Water mixing processes within a crystalline massif: Sudety mountains, SW Poland

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ABSTRACT

We present the results of a water circulation study in a small drainage basin in a mountainous area of a complicated structure. Two types of waters were found in the basin; the sulphate waters were linked to gneiss and crystalline schist rocks, while the bicarbonate waters were linked to a marble interbed. The paper looks at a number of water circulation and mixing scenarios and discusses the origin of the bicarbonate waters. Measurements and calculations helped to identify two karst water circulation systems within the marble interbed that were probably not connected to each other. The primary system collects waters migrating via fissures from a non-carbonate section of the drainage basin above. Initially these waters are of the sulphate type: acidic and corrosive to the carbonate rocks. After passing into the marble interbed, they gradually assume a bicarbonate nature by becoming saturated with products of the chemical dissolution of carbonate rocks. This karst system is drained by springs. The other system begins in a sinkhole that intercepts a portion of the stream discharge (or all of it during extreme droughts) and ends with dispersed outflows directly into the channel lower down in the drainage basin.

Key words | crystalline rocks, fissure aquifer, karst system, spring, Sudety, water mixing

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INTRODUCTION

This research project, which began in 2003, was designed to identify underground water circulation paths and water supply mechanisms in a small drainage basin of the Jaskiniec stream in the Złote mountains, a range of the Sudety mountains in southwest Poland. Special attention was focused on a small lens-shaped marble interbed including a local aquifer which was investigated for its role and impact on routes of water recharge and drainage. Consideration of these was intended to provide a contribution to a more general debate on the hydrogeology of fissured crystalline (metamorphic) massifs in the Sudety mountains. The debate concerned water storage capacity, the duration of the water exchange cycle, the depth of water penetration, mechanisms of spring supply and the role of eluvial covers in the development of underground water circulation and chemistry.

These controversial and topical issues are actively discussed with regards to the Sudety mountains as fundamental to the understanding of crystalline rock water storage capacity (Staśko 2002). Although hydrogeological research into Polish crystalline massifs tends to focus on local areas in the Sudety mountains, it is fully compatible with the global strand of hard rock hydrogeology. The hydrogeology of fissured crystalline rocks remains one of the most difficult and least developed areas of hydrogeology, both theoretically and practically (Oxtobee & Novakowski 2003; Neuman 2005), especially controversial when carbonates are concerned (Lemieux *et al.* 2006).

Frequent interbeds of crystalline metamorphic limestones (marbles), often with highly developed karst, add to the overall complexity of the hydrogeology of the Sudety mountains. Marble formations have been studied and

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reported in a number of areas known for carbonate rock clusters, including near Kletno, Wojcieszów and in the Krowiarki Massif (Pulina 1996; Bocheńska *et al.* 2002). Small marble insets, surrounded by non-carbonate metamorphic rocks, are common throughout the region (Pulina 1977, 1996). A similar small interbed of crystalline limestone is found in the study area, i.e. in the Jaskiniec stream basin. The Radochowska Cave, which developed through the dissolution of the carbonate rock, prominently features in the interbed zone (Pulina 1996).

Mixed fissured and fissured-karstic aquifers are found in carbonate and non-carbonate massifs throughout the region and, while it is difficult to study water chemistry, water supply in springs and circulation routes in areas with such a complicated structure, it is also informative and of great practical use. Indeed, karstic carbonate rocks build local aquifers in the region (Bieroński & Tomaszewski 1992; Ciężkowski *et al.* 1992; Bocheńska *et al.* 2002). It is relatively unusual to find a karst system developed in marble (e.g. Novel *et al.* 2007). Normally marble plays a marginal role in the complex aquifer (e.g. Cook *et al.* 2005); the role of the small marble interbed found in the study area is therefore worth examining.

The detailed hydrogeologic study was conducted in the Jaskiniec drainage basin located in the Złote mountains in the northeast of the Kłodzko basin. The area is built of metamorphic rocks (typically paragneiss, micacious schist and leptynite) mostly belonging to the Strońska Formation (Don *et al.* 2003) and is known for the thermal and mineral waters found nearby in Lądek Spa (Zuber *et al.* 1995). The Jaskiniec drainage basin was selected for the detailed study due to its small karst-ridden lens of marble that distorted the groundwater chemistry and circulation routes (Rzonca *et al.* 2004). The metamorphic crystalline limestones (marbles) crop out across the Jaskiniec basin in a narrow zone running SW–NE and belong to the same Strońska Formation as the rest of the basin's geology. Figure 1 depicts the approximate location of the marble outcrops zone and its quasi-linear shape. It is, however, controversial, if the marble interbed is continuous. The Jaskiniec stream has no alluvium, but there are some eluvial deposits on the surrounding slopes.

The Radochowska Cave is found within this outcrop and was long regarded as the largest cave in the Sudety mountains (265 m long) until the discovery of the Niedźwiedzia Cave at Kletno. In 1964, the Radochowska Cave was named a "monument of unanimated nature" and is currently an established regional tourist destination, often mentioned in the literature (Walczak 1956; Pulina 1996).

