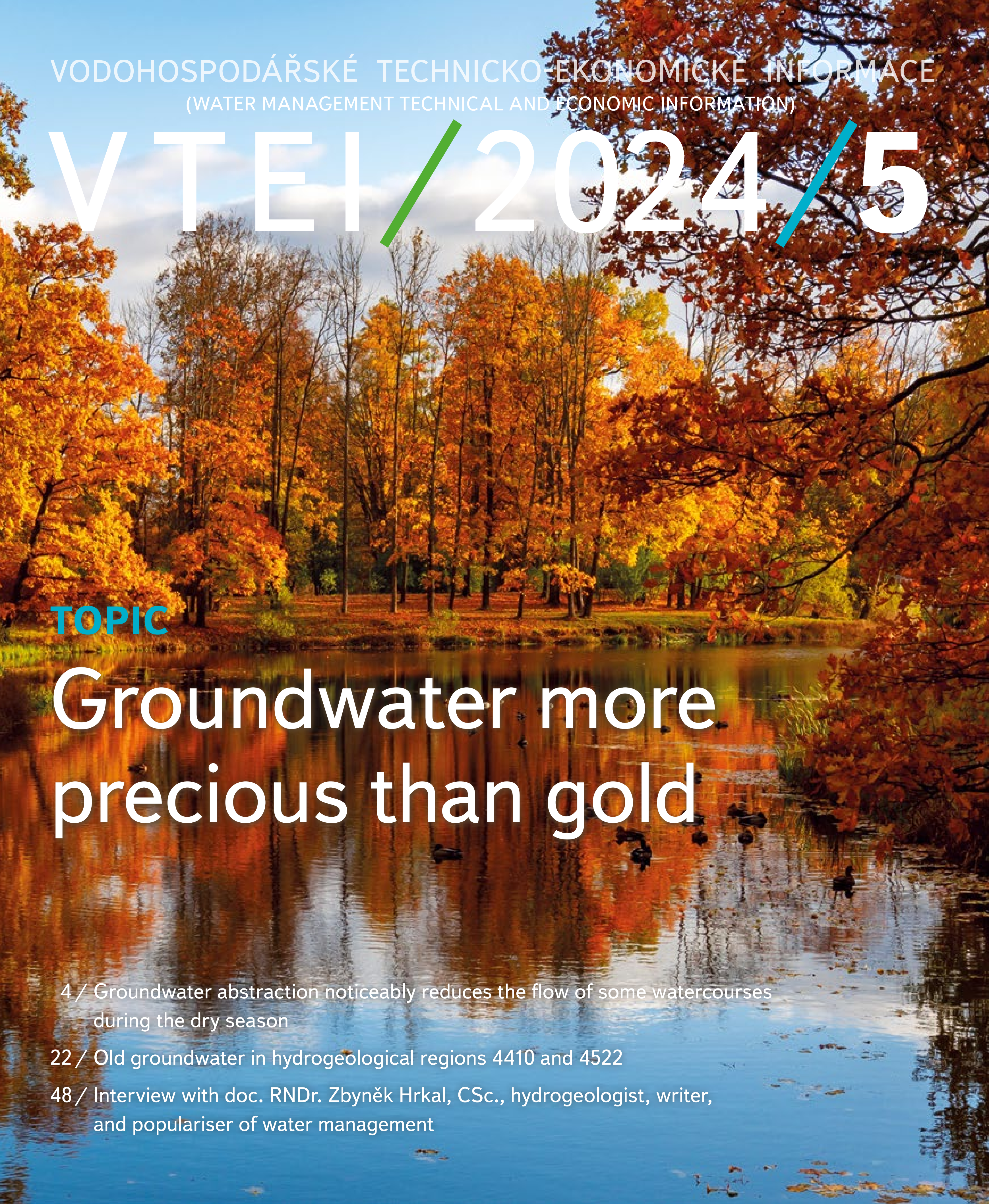


VODOHOSPODÁŘSKÉ TECHNICKO-EKONOMICKÉ INFORMACE
(WATER MANAGEMENT TECHNICAL AND ECONOMIC INFORMATION)
VTEI/2024/5

TOPIC

Groundwater more precious than gold

60 years ago in VTEI

In VTEI No. 6 from 1964, Ing. Jaroslav Sekera from the Department of Waterworks Constructions (OVHS) in Kroměříž wrote about a new waterworks sealing material – softened polyvinyl chloride (PVC). The article was peer-reviewed by Dr. Ing. J. Kurkat from Prague Waterworks.

In the operation of water supply systems, especially in the fitting of pipe distribution networks, there are permanent failures caused by defective sealing material on gate valves, hydrants, joints, etc. Failures in the leakage of main and section gate valves and hydrants cause the suspension of water supply for the population and industry.

Leather and rubber are used as sealing material. The OVHS Kroměříž employees thought about replacing it and designed a material made of softened PVC. Softened PVC in sheets in light yellow is a very suitable and durable sealing material and has proven itself in practice. The most commonly used plate thickness for water fittings is 3–4 mm. The gasket is easy to carve, even easier than rubber plates and leather. It is used for pipes with cold water distribution and as a seal for taps (rubbers). We also use it as a seal between flanges.

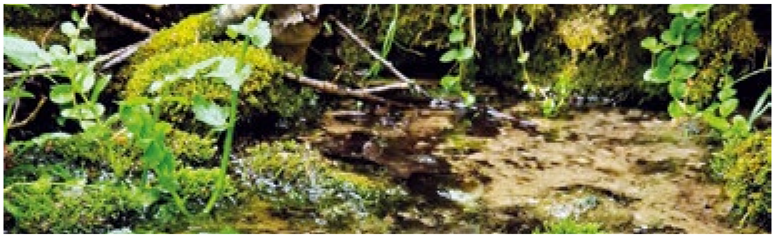
Using softened PVC ensures longer durability and 100% tightness. OVHS Kroměříž has had fittings and pipes with seals made of softened PVC installed in the ground for three years in very vulnerable places without any leaks occurring. The savings that arise from using this sealing material are significant and long lasting. It means fewer failures and less water loss. Also, the number of excavations during fault repair is reduced.

Softened PVC with a plate thickness of 3–4 mm can be bought at Sempo. In the event that other OVHS were not able to get the softened PVC, OVHS Kroměříž can help and secure the plates at Fatra Napajedla State Enterprise.

From the TGM WRI archives

VTEI Editorial office

Content



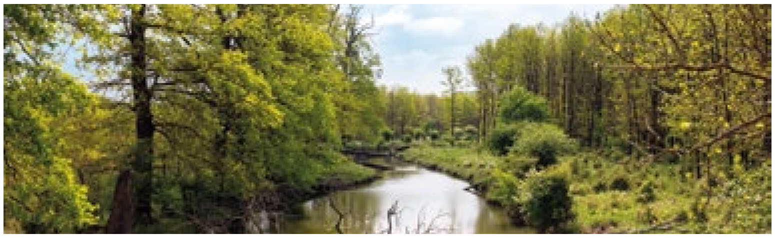


Photo: 123RF.com

Dear readers,

before we guide you through the October issue of VTEI, which is focused on hydrology and hydrogeology, we would like to give you some news. Since February 2022, the journal has been published not only in Czech, but also in an online English version. This step was reflected in the increased visibility and citation of published articles and created one of the basic conditions for VTEI's acceptance into prestigious bibliographic and citation databases. Currently, VTEI is undergoing an evaluation procedure for admission to the second most important abstract and citation database of peer-reviewed literature (Scopus) and to the Directory of Open Access Journals (DOAJ). We are also working on improving our chatbot, which has been part of the VTEI website for some time. Our aim is for this AI tool to be able to work with individual posts saved in PDF as well as with images. For our readers, this would mean the possibility of creating, for example, a brief summary of selected posts.

And what exactly is the content of our October issue? The first expert article "Groundwater abstraction noticeably reduces the flow of some watercourses during the dry season" by Martina Peláková and Pavel Eckhardt draws attention to the relationship between groundwater abstractions and the drying up of important watercourses during droughts. The article provides a summary of the most affected important watercourses in the Czech Republic. The result of the published analysis is the identification of 13 locations where the amount of groundwater abstracted exceeds 30 % of the watercourse flow in the dry season.

The second expert article by Barbora Krijt and Jiří Mls "Influence of retention curve parameter α on capillary barrier efficiency" is focused on the calculation of parameter α of the retention curve wetting branch and on the influence of its value on capillary barrier efficiency. The authors compared the effectiveness of several capillary barriers that differed in the capillary layer determined by the tested choices of parameter α. It is evident from the obtained results that the most accurate determination of retention curve parameters plays an essential role in determining the capillary barrier effectiveness.

The third expert article, "Old groundwater in hydrogeological regions 4410 and 4522" by Jakub Mareš, Martin Slavík, and Josef Vojtěch Datel, brings details of the project focused on the old groundwater status in selected hydrogeological regions. Old groundwater with negligible concentrations of tritium can be considered a strategic resource because it is less susceptible to contamination. The aim of the article is to give a brief hydrogeological description of the area of interest, to present the results from the first year of the project *"Knowledge, quantification and protection of strategic groundwater resources of the Czech chalk basin of deep circulation in hydrogeological regions 4410 and 4522"* and to describe the uncertainties of existing information.

The last expert article of this issue describes the methodology for creating the *Map of vulnerability of the quantity of natural groundwater resources to drought for the Czech Republic*. An expert interactive map is created using precipitation normal and regression relationships between precipitation and total and base runoff. The purpose of the *Map of vulnerability of the quantity of natural groundwater resources to drought* is to objectively compare the vulnerability of natural groundwater resources throughout the country. The article a collective work of Jiří Bruthans, Jiří Grundloch, Renáta Kadlecová, Tuna Karatas, Kateřina Šabatová, and Radek Vlnas.

As always, we have an interview in this issue. This time Pavel Eckhardt interviewed our well-known hydrogeologist, writer, and water management populariser Zbyněk Hrkal.

The last part of the October edition of VTEI is devoted to informative articles, namely the Danube Lighthouse Initiative project and the issue of hydrogeological aspects of wells for heat pumps.

Dear readers, as always, we wish you a pleasant and inspiring read.

VTEI Editorial Office

Groundwater abstraction noticeably reduces the flow of some watercourses during the dry season

MARTINA PELÁKOVÁ, PAVEL ECKHARDT

Keywords: minimum groundwater level — water abstraction — groundwater — flow — drought — watercourse

ABSTRACT

The paper highlights the fact that some significant watercourses dry up during periods of minimal flows due to groundwater abstraction. It provides a summary of the most affected significant watercourses in the Czech Republic. Large concentrated groundwater abstraction has a considerable impact on small and medium-sized watercourses.

To select the most significant effects of abstraction on stream flows, we used the ratio of abstraction to 355-day flows from 1931–1960. Watercourses exceeding 30 % were selected. In half of the selected cases the following relationship was confirmed: the 355-day flow from 1931–1960, reduced by the abstraction rate, is approximately equal to the 355-day flow from 1991–2020. The cases where this relationship does not apply can be explained by changes in abstraction volumes, declining groundwater levels and flows in the wider area due to groundwater collection and the use of static groundwater reserves. The effect of climate change is unlikely to be present in the baseflow in the cases studied.

