The largest velocity values were observed in the Dłubnia valley, which has tectonic foundations, and in the SW part of the area modelled. The lowest values occur in the watershed area and they are similar to flow the velocities of a pore-dominant system (from several tens of centimetres to a dozen or so metres per year).

The areas of small thickness of the saturation zone are more subjected to pollution than the areas where this zone is thick. The thickness of this zone in the Upper Jurassic aquifer increases from 20–50 m in the western and southwestern part to more than 250 m in the northeastern part (Fig. 3F).

In the area studied, loess soils occur (brown soil). Only in the northwestern part do locally-derived soils and loamy sand predominate. A typical rendzina (limestone soil) occurs sporadically (Fig. 3G).

Table 2 shows the applied interval division for individual factors (3–6) together with ratings for individual intervals (from 1 — the lowest vulnerability to 10 — the highest vulnerability).

As a result of computer-based combining of seven hydrogeological and geological factors maps, a synthetic map of the vulnerability of the Upper Jurassic aquifer to pollution penetration from the ground surface was obtained. The values of vulnerability index for individual calculation blocks of the digital model were obtained as a sum of seven ratios assigned to the size of ratings and weighting from the individual final indicatory maps which describe individual features.

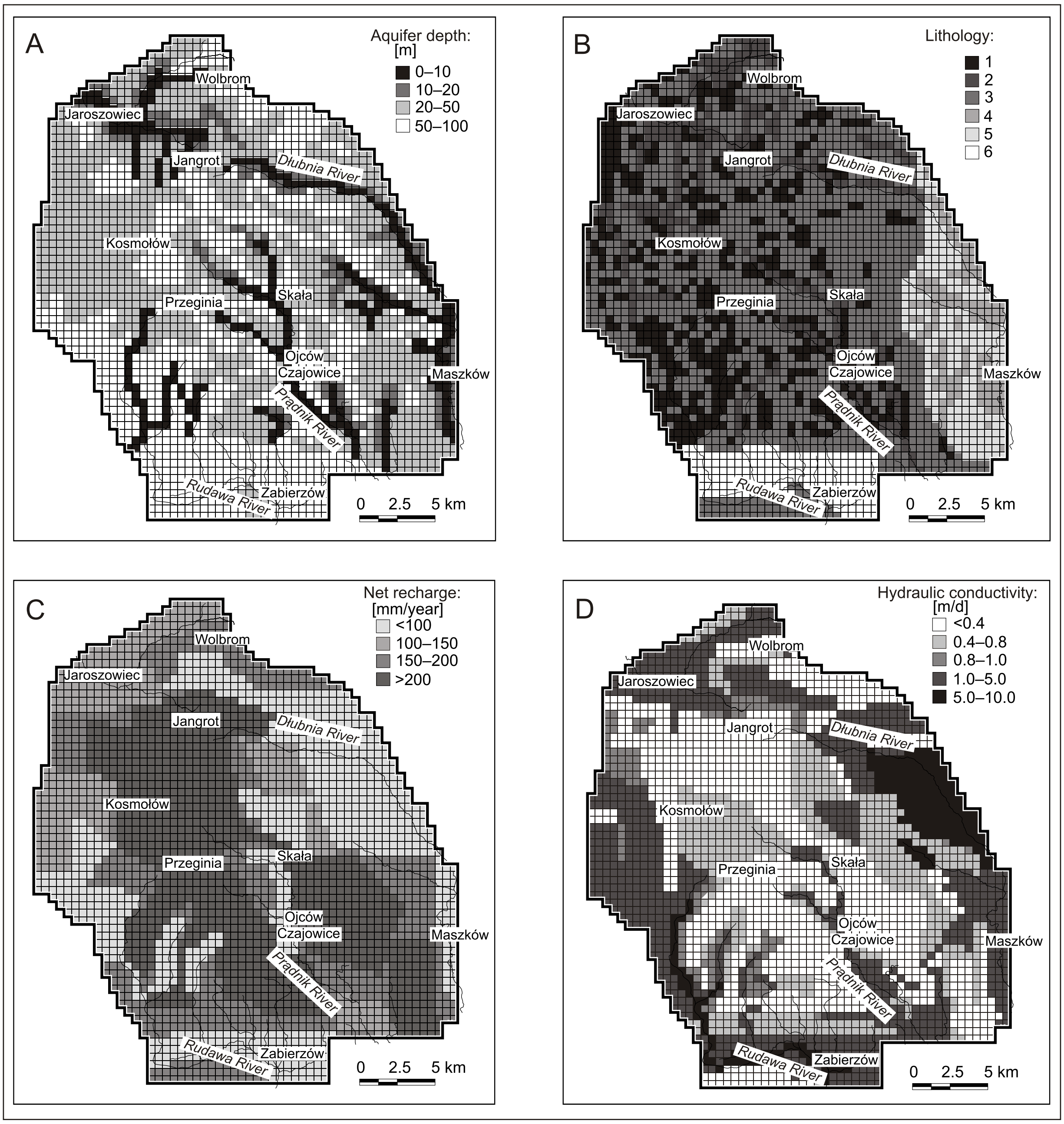
The values of vulnerability index are in the range from 52 to 180 points on the vulnerability map of the Upper Jurassic aquifer. According to international standards (Vrba and Zaporozec, 1994) five classes of groundwater vulnerability to pollution have been distinguished, taking into account the specificity of karst. They include the following classes: extremely high, very high, high, medium and low (Table 3, Fig. 4).

