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THEMATIC ISSUE

Influence of fissuring and karstification of the carbonate aquifer unsaturated zone on its vulnerability to contamination (Cracow Upper Jurassic Region, Poland)

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Abstract The carbonate fissure–karstic aquifer of Upper Jurassic age is the main aquifer in the Cracow Upper Jurassic Region (CUJR). The aquifer is recharged directly or indirectly by Quaternary or Quaternary–Cretaceous overburden of varying permeability, which predominates diffused recharge. Concentrated recharge occurs locally and has a diverse nature. Field studies carried out in 20 quarries show moderate permeability of the unsaturated zone of carbonate massif. Karst funnels are filled with rubble and clay material and dominate filled fissures with an opening $b < 10$ mm. The average surface fissure porosity of massive with chalky limestones and bedded limestones reach 0.12 and 0.45 %, respectively, while fissure permeability coefficient is, respectively, k_S 6.60×10^{-5} and 1.27×10^{-3} m/s. The average karstification in quarries was determined as $n_k = 2.5$ %. Tracer studies, carried out in an unconfined carbonate Zakrzówek horst in Cracow (Kraków), document vertical migration of infiltrating water through the systems with different hydraulic resistance, with a flow rate from 8.1×10^{-6} to 4.9×10^{-5} m/s and the lateral migration velocity between communicated caves from 6.94×10^{-6} to 1.06×10^{-4} m/s. The significant presence of poorly permeable overburden and moderate fissuring and karstification of rock in the unsaturated zone of CUJR are reflected in the assessment of the Upper Jurassic aquifer vulnerability to contamination, performed by a modified DRASTIC method. In the area of unconfined karst, occupying 55 % of the area, vulnerability to contamination is high, while as much as 45 % of the area is characterized by medium and low vulnerability.

Keywords Vulnerability · Unsaturated zone · Cracow Upper Jurassic Region

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Introduction

The Cracow Upper Jurassic Region (CUJR), located in southern Poland, represents a southern part of the Upper Jurassic Limestone Upland (UJLU) belt stretching from Cracow in the southeast to Wielun in the northwest. CUJR located within the limits of Cracow–Silesia monocline is an example of typical upland karst of incomplete development and diversified inner structure. Upper Jurassic sediments are covered partly by Cretaceous and Tertiary deposits, while in most parts by Quaternary deposits. The Cretaceous sequence of thickness from 1 to 30 m, represented mainly by marls of Senonian age, occurs on the east slope of the CUJR. The Miocene clayey sediments, thick up to 80 m, occur in overburden in the southern part of the region, in the area of Krzeszowice Graben (Fig. 1). The Quaternary sediments, thick from 1 to 40 m, are represented by loams and sands in river valleys while by loesses and diluvium deposits on uplands. Carbonate fissure–karstic–porous aquifer of Upper Jurassic age is the main aquifer in the CUJR (Fig. 2). The aquifer is recharged directly at the outcrop area or indirectly by Quaternary or Quaternary–Cretaceous overburden of varying permeability. It predominates diffused recharge and flow in an aquifer