Our analysis identified 13 cases where groundwater abstraction is severely affecting the flow of significant watercourses. In about half of these cases, there is an alternative source of water that should be used when the flow of the watercourse is at a minimum. Another option to protect water resources is to apply the minimum groundwater level or minimum residual flow under the Water Act.

A comparison of the 13 sites most affected by groundwater abstraction showed the consequences of groundwater overexploitation. In the catchments of the Dědina, Doubrava, Bělá, Liběchovka, Úštěcký stream, Blšanka, and Jevíčka, groundwater abstraction is significant, but the hydrological regime has not yet been completely changed. In other cases, the situation is more serious, with substantial depletion over a wider area. Decreases in stream flows and groundwater levels are often felt in neighbouring catchments. According to our findings groundwater abstraction in the catchment areas of the Bechyňský stream, Rakovnický stream, Pšovka, Blata, Romže, and Svitava had the most significant impact on the hydrological regime.

INTRODUCTION

A manifestation of climate change in the Czech Republic is a steady increase in average air temperature over the last 50 years, while average precipitation totals have not changed much. Due to higher temperature (if there is enough precipitation), there is greater terrestrial evaporation, which leads to more pronounced aridity in the soil and in surface water and groundwater. Adaptation to drought is carried out through long-term plans and measures, as well as draft measures for the immediate solution of water shortage, which are part of the so-called drought plans according to Section 87b of the Water Act. Surface and groundwater resources are limited, which requires coordination of their use during drought. One of the long-term adaptation measures is to enable substitutability of water resources. Larger cities (consumers) often have more substitutable resources, but it is not the rule.

Fig. 1. Natural spring emerging from the Cretaceous sandstones of the Kokořínsko region forming part of the Liběchovka flow

Surface water abstraction undoubtedly reduces flows in watercourses in reaches of different lengths depending on the remoteness of the abstraction site and the discharge of used (waste) water. The influence of surface water abstraction on water quality is also obvious and, with low flows, quite significant. In the case of groundwater abstraction, the effect on stream flow is not so direct, but it is similar. Depletion of flows occurs in several ways. This is obvious when collecting springs that form or formed part of a watercourse flow. The depletion of watercourses also occurs through groundwater withdrawal using boreholes and wells; in fact part of groundwater forming springs (*Figs. 1* and *2*) at the site of the drainage base of the water-bearing system or inflows of groundwater into watercourses and reservoirs is abstracted. The yield of the springs decreases as a result of extraction from boreholes; sometimes they disappear completely, which is described, for example, in the Hřensko intake area [1]. Similarly, there is a decrease in groundwater discharge below the levels of watercourses and reservoirs. Another way of reducing a watercourse flow is the groundwater withdrawal in a floodplain using bank infiltration.

Fig. 2. St. Vojtěch spring in the Cretaceous sandstones of the Kokořínsko region forming part of the Liběchovka flow

METHODOLOGY

From the recorded groundwater abstraction for 2021 in the Czech Republic [2], the largest abstractions were selected and compared with the flows in watercourses that they may have an influence on. Only significant watercourses were monitored, based on Decree No. 178/2012 Coll. During the comparison, the 355-day flow (Q355d) was considered, which represents the status of low flows. With regard to the affection of stream flows by the abstractions themselves, but also by operations on the reservoirs or wastewater discharge, the values of Q355d from 1931–1960 [3] were used. Groundwater abstraction on a massive scale began to be carried out from the 1970s. Within the basin of one watercourse with a known Q355d, abstractions were combined and their values added up. As a rule, there are no significant fluctuations in water supply abstraction during the year. Annual groundwater abstraction was recalculated to the average instantaneous abstraction. By dividing the average groundwater abstraction and Q355d from 1931–1960, we get an idea of a possible reduction of a watercourse flow due to abstraction. The choice of a watercourse profile was limited by available data, so it may not be ideal for objective assessment of the influence of the abstraction on the flow. Naturally, the greatest influence of abstraction on flows occurs in cases of large abstraction and small watercourses. *Tab. 1* shows groundwater abstraction where the amount abstracted is more than 30 % of the Q355d flow of the respective watercourse. The influence of surface water abstraction, wastewater discharge, and operations on reservoirs on the flows of selected watercourses, was assessed and found to be negligible.

Natural and hydrogeological conditions of selected watercourses in connection with respective abstractions

Thirteen watercourses were selected in the manner described above. These watercourses lie at lower altitudes in the wider central part of the Czech Republic, from Ústí nad Labem to Olomouc and South Moravian Regions. The largest number of these watercourses is in the Central Bohemian Region. The areas of hydrological basins of the selected watercourses range from 51 to 384 km^2.

From a hydrogeological point of view, the selected groundwater abstractions are mainly located in permeable Cretaceous and Quaternary sediments. In contrast, the most widespread hydrogeological environment in the Czech Republic is completely absent here – the hydrogeological massif, which usually does not allow concentrated abstraction of higher groundwater discharge. From the point of view of the affected hydrogeological zones, the zones in the Czech Cretaceous basin predominate. There are nine selected reaches of the Dědina, Doubrava, Bělá, Pšovka, Liběchovka, Úštěcký stream, Blšanka, Jevíčka, and Svitava watercourses.

RESULTS

Among groundwater abstraction affecting the flow of watercourses, abstraction for treating drinking water for public water supply systems of large towns predominates in the vast majority. Water abstraction for large towns is often concentrated on abundantwater resources, where depletion is not so fundamental; however, an adequate level of use must be maintained with regard to watercourses and groundwater reserves at the abstraction site and the surrounding area.

Tab. 1 lists 13 sites in the Czech Republic where groundwater abstraction significantly affects the flow of medium-sized or small watercourses during low flow periods. In most cases, the abstracted groundwater travels to distant consumers in other basins. Only in two cases (Rakovnický stream and Romže) is

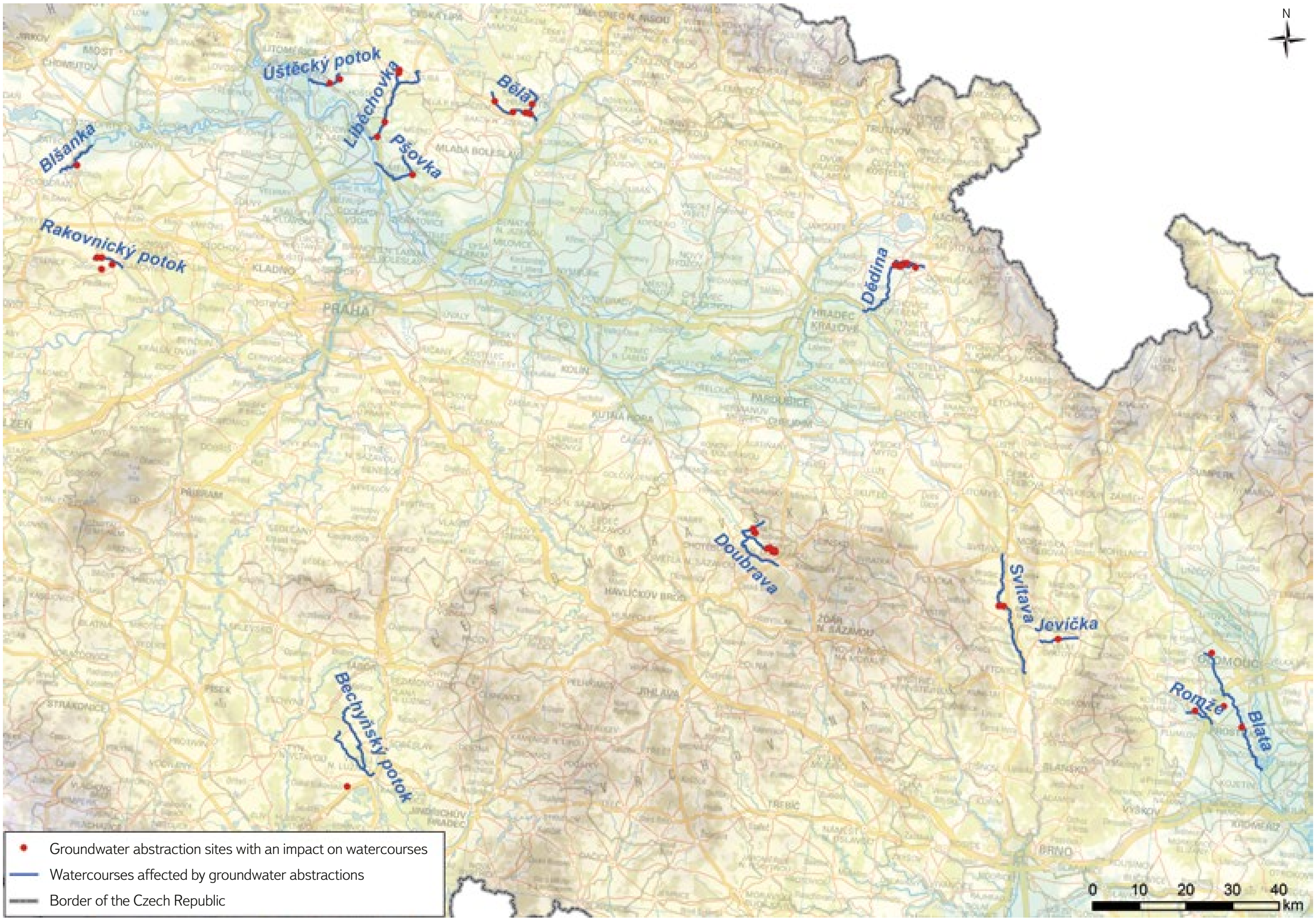


Fig. 3. Significant impacts of groundwater abstraction on stream flows have been identified at 13 locations in the Czech Republic; the map shows each affected watercourse section with the corresponding abstraction sites.

the majority of the abstracted groundwater returned to the stream by discharging wastewater at a short distance of about 5 km below the abstraction point.

Percentage evaluation of the degree of influence of abstraction on flow, as shown in *Tab. 1*, provides a general summary of the significance of abstraction in individual locations, but also depends on the location of the profile on the watercourse. Profiles with available Q355d values were used for assessment. Selected watercourses and groundwater abstraction sites that influence their flow rates are shown in the map in *Fig. 3*.

For further analyses, 355-day flows derived from observations of influenced flows in 1991–2020 were also used. In half of the cases, we can see the relationship between the average abstraction, Q355d from 1991–2020 and Q355d from 1931–1960. The sum of the average abstraction and Q355d (1991–2020) in these cases approximately corresponds to Q355d (1931–1960) for the Dědina, Doubrava, Bělá, Rakovnický stream, Liběchovka, Úštěcký stream, and Jevíčka, as shown in the graph in *Fig. 4*. The 355-day flow can be regarded as an approximate level of baseflow in the dry season. Thus, the decrease in Q355d from 1991–2020 compared to Q355d from 1931–1960 roughly corresponds to the size of the respective groundwater abstraction.