The analysis of the synthetic map shows that in the area of the Jura Krakowska where carbonate rock outcrops (and is present beneath thin Quaternary on the plateau) a high vulnerability to pollution predominates (54% of the area studied, including extremely high — 11%, very high and high — 43%). Medium and low vulnerability is typical of the area of the Krzeszowice Graben and also of watershed areas in the Dłubnia drainage basin (46% of the area studied, including low — 8%), which results from geological conditions and recharge conditions of the aquifer (Figs. 3 and 4).

Table 3

Classification of groundwater vulnerability to pollution based on the criteria of rating evaluation of vulnerability using the DRASTIC method

No.	Classes of the relative vulnerability	Index
1	Extremely high	170–200
2	Very high	140–169
3	High	110–139
4	Medium	80–109
5	Low	50–79



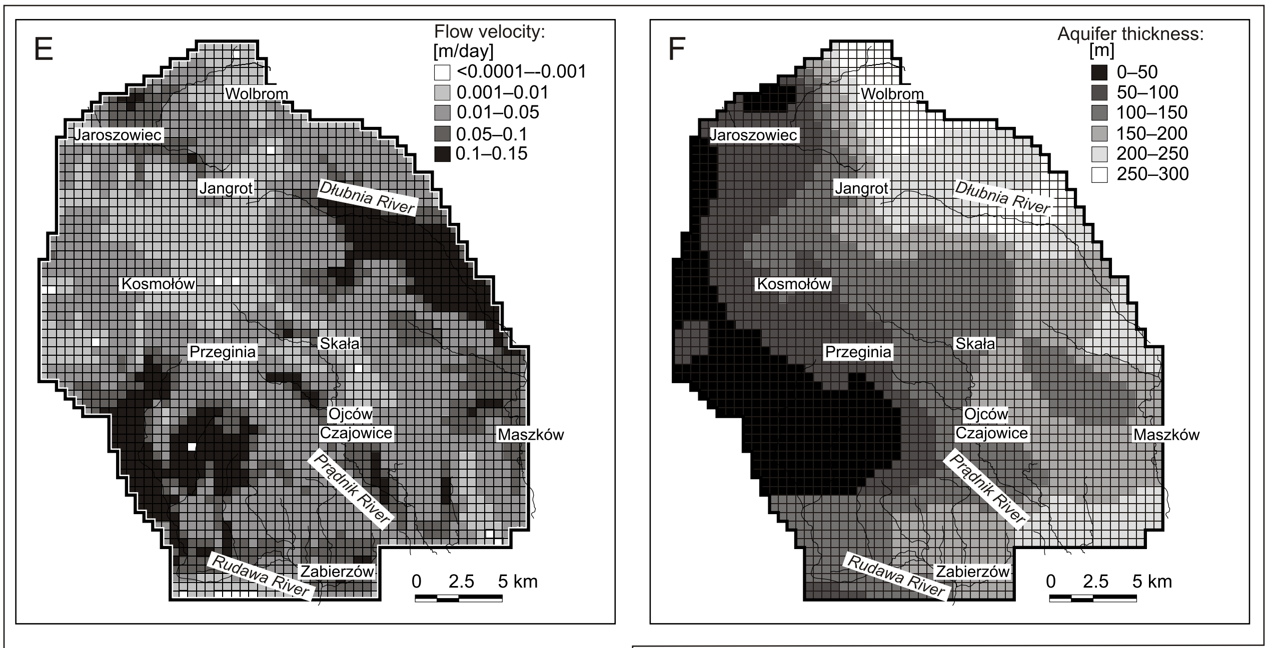
The reliability of the final vulnerability map using the DRASTIC method was verified based on current geological knowledge, results of hydrogeological field and laboratory investigations, and also the chemistry and quality of the groundwater.