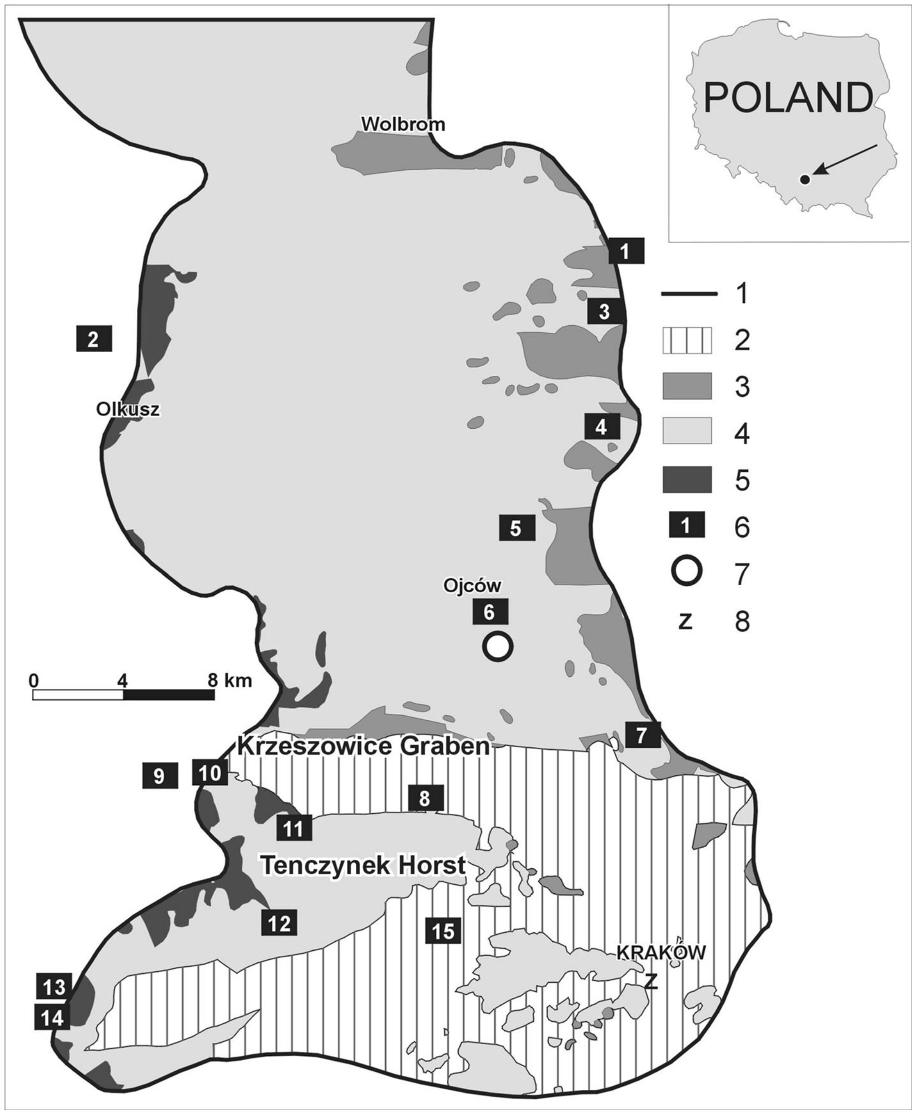

Fig. 1 Simplified geological map of the CUJR (without Quaternary deposits). *1* Limits of Upper Jurassic aquifer; deposits: *2* Neogene; *3* Cretaceous, *4* Upper Jurassic; *5* older deposits (Middle Jurassic, Triassic, Carboniferous, Devonian); *6* quarries (numbering according to Table 2); *7* sinkhole in Biały Kościół village, *8* Zakrzówek Horst

(Różkowski 2006), which delays the karst system reaction to increased recharge, contrary to the communicated system of vertical conduits—subhorizontal conduits developed in the vicinity of valleys, even in confined aquifers, e.g., in the Chalk aquifer of Upper Normandy (Janyani et al. 2014). On the other hand, tracer tests conducted by Mudarra et al. (2014) in a highly karstified massif suggest that the global response (including diffuse infiltration) of the system could be faster and more sensitive than that produced from infiltration concentrated at single points on the surface, which is explained by variation of phreatic zone thickness and by the much higher volume of diffuse infiltration water. In elevated parts of CUJR, groundwater table stabilizes at a depth of 30–70 m below ground level, while in deeply cut karstic canyons at a depth up to several meters.

This paper presents effects of fracturing and karstification of carbonate rock unsaturated zone on the vulnerability to contamination of the Upper Jurassic aquifer limited in the CUJR. In more detail are characterized locally present point recharge of the aquifer, commonly occurring river water infiltration, hydraulic structure of carbonate massif and precipitation infiltration dynamics at the unconfined karstic aquifer on the basis of tracer test conducted at the Zakrzówek horst (Cracow city). The research results were compared with the assessment of aquifer vulnerability made by the modified DRASTIC method (Różkowski 2007).

Concentrated recharge and underground flow of watercourses

Point recharge of the Upper Jurassic aquifer occurs locally. It is potentially associated with the sinkholes of suffosion–corrosive genesis, to a depth of 15 m, occurring in groups on the hilltops (up to dozens of large objects on Tenczynek