PREVIOUS RESEARCH

In May 2003, the hydrology and hydrogeology of the Jaskiniec drainage basin area were comprehensively mapped (Rzonca *et al.* 2004). The study identified two chemically different types of waters. The first type was named the sulphate waters and at ~100 mg/L total dissolved solids it had a typical mineral concentration found in the metamorphic rocks of the Sudety mountains (Ciężkowski *et al.* 1997). The waters had a distinctly acidic nature (pH 5.55–6.76) and their chemistry was dominated by the sulphate ion (60–70% meq anions), while calcium and magnesium accounted for ~40% meq of cations each. According to Altowski and Szwiec (after Macioszczyk 1987) their chemical types were: SO_4—Ca—Mg, SO_4—Mg—Ca or SO_4—HCO_3—Ca—Mg. The second water type, referred to as the bicarbonate waters, had a distinctly higher general mineralization (200–300 mg/L) and nearly neutral chemistry (pH 6.79–7.25). Their chemical composition was dominated by the bicarbonate ion (60–70% meq of anions) and calcium (70–80% meq of cations). This water type is HCO_3—SO_4—Ca.

However, the study demonstrated that the seemingly different water types were in fact very similar. Their similarity could be traced in a majority of parameters. Even the sulphate anion concentration did not differentiate those waters. The sulphates dominate in the sulphate waters because there is low bicarbonate concentration. Other non-differentiating elements were: magnesium, sodium, potassium, chloride, nitrogen ions and silica. Indeed, only the calcium and bicarbonate concentrations differentiated two water types, while other parameters such as pH, mineralization and certain geochemical ratios were secondary. The sulphate waters (springs Nos. 1, 5a, 5d and 19) occurred in the upper section of the basin built primarily of non-carbonate metamorphic rocks (Figure 1). The bicarbonate waters, on the other hand, were always linked to

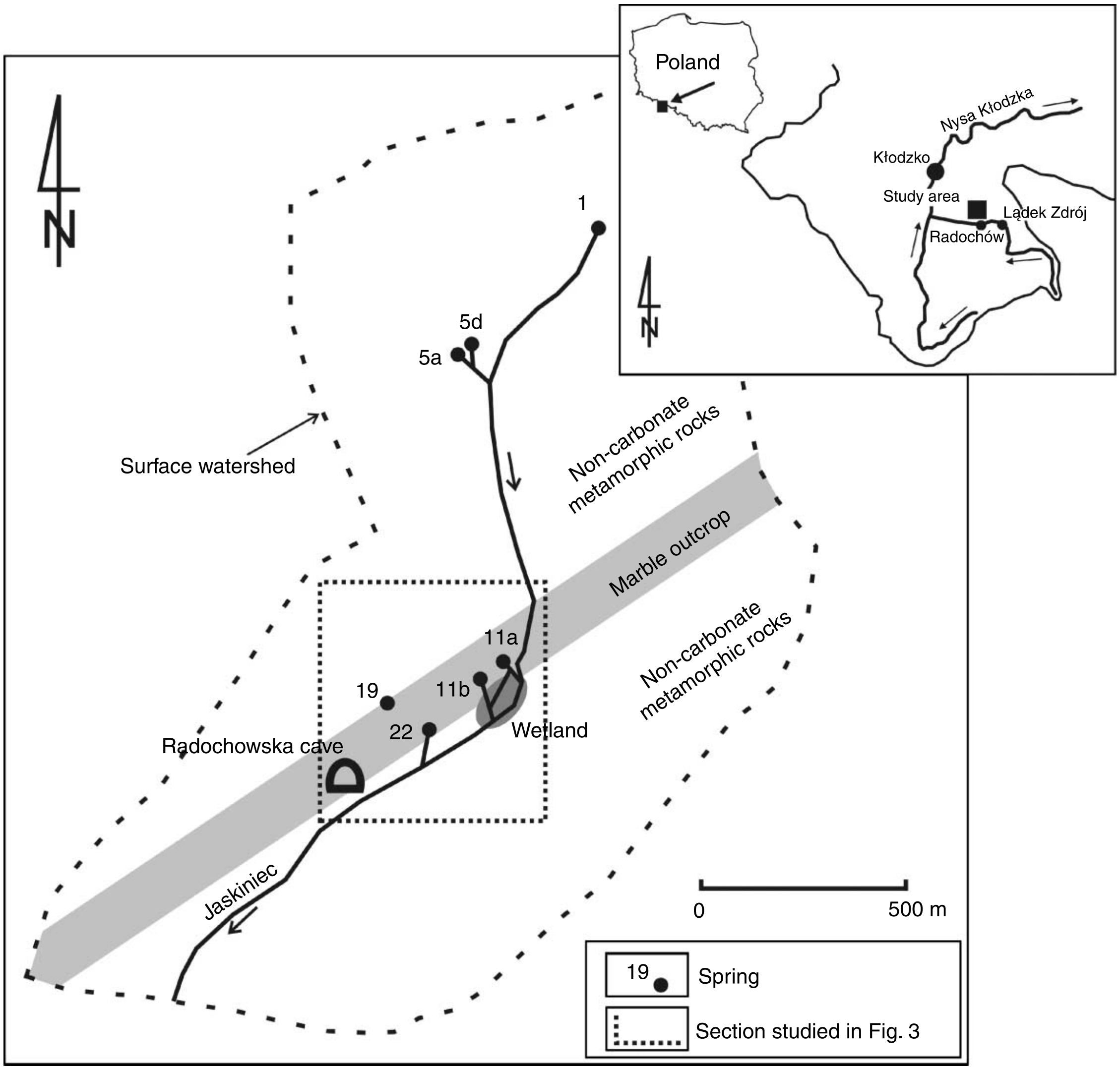

Figure 1 | The Jaskiniec drainage basin and its position in the Kłodzko Basin, Poland.

the marble rocks and were sampled from spots located on the marble outcrops, such as springs Nos. 11a, 11b, 22 and sampling points inside the cave.

