ORIGINAL ARTICLE

Determination of potential mine water discharge zones in crystalline rocks at Rozna, Czech Republic

Adam Ricka · Tomas Kuchovsky · Ondra Sracek ·
Josef Zeman

Abstract The Rozna Mine is one of the last active uranium mines in Europe. When the mine is closed and flooded, the natural groundwater flow pattern will be partly restored. Re-established groundwater flow system will be associated with an increase of groundwater discharge into draining rivers and streams. Since the groundwater inflows to streams can be contaminated by the mine water, the groundwater drainage characteristic of fractured aquifer should be carefully identified. Several methods of groundwater discharge zones identification were used including morphological analysis, thermometry, and electrical conductivity (EC) measurements. Stream temperatures and EC at more than 700 points in the area covering about 85 km^2 were measured. The measurements were performed during winter period, when stream discharges were low and there was a maximum temperature contrast. There was a frequent presence of preferential discharge zones with resulting anomalous temperatures and electric conductivity values of stream water. The results show evident correlation of discharge zones with surface morphology and geological settings. Just like the aquifer discharge characteristics, the aquifer is strongly heterogeneous. The thermometry supported by measurement of EC proved to be a useful tool for large-scale investigation of groundwater flow and drainage in fractured aquifers.

A. Ricka (✉) · T. Kuchovsky · J. Zeman
Department of Geological Sciences, Faculty of Science,
Masaryk University, Kotlářská 2, 611 37 Brno, Czech Republic
e-mail: rickaa@seznam.cz

O. Sracek
OPV s.r.o. (Protection of Groundwater Ltd), Bělohorská 31,
169 00 Praha 6, Czech Republic

Introduction

The Rozna Mine in the Czech Republic is one of the last active uranium mines in the European Union (Fig. 1). The total area extent of mining district is about 15 km^2 and is located in the northern part of study area (Fig. 1). The depth of shafts reaches 1,200 m, which corresponds to the depth of about 600 m b.s.l. After closure and flooding of the mine, an increase of groundwater levels in mining district is expected (Pelikan 1991). This will result in a partial restoration of natural groundwater flow pattern. The groundwater restoration will be controlled by mine water level driven by mine water pumping, altitude of dewatering adit, and hydraulic connection of the mine works. In contrast to present situation when active dewatering of mine occurs, groundwater flowing in the aquifer will outflow to streams and rivers in the surroundings of mining site. This may result in the appearance of uranium-bearing acid mine drainage (AMD) and contaminated waters in some sections of streams and rivers, threatening the aquatic ecosystems (Grande et al. 2005). The streams and rivers run into the Svratka River, where the large dam serving as the reservoir of water supply for 400,000 inhabitants is located.

Uranium-bearing AMD waters represent serious hazards for humans and wildlife related to the toxicity of uranium and products of its decay: radon, lead, polonium, and bismuth (Antunes et al. 2007). Release of AMD discharges may also contaminate surface waters by metals and sulfate and may cause low pH conditions (Kelly 1988; Blowes et al. 2003). In neutralized waters, increased concentration

Fig. 1 Location of the Rozna uranium mining district (*left*) and measured streams (*right*)
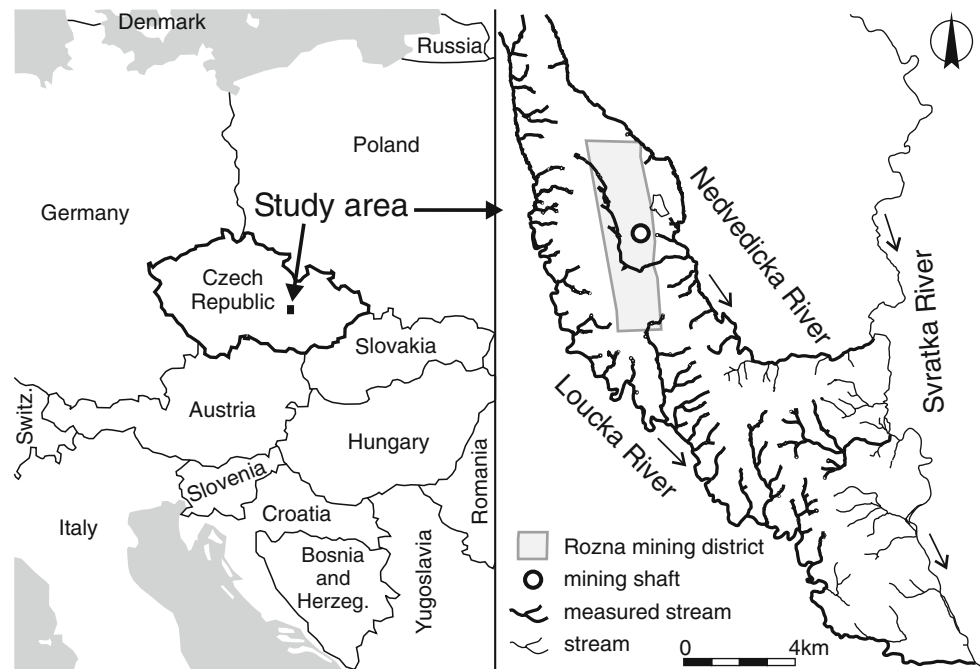
of iron is accompanied by the deposition of iron hydroxide coatings (Hoehn and Sizemore 1977).

The mining district Rozna is situated in crystalline rocks complex forming an anticline structure, where many valleys with gaining streams are present. Since the groundwater flow and transport model is prepared in effort to predict possible locations of AMD appearance, issues of aquifer homogeneity and groundwater flow characteristic are arising.

The most common techniques used to estimate groundwater flux into surface water bodies include hydrometric measurements, application of seepage meters, application of minipiezometers and tracer techniques, including event hydrograph separation (Cey et al. 1998). For example, minipiezometers and temperature measurements were used by Conant (2004); tracers such as Radon-222 and temperature measurements were used by Wu et al. (2004) and Baena et al. (2008). Surface water thermometry is a method using heat as a tracer. Gaining streams or their sections where surrounding aquifers discharge may be identified by anomalous temperatures (Taniguchi 1993; Constantz 1998; Bartolino 2003). However, a contrast between groundwater temperature and surface water temperature is necessary. Vertical temperature measurement in wells and boreholes is used for determination of groundwater flow characteristics in granitic rocks (Drury 1989; Silliman and Robinson 1989). Thermal gradient may be used to identify zones of vertical groundwater flow in a regional scale, where low thermal gradients are found in recharge zones and high thermal gradients in discharge zones (Person et al. 1996). Anderson (2005) has

summarized other examples of surface water and groundwater temperature measurement applications, e.g. determination of hydraulic conductivity of river bed sediments, outflow from aquifers to sea water, calibration of groundwater flow, heat flow models, etc.

At the Rozna mining district, differences in ground surface levels exceed 400 m over the distances of few kilometers. This favors morphology-dependent groundwater flow in the aquifer (Fig. 2). The concept of morphology-dependent flow in homogenous aquifer is commonly accepted (Tóth 1963). However, it is acceptable only in aquifers with a large depth, where a significant vertical flow component is present (Haitjema and Bruker-Mitchell 2005). Topographically induced differences in hydraulic heads lead to morphology-driven groundwater flow. The characteristic of flow depends on infiltration and permeability of an aquifer, type of boundary conditions, geometry and depth of aquifer, and local relief. The greater local relief results in more importance of local flow compared to regional flow (Tóth 1999).