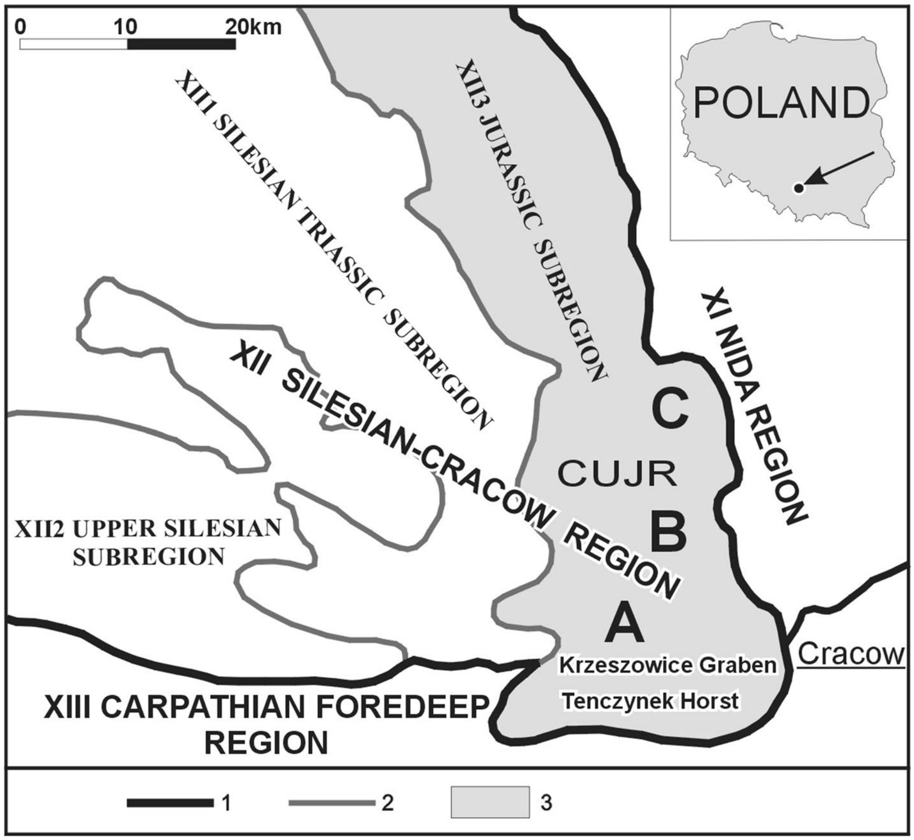

Fig. 2 Location of the CUJR in the background of hydrogeological division of Poland (Paczyński 1995 with supplement). *1* Regional boundaries, *2* subregional boundaries, *3* extension of CUJR; *A* Rudawa river catchment, *B* Prądnik river catchment, *C* Dłubnia river catchment

horst) and in the upper parts of karst ravines, as well as in a half-blind valley with swallow holes (called "łykawce"). The most famous "łykawiec" located near the village Biały Kościół, with a solution pipe of 12 m depth, has a hydraulic connection with a karst spring on the Prądnik valley floor (Fig. 1). Tracer tests documented flow through the fissure–karstic system with a velocity of 360 m/h (Gradzinski and al 2011).

In certain CUJR karstic valleys, water infiltration into the ground was observed combined with underground flow. Between the year 1992 and 2010, 330 measurements of water flow were performed on 7 main rivers and 27 tributaries, of which part was repeatedly measured by Różkowski and Sadowski, in order to recognize the recharge conditions of fissure–karst Upper Jurassic aquifer by the surface water in the area CUJR (Różkowski and Sadowski 2013). Based on the measurements, at least 23 river course sections of infiltrating character were localized. Water loses by infiltration averaged from several to tens of dm^3/s (up to 340 dm^3/s in the Prądnik River, 1998) (Różkowski and Sadowski 2013). Observed zones of surface water infiltration to the ground in the karst area CUJR mainly reflect tectonic engagement of the Upper Jurassic carbonate rock massive as well as its karstification. Regional hydrological studies document its prevalence, while numerical modeling clearly shows a small quantitative share of water courses infiltration in the balance of the Upper Jurassic aquifer. According to numerical modeling studies, presented in a paper by Różkowski et al. (2005), the average recharge of the Upper Jurassic aquifer through the river valleys zone is estimated at 3602 m^3/day, which in relation to global recharge (310,960 m^3/day), is only 1 %. Local underground water transition of some Rudawa River and Prądnik River tributaries (Fig. 2) represent channel flows, exclusively within the valley areas. River water losses can also be a component of flows between adjacent karst catchments such as Rudawa and Prądnik, Prądnik and Dłubnia, confirmed by the results of the 1998 and 2008–2010 regional hydrometric measurements, and the numerical modeling performed in the year 2000 (Różkowski 2006).

Hydraulic structure

The complexity of water circulation conditions in CUJR carbonate rock massifs results from the complex structure of the aquifer (fissure–karst–porous), as well as the spatial and time variability of geometric and hydraulic parameters in particular circulation systems (Różkowski 1990; Kiraly 2002). Regional studies of the Upper Jurassic limestone massif hydraulic structure, conducted within the unsaturated zone, demonstrate its quasi-homogeneity on a regional scale.

Quantitative assessment of the Upper Jurassic limestone massif hydraulic structure within the unsaturated zone, based on the research carried out in 1999–2006, looks as follows:

Porosity

In order to estimate the rock matrix, pore space parameters were performed in the year 1999 sampling of the Upper Jurassic limestones. Samples representing different facies were taken from 22 quarries, five mogotes, and 9 caves. In total 91 core samples and 72 surface chip samples were collected. The studies of porosity, permeability and specific yield were performed at the laboratory of the Department of Hydrogeology and Water Protection of the AGH University of Science and Technology in Cracow. The porosity of the rock matrix reached $n_o = 0.6$–27.8 %, with 4.4 % of the geometric mean value (Różkowski et al. 2001).