As the sulphate waters (acidic and corrosive in nature) transit from non-carbonate rocks into the lens of marble, they likely leach the carbonate rock and thus become enriched in calcium (Ca^{2+}) and bicarbonate (HCO_3^-). This transition turns the sulphate waters into the bicarbonate waters with a clearly higher mineralization and a neutral pH. The marble dissolving process may be observed upon the saturation index (SI) values. According to unpublished authors' data, in the sulphate waters (61 samples) SI values for calcite were from −4.06 to −1.69 (for aragonite from −4.26 to −1.89), while in the bicarbonate waters (71 samples) they were pushed towards higher values (more saturated waters) and for calcite were between −1.85 and 0.48 (for aragonite −2.06 and 0.27).

The common origin of the sulphate and the bicarbonate waters was additionally proven by demonstrating a timing correlation between concentrations of certain compounds in the two water types (Buczyński *et al.* 2007; Rzonca & Buczyński 2007). Moreover, the chemical similarity of the waters is visible in the chemical background plots (Figure 2). The plots also demonstrate the readable difference between water types in case of the marble leaching products (bicarbonate and calcium ions).

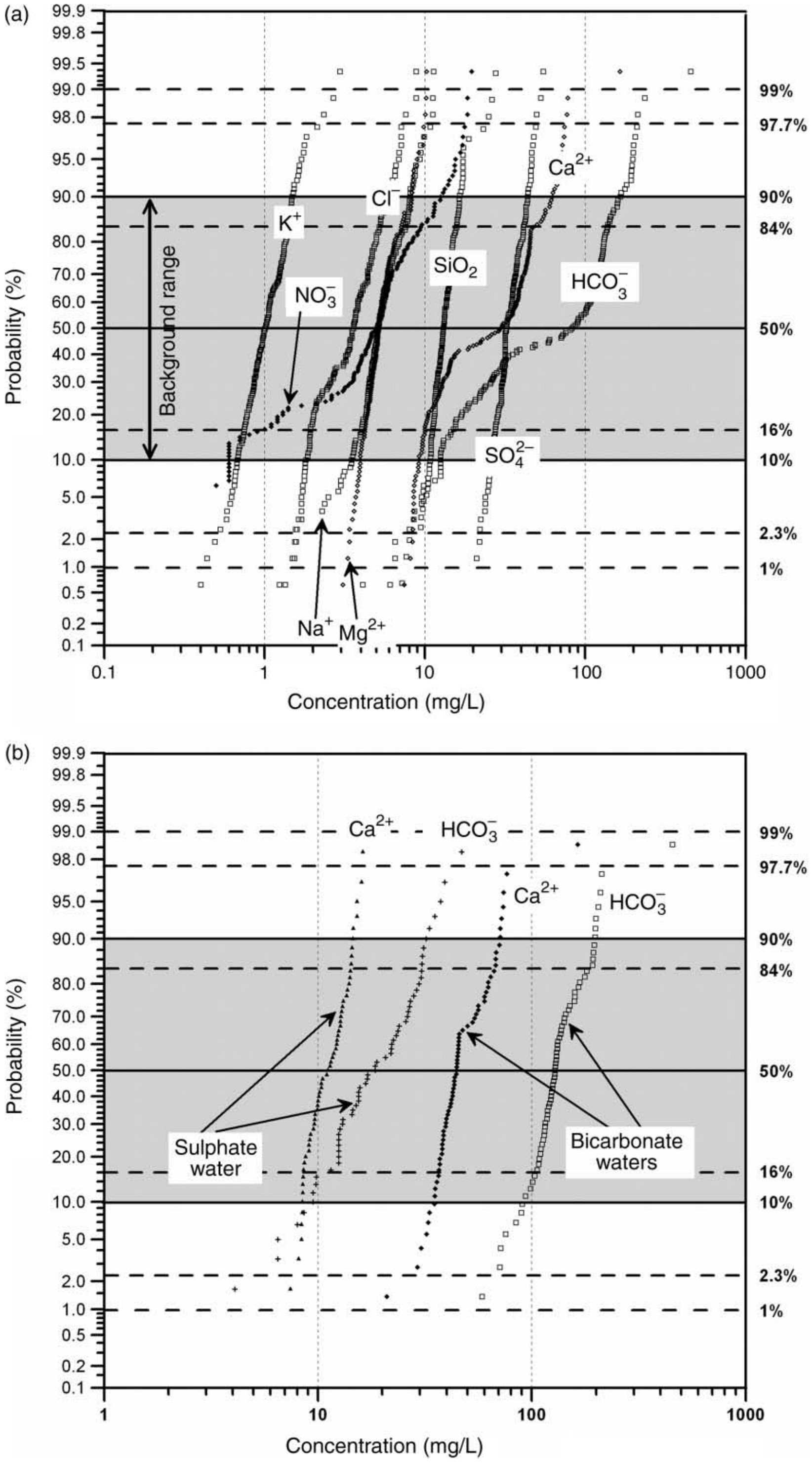

Figure 2 | Hydrogeochemical background of waters studied (total population of 160 samples analyzed): (a) cumulative plots of the major components concentrations (b) for bicarbonate and calcium ions.