DISCUSSION OF RESULTS

The modified DRASTIC method is a useful tool to evaluate the natural vulnerability of karst-fissured aquifers with a scattered recharge and drainage system, a well-developed vadose zone of variable permeability, and with delayed reaction to recharge ("Torcal" type). The aquifer investigated on a regional scale behaves in a manner similar to a porous medium (Różkowski, 2006), to which the DRASTIC method is usually applied to evaluate its vulnerability.

The method applied in this paper belongs to the group of the methods which are being developed at present to monitor natural vulnerability to contamination of groundwater aquifers in carbonate rocks, and developed with the framework of the European programme COST ACTION 620 (Zwahlen, 2003).

This modified DRASTIC method takes into account the thickness and lithology of the vadose zone (factor *O*, similarly to methods EPIK and PI), the size of effective percolation (combination of factors *O* and *P*), and also factor *K*, which describes the aquifer (percolation coefficient, velocity of horizontal flow, thickness of saturation zone). It does not consider point recharge of the aquifer (factor *C*), which reduces the protective function of the overburden in the case of aquifer recharge directly by e.g. karst dolines or shafts. This was dis-



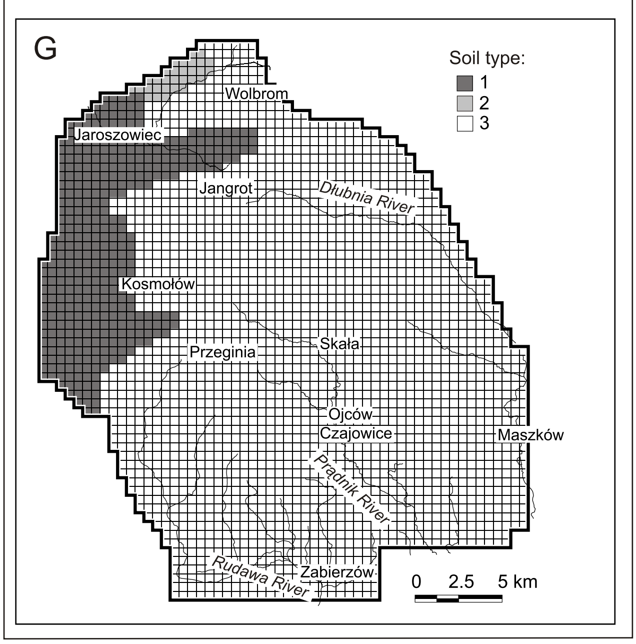


Fig. 3. Maps of criteria of rating evaluation of the Upper Jurassic aquifer vulnerability for particular factors

For further explanations see Table 1

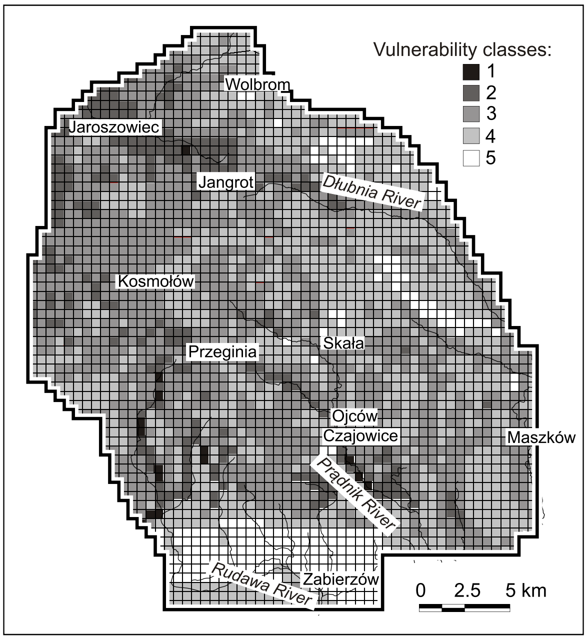


Fig. 4. Synthetic map of vulnerability of the Upper Jurassic aquifer using the DRASTIC method