The vast majority of the pore space does not participate or play a secondary role in the groundwater flow, mainly storing it, which predominate small-sized pores, capillary and subcapillary. This is evidenced by, among others, specific yield values close to 0 of 30 % of the rock samples, and the ratio of the open porosity to specific yield located mostly in the range from 0.06 to 0.09, as well as a very low value of permeability coefficient k from 2.88×10^{-10} to 3.49×10^{-7} m/s. Lack of correlation between permeability and open porosity of the carbonate rock matrix is documented in studies conducted by Rzonca in the NE part of Swietokrzyski region (Rzonca 2008). Variability of hydrogeological properties of the Upper Jurassic limestones is in turn dependent on facial diversity (Table 1). Average porosity of the samples taken from the identified deposits in the limits of CUJR area range from 5.2 to 14.0 % (Różkowski 2006).

With depth, the value of the hydrogeological parameters declines. Mean values of the Upper Jurassic limestones pore space parameters from CUJR quarries are 1.1–6.3 times higher than that observed in drill cores involving the entire profile of Upper Jurassic (Bielec 2000; Różkowski 2006). Also, fissure opening and permeability decreases with depth (Motyka 1998; Liszkowska 1990). By comparing the results of the field tests conducted in the unsaturated zone with pumping tests of 19 wells located in the vicinity of the quarries, a general decrease in fissure opening with depth from $b = 0.4$–2.0 mm (for a depth range 0–30 m below the surface) to $b = 0.1$–0.7 mm (for a depth range 30–70 m below the surface) was estimated, assuming linear fissure density invariability with depth (Różkowski 2006).

Fissuring

Fissures occurring in limestones of the CUJR form a network of polygenetic voids, oriented in space, intersecting pore space. Estimation of fissure and karst porosity was done on the basis of field tests and analysis of digital photographs covering an unsaturated zone of 20 CUJR quarries. On the basis of 1343 measurements of spatial orientation, there have been found from 1 to 4 sets of vertical fracture systems, which predominate two linked sets, orthogonally positioned, extending along the direction NE–SW (26°–47°) and NW–SE (277°–326°). Subordinately, sets occur on directions N–S (345°–0°), W–E (74°–90°). These are commonly observed as well bedding planes, on average dip angles 2°–20°. The overall linear density of vertical fractures (Γ_L) belongs to the class from medium to very low (0.24–4.92 1/m), while spacing between sets of fractures to the class from very large to average (500–37 cm) (by classification, respectively, Liszkowski and Stochlak 1976; Ford and Williams 2007).

Generally low surface fissure porosity (n_F) varies accordingly to facial division. Massive limestones characterize low density and aperture of fissure sets ($b_{Me} = 0.35$–1.30 mm) and very low fissure porosity coefficients (n_F) 0.03–0.34 %, average 0.12 %, while the bedded limestones are, respectively, $b_{Me} = 0.6$–2.0 mm and n_F 0.16–1.26 %, average 0.45 % (Różkowski 2006; Table 2). Aforementioned facies are accompanied locally by chalky limestones. Both lithofacial subpopulation complexes should be considered as very poorly fissured (Liszkowski and Stochlak 1976). Calculated fissure permeability coefficient (k_{fs10}) values, characterizing massive and bedded limestones, are as follows: 2.35×10^{-5}–1.26×10^{-3} and 7.47×10^{-5}–1.22×10^{-2} m/s, average, respectively, k_S 6.60×10^{-5} and 1.27×10^{-3} m/s, which predominate filled fissures (Table 2).

Investigations of fissuring influence on the directional distribution of filtration within selected carbonate aquifers in Poland were presented by Krajewski and Motyka (1999). The upper part of the epikarst ratio of permeability coefficients, calculated for directions $k_{\parallel}/k_{\perp}$, was close to one due to the bedrock structure degradation by hypergenesis zone processes. In the lower part of the zone, this proportion rose to 3.7, while within the transition zone (oriented rubble/partially altered parent material) and quasi-monolithic amounted already to 16.6 and 15.9.