In Figure 2(a), the cumulative plots of the major components concentrations are shown. The uniform and close to log-normal distribution of most of the components is visible, as it is demonstrated by straight plots. Exceptions (strongly bimodal) are bicarbonate (HCO_3^-), calcium (Ca^{2+}) and nitrate (NO_3^-). Nitrate content is significantly higher in the Radochowska Cave waters than spring waters, which is most likely due to the pollution of the cave. However, the bimodality of the bicarbonate and calcium data results from combining the two sample populations; higher concentrations of these two ions in the bicarbonate waters result from active dissolution of the marbles. Chloride (Cl^-) population is also bimodal, which probably results from different recharge processes. Two water types appear clearly in Figure 2(b). No waters of transitional type were found, except at the stream where the mixture of the waters is observed (stream water samples were excluded from this plot).

FIELD OBSERVATIONS

For this study, the field observations were conducted on four separate days and are summarized in detail in Figure 3. A highly detailed test of the specific electrical conductivity (SEC) was performed in the stream on 4 July 2006,

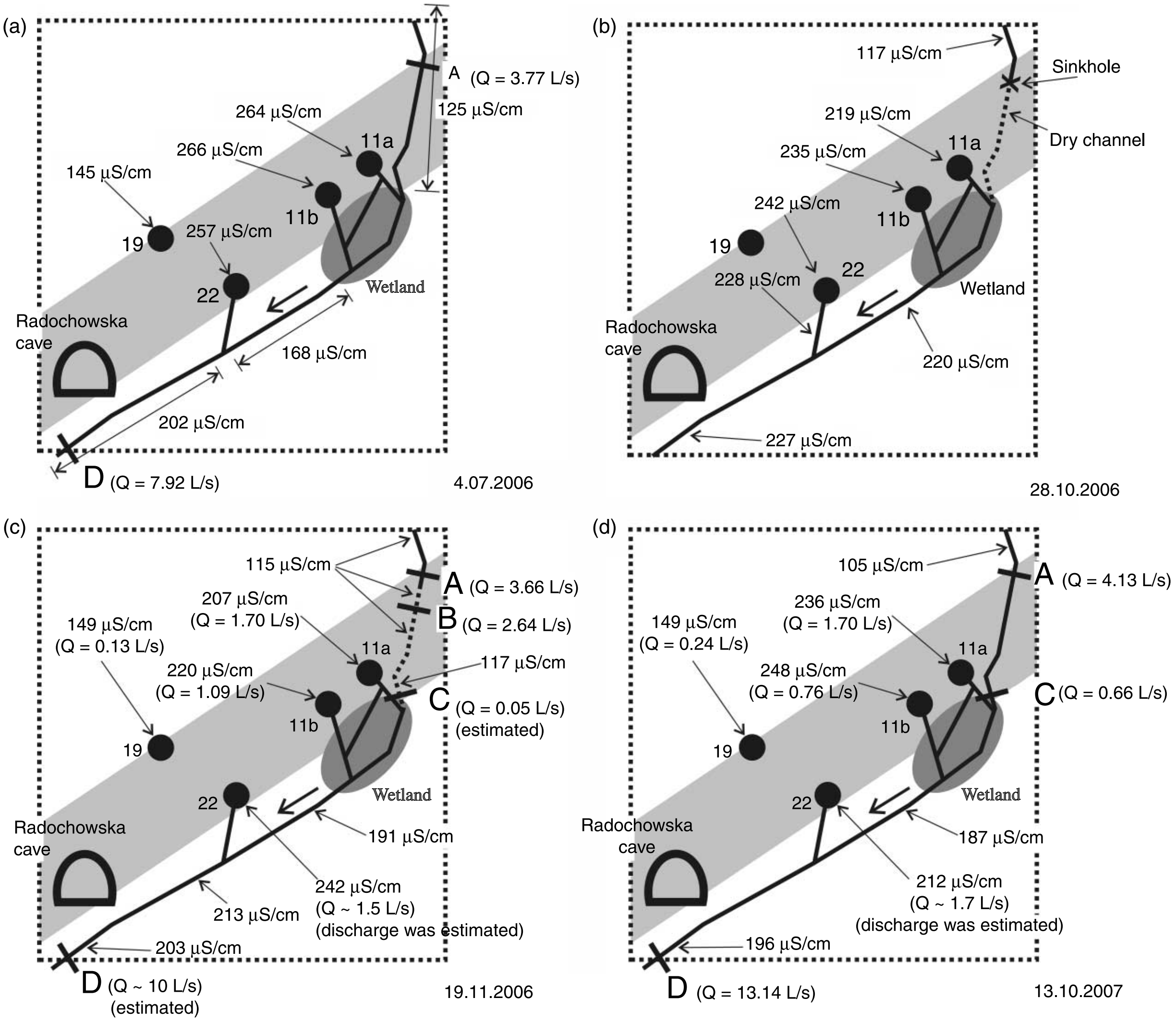

Figure 3 | Field measurements results (for scale and orientation of the studied section see Figure 1): (a) 4 July 2006 (after Rzonca & Buczyński 2007); (b) 28 October 2006; (c) 19 November 2006; and (d) 13 October 2007.

which was at medium water level (Figure 3(a)), as well as in the springs (Buczyński *et al.* 2007). Discharge was also measured at two measurement points in the stream (*A* and *D*) using the tracer method: the dilution of a single tracer dose known as the 'solution wave' (Table 1). An increase of SEC, indicating a supply of the more highly-mineralized bicarbonate waters linked to the marble interbed, was only recorded at the points where waters from springs 11a, 11b and 22 entered the channel. Thus the difference between discharges Q_D and Q_A was considered the approximate sum of the discharges of the bicarbonate water springs (Figure 3(a) and Table 1).