However, real geological settings, especially in crystalline rocks, often complicate any consideration about simple groundwater flow. Due to the presence of several rock types and fault structures, the aquifer is expected to be strongly non-homogenous. In such aquifers, the flow directions are complicated, depending on orientation of both low- and high-permeability zones with respect to principal flow directions generated by surface morphology. At Rozna mining district, the impact of both morphology-dependent flow and non-homogeneities on the aquifer drainage characteristic are expected. Based on the
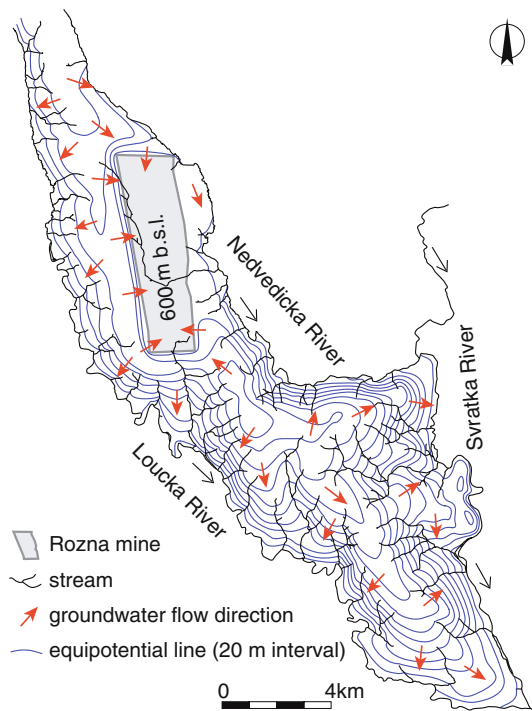
Fig. 2 Map with conceptual morphology-driven groundwater flow pattern

assumption of the morphology-dependent flow, the three bigger rivers should drain deep regional groundwater flow system, while many small streams and springs within the studied area should drain local groundwater flow systems.

The aim of the study was the identification of discharge zones in the crystalline rocks complex, where discharge of mine waters is expected after planed flooding of the Rozna Mine. We believe that methodology used in the study can be used at other mining sites with similar geological and hydrogeological conditions.

Geological settings and implications
for groundwater flow

The Rozna mining district is situated in the Bohemian Massif, in the NE part of the Moldanubian zone. The aquifer is composed of metamorphic and magmatic rocks

Table 1 Area extent of various rock types bodies in study area

Rock type	Surface of the rock bodies	
	km²	%
Paragneiss	54.4	64.3
Migmatite, orthogneiss, granite, etc.	18.2	21.5
Granulite	6.0	7.1
Amphibolite	6.0	7.1
Sum	85	100

(Table 1). The main rock type is biotitic paragneiss with enclosures of orthogneisses, amphibolites, erlanes, granulites, marbles and serpentinite bodies. Granite bodies and pegmatite and aplite dikes represent the most frequent magmatic rocks (Fig. 3). Based on expected permeability and impact on groundwater flow characteristics, rock types can be divided into four main groups:

1. Paragneisses are the least permeable rocks composing the aquifer; their bodies are relatively large compared to other rock types (Michlicek 1986).
2. Migmatites, orthogneisses, and granites (less frequently marble, quartzites, pegmatites and aplites, erlanes) do not undergo plastic deformation, fractures are not sealed, permeability of gneisses and migmatites is increasing with the degree of migmatization, granites usually exhibit higher permeability than gneisses (Stober 1996; Stober and Bucher 2007).
3. Granulites were not reviewed with respect to groundwater flow characteristics, but similar properties to the rocks in the previous group can be expected.
4. Amphibolites and ultrabasic rocks are expected to have low permeabilities caused by the presence of clay minerals in fractures (Michlicek 1986).

During the Variscan Period, the nappe overthrusting resulted in the formation of fold structures. Synclines and anticlines of regional importance are obvious from Fig. 5a. The crystalline rock complex shows impact of both ductile and brittle deformation. The following four important tectonic structures were observed during uranium prospection and mining (Fig. 4):

1. Cataclazite zone NNW–SSE with 45°–70° inclination to W–WSW: length of the zones is 10–15 km; the thickness of the zones varies from 25 to 30 m; the cataclazite zones usually contain tectonic breccias and secondary minerals originating from circulation of fluids; some parts of the zones are filled by the clay-enriched material, graphitic rocks and carbonates.
2. Diagonal fault structure 55°–70° with subvertical inclination: thickness of the fault structures is 1–2 m; their continuous lengths vary in the range from tens to hundreds of meters; the fault structures are open and not filled by the low-permeability materials.
3. Diagonal fault structure 280°–290° with inclination 68°–90° to both SW and NE: they are often filled by hydrothermal carbonates; the fractures are continuous over the distances of tens of meters.
4. Fault structure 10°–30° with incline 66°–80° to both NW and SE: the system is much less frequent.

According to observations of Kribek et al. (1997) from uranium mine drifts, the most important tectonic structures for groundwater flow are both the diagonal fault
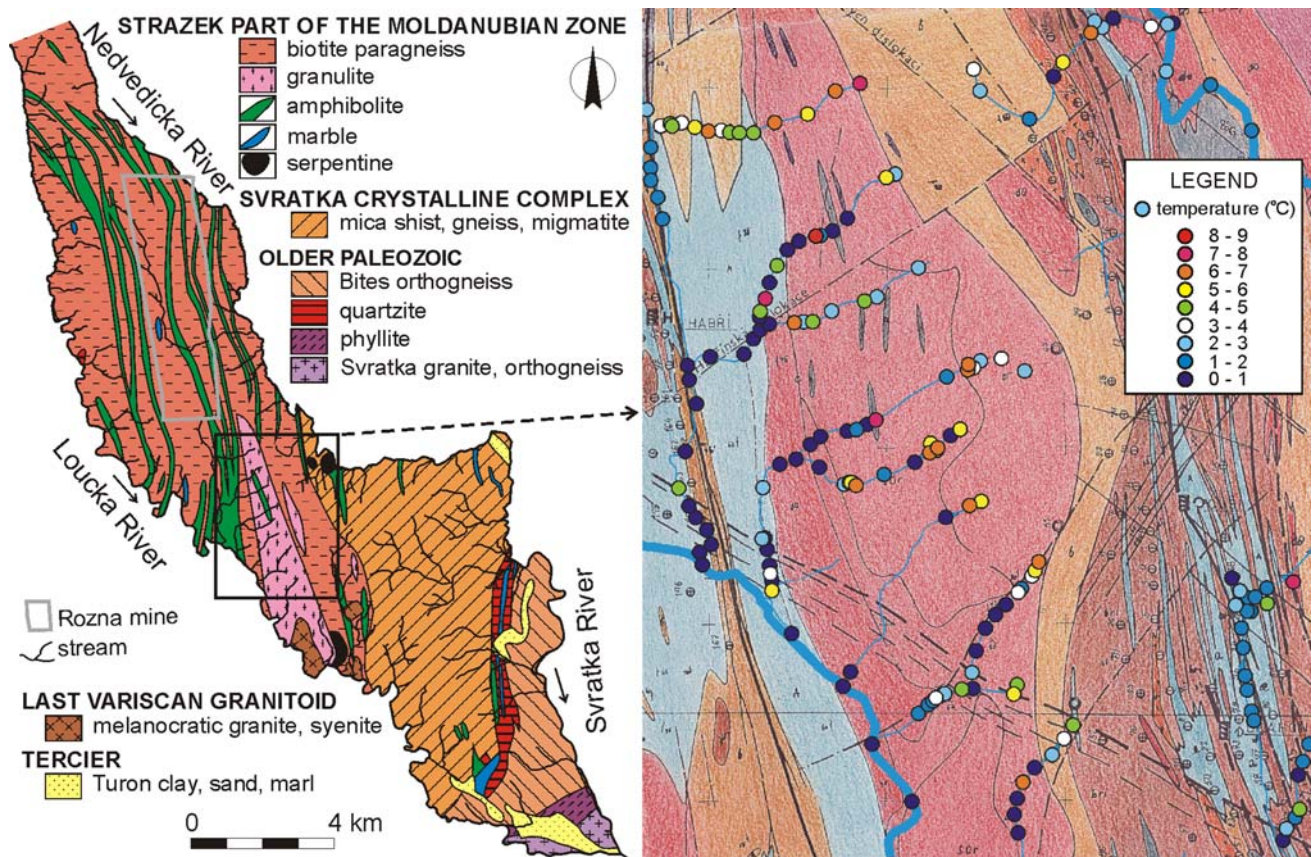
Fig. 3 Simplified geological map of the study area (*left*; modified from Svoboda et al. 1962; Starkova and Macek 2000) and detailed view of the geological map (Hajek et al. 1997) with measured temperatures of stream water (*right*)

structures 55°–70° and 280°–290°. The thickness of weathered zone of metamorphic and magmatic rocks varies from 0 to 5 m, based on the borehole data and outcrop observations.