Why is this not true in all cases? Why is abstraction in some cases greater than the original baseflow? There are several reasons:

1. Groundwater abstraction already took place to a lesser extent in 1931–1960. An example is the Březová nad Svitavou intake area, where groundwater collection by the First Březovský Water Supply System for Brno started in 1914 and, by 1975, about 300 l/s was abstracted [4, 5]. The 355-day flow in Svitava from 1931–1960 is therefore not uninfluenced. Similar cases are: Smržice intake area, near Prostějov, in the Romže basin, which has been used since 1906; Holedeč intake area, near the Blšanka, with a water treatment plant from 1933 supplying water to Žatec district; Vrutice intake area, supplying water to Litoměřice since 1903; and Rakovnický stream intake area, which became the main source of water for Rakovník in 1944.

2. Collecting groundwater also depletes resources in the wider area in the basin of other watercourses, reducing their flow. Examples are the intake areas of Mělnická Vrutice, Holedeč, Dolní Bukovsko, and the intake area in the Blata basin. Water collection can cause a change in the direction of groundwater flow, thereby increasing the extent of the area from which

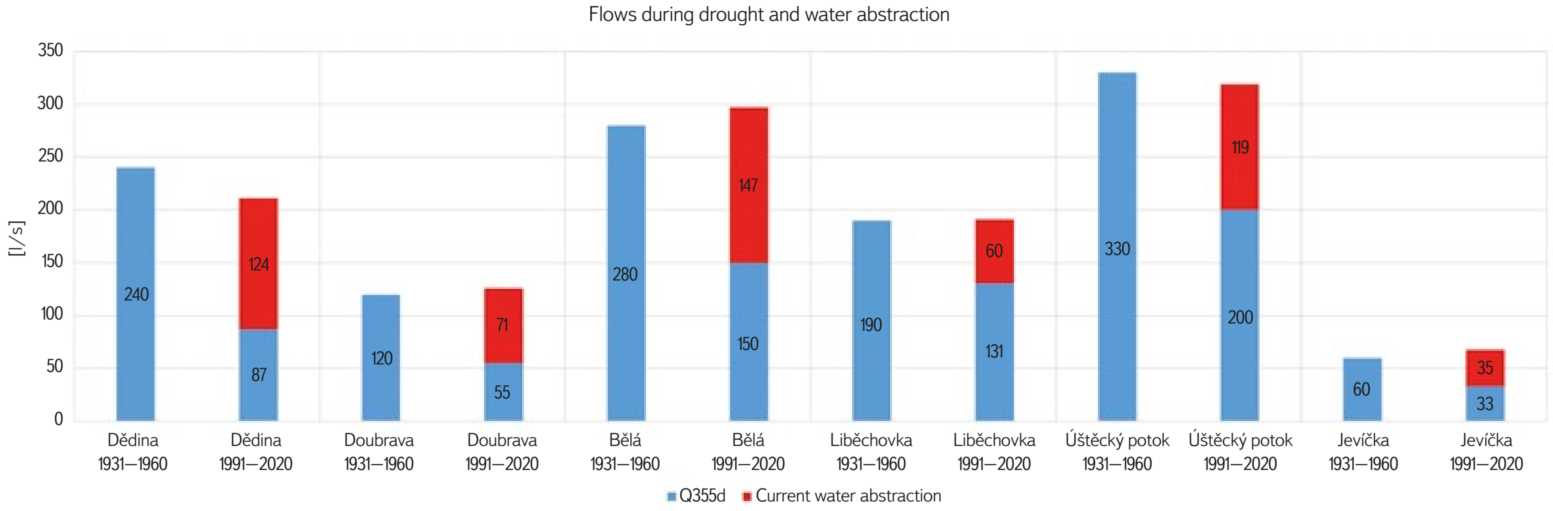


Fig. 4. Comparison of 355-day flows, past and present. The reduction in 355-day flows corresponds to the amount of groundwater abstracted in the selected catchments. Cases of abstraction affecting larger areas across catchment boundaries are not shown.

groundwater flows to the collection points. In the case of deeper boreholes, deeper aquifers may be affected, often draining at a great distance from the point of abstraction into distant watercourses.

3. Groundwater can also be temporarily pumped from static reserves, which is described in the cases of the Mělnická Vrutice [6], Dolní Bukovsko [7], and Rakovnický stream [8] intake areas.

4. Groundwater abstraction from 1991–2020 was, in some cases, less than in 2021, which was used for the analysis. In the case of abstraction in the Bělá, Blata, Romže, and Jevíčka basins, the increase in the amount of abstracted water (up to 20 %) probably caused a slight discrepancy. With the slightly reduced abstraction values in these four cases, the sum of abstraction and Q355d (1991–2020) is closer to that of Q355d (1931–1960).

5. Groundwater abstraction from 1991–2020 was, in some cases, greater than in 2021. The slight decrease in the amount abstracted explains the slight discrepancy in the values in the Dědina basin on the same principle as stated in point 4. The decrease in abstraction for Malešov water treatment plant contributes to the explanation of the discrepancy at the Úštecký stream.

6. The influence of climate change can also play a role. By comparing the 355-day flows from 1931–1960 and 1991–2020 in watercourses not significantly influenced by surface water abstraction, discharge, and operations on reservoirs, we find that there has been a decrease in some of the watercourses (*Fig. 5*). Higher temperatures in the later period caused more evapotranspiration from the catchment if water is available in the surface layer; therefore, runoff from the catchment may be lower. Minor changes in precipitation totals in some parts of the Czech Republic do not have a major effect on Q355d.

7. Values of 355-day flows may be affected by errors in observation, evaluation, and derivation of flows.

It was quite surprising to find that the difference between the current Q355d and the historical Q355d from 1931–1960 can be explained in all cases examined by the size of current abstraction and the reasons 1–5 mentioned above. Based on our findings, climate change does not play a significant role here. The reason may also be the fact that 1931–1960 is one of the drier periods.

Weakening of baseflow from Cretaceous aquifers as a result of climate change probably does not occur for the reason that the replenishment of the aquifers takes place mainly from winter precipitation, which is not reduced in quantity, and from watercourses in their loss reaches (e.g. at the outcrops of aquifers). Water resources in the Cretaceous sandstone aquifers are large and provide year-round continuous replenishment of the watercourses. Total annual runoff for most watercourses is reduced due to climate change [9]. The reason is mainly the weakening of subsurface runoff (interflow) in the growing season, when evapotranspiration is higher due to higher air temperature.

Reduction of watercourse flows and groundwater levels caused by groundwater abstraction has been observed in many locations in the Czech Republic over the recent decades. One of the tools for rectifying such conditions is the minimum groundwater level and minimum residual flow under the Water Act, which have been applied successfully in several cases. For example, in the past, groundwater abstraction in the Podlažice intake area greatly influenced the flow of the Žejbro in the Chrudimka basin, until it dried up. A minimum groundwater level was introduced for the intake area with four groundwater levels in the monitoring borehole, according to which the maximum possible amount of groundwater abstraction is governed. Given that there are other sources of drinking water in the area (e.g. Seč and Křižanovice reservoirs on Chrudimka), the Žejbro has not dried up since the introduction of the minimum groundwater level.

Of the 13 groundwater abstraction sites that are the subject of our analysis, the minimum groundwater level is applied in the intake areas of Litá, Dolní Bukovsko, Mělnická Vrutice, and Březová. Moreover, for the Dolní Bukovsko intake area, there is a minimum residual flow of 50 l/s in the Bechyňský stream. For the Litá intake area, restriction of groundwater pumping to protect marsh communities only applies from 21 March to 15 July. The introduction of these limits has improved the status slightly; however, due to the long period of time for which groundwater abstraction has been carried out, the natural state of surface water and groundwater is not well known; not many people remember it, and therefore it is not enforced. The determination of the value of minimum groundwater level itself does not always correspond to the definition provided in Section 37 of the Water Act: *"The minimum groundwater level is the level that still allows sustainable use of water resources and that ensures achievement of good ecological status of related surface water bodies and excludes significant damage to terrestrial ecosystems."* Further application of the aforementioned minimum

Tab. 1. Groundwater abstraction in 2021 that greatly affected watercourses (in hydrological order)

Abstraction point name	Region	Hydrogeological region (HGR)	Urban areas supplied	Total average annual abstraction [l/s]	Affected watercourse – profile (catchment area)	Q355d 1991–2020 [l/s]	Q355d 1931–1960 [l/s]	Ratio of abstraction/flow Q355d 1931–1960 [%]	Possible source replacement
Litá	HKK	4222 Cretaceous of the Orlické hory (Mts.) piedmont in the Orlice River catchment	Hradec Králové	124	**Dědina** – Mitrov (291 km^2)	87	240	52	Orlice – Hradec Králové VSVČ and other sources of the VSVČ
Studenec	VYS	4320 Dlouhá mez – southern part	Havlíčkův Brod, Chotěboř, Ždírec, Přibyslav, Hlinsko	71	**Doubrava** – below Cerhovka (101 km^2)	55	120	59	VN Hamry
Kladruby, Lhůta		4330 Dlouhá mez – northern part							
Bělá pod Bezdězem and its surroundings	STC	4410 Cretaceous of the Jizera River, right-bank part	Mladá Boleslav and surroundings	147	**Bělá** – mouth (158 km^2)	150	280	52	None
Dolní Bukovsko	JHC	2151 Třeboň Basin – northern part	Jindřichův Hradec, Veselí n. L., Týn n. Vlt.	97	**Bechyňský stream** – mouth (128 km^2)	68	110	88	Partially VN Římov
Rakovník and its suroundings	STC	5131 Rakovník Basin	Rakovník	54	**Rakovnický stream** – above Lišanský stream (164 km^2)	15	60	90	None
Mělnická Vrutice	STC	4522 Cretaceous of the Liběchovka and Pšovka Streams	Mělník, Neratovice, Kralupy, Kladno, Slaný	344	**Pšovka** – mouth (158 km^2)	-	190	181	Partially VN Švihov, VN Klíčava
Pavličky	LBK	4522 Cretaceous of the Liběchovka and Pšovka Streams	Litoměřice (VS Žernoseky)	60	**Liběchovka** – mouth (157 km^2)	131	190	32	(Vrutice and Malešov, Močidla)
Tupadly and Liběchov	STC		Mělník a okolí						(Mělnická Vrutice)
Vrutice and Malešov	ULK	4523 Cretaceous of the Obrtka and Úštěcký Streams	Litoměřice (VS Žernoseky)	119	**Úštěcký stream** – mouth (217 km^2)	200	330	36	(Pavličky, Močidla)
Holedeč	ULK	4550 Holedeč	Žatec	26	**Blšanka** – above Klučecký stream (384 km^2)	65	70	37	VN Žlutice
Velké Opatovice	JHM	4280 Cretaceous of the Velké Opatovice area	Boskovice	35	**Jevíčka** – below Uhřický stream (51 km^2)	33	60	59	VN Boskovice (unused backup resource)
Senice	OLK	1623 Plio-Pleistocene of the Blata River	Olomouc	86	**Blata** – Klopotovice (296 km^2)	13	45	191	Sources of the group water supply in the Morava floodplain
Dubany and Hrdibořice			Prostějov						None
Smržice	OLK	1624 Quaternary of the Valová, Romže and Haná Streams	Prostějov	47	**Romže** – above Hloučela (125 km^2)	-	40	118	None
Březovské water supply	PAK	4232 Ústí n. Orl. Syncline in the Svitava River catchment	Brno	852	**Svitava** – Rozhraní (223 km^2)	185	660	129	VN Vír