On 28 October 2006, a swallow hole was discovered in the stream bed under extreme drought conditions (Rzonca & Buczyński 2007). Additionally, the authors learned (W. Rogala 2006, personal communication) that the drainage of the Jaskiniec stream waters by the karst system in the marbles had already been observed. The stream flow ended right below the suspected upper limit of the marble rocks (Figure 3(b)). The stream channel remained entirely dry between the swallow hole and a place where the stream received water from spring 11a. SEC tests were also performed (Figure 3(b)).

SEC and discharge testing was also performed on 19 November 2006, immediately after a shower of rain preceded by a period of drought. The volumetric method was used for the precision discharge measurement. Discharges were estimated where satisfactory measurement could not be done (Figure 3(c)).

The most complete set of discharge (volumetric method) and SEC results was obtained on 13 October 2007 (Figure 3(d)), under medium water level conditions. This was also the first time when an exact volumetric flow measurement was successfully taken of the *D* measurement point ending the basin (Table 1). Then, the swallow hole was only draining a part of the stream discharge, thus allowing an exact calculation of the swallow hole's capacity (Q_A minus Q_C). It is likely to vary, however, depending on the distribution of head within the aquifer at any particular moment.

RESULTS AND DISCUSSION

A simple mixing model

Understanding of the water circulation system in the basin gradually increased during the course of fieldwork. Initially, the authors did not know about the swallow hole in the stream bottom and assumed that the stream played a drainage role along its entire length (Figure 4(a)). The possibility of a karst system in the marbles draining the stream seemed unlikely in the light of the fact that one of the springs (11b) recharged from the marble-circulating waters was located $\sim$10 m above the watercourse (Buczyński *et al.* 2007). Surveys have shown that the upper course of the Jaskiniec stream typically contained the lightly mineralized sulphate waters linked to the non-carbonate upper section of the drainage basin. Downstream, the bicarbonate waters coming from springs 11a, 11b and 22 supply the stream and then the mineralization of stream water increases. The mixing of two types of waters takes place in the stream only (Figures 4(a) and 5(a)).

The karstic marble interbed, underlying the non-carbonate rocks over a large area, is a collecting medium for waters of various origins. These include waters (Figure 4(a)): (1) circulating deep within the massif via a network of minor fissures and gradually moving from non-carbonate into the carbonate rocks; (2) migrating within eluvial covers; and (3) infiltrating directly into the relatively small marble outcrops. Waters (1) and (2) start as the sulphate waters, but within the marble layer modify their

Table 1 | Examples of the stream discharge measurements

Sulphate water inflow at point *A* (measured) (L/s)	End of basin discharge at point *D* (measured) (L/s)	Bicarbonate water inflow (calculated: $D - A$) (L/s)	Method and date	Details
3.77[*] (47.6%)	7.92[*] (assumed: 100%)	4.15 (52.4%)	Tracer; 4.07.2006	(Buczyński *et al.* 2007)
4.13[†] (31.4%)	13.14[†] (assumed: 100%)	9.01 (68.6%)	Volumetric; 13.10.2007	Figure 3(d)

[*] Average of two experiments with result spread less than 5%.
[†] Average of three measurements with result spread less than 5%.

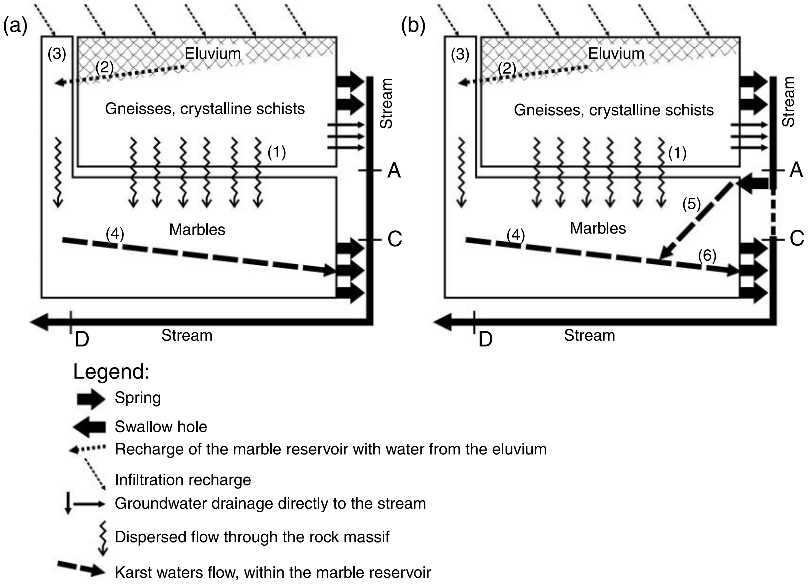

Figure 4 | Flow charts representing conceptual models of the water circulation patterns of the basin: (a) early stage of understanding and (b) stage of understanding after the discovery of the swallow hole; the recharge of the karst system with stream water (5) was included.

composition, becoming the bicarbonate waters. Waters (1)–(3) are drained by an existing karst system (4) within the marble lens, when their composition of the bicarbonate waters may be already almost fully developed. The stream drains the sulphate waters from the gneiss and crystalline schists part via springs as well as directly into the channel in the upper part of the basin, and the bicarbonate waters via springs recharged by the karst system (4).

For this scenario, a simple set of equations can be used to determine the proportions of the two water types independently from the field measurements. The quantity of the mixture and its components are linked with the concentrations of any substance in a mixture and its components (Sklash & Farvolden 1979). The concentration in a mixture is a weighted average of the concentrations in the components, where the quantities of components are the weights.