cussed by Witkowski *et al*. (1997), Davis *et al*. (2002) and Gogu *et al*. (2003). It should be however underlined that the process of concentrated recharge in the area of Jura Krakowska have been observed only sporadically and is poorly recorded. The precipitation regime shows evidence of external influences, and does not show any differentiations on scale of a catchment basin or a region (except as regards extreme precipitation, e.g. in July 1997), but it shows clear variability at the scale of a whole country or of a continent.

The conditions of scattered recharge. My analysis of about 230 profiles of geological boreholes in the area of Jura Krakowska shows that among all the vulnerability criteria, the thickness of clays and marls in the vadose zone (reaching 100 m in the tectonic grabens) was the most important (not soil cover and epikarst development). My field investigations carried in 15 quarries in Jura Krakowska and laboratory investigations (Różkowski *et al*., 2001*b*, 2005) in the area of bare and green karst reveal the changeability of hydraulic structure of the vadose zone. The open porosity of the rock medium of the Upper Jurassic limestones changes from 0.6 to 27.8%. The fissure surface porosity (for geometrical weighted opening widths <10 mm) is in the range from 0.03 to 0.36% (Różkowski *et al*., 2005). The porosity of fissures widened by karst processes changes from 0.5 to 10% with low geometric mean of 2.2%. In the walls of the quarries (to a depth of 30 m below ground level) there is a limited occurrence of karstic dolines and depressions, and the average opening of fissures is only 0.1–5.0 mm with a depth decreasing trend. In the literature, there are descriptions of ponors, which occur sporadically and are locally called „łykawce".

The conditions of scattered drainage. Multispectral investigations of the zone of spring drainage documented the domination of scattered drainage associated with local circulation, as was confirmed by modelling investigations of groundwater renewal (Różkowski *et al*., 2001*a*; Różkowski, 2006). On the other hand, a hierarchy of karst conduits of unknown range occurs. This is confirmed by higher mean values of specific discharges of wells in the areas of natural drainage (by springs) — 6.5 m^3/h/mS, than in the recharge areas — 3.5 m^3/h/mS (Różkowski, 2006). It is therefore questionable whether the development and direction of the unrecognised, deep karst system is the most important factor. This concerns also the analysis of curves of spring recession in the conditions of scattered drainage predomination (REKS). In addition, the hitherto devised models of discharge and transport do not simulate the development of channel systems (Bakalowicz, 2005).

The problems of intrinsic vulnerability to contamination of karst-fissure groundwater aquifers are examined in detail by hydrogeologists who study karst, and the methods applied are constantly verified and extended. The "European approach" developed in the framework of COST Action 620 shows the limitations of all individual application methods (Zwahlen ed., 2003). The comparative studies carried out by Gogu *et al*. (2003) in the area of Condroz (Belgium), where as many as 5 methods were tested (EPIK, DRASTIC, German method, GOD, ISIS) show significant differences of results obtained by individual methods, and their limitations. For example EPIK is applied only for karstified limestones. A wide range of selection in the nomograms of parameters of an aquifer in the DIVERSITY method, with specific conditions of recharge (scattered) and a complex hydraulic structure of the Upper Jurassic aquifer makes this method subjective and imprecise.

The map of vulnerability prepared based on calculations of the time of percolation of possible pollution from the ground surface (Różkowski *et al*., 2006) appeared to be very similar to the map proposed here of vulnerability using the modified DRASTIC method. In both cases of crucial importance for the evaluation of the vulnerability of karst-fissured aquifer to pollution is the thickness and permeability of the vadose zone and the amount of recharging infiltration.

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