Table 1 Statistical characteristic of the hydrogeological parameters of Upper Jurassic limestones pore space from southern part of the Cracow–Czestochowa Upland

Lithology	Hydrogeological parameters	Unit	Number of observation	Min.	Max.	Range	Arithmetic average	Median	SD	Coefficient of variation (%)
Population	n_o	(–)	163	0.006	0.278	0.272	0.060	0.045	0.050	82
	k	(m/s)	90	2.88E−10	3.49E−07	3.49E−07	1.87E−08	2.37E−09	5.23E−08	280
	μ	(–)	78	0.000	0.130	0.130	0.009	0.001	0.021	222
	S	(–)	78	0.000	0.468	0.468	0.087	0.026	0.121	139
Massive limestones	n_o	(–)	80	0.007	0.160	0.153	0.048	0.039	0.033	69
	k	(m/s)	42	6.26E−10	6.25E−08	6.25E−08	8.68E−09	2.37E−09	1.36E−08	156
	μ	(–)	42	0.000	0.056	0.056	0.005	0.001	0.010	197
	S	(–)	42	0.000	0.442	0.442	0.068	0.027	0.088	130
Chalky limestone	n_o	(–)	23	0.023	0.278	0.255	0.124	0.110	0.068	55
	k	(m/s)	18	5.55E−10	3.49E−07	3.49E−07	6.47E−08	7.30E−09	1.05E−07	162
	μ	(–)	18	0.000	0.130	0.130	0.026	0.007	0.037	142
	S	(–)	18	0.005	0.468	0.463	0.155	0.049	0.176	114
Bedded limestones	n_o	(–)	29	0.017	0.189	0.172	0.076	0.071	0.043	57
	k	(m/s)	19	2.88E−10	3.02E−08	3.02E−08	4.92E−09	2.10E−09	7.60E−09	154
	μ	(–)	19	0.000	0.024	0.024	0.004	0.001	0.007	179
	S	(–)	19	0.000	0.303	0.303	0.043	0.014	0.076	175
Massive limestones sampled from caves	n_o	(–)	31	0.006	0.103	0.097	0.030	0.023	0.024	80
	k	(m/s)	11	4.86E−10	3.60E−08	3.60E−08	5.14E−09	1.78E−09	1.04E−08	201
	μ	(–)	11	0.000	0.009	0.009	0.001	0.0004	0.003	224
	S	(–)	11	0.000	0.304	0.304	0.058	0.011	0.099	170

n_o, open porosity; k, permeability coefficient; μ, specific yield; S, specific yield degree

Table 2 Selected parameters of fracturing and hydrogeological properties of fissure space in the Upper Jurassic limestones of the CUJR

Location of quarries	1 Wielkanoc (M)	2 Bogucin (B, M)	3 Ulina Wielka (M)	4 Minoga (B)	5 Skała (M)	6 Czajowice (M)	7 Januszowice (M)	8 Zabierzów (M)
b_{Me} (mm)	0.85	2.00	1.00	1.80	1.00	0.95	0.45	0.40
Γ_L (1/m)	1.32	4.92	1.93	0.93	1.50	0.62	1.33	3.25
k_s (m/s)	2.35×10^{-5}	1.22×10^{-2} (B)	1.55×10^{-4}	7.47×10^{-5}	5.35×10^{-4}	7.93×10^{-5}	5.82×10^{-5}	1.46×10^{-4}
n_s (%)	0.17	1.26 (B)	0.05	0.36	0.19	0.12	0.10	0.30
Location of quarries	9 Gwozdziec (M)	10 Nawojowa Góra (B)	11 Mlynka (B)	11 Mlynka (M)	12 Czulów (M)	13 Mirów (B)	14 Podleze (B)	15 Kryspinów (M)
b_{Me} (mm)	0.70	0.60	1.30 (B, M)	0.90	1.80	1.50	0.35	
Γ_L (1/m)	0.98	0.96	1.06	0.27	0.72	2.45	0.69	1.70
k_s (m/s]	2.21×10^{-4}	9.26×10^{-5}	1.32×10^{-3}	1.26×10^{-3}	7.44×10^{-5}	3.61×10^{-3}	6.71×10^{-3}	7.35×10^{-5}
n_s (%]	0.18	0.16	0.29	0.03	0.11	0.94	0.72	0.34
Average for population	Massive limestones (M)	b_{Me} (mm)	Γ_L (1/m)		k_s (m/s)	n_s (%)		
		0.90	1.69		6.60×10^{-5}	0.12		
	Bedded limestones (B)	b_{Me} (mm)	Γ_L (1/m)		k_s (m/s)	n_s (%)		
		1.50	1.84		1.27×10^{-3}	0.45		

Parameter values and the average for the population of: massive limestones (M), bedded limestones (B)

b_{Me}, median value of aperture opening; Γ_L, cumulative density of vertical cracks systems; k_s, fissure conductivity for $b < 10$ mm; n_s, fissure porosity

Karstification

Within the boundaries of the Upper Jurassic Limestone Upland (UJLU) were inventoried 1804 caves, with a 31,233 m total length of the corridors, but only 47 objects have a length exceeding 100 m, and 20 cave systems over 200 m. The longest cave has 1027 m total length of the corridors (Gradziński and Szelerewicz 2004). Karstic systems follow the spatial distribution of fracture sets. In the area of the CUJR, prevailing directions in the development of karst corridors are 45°, 70° and 130–140°, while at the area of Zakrzówek horst 20°–30° and 110°–120° (Gradziński 1962; Postawa 1995).