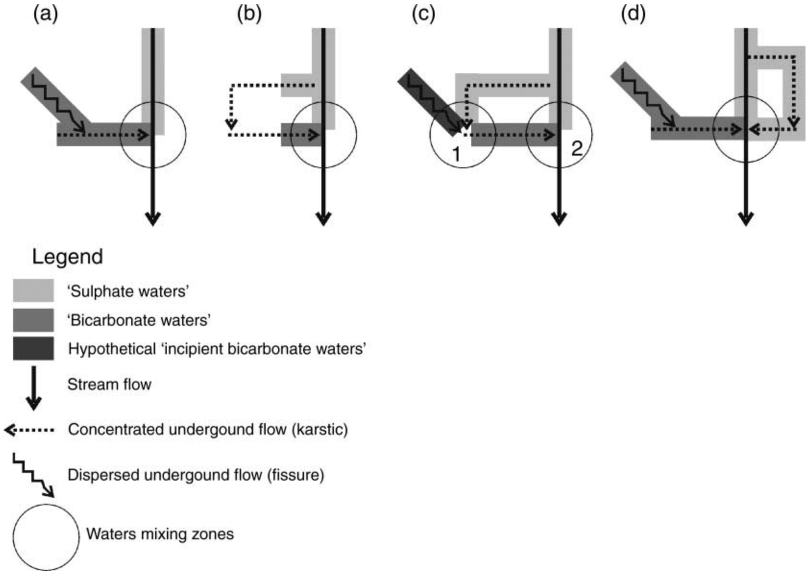

Figure 5 | (a–d) Alternative mixing patterns of the waters circulating in the catchment.

By dividing both equations by time, instead of the quantities one obtains the discharges (Q_n) and the final set of equations is:

$$Q_1 + Q_2 = Q_3 \tag{1}$$

$$C_1Q_1 + C_2Q_2 = C_3Q_3 \tag{2}$$

where Q_1, Q_2 are component discharges, Q_3 is mixture discharge; C_1, C_2 are concentrations of any substance in the components; and C_3 is concentration in the mix. Field SEC measurements results were used in solving these equations and substituted for 'concentrations' (Table 2). SEC values were used for these calculations on the assumption that SEC may be considered the conservative factor for a short time reaction (i.e. current waters mixing). For the region it was also proved that SEC is a nearly linear function of mineralization when waters transform between two types (Modelska *et al.* 2005). The discharge of the mix, $Q_3 = 100\%$, was adopted as the fourth variable necessary to solve the set of equations. This yielded percentages of components in the mix making the calculation entirely independent of the watercourse discharge measurements.

Both direct measurements (Table 1) and calculations (Table 2) clearly indicated that the waters drained by the watercourse within the marble outcrop, identified as the bicarbonate waters, generated more than one half (52.4–81.5%) of the stream's total discharge despite the minor proportion of the rock in the overall basin geology. These calculations were the base of the water circulation model initially proposed (Buczyński *et al.* 2007) where the marble layer played the role of a drain and a reservoir collecting the waters from higher located non-carbonate formations. In fact, the drain was not so much the marble lens itself, but the karst system developed within it (Figure 4(a)).

Mixing models accounting for the swallow hole

During the course of the investigations, the simple mixing model (Figure 5(a)) in which the sulphate and the bicarbonate waters only mixed in the watercourse, was deemed incomplete. Indeed, it failed to account for the infiltration of stream water into the karst reservoir via the swallow hole. Still, other possibilities had to be looked at if the investigation were to be able to identify the detailed pattern of water circulation. Certain theoretical options are depicted in Figure 5(b)–(d).

Firstly, it could be assumed (Figure 5(b)) that as the sulphate waters were swallowed up by the swallow hole, they were subject to gradual transformation into the bicarbonate waters in the karst system without any intrusion of other waters circulating within the massif. This pattern, however, does not account for the fact that when the stream enters the marble outcrop its discharge initially drops (in the swallow hole zone), but it is actually very significantly increased overall, as documented by direct testing (Table 1). If one excluded recharging by additional waters within the marble interbed, the waters discharges would not balance at all. After all, the field measurements showed the marble zone 'produces' over 50% of the stream water. Thus the scheme from Figure 5(b) must be rejected. Additionally, it seems rather unlikely that waters running very rapidly through the karst system would have their chemical composition modified to such an extent by the mere leaching of carbonate rocks.

A far more probable scenario seems the option shown in Figure 5(c) where the stream waters are swallowed by the swallow hole and mix with waters circulating inside and migrating from the supply zones on the outcrops. This is depicted in Figure 4(b), where the karst system (4) plays the role of a drain collecting distributed waters (1), (2) and (3), but also the role of a place where these waters mix with

Table 2 | Proportions of the two types of water inflow (scenarios from Figures 5(a) and (d))

			Calculated stream recharge by:			
A point (μS/cm)	Springs 11a, 11b and 22* (μS/cm)	*D* point (μS/cm)	Sulphate waters (%)	Bicarbonate waters (%)	Date	Details
125	261	202	43.4	56.6	4.07.2006	Figure 3(a)
115	223	203	18.5	81.5	19.11.2006	Figure 3(b)
105	228	196	26.0	74.0	13.10.2007	Figure 3(c)

*Weighted average values; measured or calculated discharges were used as weights.

waters originating in the stream (5). Since waters found in springs (6) (referred to as the bicarbonate waters) have a much higher mineralization than the sulphate waters, then in this circulation model they must be a mixture of the sulphate waters drained from stream (5) and some hypothetical more highly-mineralized waters (Figure 5(c)). The latter could be named incipient bicarbonate waters (Rzonca & Buczyński 2007). Finally, this model would yield two clearly separated mixing zones for waters of different types, i.e. the karst system and the watercourse (Figure 5(c)).