Abbreviations: Q355d = 355-day flow; VN = reservoir; VSVČ = Water supply system of Eastern Bohemia; Number derived from own data are in italic

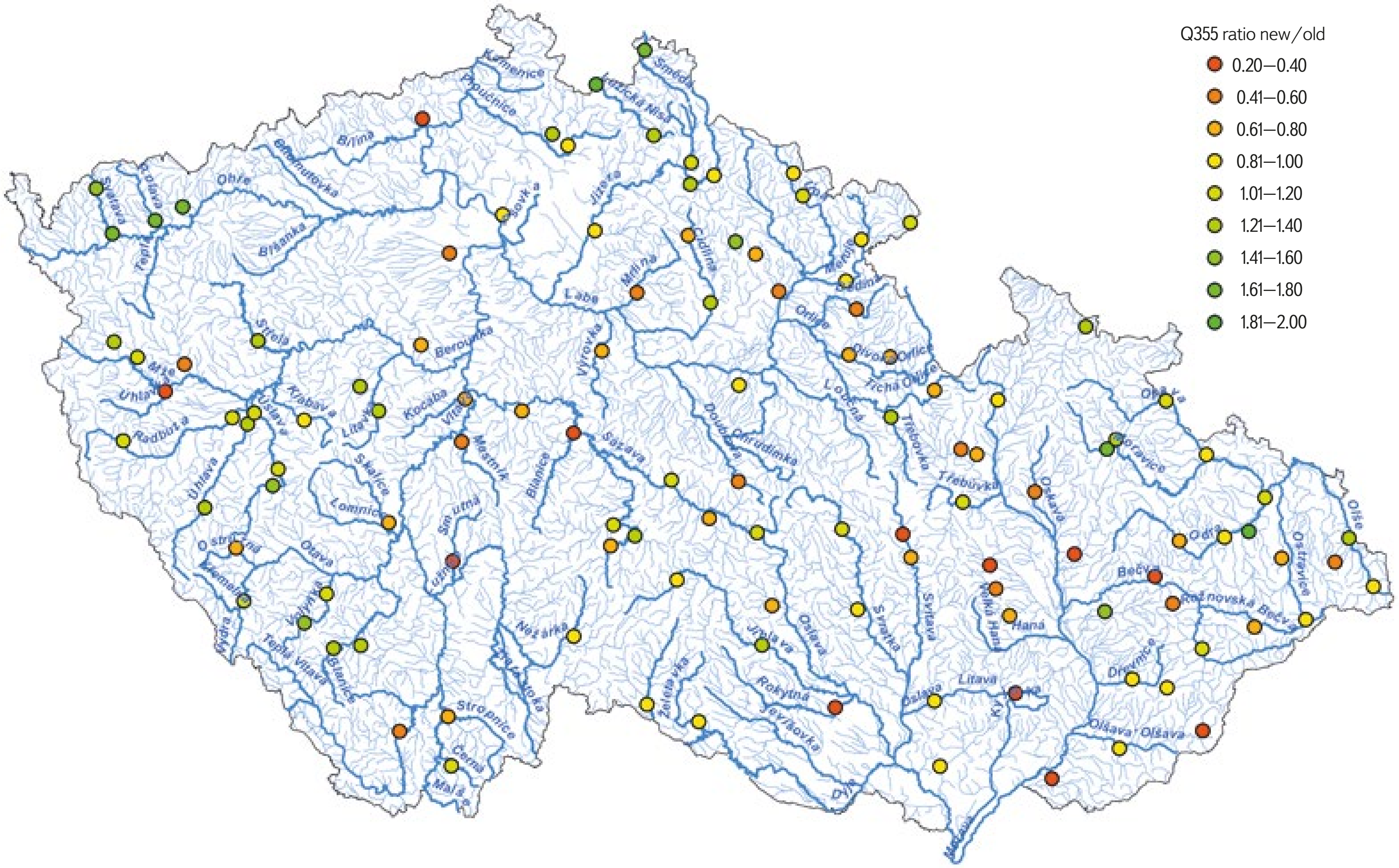


Fig. 5. Change in 355-day flow in stream profiles; coloured points show the ratio between Q355d from 1991–2020 and Q355d from 1931–1960

groundwater level and minimum residual flow is appropriate in cases of overexploitation of water resources, the most significant cases are listed in *Tab. 1*.

Tab. 1 also contains information on urban areas supplied from assessed sources. Only larger towns that consume vast majority of water are listed. In the last column of *Tab. 1*, possible alternative water sources for the given consumption facilities are proposed. These are often reservoirs that have sufficient capacity. Some sources are normally used, others are only supplementary due to the higher price of abstraction and surface water treatment, and others are shut down (Boskovice reservoir). In some cases, no other major source is connected to the water supply system, it can be a risk for reliable water supply in general, but also for watercourses and water-dependent ecosystems, which can be damaged or destroyed during drought due to large irreplaceable abstraction.

Sufficient groundwater reserves, which are often claimed by water supply operators, do not always go hand in hand with sufficient water in rivers, as was shown at the 13 surveyed locations. For the sake of interest, we can mention the opposite situation, when pumped groundwater flows after use into a watercourse, which is not the drainage base of the aquifer from which it was pumped. It therefore has an improving effect for flow rate in the watercourse and this is appreciated during drought.

DISCUSSION

In the works of Prchalová [10] and Venera [11], groundwater abstraction is compared with natural groundwater resources, or with the exploitable amount of groundwater on the scale of hydrogeological zones. This paper compares groundwater abstraction with dry season stream flows consisting predominantly of baseflow at the scale of 51 to 384 km^2 catchments. Based on the results of the studies [10, 11] and this article, areas of excessive groundwater extraction, unsurprisingly, coincide in many cases. Due to the different investigated sources (groundwater and watercourses), there is no agreement if the drainage base of the "affected" hydrogeological zone is a large watercourse. Its flow will not be affected by groundwater pumping in a significant way, despite the fact that groundwater reserves are overexploited. Furthermore, there is understandably no agreement in cases where the basin of the examined watercourse only forms a small part of the hydrogeological zone (HGR). In contrast to previous works [10, 11], a significant influence of groundwater abstraction in the Bělá basin was identified in HGR 4410 Cretaceous of the Jizera River, right-bank part, where groundwater resources are plentiful; however, the 355-day flow of the Bělá at the confluence with the Jizera is currently roughly half that of the period before building a group water supply system for Mladá Boleslav. In addition to the influence of increased abstraction in recent years, the method of determining exploitable reserves for HGR 4410 in the "*Rebalancing of groundwater reserves*" project, which is the basis of the Venera publication [11], also plays a role here.

The relationship between groundwater abstraction and watercourse flows is also dealt with by individual River Basin Authorities. In a report from the Vltava River Basin Authority [12], it is stated that the main drainage stream for HGR 2151 is Bechyňský stream, and the baseflow here is significantly influenced by the abstraction of groundwater in Dolní Bukovsko. In HGR 5131 Rakovník Basin, the pumping of a large amount of groundwater reserves, which then cannot flow away by gravity to their natural drainage bases – the Rakovnický stream and its tributaries, can be seen in the vicinity of Rakovník [8].

The Pšovka, Liběchovka, Úštěcký stream, and Blšanka watercourses are investigated within the territorial scope of the Ohře River Basin Authority. It is these watercourses that periodically experience a stressed water management balance [13], i.e. the average monthly flows fall below the Q355d value. Among other things, excessive groundwater abstraction by waterworks contributes to the decrease in flow rates of some of these watercourses [13]. The greatest negative impact is recorded on the Pšovka, whose part has been drying up completely in the summer months [14]. Furthermore, the Blšanka water bearing is significantly affected by groundwater abstraction from the Holedeč intake area [11] in HGR 4550 Holedeč, from which the groundwater is drained into the Blšanka through numerous fractures [14]. The Liběchovka flow is dealt with in the final report of the "*Rebalancing of groundwater reserves*" project [6], within which measurements of gradual profile flows were carried out. In the reach of the Liběchovka between Chudolazy and Želízy, where the Tupadly intake area is located (*Fig. 6*), the Liběchovka flow decreased by around 30 l/s in October 2013 and June 2014. The average monthly abstraction in the Tupadly intake area was 33 l/s in October 2013 and 37 l/s in June 2014. The annual average abstraction in 2021 and 2022 was 37 and 44 l/s.

The Morava River Basin Authority manages the investigated watercourses Jevíčka, Blata, Romže, and Svitava. On the Blata watercourse, a stressed balance status has appeared repeatedly since 2009. One of the reasons is the abstraction of groundwater in the floodplain between the Morava, Blata, and Romže [15]. Similarly, a stressed balance status is very common on the Svitava. The main reason is the significant volumes of groundwater abstraction for First and Second Březovský Water Supply Systems [15]. Compensation for the amount of water abstracted is provided by Letovice reservoir on the Křetínka which flows into the Svitava at river km 19, below the Březová intake area. The balance status of the Jevíčka and Romže is not assessed; however, the influence of abstraction on the Romže in the Smržice intake area is evident because the collection system is based on bank infiltration from Romže. Two weirs have been built on the Romže in order to store water for the Smržice intake area, where seven collection points are excavated along the Romže [16]. In Velké Opatovice, the Zámecké springs (which feed the Jevíčka) are captured. The groundwater of aquifer B is exploited by a syphoning the natural springs as well as by a series of boreholes [17].

In relation to groundwater abstraction in hydrogeological zones 4222 and 4410, the report of the Labe River Basin Authority [18] states that abstraction in the Dědina (HGR 4222) and Bělá (HGR 4410) basins do not cause a reduction in static groundwater reserves. Whether or not the mentioned abstraction reduces the flows in the Dědina and Bělá has not been assessed. Furthermore, the report [18] states that groundwater abstraction in the Doubrava basin (HGR 4320 and 4330) cannot fundamentally threaten the natural resources of the groundwater body, and the reduction in flow in the Doubrava caused by abstraction is compensated by Pařížov reservoir. Based on our knowledge, improvement of the Doubrava flow rate during drought is not expected due to the complete emptying of the reservoir active storage in the past drought periods. The main purpose of Pařížov reservoir is to mitigate the passage of floods and, among other things, to produce electricity.

Comparison of *M*-daily flows for 1981–2010 and 1991–2020 is provided in the article by Kukla [19]. Decreases in 355-day flows amount to an average of 13.4 % in a set of 304 water gauging stations in the Czech Republic. Kukla notes that, in general, there was more water in 1981–1990 than 2011–2020. Prolonged periods of minimum flows were observed during 2014–2019 when there were long periods without precipitation. This explains the difference between the 355-day flow values in the compared periods. Our comparison of 355-day flows from 1931–1960 and 1991–2020 at 129 water gauging stations shows an average decrease of 3 %; stations with little influence on flows by human activity were selected. Considering the inaccuracies of the observed and derived values, a decrease of 3 % can be considered insignificant. The ČSN 75 1400 standard gives an indicative value of the probable error of the 355-day flow values of 20 %.