Morphological setting and implications for groundwater flow

Surface morphology in the studied area shows important local differences. Using the concept of average vertical relative distance presented by Demek (1984), the area can be divided into three parts (Fig. 5b). The relative vertical distance reflects differences between the highest and the lowest place in the squares of 500 × 500 m size covering the whole area. The vertical distance values were divided into 12 intervals from 20 to 240 m. The northern part with relatively flat relief is comprised of two ridges separated by the Rozsochy syncline (Fig. 5a). An average relative vertical distance is 39 m (weight average of all intervals). The middle part shows more jagged morphology. The ridge of the Rozna-Olsi anticline is separated by the Rozsochy and the Olsi syncline. The ridge is transversally intersected by deep stream valleys sloping toward the Loucka River and

the Nedvedicka River. This results in higher average relative vertical distance of 71 m. The southern part of the studied area shows the largest relative differences in ground surface levels. The differences are increasing toward the Svratka River, with its channel being at the lowest morphological position in the observed area. The average relative vertical distance is 95 m. When compared to the directions of tectonic structures, it becomes obvious that stream valleys in both the middle and the southern parts of area follow mainly the cataclazite zones NNW–SSE and the diagonal fault structures 55°–70°, respectively. According to the theory of morphology-dependent flow, less frequent groundwater drainage zones should be found in the northern part of the area.

Materials and methods

Thermometry of surface streams was chosen as a method to identify the aquifer discharge zones. Since a low contrast in water/air temperatures may have a negative impact on the reliability of thermometry, the choice of an appropriate season for field measurement was an important issue.
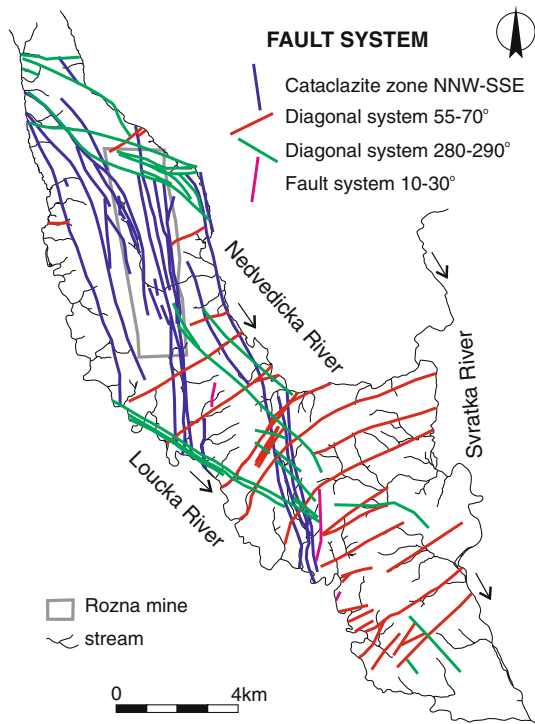
Fig. 4 Mining district Rozna fault system map (modified from Hajek et al. 1997)

These measurements were performed in winter period during 3 weeks in unusually cold February 2006. The air temperatures were permanently below water freezing point, in the range from −3 to −15°C. Ground surface was covered by snow layer with a thickness from 0.3 to 0.7 m. Stable climatic conditions were present during the observation period, no precipitation and snow melting occurred.

Daily discharge measurements in a spring located in the studied structure confirmed the aquifer recession during the measurement period.

The WTW 340i equipment with TetraCon325 cell was used for the measurement of both temperature and electrical conductivity (EC) values. Sensitivity of the device is 0.1 µS/cm and 0.1°C for EC and temperature measurements, respectively. The relative error of EC measurement was 0.01%, the error of temperature measurement was ±0.2 K. For the EC, cell constant was 0.475 cm^{-1} (±1.5%). The cell was daily calibrated according to the reference manual.

The boundaries of the observed area were set to the natural groundwater flow boundaries, formed by the most important rivers—the Svratka River, the Nedvedicka River and the Loucka River (Fig. 2). Observed area has covered 85 km^2 and total 744 points were measured. Mapping tours were oriented according to the stream flow and every single point with visually detectable groundwater discharge was noted (springs, waterlogging areas, gaining sections of streams, etc.). Steps between measured points in streams were 50 m in the cases where no discharge increase was observed. Coordinates of measured points were determined using GPS navigation Garmin eTrex Vista and then compiled with Microstation V8 to map projection. Measured data were statistically evaluated according to factors affecting the groundwater flow characteristics. Following features were monitored at every single point of groundwater discharge: rock type, presence or absence of tectonic structures, contact of different rock types and type of discharge. Based on these factors, groundwater discharges were divided into several groups (Table 2). The data were acquired from geological map 1:20,000 compiled by Hajek

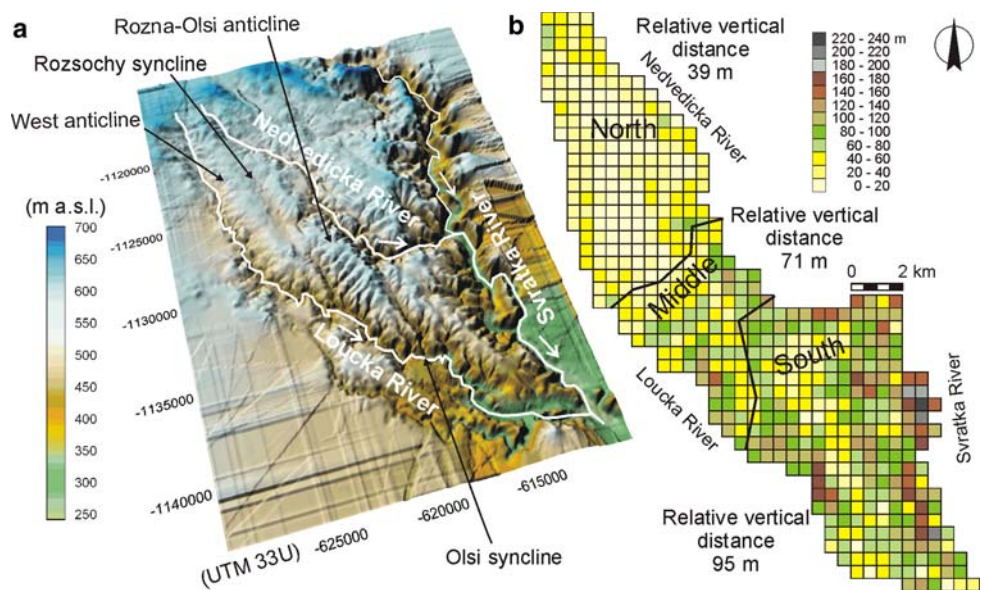**Fig. 5** Surface morphology (**a**) and model of relative vertical distance (**b**) in the study area

Table 2 Distribution of the groundwater discharge types according to evaluated factors

Evaluated factor	Frequency of the discharges	
	Number	%
Morphology		
Group 1: North, flat	81	34.0
Group 2: Middle, jagged	67	28.6
Group 3: South, steep	89	37.4
Rock type		
Group 1: Paragneiss	88	37.1
Group 2: Migmatite, orthogneiss, granite etc.	79	33.3
Group 3: Granulite	45	19.0
Group 4: Amphibolite	25	10.5
Fault system		
Group 1: Cataclazite zone	58	24.5
Group 2: Diagonal zone 55°–70°	65	27.4
Group 3: Diagonal zone 280°–290°	21	8.9
Group 4: Fault system 10°–30°	4	1.7
Group 5: Fault intersection	23	9.7
Group 6: Without faults	66	27.8
Discharge type		
Group 1: Stream springs	58	24.5
Group 2: In the stream	24	10.1
Group 3: <1 m up the stream	121	51.1
Group 4: >1 m up the stream	34	14.3

et al. (1997). Only the highest temperatures measured at a single discharge point were used for evaluation; the data measured in temperature aureoles down-stream were discarded.