Analysis of drilling profiles was served by Nowak (1993) to determine the extent of the underground karstification of carbonate rocks in the northern part of UJLU. He examined 484 drilling profiles (1 drilling per 2.3 km^2), with a total length of more than 31 km, registering recorded voids, as well as filled cavities. In 46 % of the examined drilling profiles were found signs of karst. The statistically karstified part of the limestone layer is 5.5 m thick (10.5 % of the drilling length), including the share of the karst cavities of only 0.2, 4.6 % of filled cavities, and 5.7 % of karstic fissures (empty and filled). Prevail forms are filled with residual material, subordinately allochtonic. Furthermore, Liszkowska (1990) provides data from experimental catchment, located in the region of Częstochowa, where as many as 96 % of deep karst forms are filled. Analysis of drilling profiles defined a linear channel porosity of "active" voids to $n_k = 0.4$ %, and 2.5 % to filled forms. In turn, research done in quarries exploiting Upper Jurassic limestones of CUJR, allowed by Różkowski and Polonius (2006), estimated the average size of porosity in the upper part of the unsaturated zone to 2.5 %. The authors' observations confirmed that the karst tunnels are filled mainly with rubble and clay material. The value of karstic porosity of the CUJR Upper Jurassic limestones was determined, in turn, on the basis of the reserves documentation changes in the range from 0.2 to 4.5 %.

Tracer tests conducted at zakrzówek horst

Zakrzówek horst is built of the bedded limestones, locally massive limestones, of a thickness up to 225 m. Over them locally lie Cretaceous deposits, in the form of isolated patches. The horst is surrounded by Miocene clays filling tectonic depressions. Quaternary represents sandy-gravel deposits of Pleistocene and sandy-clayey sediments representing Holocene (Fig. 3). Upper Jurassic limestones are cut by the sets of fractures on the directions NE–SW (45°–50°) and SE–NW (120°). Arrangement of fractures correspond to karst systems developed inside the horst (Postawa 1995). At Zakrzówek horst, 16 caves (Szelerewicz and