Fig. 6. Groundwater abstraction facility at Tupadly in the Liběchovka catchment

CONCLUSION

The result of our analysis is the identification of 13 locations where the amount of groundwater abstraction exceeds 30 % of a watercourse flow in the dry season. This article deals only with major groundwater abstraction and its impact on important watercourses. Lower groundwater abstraction has a similar effect on smaller watercourses of local importance. The drying up of watercourses is already observed in the driest regions in the Czech Republic. However, in the cases of watercourses considered in this article, the cause of severely depleted flows is water abstraction. Controlling the rate of abstraction from surface and groundwater sources is influenced, among other things, by the level of fees for abstracted water, which manifests itself in greater pressure on groundwater, which in this respect is significantly cheaper than surface water. Within water supply systems, there are often sources of surface water, the greater use of which is possible and would be supported by the equalization of fees for the abstraction of groundwater and surface water. These are mainly reservoirs intended for water supply. Another positive effect of most of these reservoirs is the improvement of flows in watercourses during dry periods.

In the future, climate change will bring with it a further rise in temperatures, which will be most evident in watercourses where the situation is already stressed and drying up is underway. It is necessary to prepare for issues and use or look for other sources of water. We should ensure the possibility of using existing unused reservoirs for water supply purposes and to consider the construction

Photo: M. Peláková

of new reservoirs. The advantage of reservoirs is that, unlike groundwater aquifers, the outflow of the retained water can be regulated. Another contribution to the increase of groundwater reserves, i.e. the flow of watercourses in the dry season, is the support of rainwater infiltration into the rock environment, for example by means of infiltration features. It is also important to protect significant infiltration areas from construction and pollution. Flows in dry periods can also be enhanced by removing inappropriate drainage facilities on both agricultural and forest land. If long-term conceptual measures are missing, water authorities must take measures in dry periods to limit water consumption by households, which are the main consumers of groundwater.

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Explanation of terms used

355-day flow – flow that is reached or exceeded on a long-term average for 355 days a year.

Aquifer – an underground layer of water-bearing material.

Baseflow – part of stream flow maintained by groundwater discharge, usually keeping at least some water in the stream even during extended dry periods; it is one of the three components of the total runoff, with the others being surface runoff and subsurface runoff.

Drainage base – the place where groundwater from the water-bearing system flows to the earth's surface under the influence of gravity

Dynamic groundwater reserves – the amount of groundwater flowing from aquifers to waterways or other aquifers; in natural conditions, they correspond (in the long-term) to natural groundwater resources and form baseflow.

Evapotranspiration – the combination of water evaporation and plant transpiration, i.e. water vapour from the surface of the earth and release of water vapour through the surface of plants.

Groundwater body – volume of groundwater within an aquifer.

Groundwater collector – a permeable rock environment with the ability to accumulate water.

Hydrogeological zone – area with similar hydrogeological conditions, type of aquifer, and groundwater circulation.

Natural (renewable) groundwater resources – the amount of water under natural conditions replenished in the long term by infiltration into an aquifer or water-bearing system (definition from Annex No. 8 of Decree No. 369/2004 Coll.).

Natural resources are usually determined as the value of uninfluenced baseflow from the hydrogeological structure. Baseflow naturally changes over time depending on the season and the weather in the previous period. The characteristic value for the given period can then be median or average baseflow.

Bank infiltration – interaction between surface water and groundwater; taking water from a watercourse caused by the difference in levels in the stream and at the place of groundwater collection objects in the floodplain.

Static groundwater reserves – the amount of groundwater that does not flow from aquifers to waterways or other aquifers (if they are pumped, there may be a permanent drop in the groundwater level).

Uninfluenced flow – natural flow that is not influenced by reservoirs, abstraction, and discharge.

Exploitable amount of groundwater – the amount of groundwater that can actually be used from an aquifer or water-bearing system without negatively affecting groundwater or the surrounding environment (definition from Annex No. 8 of Decree No. 369/2004 Coll.).

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Influence of retention curve parameter α on capillary barrier efficiency

BARBORA KRIJT, JIŘÍ MLS

Keywords: capillary barrier — numerical modelling — retention curve — hydraulic characteristics — hysteresis

ABSTRACT

This study is focused on the calculation of parameter α of the wetting branch of the retention curve and on the influence of its value on the efficiency of capillary barriers. The capillary barrier is a simple method of insulating landfills. The effectiveness of the capillary barriers was tested using numerical models, which allow greater testing variability compared to physical measurement. Thanks to numerical models, it was possible to evaluate the direct effect of changing the parameters of retention curves on the functioning of capillary barriers. Hysteresis of retention curves was included in the construction of the numerical models, and then its effect on the agreement of the model results with the measured data was evaluated. Numerical modelling is a suitable and reliable tool for verifying the efficiency of capillary barriers. Due to the sensitivity of the results to the parameters of the task, it is necessary to determine as precisely as possible all the necessary input parameters so that the resulting model has real informative value.

INTRODUCTION

A capillary barrier, possibly in combination with another component [1], is an effective tool used to cover landfills and to protect an area against groundwater penetration. Its principle is based on the different hydraulic properties of two soil layers, usually different sands or sand and gravel. The finer-grained overlying layer composed of fine- to medium-grained sand is called the capillary layer. The bottom layer of coarser-grained material, usually medium-grained gravel, is called the capillary block. The interface between the capillary layer and the capillary block is referred to as the capillary interface. The hydraulic conductivity of the capillary layer is higher than the hydraulic conductivity of the capillary block under certain pressure conditions. This applies to lower pressure heads where the capillary block is almost impermeable. Thanks to this, the water flows through the capillary layer rather than penetrating into the capillary block [2, 3]. In some cases, to increase efficiency or for greater security, a simple capillary barrier is supplemented with a geotextile layer inserted at the capillary interface. Capillary barriers assembled in this way are called combined [4, 5]. A combined barrier is used in case of failure of a single capillary barrier.

The European Landfill Directive (Council Directive 1999/31/EC) requires the use of two independent components to cover Class II waste landfills. This is usually ensured by an artificial and mineral layer. An alternative is to use an artificial seal (geotextile) in combination with a capillary barrier. In this case, the artificial layer can be placed above or below the capillary barrier; however, inserting an artificial seal between the capillary block and the capillary layer is recommended by TASi (German: *Technische Anleitung zur Verwertung, Behandlung und sonstigen Entsorgung von Siedlungsabfällen; Technical instructions for the recovery, treatment and other disposal of municipal waste*). Compared to a classic combined seal, the combined capillary barrier created in this way is cheaper, has more structural advantages, and is less prone to damage by consolidation. Only the minimum slope requirement remains [6–8, 1].

The basis of the water flow mathematical model in the generally unsaturated zone is the Richards equation. However, the equation alone is not enough to correctly define the issue; two constitutive relationships need to be supplied, namely hydraulic conductivity and retention curve. Since the retention curve can be considered a simple function in a certain sense, i.e. when hysteresis is included, we have two options: the diffusion and the capacitance form of the Richards equation. In most cases, the capacitance form, which we will continue to work with, is more suitable.

In general, the retention curve is not a simple function; the relationship between pressure head and moisture is characterized by hysteresis. When designing and testing capillary barriers, hysteresis is often neglected [4, 9]; however, more detailed studies show that it has a non-negligible effect on its efficiency [10–13].

Experimental determination of the retention curve is not simple; as a rule, only the main drainage branch is determined. Much more demanding measurement of the wetting branch is not available. If we use the drainage branch of the retention curve in flow modelling, we overestimate the efficiency of the barrier. Since the loading of the capillary interface (and its possible breaking) occurs with increasing moisture in the capillary layer, it is more correct to include hysteresis in the model. Below we describe in detail how we implemented the wetting branch in the mathematical models used.

This study focuses on determining parameter α for the wetting branch of the retention curve (i.e. α^w) and its influence on the efficiency of capillary barriers. In addition to the standard relationship between parameters α of the wetting and drainage branches, $\alpha^w=2\alpha^d$ [14], an analogy was also used based on the results of measurements of the drainage and wetting branches of the retention curve performed by Trpkošová [15]. The calculation of parameter α^w was dealt with by Likos et al. [16], when they determined the van Genuchten parameters α, m, and n from the results of experiments with the wetting branch.

Numerical modelling is used to test capillary barrier effectiveness at different values of parameter α. Due to the difficulty of experimental testing of capillary barriers, the repeatedly proven fact that mathematical models are efficient and accurate enough to reliably simulate experimental measurements is used; see for example [1, 17–20]. Using separate models for the main drainage and main wetting branches of the retention curve, it was also possible to evaluate the potential influence of hysteresis on the functioning of capillary barriers.

Hydromechanical characteristics of the environment

To numerically model the flow of water in capillary barriers, we use the capacitance form of the Richards equation in two spatial variables. The constitutive relationships used are the hydraulic conductivity *K(h)* and the retention curve in the form *θ(h)*, where *h* is the pressure head and *θ* is moisture.

Richards equation is thus expressed as follows:

$$C(h)\,\frac{\partial h}{\partial t} = \frac{\partial}{\partial x_i}\left(K(h)\,\frac{\partial}{\partial x_i}\,(h + x_2)\right) \qquad (1)$$

where:

$C(h) = \partial\theta / \partial h$ [L^{-1}]	is	capacitance function
t [T]		time
x_1, x_2 [L]		Cartesian coordinates
x_2 axis		placed vertically upwards

The retention curve is an equilibrium constitutional relationship indicating the value of moisture as a function of pressure head. To express it, van Genuchten equation [21] is usually used:

$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{(1 + (-\alpha h)^n)^m} \quad \text{pro } h < 0 \quad \text{a} \quad \theta(h) = \theta_s \quad pro \quad h \geq 0, \qquad (2)$$

where:

θ_r and θ_s [-]	are	residual and saturated moisture
α [L^{-1}], m [-], and n [-]		van Genuchten parameters

In general, $\alpha > 0$, $m \,\varepsilon\, (1;0)$ and $n > 1$ applies. As a rule, we also assume $m = 1\text{-}1/n$. The RETC program [22] is used to determine these parameters from the measured data of the retention curve.

In the numerical simulations carried out in this study, the usual distribution model was used to express the dependence of hydraulic conductivity on pressure head:

$$K_s \sqrt{\frac{\theta - \theta_r}{\theta_s - \theta_r}} \left(\frac{1 - F(\theta)}{1 - F(\theta_s)}\right)^2 \qquad [LT^{-1}]\ (3)$$

where:

$$F(\theta) = \left(1 - \left(\frac{\theta - \theta_r}{\theta_s - \theta_r}\right)^{1/m}\right)^n \qquad [-]\ (4)$$

see [23, 21].

Hydraulic conductivity enters the capacitance form of the Richards equation as follows:

$$K(h) = \frac{K_s}{\sqrt{(1 + (-\alpha h)^n)^m}} \left(1 - \left(1 - \frac{1}{(1 + (-\alpha h)^n)}\right)^m\right)^2, \qquad [LT^{-1}]\ (5)$$

which we get by substituting the appropriate branch of the retention curve (2) into *Equation 3*.