To determine if there are statistical significant differences between temperature and EC of groundwater discharge groups for evaluated factors, the groups were compared using analysis of variance (ANOVA) designed by Snedecor and Cochran (1989). Multiple range test based on Fisher's least significant difference (LSD) was used to determine which groups of discharges are significantly different from the others (Fisher 1935) at the 95% confidence level. The computer program Statgraphics Centurion XV.II was utilized to statistical analysis.

For each group of the effluents, statistical parameters were calculated and visualized by box-and-whisker plots (temperature and EC). Temperature frequency was evaluated in nine intervals with a step of 1°C (temperature of identified effluents varied from 0 to 9°C). The sum of the percentage frequencies of discharges with temperature exceeding 4°C was chosen as a maximum value, allowing the differentiation of all groups.

Results and discussion

Measurements of temperature and EC were performed at 744 points and 237 groundwater discharge zones were identified (Table 2). Based on the discharge type, 58 points corresponded to springs and 24 points were identified directly in the streams. The rest of points were found less than 1 m above the streams (121 points) and 34 points were located in a distance more than 1 m above the stream, forming marshes spreading over several square meters.

Results of ANOVA and LSD procedure are given in Table 3. Since the p value of the F test is less than 0.05, there is a statistically significant difference between the temperature measurements and EC of the groundwater discharges groups for evaluated factors at the 95.0% confidence level. The LSD procedure of multiple range test indicated statistically significant differences between some pairs of groundwater discharge groups at the 95.0% confidence level. The ANOVA proved statistically significant differences between all evaluated variables at 95% confidence level and on one occasion at 92% confidence level (EC of morphology groups with p value of 0.080). In general, the results of ANOVA and LSD procedures indicated statistically significant differences between groundwater discharge groups.

Table 3 Results of ANOVA mean temperature (*T*) and EC for the evaluated factor and results of LSD difference determination between groundwater discharge groups

ANOVA								LSD	
Evaluated factor	Degrees of freedom	Means square		Variance ration (*F* ratio)		Probability under null hypothesis (*p* value)		Significant difference between groundwater discharge groups[a]	
		T	EC	T	EC	T	EC	T	EC
Morphology	2	9.9	95616.1	3.8	2.6	0.023	0.080	1–2; 2–3	1–2
Rock type	3	6.9	94310.4	2.9	2.8	0.040	0.045	2–3; 1–3	2–4
Tectonic	2	7.8	296759.8	3.3	6.8	0.040	0.001	1–2	1–2; 1–3

[a] Group numbers are explained in Table 2

Impact of morphology on groundwater flow

Results of evaluation of both temperature and EC measurements show a clear link to the morphology of studied area. This is obvious from comparison of groundwater discharges characteristics in three separated parts. Totally 81, 67, and 89 groundwater discharge points were found in the northern, middle and southern parts of the studied area, respectively. Dividing the number of discharge points by the areal extent of each area, areal frequency of the discharges is obtained. There is a significant difference in areal frequency of discharges (Table 4). The lowest frequency 2.0 groundwater discharge points per km^2 is in the

northern part, with relatively flat morphology. The middle and the southern parts both show much higher areal frequency of groundwater discharges: 2.9 and 4.0 discharge points per km^2, respectively.

Similar results were achieved by the evaluation of temperature measurements of groundwater discharges. Distribution of temperature in three parts of studied area is shown in Fig. 6a. The lowest average groundwater discharge temperatures 3.5°C were found in the northern part. The highest average temperature 4.2°C was observed in the middle part, while in the southern part the average temperature was only 3.7°C (Fig. 6b). Whereas the average EC value was the highest in the northern part (437 µS/cm), the EC values were typically the lowest in the middle part; the average EC value of the discharges was 397 µS/cm. The average EC of the groundwater effluents in the southern part is 422 µS/cm. The EC values in the middle part showed a smaller variability (Fig. 6d).

Comparing the discharge types, the highest percentage (95%) of springs and groundwater discharges close to streams is in the northern part (Fig. 6c). In contrast, lowest percentage of discharges located more than 1 m above the streams (5%) was detected here. Groundwater discharges at

Table 4 Frequency of the groundwater effluent according different parts morphology

Morphology	Extent of the area (km^2)	Number of the effluents	Frequency of the effluents (effluent/km^2)
North, flat	40	81	2.0
Middle, jagged	23	67	2.9
South, steep	22	89	4.0

Fig. 6 Discharge points and their relation to the Morphology factor **a** frequency distribution and **b** statistical parameters of temperature, **c** frequency distribution of discharge types and **d** statistical parameters of electrical conductivity
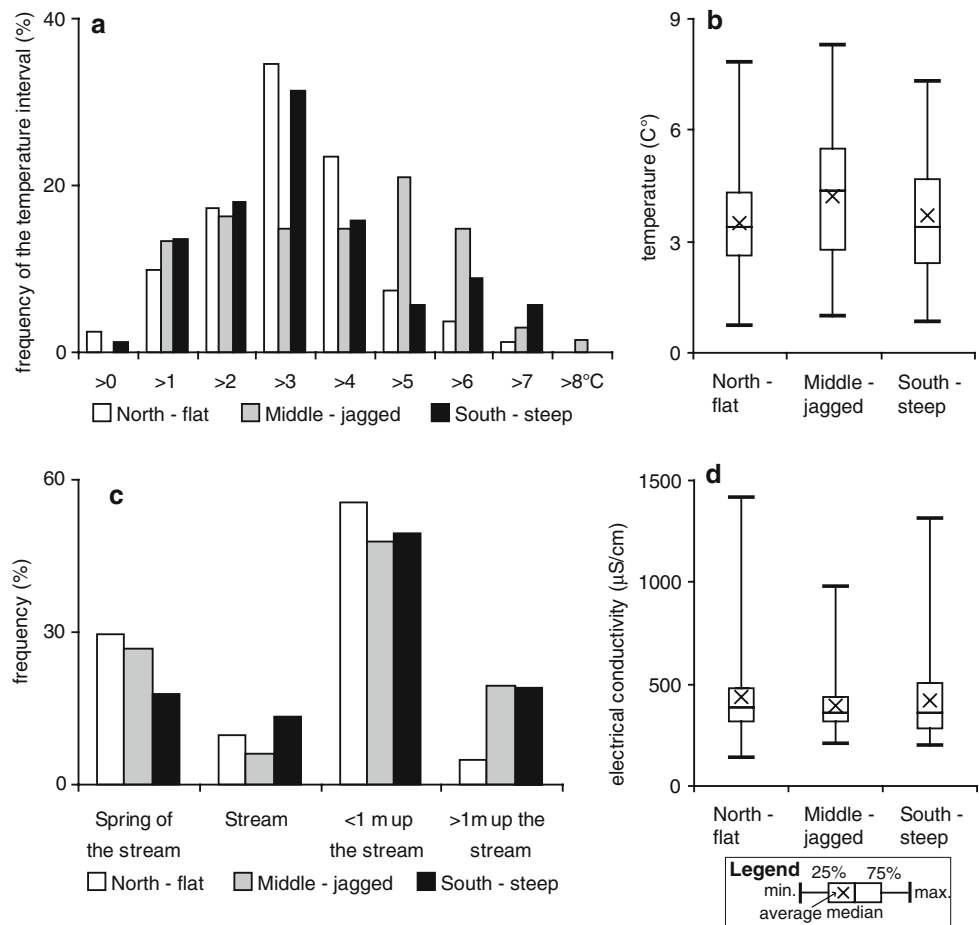
higher levels above the streams were present more frequently in the middle part (20%). The southern part showed a similar distribution of discharge types as the middle part, with higher frequency of discharges in streams and lower frequency of springs.