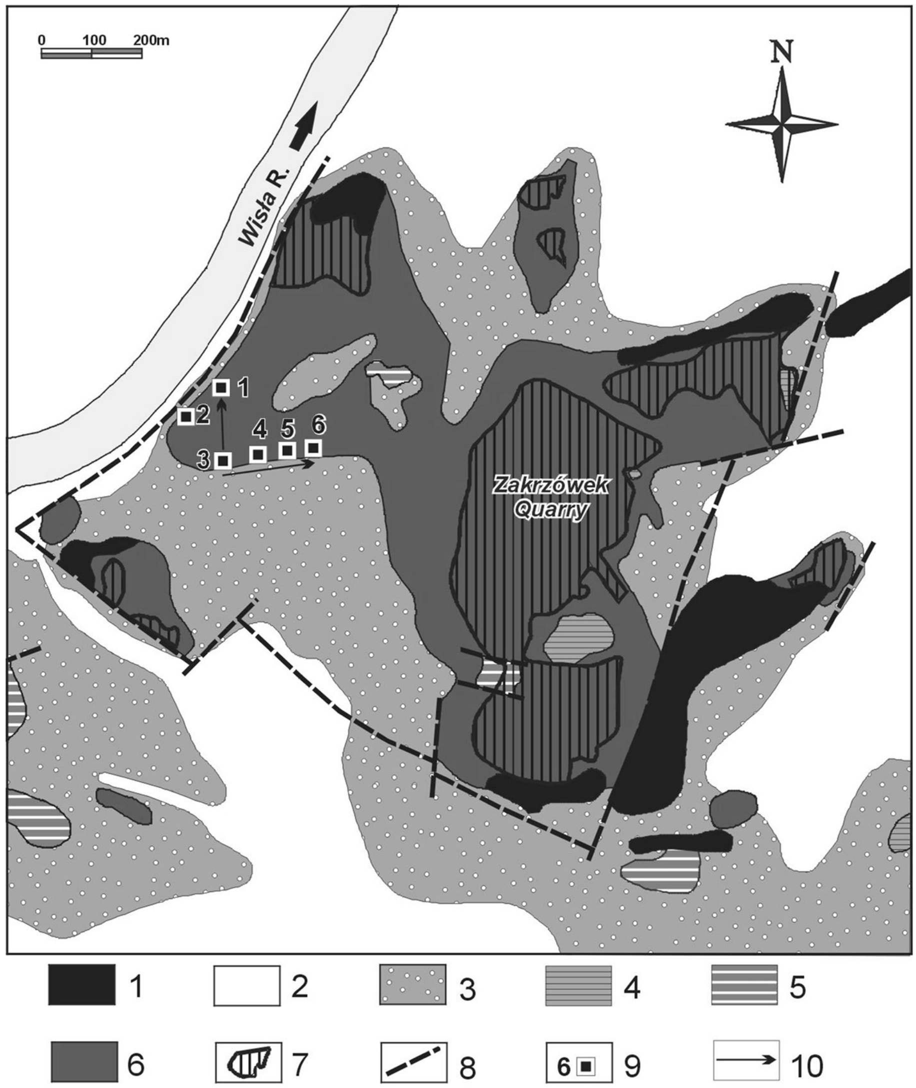

Fig. 3 Sketch of Zakrzówek horst geology (Kulma et al. 1991 with supplement). *1* Burrows and embankments, *2* alluvium, slope wash and loess (Quaternary), *3* sand (Quaternary), *4* clay (Tertiary), *5* marl, marly limestone (Cretaceous), *6* bedded limestone (Jurassic), *7* quarries, *8* faults, *9* caves: *1-Jasna, 2-Wywiew, 3-Z kulkami, 4-Niska, 5-Pod Nyża, 6-Twardowski*, *10* identified directions of horizontal tracer migration

Górny 1986) were inventoried, with a total length of the corridors from 3 m ("Schronisko Rurka") up to 500 m (Twardowski Cave). Six monitored unsaturated zones above caves are interconnected (Różkowski 2008). The open porosity determined for limestones of Zakrzówek horst, tested on a population of 418 samples, changes in the range from 0.007 to 0.167 (arithmetic mean 0.073) (Motyka and Postawa 2000), while karst porosity reaches 1 % (Motyka et al. 2002).

Tracer studies were conducted at the area of Zakrzówek horst in the years 1997–1999. By comparing the time shifts between the peaks of precipitation and local minima in the chloride ion concentration in cave drippings is obtained the vertical velocity of water infiltration in the unsaturated zone ranging from 0.7 to 4.2 m/day (8.1×10^{-6}–4.9×10^{-5} m/s). Studies using artificial tracers were carried out in caves: Z kulkami, Niska, Pychowicka. Over the sampled drippings was poured brine of a concentration of 200 g Cl/dm^3 on an area of about 1 m^2. Estimated velocity of migration through the overburden to the Z kulkami Cave in July 1997 amounted to f1.1 m/day (1.27×10^{-5} m/s). In the period from 3 weeks to about 3 months after the start of the experiment, elevated concentrations of Cl ion appeared in drippings located in the neighboring caves: Jasna and Twardowski (Fig. 3). Determined horizontal speed of tracer migration reached from 0.6 to 3.3 m/day (6.94×10^{-6}–3.82×10^{-5} m/s). In October 1999, there was observed a flow from the area of the experiment (Z kulkami Cave) to Twardowski Cave. The determined speed reached 59 m/day (6.83×10^{-4} m/s). On the basis of the test carried out above, for the Niska Cave in July 1998, the vertical speed was estimated as 1.25 m/day (1.45×10^{-5} m/s), while the horizontal velocity in the direction of the Twardowski Cave was 9.2 m/day (1.06×10^{-4} m/s). Horizontal migration is associated with a privileged network based on a system of anastomoses, developed on karstic dissolved bedding planes (Różkowski 2008).