The course of wetting and the course of drainage are not determined by a single function. General change in moisture depends on the ongoing process (increasing or decreasing pressure head) and on the values of moisture and pressure head at the turning points; the introduction of hysteresis into the mathematical flow model means the loss of the unambiguity of the function *θ(h)*. A simple, yet sufficiently reliable hysteresis model is presented in the article [24]. The model uses the simplification $\theta_r^{d} = \theta_r^{w} = \theta_r$, $n^d = n^w = n$ and $\alpha^d < \alpha^w$ [25]. Here, and later, the superscripts *d* and *w* indicate the drainage and wetting branches. The authors further introduce into *Equation 2* a non-zero input air value according to [26], the relationship $\alpha^w = 2\alpha^d$ and the assumption that no air is closed in the pores during the wetting phases, i.e. that $\theta_r^{d} = \theta_r^{w} = \theta_r$ applies. Drainage or wetting branches of higher orders of the retention curve then receive a simple linear transformation based for a given turning point on the difference between the values of the current moisture and the moisture given by the main drainage branch for the current pressure head, or on the difference between the values of the current moisture and the moisture given by the main wetting branch for the current pressure head. For the needs of this article, it is important that the proposed method gives, in the case of the main drainage and main wetting branches, not only different air input values, but also different values of pressure heads of the inflection point of both branches.

In this study, we consider the retention curve as a unique function given by the main wetting branch. This corresponds to the above fact that the critical process in the capillary barrier is the increasing pressure head. Since in each phase of the real process, at a given value of pressure heads, the moisture is equal to or higher than the moisture given by the main wetting branch, the hydraulic conductivity of the capillary layer may be somewhat underestimated by the given simplification, and thus the efficiency of the capillary barrier may be underestimated as well. However, comparison of the results with the available experiments shows very good agreement and confirms the reliability of the method used. Moreover, this finding is consistent with the conclusions presented in the publication [24].

METHODOLOGY

Studied materials and their parameters

For the purpose of this study, one real, well-documented capillary barrier was taken to serve as a standard for comparison with other variants, and one hypothetical material was generated as a suitable alternative capillary layer. The three basic materials thus obtained, two different capillary layers and one capillary block, were then used to create several possible variants of the main wetting branches (still with the possibility of comparison with the measured wetting branch) generated according to the rules stated in the professional literature. The initial materials of the capillary layer and the capillary block were taken from the documentation of the capillary barrier experimental testing carried out at Ruhr University Bochum [27] and the laboratory measurement of the used materials carried out at the Faculty of Science of the Charles University [1, 28]. For the capillary block, it is a homogeneous material (hereinafter referred to as B_0) with a grain size of 2–8 mm. According to Powers' classification [29], it is in the "subrounded" category; particles have well rounded edges and less rounded vertices. For the capillary layer, it is a material (hereinafter referred to as L_0) created in the river environment, from which calcareous parts and larger grains have been removed. According to Powers' classification, it belongs to the "rounded" category; the particles have rounded edges as well as vertices.

Using the tension apparatus designed according to Havlíček and Myslivec [30], the drainage and wetting branches of the retention curves for both materials were measured. Based on this, it was possible to use the obtained characteristics to compare the numerical results with the results of laboratory measurements in a tipping trough and subsequently, after confirming the reliability of the numerical simulations, to evaluate the influence of hysteresis in the mathematical modelling of capillary barriers. Main drainage, or the main wetting branch of the capillary layer material, are referred to as L_0^d or L_0^w, respectively. Similarly, we refer to the main drainage branch and the main wetting branch of the capillary block as B_0^d and B_0^w.

In order to further study the influence of the capillary layer parameters on the barrier efficiency, using Rosetta software [31], a proprietary capillary layer material marked L_1 was generated and defined by a set of parameters θ_r, θ_s^d, α^d, n^d so that the material determined by these parameters meets the requirements for capillary layer material with its granular properties according to Pícha [2].

The unsaturated hydraulic conductivity of the tested materials was determined using Equation (5), with saturated conductivity $K_s = 1.18 \times 10^{-4}$ m/s taken from material L_0. The hydraulic conductivities of materials L_1 and B_1 of the capillary layer and the block corresponding to the drainage branches of the retention curves are shown in *Fig. 1*. The graph shows how the two functions differ and how their difference changes with changing pressure head.

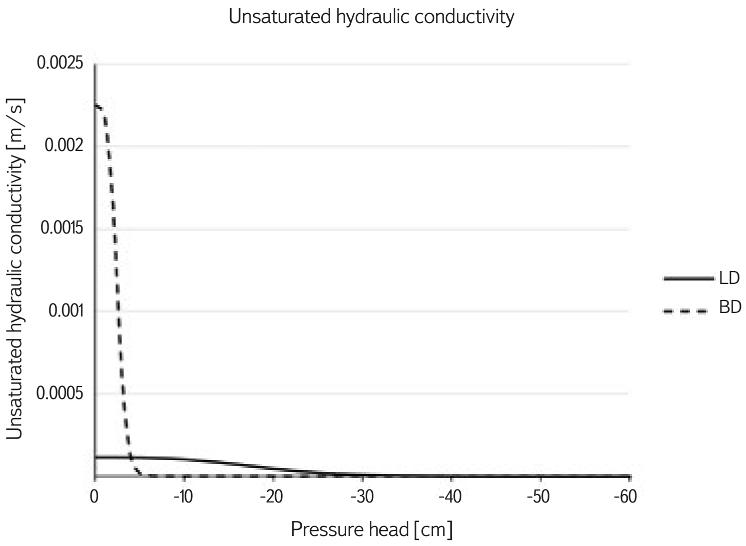

Fig. 1. Unsaturated hydraulic conductivity of the capillary barrier. The curve of dependence unsaturated hydraulic conductivity on the pressure head for capillary layer LD and capillary block BD. The data correspond to the drainage branch of the retention curve

Given that, in general, it is not possible to neglect hysteresis in the mathematical model of the capillary barrier and work only with the main drainage branch, in this study we focus in more detail on the construction of the main wetting branch from the usually measured parameters of the drainage branch, specifically the possibility of changing only the α parameter [14, 24].

In general, $\alpha^w > \alpha^d$ applies. Two basic approaches for determining α^w parameters were considered. In the first case, the results of laboratory measurements from previous studies [11] were used and the interrelationship of parameters α of the wetting and drainage branches of the retention curve was evaluated. The measurement results show the conversion relationship $\alpha^w = 1.1\alpha^d$ for the capillary block and $\alpha^w = 1.4\alpha^d$ for the capillary layer. Furthermore, the above-cited relationship $\alpha^w = 2\alpha^d$ according to Scott et al. was examined [14].

The input parameters of the numerical models for the drainage and wetting branches of the retention curves of the studied capillary barrier materials are summarized in *Tab 1*.

To obtain the parameters α^w and n^w from the known parameters α^d and n^d, we therefore chose the simplification $n^d = n^w$ proposed in the study by Dohnal et al. [24], where its sufficient accuracy is confirmed by comparing numerical simulations with experimental measurements. It follows from the given data that only the values of parameter α for the wetting branch of the retention curve were changed. Variant No. 1 corresponds to the use of the relationship $\alpha^w = 2\alpha^d$ according to [14]. For variant No. 2, the conversion relationship $\alpha^w = 1.4\alpha^d$ was used for both the capillary layer and the block. In variant No. 3, the relationships $\alpha^w = 1.4\alpha^d$ for the capillary layer and $\alpha^w = 1.1\alpha^d$ for the capillary block were considered. The retention curves of the studied materials corresponding to the aforementioned variants of parameter α^w of the capillary layer and the capillary block of the barrier are shown in *Figs. 2* and *3*. The differences between the drainage and wetting branches are visible in them.

For comparison, *Fig. 4* shows the wetting branches of the capillary block retention curve according to the change in parameter α^w.

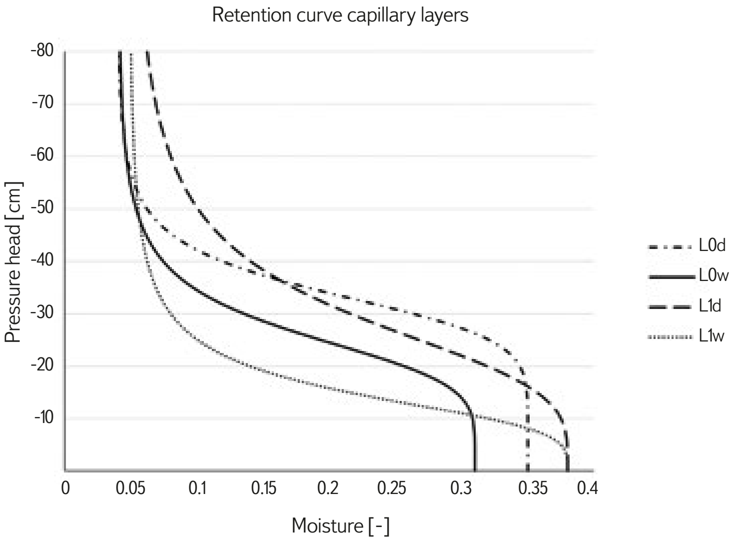

Fig. 2. Main drainage and main wetting branches of the retention curve of real (L_0) and composed (L_1) capillary-layer materials

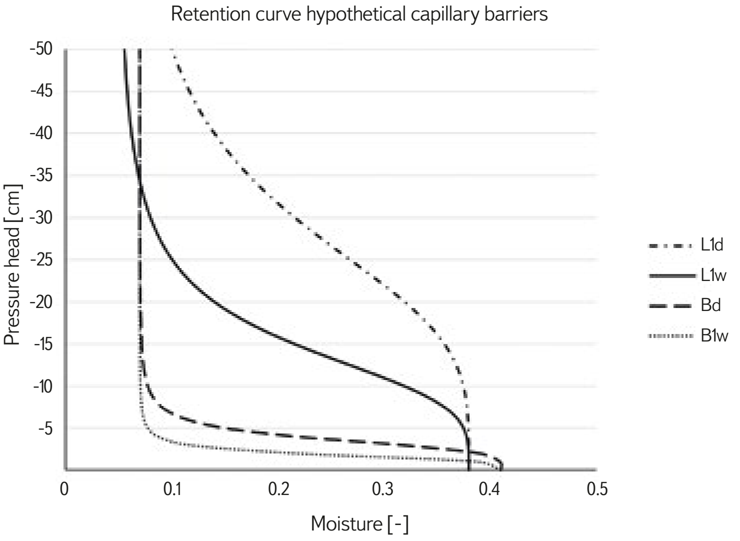

Fig. 3. Retention curve hysteresis of capillary layer and capillary block of the hypothetical capillary barrier. Curves L1d and Bd represent the drainage branch of the retention curves of the capillary layer and the capillary block; L1w and B1w depict the wetting branch of the retention curves of the capillary layer and the capillary block