The last theoretical option (Figure 5(d)) involves stream water swallowed in the swallow hole returning into the channel downstream without merging with the underground waters circulating in the carbonate formation. A confirmation of this option would in fact mean a return to the initial model (Figures 4(a) and 5(a)), because there would be no water mixing within the carbonate formations and the composition of the bicarbonate waters found in the springs would generally be representative for overall waters in the karst aquifer. This is why only one mixing zone was symbolically marked in Figure 5(d), i.e. in the stream, which for all purposes corresponds with the option on Figure 5(a). Moreover, the stream waters disappearing in the swallow hole and resurfacing downstream would have no impact on the water balance between the measurement points *A* and *D*. Whether the underground path of the stream water would, under this option, lead through a karst system insulated from one that feeds the bicarbonate waters springs or through the eluvia lining the watercourse is an entirely different question.

Do the incipient bicarbonate waters exist?

Out of the four mixing mechanisms depicted in Figure 5, only two options are probable (5(c) and 5(d)). The other two either do not take into account the swallow hole (5(a)) or do not correspond to the final water balance (5(b)). The question must now be asked, which of the probable options is right and, consequently, are there waters with a higher mineralization within the massif?

Using the option with two mixing areas (Figure 5(c)), one can theoretically derive the properties and quantities of the hypothetical incipient bicarbonate waters by constructing two sets of equations quantitatively describing the mixing process. For the inside-massif mixing (marked '1' on Figure 5(c)), the set of equations presented above can be used, where Q_1 is discharge of the sulphate waters infiltrating into the massif (i.e. the intake capacity of the swallow hole zone); Q_2 is discharge of the hypothetical incipient bicarbonate waters (sought); Q_3 is discharge of the mix (i.e. the quantity of the bicarbonate waters supply passed into the watercourse); C_1 is specific electrical conductivity (SEC) of the sulphate waters entering through the swallow hole (watercourse at the *A* measurement point); C_2 is SEC of the hypothetical incipient bicarbonate waters (sought); and C_3 is SEC of the mix (i.e. of the bicarbonate waters in the springs).

For the other mixing area (the stream marked '2' on Figure 5(c)), a corresponding set of equations can be used:

$$Q_3 + Q_4 = Q_5 \tag{3}$$

$$C_3Q_3 + C_4Q_4 = C_5Q_5 \tag{4}$$

where Q_4 is watercourse discharge at profile *C*; Q_5 is discharge of the mix (i.e. watercourse discharge at the *D* measurement point); C_4 is SEC of watercourse at the *C* point (practically equal to C_1); and C_5 is SEC of the mix (i.e. watercourse at the *D* point).

Both sets of equations can be solved in combination, which is useful because it eliminates some variables. By substituting Equation (1) into Equation (3) and substituting Equation (2) into Equation (4), the following set of equations is obtained:

$$Q_1 + Q_2 + Q_4 = Q_5 \tag{5}$$

$$C_1Q_1 + C_2Q_2 + C_4Q_4 = C_5Q_5 \tag{6}$$

In this way, variables Q_3 and C_3 are eliminated. Variables Q_2 and C_2 remain unknown (discharge and SEC of the hypothetical incipient bicarbonate waters).

All data used in the calculations were measured on 13 October 2007 and included: $Q_1 = 3.47\,\mathrm{L/s}$ (capacity of the swallow hole, $Q_A - Q_C$); $Q_4 = 0.66\,\mathrm{L/s}$ (discharge Q_C); $Q_5 = 13.14\,\mathrm{L/s}$ (discharge Q_D); $C_1 = 105\,\mu\mathrm{S/cm}$ (the *A* measurement point); $C_4 = 105\,\mu\mathrm{S/cm}$ (the *C* point); $C_5 = 196\,\mu\mathrm{S/cm}$ (the *D* point).

The computations yielded two measures of the water supply to the system studied: SEC (C_2), at $238\,\mu\text{S/cm}$ and discharge (Q_2), at 9.01 L/s. While the latter is simply the difference between discharges at the measurement points A and D (see Table 1), the former surprisingly corresponded with the values typically measured in the bicarbonate waters in springs 11a, 11b and 22 (see Figures 3(a)–(d)). The theoretical calculation clearly rules out the existence of any waters within the marble lens other than the bicarbonate waters. This would favour the option depicted in Figure 5(d) and a rejection of the possibility of the incipient bicarbonate waters.

Final mixing model

The solution of mixing formulae practically eliminated the scenario, where the higher mineralized waters exist inside the massif (Figure 5(c)). The model including two unmerged flow systems therefore appears as the only possible model: karst collecting the bicarbonate waters within the massif and karstic or other (eluvial) flow between the swallow hole and lower part of the stream channel (Figures 5(d) and 6).