Higher frequency of aquifer discharge points is in a good agreement with more jagged morphology. This indicates an important role of the deeper regional groundwater flow and a minor importance of local groundwater flow in the northern part of the studied area. Comparison of temperature and EC values in the northern and the middle parts of area confirms this conclusion. Shallow flow related to the flat morphology results in lower temperatures at groundwater discharge zones. Longer flow path in regional flow system results in longer transition time of groundwater in rock environment and, thus, in higher EC values.

The higher groundwater discharge frequency, the highest temperature, and the lowest EC in the middle part are linked to the deep and fast groundwater flow caused by the jagged surface morphology.

The highest frequency of the drainage sites was found in the southern part of the studied area. However, the highest average temperature was observed in the middle part, not in the southern part, as expected. The lower average temperature of the groundwater discharges was characteristic for the southern part. This was probably caused by the proximity of the main drainage base—the Svratka River.

Impact of rock type on groundwater flow

Since there is some disagreement between discharge characteristics and the theory of morphology-dependent groundwater flow, geological setting of discharge points was also assessed. About 30% of groundwater effluents were identified inside large bodies of selected rock types, out of positions of tectonic structures and rock type contacts. This enables to separate the evaluation of drainage characteristics for each rock type from the morphology. Percentages of groundwater discharges in selected rock types and areal extents of rock types are shown in Fig. 7 for northern, middle and southern parts of studied area. It is obvious that some rock types are more favorable for groundwater discharge from the aquifer. Typically, the number of discharges in granulites highly exceeds their areal extent. This is similar in all three parts of the studied area with different conditions resulting from surface morphology. In contrast to granulites, paragneisses exhibit lower number of discharges when compared to their areal extent.

Paragneiss is the most common rock type in the observed area. In this rock type, groundwater discharges show the lowest average temperature 3.7°C and lowest percentage of discharges with temperature exceeding 4°C
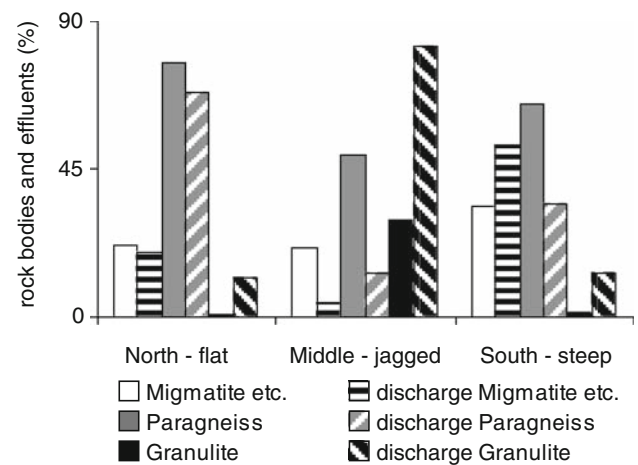

Fig. 7 Comparison of frequency distribution of various rock types bodies and groundwater discharges non-affected by tectonics and rock contacts within the groups with different surface morphologies

(31%). Just 41% groundwater discharges in granulites exceed 4°C (Fig. 8a). However, their average temperature of 3.8°C and the 75th percentile (5.5°C) refer to a limited number of discharges with higher temperature (Fig. 8b). This results in bimodal frequency trend of temperature intervals in granulites (Fig. 8a). Groundwater discharge with the highest temperature of 8.3°C was detected in the granulite body located in the southern part of studied area. The group of migmatites, orthogneisses, and granites shows high percentage of discharges with temperature exceeding 4°C (49%); the average temperature is 3.8°C. Groundwater discharges in amphibolites show surprisingly similar results: 48% of discharges exceeded value 4°C and average temperature was 4.0°C, i.e. the highest average temperature found in all rock types. This does not match with the assumptions arising from permeability of rocks, where high-permeability migmatites were expected to conduct groundwater more easily than less permeable amphibolite. Comparison of EC values suggests the explanation for such temperature distribution. While the discharges in the group of migmatites, orthogneisses, and granites show the lowest average EC value of 353 µS/cm, the discharges in amphibolites show highest average EC 502 µS/cm among all selected rock types (Fig. 8d). Migmatites, orthogneisses, and granites allow relatively rapid groundwater flow and their morphological positions in studied area result in the discharge of deeper groundwater flow. In contrast, amphibolites form narrow bodies oriented in the NNW–SSE direction parallel to anticlines ridges (Figs. 3, 5). Their position results in the intersection of groundwater flow from regional divide to stream valleys of the NNW–SSE direction. Formation of low-permeability barriers causes decrease of flow velocities. It also causes the highest frequency of different groundwater discharges (more than 1 m above the stream) in amphibolite (Fig. 8c).
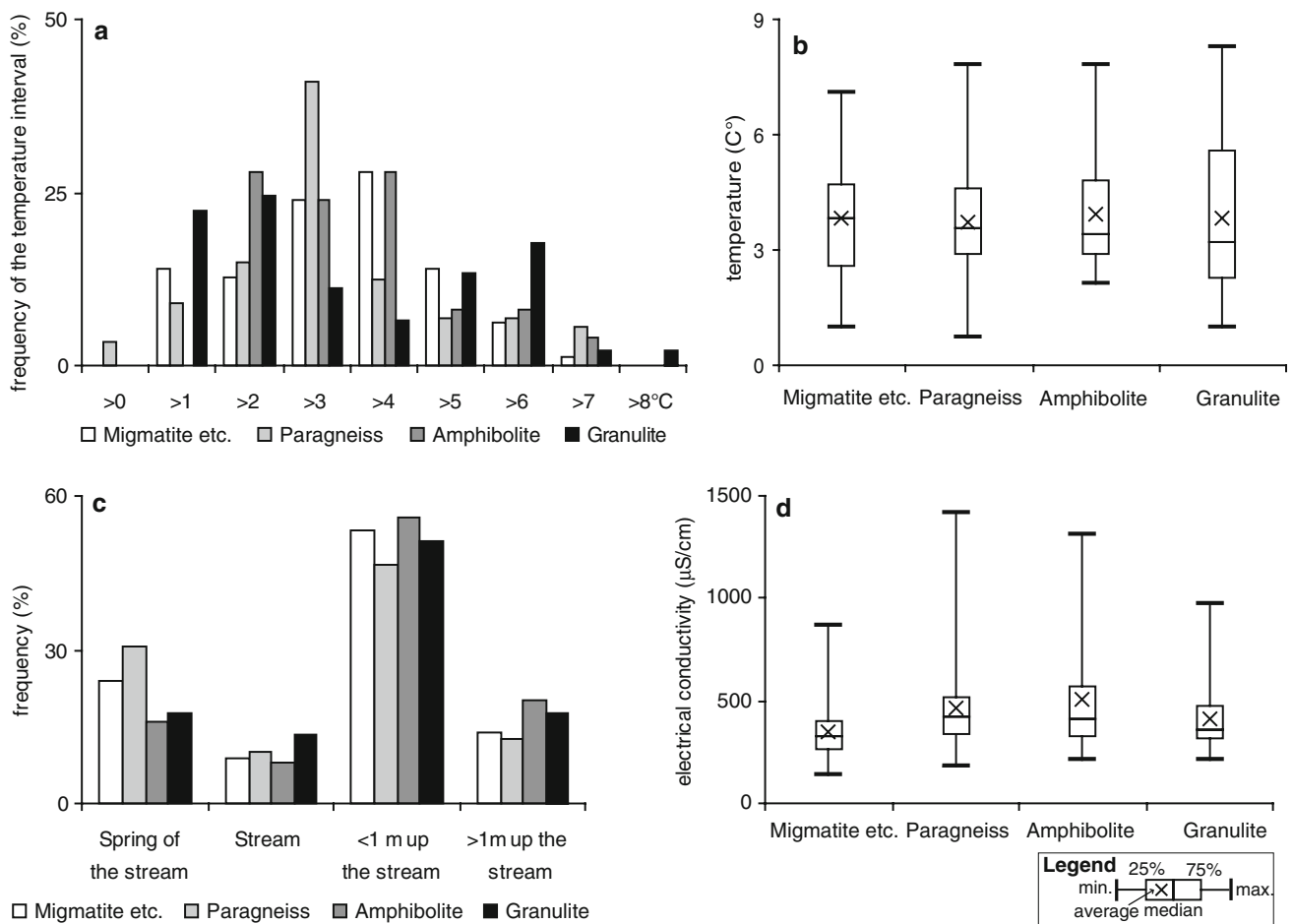
Fig. 8 Discharge points within Rock type factor **a** frequency distribution and **b** statistical parameters of temperature, **c** frequency distribution of discharge types and **d** statistical parameters of electrical conductivity