Tab. 1. Parameters of the tested materials

	Ks [m/s]	Θr	θs^d	θs^w	α^d [cm^{-1}]	α^w [cm^{-1}]	n^d	n^w
L_0	1.18E-04	0.04	0.35	0.31	0.03	0.04	7.39	5.24
B_0	2.25E-03	0.07	0.41	0.41	0.29	0.32	4.56	4.17
L_1	1.18E-04	0.048	0.38	0.38	0.037	0.074	3.89	3.89
B_1	2.25E-03	0.07	0.41	0.41	0.29	0.58	4.56	4.56
L_2	1.18E-04	0.048	0.38	0.38	0.037	0.052	3.89	3.89
B_2	2.25E-03	0.07	0.41	0.41	0.29	0.406	4.56	4.56
L_3	1.18E-04	0.048	0.38	0.38	0.037	0.052	3.89	3.89
B_3	2.25E-03	0.07	0.41	0.41	0.29	0.32	4.56	4.56

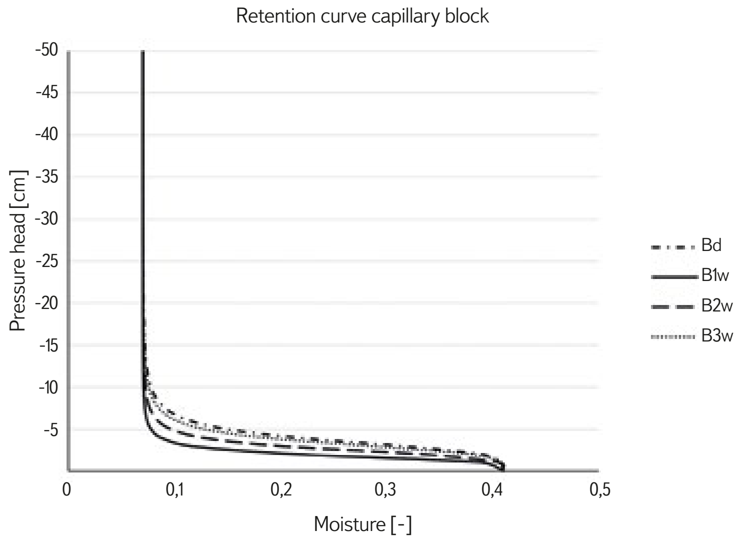

Fig. 4. Capillary block retention curves with different values for parameter α^w. Comparison of the capillary block retention curves for draining branch BD and the three variants B1w, B2w and B3w of the wetting branch reflecting the changes in the parameter α_w

Influence of parameter α on models of capillary barriers

We can consider parameter α as a decisive factor in expressing change in the retention curve when changing the process from drying to wetting and vice versa. Experimentally measured data of the main wetting branches of materials B_0 and L_0 [1] made it possible to determine the parameters of these main wetting branches using the RETC program. In addition to the closed air effect, changes were recorded not only in parameter α, but also in parameter n, compared to the corresponding main drainage branch. However, this could be due to the fact that the main drainage branch was not considered. Research on processes in which the direction of moisture change repeatedly altered [24] shows that the mathematical model including hysteresis using parameters α^d, α^w and n^d gives a sufficiently accurate simulation of processes involving both directions of moisture change.

As we focused on the influence of the choice of parameter α^w on the efficiency of the capillary barrier, we worked with numerical models of several variants of this choice. Mathematical models were formulated in two spatial variables (in a vertical section guided by the barrier fall line). The S2D_dual program [32] was used for the calculations, which solves the capacitance form of the Richards equation using the finite element method. With the help of numerical models, it was possible to follow the development of irrigation in space and time depending on the changing parameters. A capillary barrier model with basic values of hydromechanical characteristics was built. The initial pressure head was set to -40 cm [1]. Boundary conditions vary depending on the boundary location. At the point of infiltration, a Neumann boundary condition corresponding to a linearly increasing value of irrigation was set, thanks to which it was possible to compare individual versions of the models and to evaluate the time of breaking the capillary barrier affected by the changing parameters. Outflow from the capillary barrier was modelled using the Seepage face boundary condition at the drainage points of the capillary barrier. A zero Neumann boundary condition was set at the remaining edge of the modelled area, which is represented by an impermeable boundary. The boundary conditions are shown in *Fig. 5*.

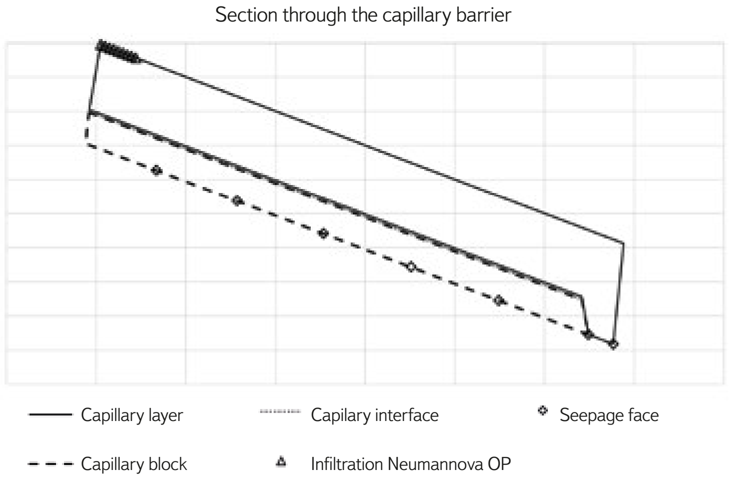

Fig. 5. Section through the capillary barrier with marked boundary conditions for infiltration corresponding to the non-zero Neumann boundary condition and drainage from the capillary block as a Seepage face boundary condition. The remaining part of the boundary is the zero Neumann boundary condition. The length of the capillary barrier is 6 m and the height is 60 cm

Irrigation was identical for all calculated variants so that the outputs could be compared. The drainage and wetting branches of the retention curve were modelled as separate versions of the models with different input parameters. It was therefore possible to evaluate and verify the influence of hysteresis and

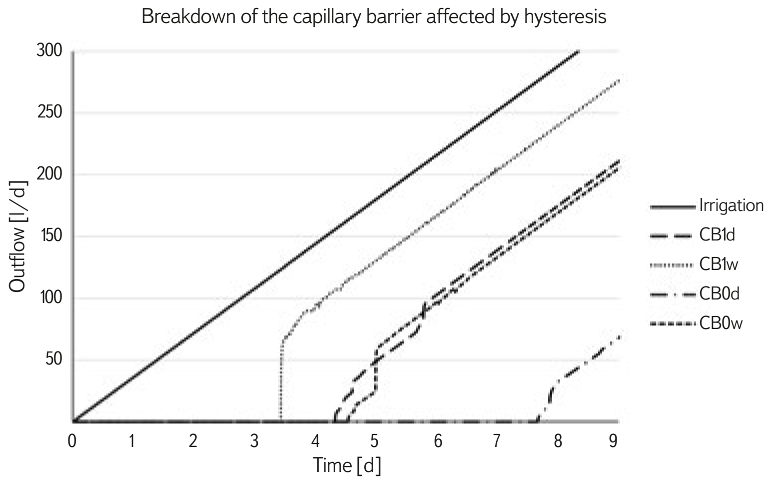

Fig. 6. Capillary barrier efficiency affected by hysteresis. The graph shows linearly increasing irrigation (the same for all simulations), outflow from capillary block CB0d and CB0w for the drainage and wetting branch of the default capillary barrier retention curve, and CB1d and CB1w for the drainage and wetting branch of the retention curve of variant 1 of the hypothetical capillary barrier according to Scott et al. [14]

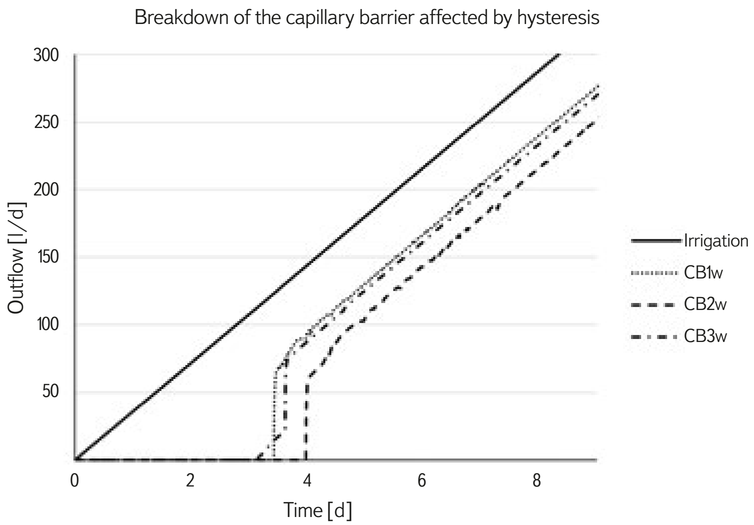

Fig. 7. Capillary barrier efficiency depending on the choice of parameter α^w of the retention curve wetting branch. Irrigation in the chart shows a linearly increasing intensity of irrigation; wetting curves 1, 2, and 3 correspond to the outflow from the capillary block for three variants of calculation α^w of the wetting branch retention curve

the choice of parameter α^w on the functioning of capillary barriers in all modelled variants (*Fig. 6*).

In addition to the basic variant of the capillary barrier model for the drainage branches of the retention curve, three variants were modelled for the wetting branches of the retention curve. The calculation variants for different wetting branches are based on the changing parameter α^w of the wetting branch of the capillary layer retention curve, possibly also of the block. The results are shown in *Fig. 7*.

DISCUSSION AND CONCLUSION

In this study, we compared the efficiency of several capillary barriers that differed in the capillary layer determined by the tested choices of parameter α. Since the results of experimental tests are available for the starting material, we were able to confirm that the mathematical model of the barrier gives sufficiently accurate results even when using the main wetting branch alone. Comparison with experimental results further showed that, in the case of barrier efficiency, one cannot neglect hysteresis and only work with the capillary barrier drainage branch. Previous experiments [11, 28] were thus confirmed.

A series of tests focused on derivation of the main wetting branch in known (i.e. measured) parameters of the main drainage branch showed that determination of the α^w parameter plays an important role in this step, and that it is even possible, as suggested by the cited publications, to keep parameters θ_r^d, n^d, possibly also θ_s^d, and define the main drainage branch only with a suitably determined parameter α^w. It transpires that the initially proposed (and in some cases proven) choice $\alpha^w = 2\alpha^d$ may not be the best solution. In the case of the initial barrier B^0, L^0, it is obvious that parameter α^w chosen in this way could lead to underestimating the barrier efficiency.

It is evident from the results that the most accurate determination of the retention curve parameters plays an essential role in determining capillary barrier efficiency. If we have two physically existing materials, a capillary block and a capillary layer, and we want to determine the effectiveness of the capillary barrier created by them, then we can rely on a test performed by a mathematical model. In this case, the parameters of the main drainage branch are sufficient for the capillary block. For the capillary layer, due to the sensitivity of the result to the value of parameter α^w, it is advisable to determine the parameters of the main wetting branch by measurement. If we only have the parameters of the main drainage branch at our disposal, it is appropriate to use a model of the main wetting branch based on changing only parameter α. The results of this study show that in such a case, a suitable value for α^w should be chosen in the interval $1.1\,\alpha^d \le \alpha^w \le \alpha^d$.