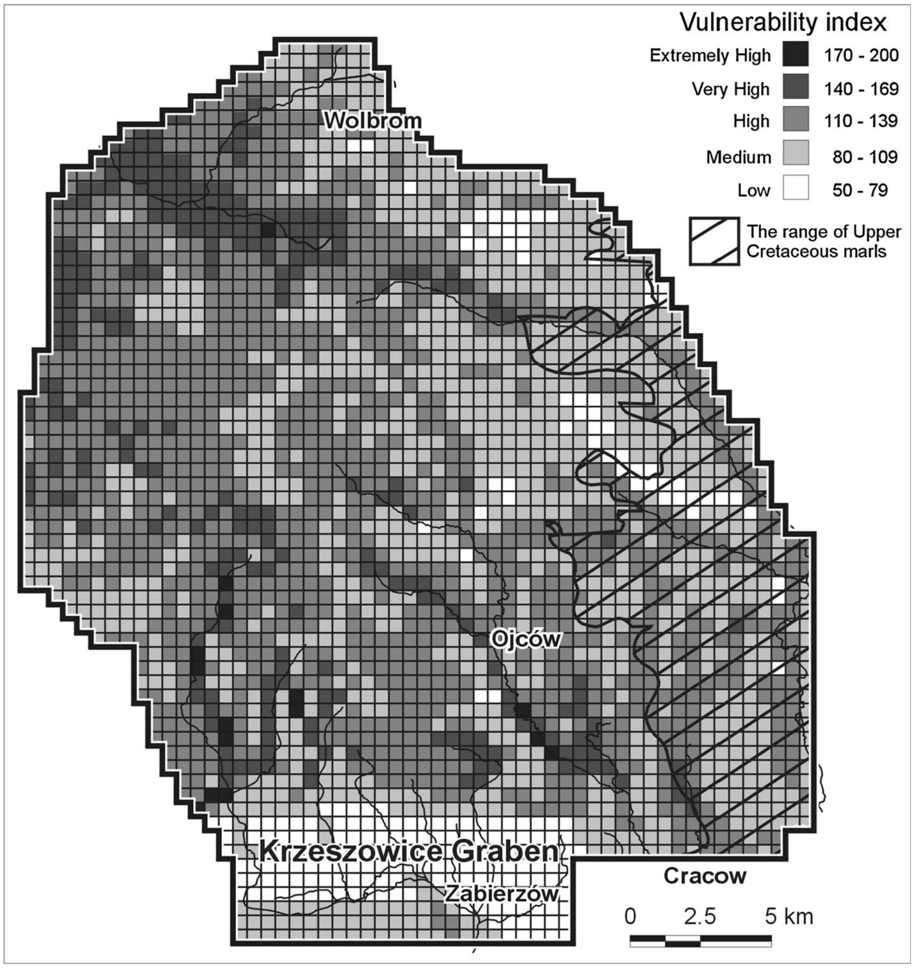

Fig. 4 Schematic map of the Upper Jurassic aquifer vulnerability created using a modified DRASTIC method (Różkowski 2007 with supplement)

Assessment of the vulnerability performed by a modified drastic method

The vulnerability of fissure–karst groundwater to contamination in a karst area of CUJR was assessed using a modified DRASTIC ranking method (Różkowski 2007), which shows high variation conditioned mainly by lithology and thickness of the overburden. A modified method used by Witkowski et al. (2003), with additions of Różkowski (2007), is a combination using a simulation model of the aquifer (indicators: 1—effective infiltration, 2—horizontal permeability coefficient, 3—filtration velocity) and spatial characteristics (4—depth of groundwater table, 5—lithology of unsaturated zone, 6—Upper Jurassic aquifer thickness), additionally taking into account the soil criterion (7). For the aforementioned vulnerability assessment criteria's rank, the following weights were adopted: 1–4, 2–2, 3–3, 4–5, 5–5, 6–1, 7–2.

Interpretation of the prepared synthetic map of the vulnerability revealed that within the karstic area of the CUJR extremely high and very high vulnerability (IP = 140–200) covers only 10.3 % of the area, while high vulnerability takes about a half of the Upper Jurassic aquifer limits (54 %). In contrast, the average vulnerability, occurring mainly in the eastern part of the area, as well as low (IP = 50–109), characteristic to the graben, located in the southern part of the area, filled with Miocene clays, takes up 46 % of the study area (Fig. 4) (Różkowski 2007).

Conclusions

The fissure–karstic aquifer of the CUJR characterizes diverse vulnerability to contamination. Almost half of the CUJR area has an average and low vulnerability to contamination, which results from the presence of the loess cover in the overburden and good isolation of groundwater in Krzeszowice Graben by thick Miocene clays. Exceptionally, within tectonic horsts with exposed limestones, vertical filtration velocities are high, as documented by tracer tests conducted at the Zakrzówek horst. Vulnerability to groundwater contamination is limited by domination of diffuse recharge. Point recharge has only a local meaning and is poorly documented. Infiltration of water from watercourses plays practically no role in the recharge of the Upper Jurassic aquifer. Underground flows of watercourses are likely to take place mostly in the shallow valley zone. Quantitative assessment of the hydraulic structure of the unsaturated zone of the Upper Jurassic limestone massif, done on the basis of research conducted in quarries, indicates the accumulative capabilities of the rock matrix and its overall blockage. Fissure–karst systems, which are a "conductive" element, have low hydraulic capacity, due to, among others, the low degree of massif fracturing, small crack extent and filling with clay material. The significant presence of poorly permeable overburden and moderate fissuring and karstification of rock in the unsaturated zone of the CUJR are reflected in the assessment of the Upper Jurassic aquifer vulnerability to contamination, performed by a modified DRASTIC method.

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