Average EC value of discharges in granulites 413 μS/cm indicates relatively fast groundwater flow. Higher average EC values of discharges in paragneisses 462 μS/cm indicate relatively slow groundwater flow compared to granulites and migmatites.

Both temperature and EC measurements at discharge zones of the aquifer show differences in groundwater flow in selected rock types.

In effort to specify impact of rock types with different permeabilities, groundwater discharges at contacts of two different rock types were evaluated. Totally 52 groundwater effluents were found. However, only few discharges were observed at contacts of paragneiss/granulite and migmatite/granulite. The lack of data does not enable the evaluation for contacts of these rock types. In the following discussion, the first noted rock type at contact was located upgradient with respect to groundwater flow. The lowest percentage of discharges exceeding 4°C (33%) and average temperature (3.5°C) was detected at the contact of paragneisses with amphibolites (Fig. 9a, b). Discharges located at the contact of both groups of migmatites and granulites,

respectively, with amphibolites and/or paragneisses were significantly different. The average temperatures of discharges in the contact of migmatites and granulites with amphibolites were 4 and 5.6°C, respectively. The average temperature at the contact of migmatites with paragneisses was 4.6°C. The percentages of discharge temperatures are evident from Fig. 9a. The maximum of discharges (equal to 11 points) exceeding 4°C was observed at the contact of granulites with amphibolites. The temperature of remaining rock type contacts (migmatites/amphibolites and migmatites/paragneisses) is lower compared to granulites/amphibolites contacts, but significantly higher compared to paragneisses/amphibolites contacts. Similar distribution shows the EC values (Fig. 9d).

The highest average EC value of 586 μS/cm was typical for discharges at paragneisses/amphibolites contact, while the lowest average EC value of 400 μS/cm was found at the contact of granulites/amphibolites. Other evaluated contacts are similar to granulites/amphibolites contact.

Distribution of temperatures and EC values of groundwater discharges at contacts of rocks support the

assumption about the impact of different permeability crystalline rocks on groundwater flow. Paragneisses and amphibolites are the least permeable rocks compared to other rock types. Observed temperatures and EC values of groundwater at discharge points indicate relatively shallow and slow groundwater flow. In contrast, temperature and EC values at discharge points related to the boundaries of granulite and migmatite bodies indicate faster and deeper groundwater flow compared to other rock types. The highest number of the groundwater discharges located more than 1 m above the stream at the contacts migmatites/ amphibolites and granulites/amphibolites is linked to significant difference in the permeability of these rock types (Fig. 9c).

Impact of tectonic structures on groundwater flow

In the study area, the fractured aquifer formed by crystalline rocks contains four important tectonic structures. Since the tectonic structures are important non-homogeneities

disturbing simple morphology-dependent groundwater flow, groundwater discharges were also evaluated with respect to their presence.

Significant differences were observed among three systems of tectonic structures, the fourth fault system 10–30° was not evaluated due to the lack of related discharges. Groundwater discharges close to the diagonal fault structure 55°–70° show highest average temperature 4.1°C compared to other tectonic structures. The values are 3.5 and 3.4°C in the diagonal fault structure 280°–290° and the cataclazite zone NNW–SSE direction, respectively. The variability of discharge temperatures related to the tectonic structures is shown in Fig. 10a, b. Despite identical average temperatures of discharges in the cataclazite zone and the diagonal fault structure 280°–290°, the cataclazite zone discharges exhibit much higher variability. The lowest average EC value of 320 μS/cm exhibits discharges in the diagonal fault structure 280°–290°, while in the diagonal fault structure 55°–70° and the cataclazite zone there were average EC values 399 and 498 μS/cm, respectively
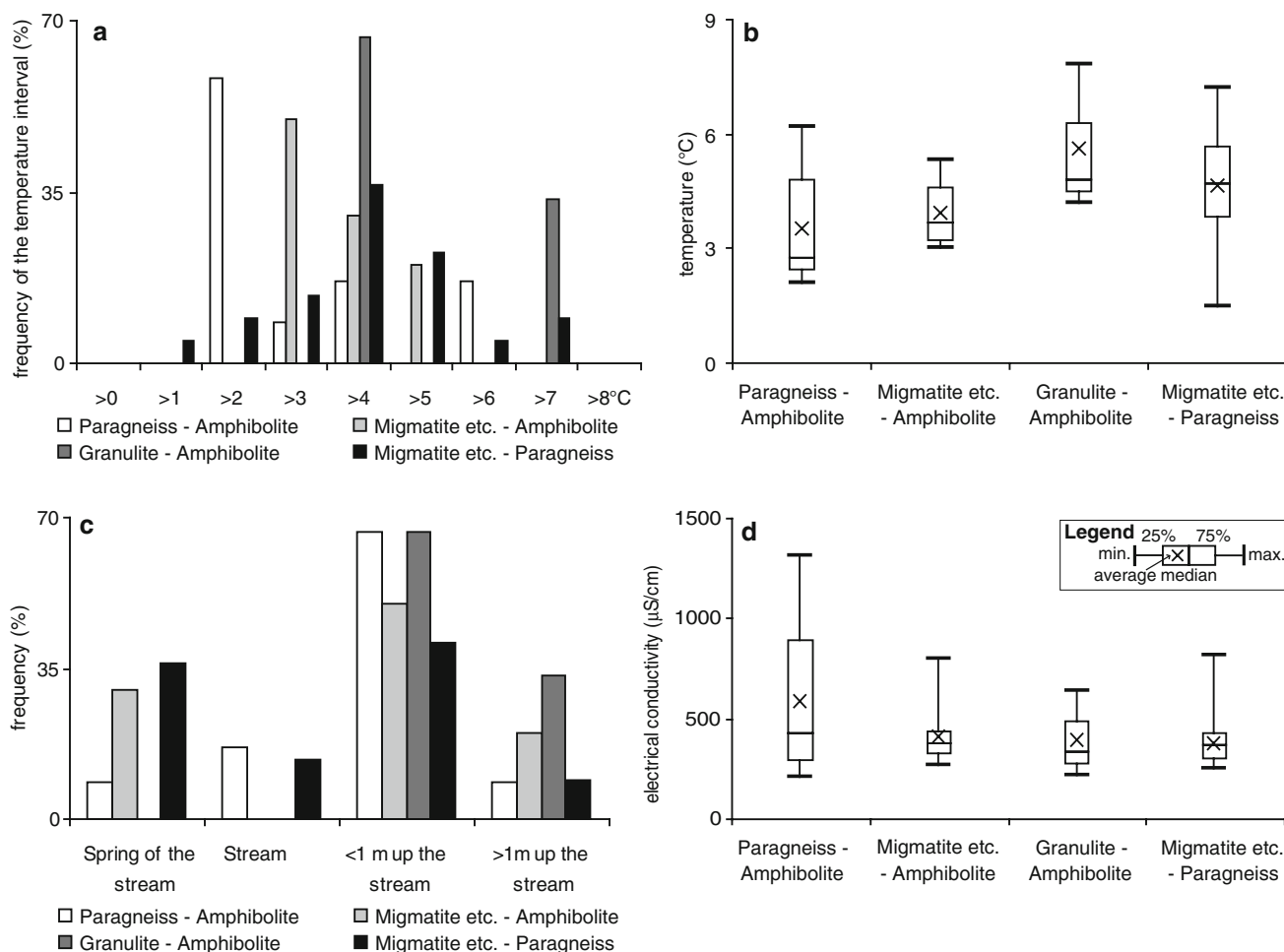