There are two other important facts that also substantiate the Figure 5(d) option. Firstly, this pattern plausibly explains the 'paradox of spring 11b' mentioned earlier, where the swallow hole in the stream bed is located below the spring that draws its water from the karst reservoir. It was precisely because of the location of spring 11b that the original concept held the watercourse to be of the draining type; any swallow hole existence was ruled out and, indeed, it was not discovered until much later. When that happened (at a low water level, Figure 3(b)), the explanation of the spring's supply became flawed, leading to the speculation of a possible discontinuity in the marble aquifer. The Figure 5(d) option deals with this problem very simply: the swallow hole does not supply water to the marble formation from where the bicarbonate water springs take their water (including 11b). It supplies water only to a subterranean stream water path that has no hydraulic connection to the waters supplying the springs (Figure 6).

Secondly, the Figure 5(d) option provides a previously missing explanation of the fact that the mineralization of surface waters in the lower section of the basin (below spring 22) often dropped, sometimes along very short distances in the watercourses. While measurements only provided incidental documentation of this fact, the phenomenon could be seen in the testing results (see Figures 3(b) and (c)). One possible solution where the watercourse would be draining some shallow and lightly mineralized waters could not be accepted as some samples, e.g. from 28 October 2006 (Figure 3(b)), were taken during extreme drought when shallow groundwater was simply not available. The probable solution is that below spring 22 there is a zone draining waters previously swallowed by the swallow hole, i.e. the lightly mineralized sulphate waters (Figure 6).

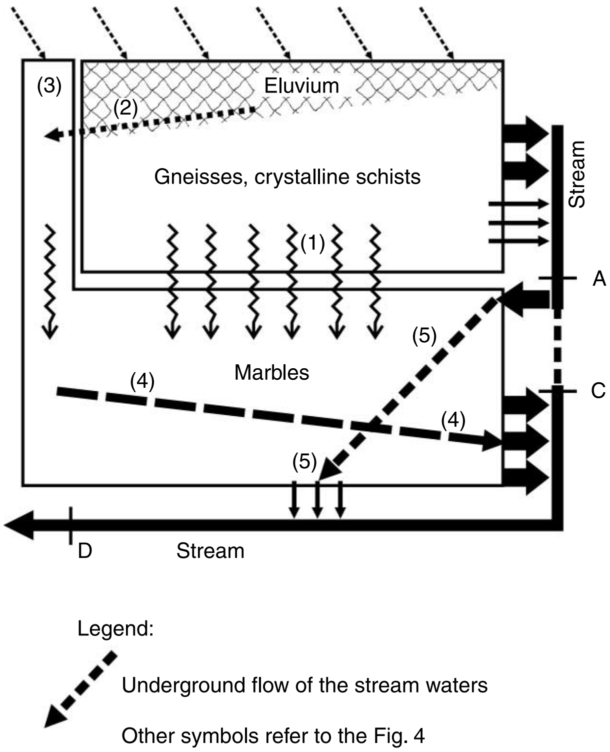

Figure 6 | Final bloc-diagram of the catchment investigated, referring to the scenario depicted in Figure 5(d). It shows a direct supply of the bicarbonate water into the springs from the waters draining from the karst system of the marbles (4); another, unconnected system channels the sulphate waters swallowed by the sinkhole (5) and recharges them directly back into the stream channel. The lack of mixing of the two types of waters—(4) and (5)—is the fundamental difference from Figure 4(b).

CONCLUSIONS

In the Jaskiniec drainage basin two types of underground waters were identified: sulphate and bicarbonate waters.

They differ in the degree of mineralization, chemical composition, pH and several other parameters. The objective of this study was to identify relationships between these two types of waters and their mixing processes. The authors proposed and discussed a number of scenarios of water circulation and mixing, taking into account their origin and the processes shaping their chemical composition, as depicted on flowcharts.

The key to the identification of water circulation paths in the basin proved to be the mixing processes, which lent themselves to quantitative determination with simple equations describing concentrations in both the components and the mixes. The results of field measurements of stream and spring water discharges and SEC values were used to solve the equations.

The study basin proved to be a complicated hydrological system, probably featuring two unconnected karst systems (Figures 5(d) and 6). One of them plays the role of a drain that collects waters infiltrating from overlying rock formations and feeds the waters into the stream as the bicarbonate waters. The proportion of the bicarbonate water in the stream discharge is always higher than 50%, although it varies from period to period. The other system (also probably karstic) swallows the stream water underground via the swallow hole and returns the water directly into the stream channel in a lower section of the basin.

The adoption of the model featuring two unconnected karst systems stems directly from the interpretation of the quantitative calculations of the mixing process. It also offers a highly plausible explanation for a number of observations. The crucial factor here is that spring 11b (the bicarbonate water) is located much above the swallow hole, which the scenario with a single karst water circulation system could not explain. A consequence of the twin-system model being adopted is the return to the simple mixing system (Figure 5(a)). Indeed, the scenarios shown in Figures 5(a) and 5(d) are identical from the perspective of how the two types of waters are mixed and what the origin of the bicarbonate waters is, as the route that leads through the swallow hole does not affect the balance between the two types of water in the overall stream water supply (Tables 1 and 2).

The paper demonstrates the evolution of the authors' knowledge and shows how easy it was to make false conclusions. The most serious mistake was made when no swallow hole was found during the earlier field works. The authors had assumed that the Jaskiniec stream had a draining nature along its entire course and thus missed the swallow hole. The assumption seemed the obvious one to make considering the existence of spring 11b above the stream channel. The swallow hole was discovered at a later stage and the problem was solved with water mixing models developed as the two water types were identified in the area. Drawing from this experience, the authors recommend that in future studies of mountainous fissure and/or karst environments, flows should be measured along the entire stream course and without prior assumptions about draining or recharging.

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