Fig. 9 Discharge points within the Rock type contact factor **a** frequency distribution and **b** statistical parameters of temperature, **c** frequency distribution of discharge types and **d** statistical parameters of electrical conductivity
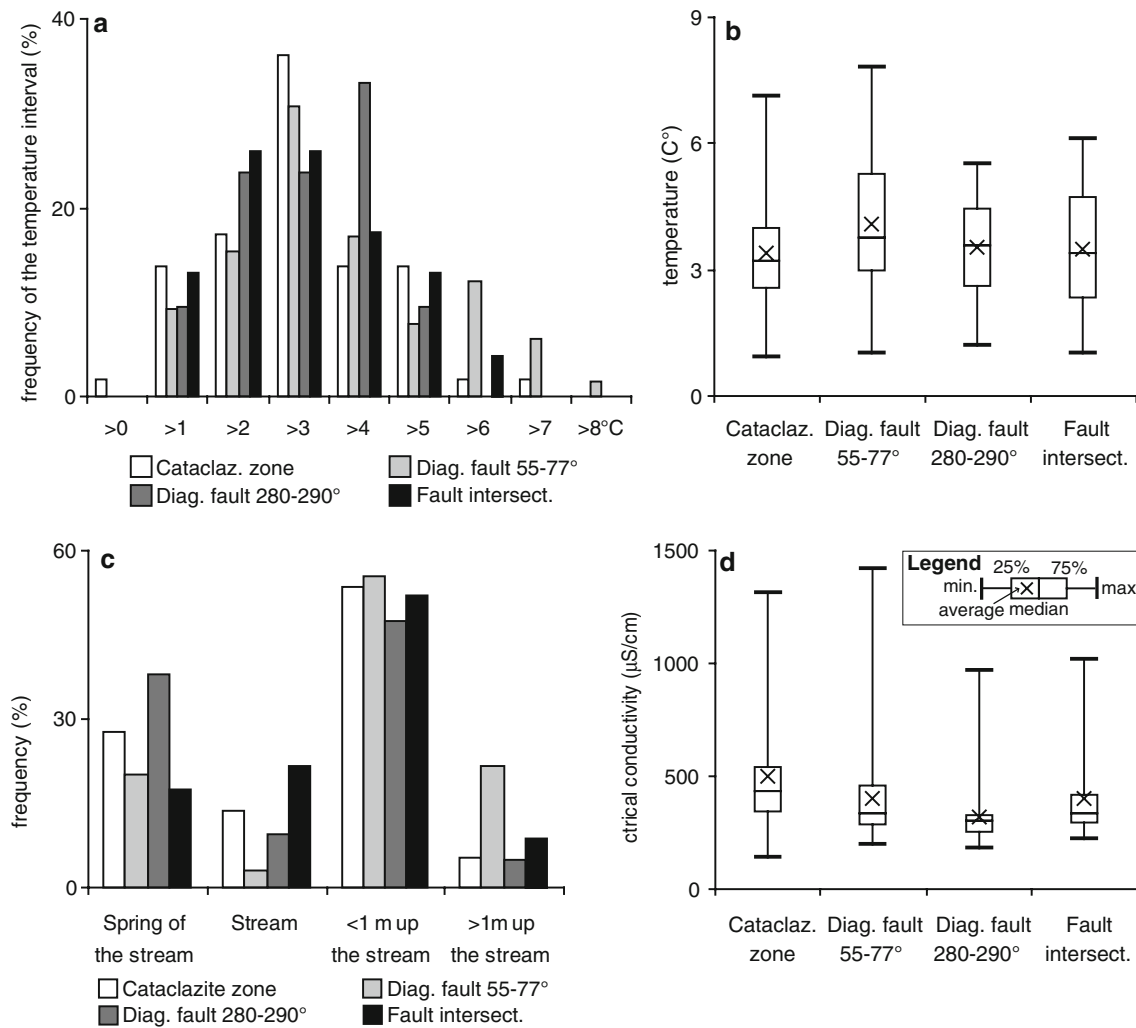
Fig. 10 Discharge points within Fault system factor **a** frequency distribution and **b** statistical parameters of temperature, **c** frequency distribution of discharge types and **d** statistical parameters of electrical conductivity

(Fig. 10d). The average EC value observed in discharges located at the cataclazite zone is significantly higher and is close to that observed in amphibolites. Temperatures observed at fault intersection do not exhibit higher average value (Fig. 10b) and, thus, the fault intersections do not seem to cause deeper groundwater flow. The average EC value of 400 μS/cm is higher than values detected in both diagonal fault structure systems (Fig. 10d).

There is an obvious difference in characteristic of discharges from different tectonic structures (Fig. 10c). While 22% of effluents in the diagonal fault structure 55°–70° are situated more than 1 m above the stream, the percentages for other tectonic structures are much smaller (about 5%). When comparing discharges exceeding 4°C, 100% of effluents in the diagonal fault structure 55°–70° are situated above the stream. This indicates, together with the evaluation of temperatures and EC values, specific impact of the diagonal fault structure 55°–70° on groundwater

flow. The diagonal fault structure 55°–70° is more permeable than other tectonic structures in studied area. Based on relatively lower EC values and higher temperatures, it drains groundwater from morphologically higher parts of catchment. The structure is usually drained at intersections with streams or stream slopes. An important drainage role results in transmitting of relatively large volumes of groundwater. This causes the rise of groundwater table close to the interface with streams and formation of frequent groundwater effluents. With respect to the lengths of the structures, the drainage effect of the diagonal fault structures 55°–70° is extensive. Both low temperatures and EC values of the discharges at the diagonal fault structure 280°–290°, combined with short lengths of structures, suggest drainage of only local flow systems. The cataclazite zone is the least permeable tectonic structure at observed site. This is confirmed by both low temperatures and high EC values of discharges. In most cases, fault
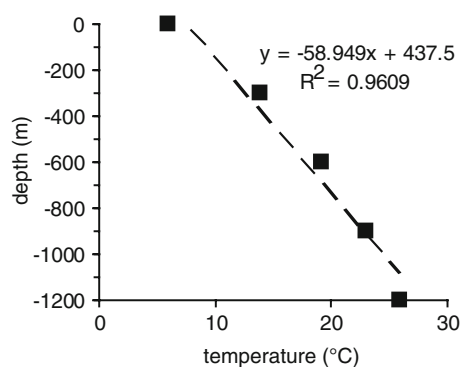
Fig. 11 Schematic temperature–depth profile at the Rozna uranium mine shaft

intersections are formed as an intersection of the cataclazite zone with one of the diagonal fault structure systems. When the cataclazite zone is not a flow barrier to groundwater flow, there should be a formation of discharges at intersections with permeable diagonal fault structure systems. However, this situation was not found. This confirms that the cataclazite zone is not a significant barrier to the groundwater flow, even when it is the least permeable tectonic structure in the study area.

When the groundwater temperature changes along flow path during upward flow in discharge zones are ignored, the highest groundwater temperatures at discharge points indicate that a minimum depth of groundwater flow is about 100 m. This is based on the depth–temperature profile compiled from the measurements in Rozna uranium mine drifts shown in Fig. 11. However, the depth of the groundwater circulation is probably underestimated, because the surface was cooled during long-term low temperature period.

Conclusions

Stream thermometry proved to be a useful tool for the investigation of aquifer flow and drainage characteristics. The aquifer at Rozna uranium mining district is a typical aquifer in crystalline rocks complex. Based on the evaluation of temperature and EC values of groundwater discharge, the aquifer is strongly heterogeneous. Only about 30% of all discharge points in the aquifer are situated within a single rock type, far from the contact with different rock types or tectonic structures. For this reason, a compilation of any groundwater flow and transport model in such aquifer may be very complicated and unrealistic task.

Impact of surface morphology at a regional scale on groundwater flow was confirmed. This is obvious from the comparison of the northern flat part of studied area with both middle jagged and southern steep parts. Morphology

and resulting hydraulic gradients are the principal driving mechanisms of groundwater flow. However, non-homogeneities formed by geological settings strongly affect groundwater flow characteristics. They may be considered as another factor in the morphology-dependent flow. The relatively deeper and faster groundwater flow is typical for zones of the aquifer composed of granulites, migmatites, orthogneisses, and granites. Amphibolites represent the least permeable rocks in the studied aquifer. Most of the aquifer discharge points are situated at the contact of amphibolites with more permeable rocks. Surprisingly, the impact of tectonic structures of both local and regional importance is comparable to the impact resulting from differences in the permeability of rocks. This is typical for low-permeability fault structures. Open fault structures of regional importance may act as drainage systems; this is the case of the diagonal fault structure 55°–70°.

In summary, discharge zones in crystalline rocks forming the aquifer at Rozna mining district can be identified using temperature and EC measurements. The maximum depth of groundwater circulation depends on local morphology. Findings from this stage of the project will be used for monitoring of potential impact of mine flooding on surface water bodies in future.

References

Anderson MP (2005) Heat as a ground water tracer. Ground Water 43:951–968

Antunes SC, Pereira R, Gonçalves F (2007) Acute and chronic toxicity of effluent water from an abandoned uranium mine. Arch Environ Contam Toxicol 53:207–213. doi:10.1007/s00244-006-0011-9

Baena CL, Andreo B, Mudry J, Cantos FC (2008) Groundwater temperature and electrical conductivity as tools to characterize flow patterns in carbonate aquifers: the Sierra de las Nieves karst aquifer, southern Spain. Hydrogeol J (published online)

Bartolino JR (2003) The Rio Grande-Competing demands for a desert river. In: Stonestrom DA, Constantz J (eds) Heat as a tool for studying the movement of ground water near streams. US Geological Survey Circular 1260, pp 7–16

Blowes DW, Ptacek CJ, Jambor JL, Weisener CG (2003) The geochemistry of acid mine drainage. In: Lollar BS (ed) Environmental geochemistry, vol 9: treatise on geochemistry. Elsevier-Pergamon, Oxford, pp 149–204

Cey EE, Rudolph DL, Parkin GW, Aravena R (1998) Quantifying groundwater discharge to a small perennial stream in southern Ontario, Canada. J Hydrol 210:21–37. doi:10.1016/S0022-1694(98)00172-3

Conant B (2004) Delineating and quantifying ground water discharge zones using streambed temperatures. Ground Water 42:243–257. doi:10.1111/j.1745-6584.2004.tb02671.x

Constantz J (1998) Interaction between stream temperature, stream-flow, and groundwater exchanges in alpine streams. Water Resour Res 34:1609–1615. doi:10.1029/98WR00998

Demek J (1984) Obecná geomorfologie I. [General geomorphology I.]. Univerzita J.E. Purkyně, Brno

Drury MJ (1989) Fluid flow in crystalline crust: detecting fractures by temperature logs. In: Beck AE, Stegena L, Garven G (eds) Hydrogeological regimes and their subsurface thermal effects. AGU Monograph 47, American Geophysical Union, Washington, DC, pp 129–135

Fisher RA (1935) The design of experiments. Oliver and Boyd, Edinburgh

Grande JA, Beltrán R, Sáinz A, Santos JC, Torre ML, Borrego J (2005) Acid mine drainage and acid rock drainage processes in the environment of Herrerías Mine (Iberian Pyrite Belt, Huelva-Spain) and impact on the Andevalo Dam. Environ Geol 47:185–196. doi:10.1007/s00254-004-1142-9

Haitjema HM, Bruker-Mitchell S (2005) Are water tables a subdued replica of the topography? Ground Water 43:781–786

Hajek A, Tomasek J, Pech E, Ingerle J, Babacek J (1997) Likvidační záměr, Část B, Začerpání a uložení odkalištních vod do hlubokých horizontů dolu Rozna [Liquidation disposal, Part B, Deposition of the sludge bed's water to the deep part of the mine Rozna]. Diamo s. p., o. z. Geam, Dolní Rožínka

Hoehn RC, Sizemore DR (1977) Acid mine drainage (AMD) and its impact on a small Virginia stream. Water Resour Bull 13:153–160

Kelly M (1988) Mining and freshwater environment. Elsevier, New York

Kribek B, Hrazdira P, Sixta V, Sikl J, Miksovsky M, Venera Z, Sobotka M (1997) Strukturní, hydrogeologické a geochemické zhodnocení horninového prostředí ložiska Rozna s ohledem na uložení odkalištních vod [Evaluation of the tectonic, hydrogeological and geochemical conditions of the Rozna mine district with respect to deposition of the sludge bed's water]. ČGÚ, Praha

Michlicek E (1986) Hydrogeologické rajóny ČSR, Svazek 2, Povodí Moravy a Odry. [Hydrogeology districts of the Czechoslovakia, vol 2: catchment of the Morava River and Odra River]. Geotest, Brno

Pelikan V (1991) Studie možnosti uložení nadbilančních vod z odkaliště CHÚ DIAMO do nejhlubší části důlních děl ložiska Rozna [Study of the possibility to deposit the sludge bed's water to the deepest part of the mine Rozna]. VUGI, Brno

Person MJP, Raffensperger SGe, Garven G (1996) Basin-scale hydrogeological modeling. Rev Geophys 34:61–87. doi:10.1029/95RG03286

Silliman SE, Robinson R (1989) Identifying fracture interconnections between boreholes using natural temperature profiling. I. Conceptual basis. Ground Water 27:393–402. doi:10.1111/j.1745-6584.1989.tb00463.x

Snedecor GW, Cochran WG (1989) Statistical methods, 8th edn. Iowa State University Press, Ames

Starkova M, Macek J (2000) Geologická mapa, 1:50,000, list 24-13 Bystřice nad Pernštejnem [Geologic map, scale 1:50,000, map sheet 24-13 Bystřice up Pernštejn City]. ČGÚ, Praha

Stober I (1996) Researchers study conductivity of crystalline rock in proposed radioactive waste site. EOS Trans Am Geophys Union 77:93–94. doi:10.1029/96EO00062

Stober I, Bucher K (2007) Hydraulic properties of the crystalline basement. Hydrogeol J 15:213–224. doi:10.1007/s10040-006-0094-4

Svoboda J, Kodym O, Zoubek V, Novák S, Pavlik J (1962) Geologická mapa ČSSR, 1:200,000, M-33-XXIII Česká Třebová [Geologic map of the Czechoslovakia, scale 1:200,000, map sheet M-33-XXII Česká Třebová City]. ÚÚG, Praha

Taniguchi M (1993) Evaluation of vertical groundwater fluxes and thermal properties of aquifers based on transient temperature–depth profiles. Water Resour Res 29:2021–2026. doi:10.1029/93WR00541

Tóth J (1963) A theoretical analysis of groundwater flow in small drainage basis. J Geophys Res 68:4795–4812. doi:10.1029/JZ068i008p02354

Tóth J (1999) Groundwater as a geologic agent: an overview of the causes, processes and manifestations. Hydrogeol J 7:1–14. doi:10.1007/s100400050176

Wu Y, Wen X, Zhang Y (2004) Analysis of the exchange of groundwater and river water by using Radon-222 in the middle Heihe Basin of northwestern China. Environ Geol 45:647–653. doi:10.1007/s00254-003-0914-y