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Old groundwater in hydrogeological regions 4410 and 4522

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Keywords: groundwater — Bohemian Cretaceous basin — source of drinking water — dating —tritium — quantification of water sources — protection of surface water and groundwater — conceptual model

ABSTRACT

The article presents a project from the Technology Agency of the Czech Republic dealing with the hydrogeology of old waters in hydrogeological regions 4410 and 4522. The aim of the paper is to present a brief hydrogeological characterization of the area of interest, to present the results after the first year of the project, and to describe the uncertainties of existing information. Old groundwaters that have negligible concentrations of tritium can be considered a strategic resource because they are less susceptible to current contamination. In order to quantify the usable amount of these waters, discharge from springs with low tritium concentrations is measured regularly. At the same time, water samples have been taken from the most important water supply facilities in the area. The chemical composition and tritium activity of these waters have been determined and physico-chemical parameters measured. On the basis of known groundwater level patterns, lithology and measured values, a conceptual model of the flow pattern of this old water was outlined, which will be further verified and supplemented during the project using the newly acquired knowledge. Due to the relatively low electrical conductivity of the old groundwater, it is expected that the water would have infiltrated in areas where there are no outcrops of calcareous sandstones, as bicarbonates would increase the conductivity significantly. For this reason, we assume that the water infiltrates near Bezděz, where there are outcrops of quartz sandstone. From there, the water flows to springs and water collecting facilities, where, especially in the lower parts closer to the drainage areas (the Jizera and Elbe rivers), it can be further mixed with outflow from the Cenomanian aquifer. Nevertheless, there are places in the area that are not fully consistent with this assumption, and the origin of these groundwaters is also the subject of further research. The next phase of the project will focus on a detailed analysis of the age of the waters using other tracers, such as CFC or SF_6. This information will lead to a better understanding of groundwater flow in the most important hydrogeological structure in the Czech Republic.

INTRODUCTION

The Czech Republic is relatively rich in groundwater resources. Most of the collected water has a short circulation time (typically just a few decades). In the event of a potential large-scale catastrophic event, these shallow water supply resources cannot be used to supply drinking or commercial water.

Fossil waters, cut off from the current hydrologic cycle, are usually of low quality and limited supply because they are not recharged. However, in part of the Czech Cretaceous Basin there are also actively flowing waters with a residence time of at least 70 years and in some cases significantly more, as described in the project *"Rebilance zásob podzemních vod (Rebalancing of groundwater supplies)"* [1, 2]. We continue to call these waters with a relatively longer mean residence time "old waters" in the paper. Namely, there are two Cretaceous hydrogeological regions (HGR): HGR 4410 Cretaceous of the Jizera river, right-bank part; and HGR 4522 Cretaceous of the Liběchovka and Pšovka streams.

This article describes the study of hydrogeological issues of these parts of the Czech Cretaceous Basin as part of project No. SS06010268 *"Poznání, kvantifikace a ochrana strategických zdrojů podzemní vody české křídové pánve hlubokého oběhu v hydrogeologických rajonech 4410 a 4522 (Identification, quantification and protection of strategic deep-flow groundwater resources in the Bohemian Cretaceous Basin, in hydrogeological regions 4410 and 4522)"*.

As part of the project, the area will be described in detail from a hydrogeological point of view. There is a relatively small amount of information about these waters – often expert estimates that need to be verified. Although it is a significant accumulation of high-quality groundwater (the area includes, for example, the important water supply facilities of Řepín and Bělá), the tritium analyses so far only come from a few springs. Uncertainties also surround the usable amount of these waters and the place of their infiltration. The aim of the project is to remove and resolve these uncertainties. In the current phase, available literature and data sources are collected about the area of interest, and field data collection and sampling are being carried out for hydrochemical and tritium groundwater analyses (already underway or completed). The aim of the article is to provide a brief hydrogeological description of the area of interest based on a literature search, to present partial results from discharge measurement and sampling and to describe the current uncertainties of existing information.

AREA DESCRIPTION AND METHODOLOGY

In order to obtain a comprehensive picture of the current state of knowledge about the area of interest, available relevant information sources have been collected. These are stratigraphic correlation sections, hydraulic models of groundwater flow, hydrochemical analyses, and groundwater dating results. In the research part, we present the basic concept of groundwater flow formulated in the previous project *"Rebilance zásob podzemních vod (Rebalancing of groundwater supplies)"* [1, 2], which will subsequently be verified, critically evaluated, supplemented, or changed as part of the project – with the use of newly acquired data and knowledge.

On the basis of a literature search, archival data of tritium analyses [1–3] and thermometry measurements [4], objects of interest (springs, boreholes) were selected for sampling and monitoring (hydrochemical analyses, dating techniques, discharge).

Basic geological and hydrogeological characteristics of the area of interest

This section describes the basic geology and hydrogeology of the area of interest (*Fig. 1*). The area falls partly into HGR 4410 (Cretaceous of the Jizera river, right-bank part), which forms a transitional facies between the mostly sandy development WNW of the Jizera and the predominantly clayey development ESE of the Jizera. There is a significant occurrence of calcareous and quartz sandstones of the Middle to Upper Turonian of the Jizera Formation [5, 6]. The second HGR in the area is 4522 (Cretaceous of the Liběchovka and Pšovka streams), which is also the most hydrogeologically significant aquifer of the Jizera Formation, which thickens upwards from calcareous siltstones and marlstones to coarse-grained quartz sandstones with conglomerates [2]. The third HGR in the area is 4720 Cretaceous basal aquifer between Hamr and the Elbe river valley. From a hydrogeological point of view, however, it does not have to be an isolated region and outflow can occur from the upper regions to the lower region and vice versa through aquitard or aquicludes [7].

Fig. 1. Map of the area of interest showing the two hydrogeological regions (red borders). The map shows the cross sections (thin black lines) depicted in *Figs. 5* and *6*. Adapted from mapy.geology.cz

In the area of interest, the Peruc–Korycany Formation, Bílá Hora, Jizera, Teplice Formations and Rohatec Strata are divided from lithostratigraphic point of view (from the oldest), ranging in age from the Cenomanian to the Coniacian. Younger Cretaceous assemblages have not been preserved. The stratigraphy of the area of interest in HGR 4410 in a section from NW (Bezděz) to SE (Mladá Boleslav, Jizera) is clearly shown in *Fig. 2*, which shows the stratigraphic scheme according to lithostratigraphy (formation), chronostratigraphy (age), and genetic stratigraphy [8]. In *Fig. 2*, aquifers A (Cenomanian) and C (Turonian) are also defined, with a division into sub- aquifers Ca and Cb (in some studies, sub-aquifer Cc is also mentioned [1, 4]). The stratigraphy in HGR 4522 is clearly shown by the section from S to N in *Fig. 3*.

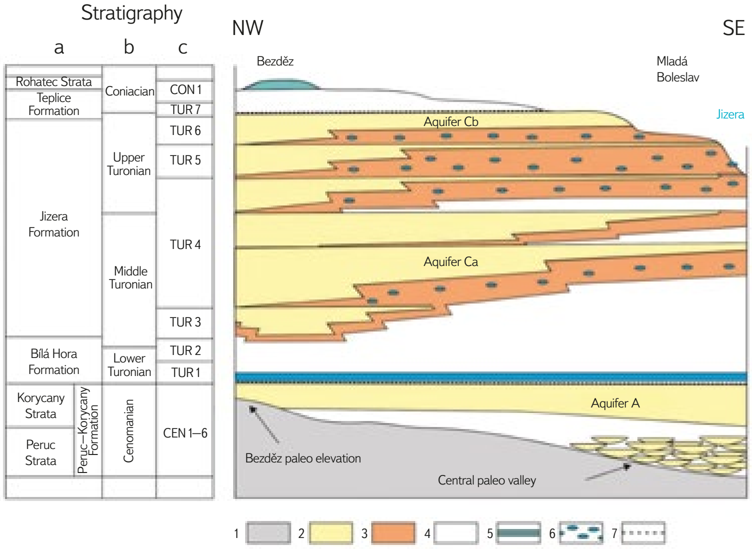

Fig. 2. Stratigraphy and aquifers of regions 4410. 1 – Cretaceous bedrock; 2 – Quartz sandstone; 3 – Calcareous sandstone; 4 – Marlstone, siltstone, claystone; 5 – Micrite limestone; 6 – Concretion limestone; 7 – Glauconite-phosphate horizon; a – lithostratigraphy [9]; b – chronostratigraphy; c – genetic stratigraphy [8]. Modified after [1]

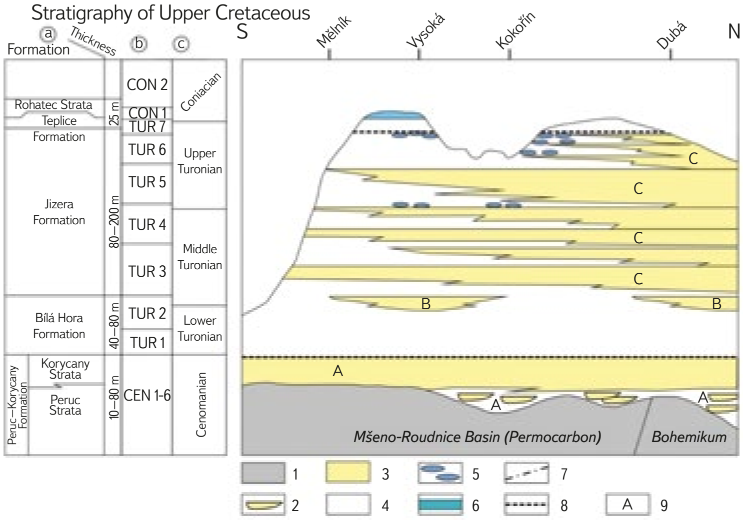

Fig. 3. Stratigraphy and aquifers of region 4522. 1 – Cretaceous bedrock; 2 – Fluvial channel sandstone; 3 – Sandstone; 4 – Marlstone, siltstone, claystone; 5 – Limestone; 6 – Silicified claystones; 7 – Tectonic zones; 8 – Glauconite-phosphate horizon; 9 – Aquifers; a – lithostratigraphy [9]; b – genetic stratigraphy [8]; c – chronostratigraphy. Modified after [2]

The Peruc–Korycany Formation (Middle to Upper Cenomanian) is not lithologically homogeneous and represents clastic sediments of fluvial, estuarine, and marine sedimentation regimes. From a hydrogeological point of view, marine quartz sandstones are important, which form here a basal aquifer referred to as A. It is mostly a confined aquifer that comes to the surface only in a narrow strip along the Lusatian fault. Water infiltrates into it either directly through surface rock outcrops, or through outflow from upper aquifers. The general direction of water flow is from the Lusatian fault SSW to the Elbe, where the water drains. The thickness of the formation is variable; around Bezděz, it is 10–15 m, and increases towards the N and SE.

The Bílá Hora Formation (Lower to Middle Turonian, genetic stratigraphy TUR1 and TUR2) was defined as a pelitic interval (marlstone, silty marlstone, calcareous claystone) in HGR 4410 with a thickness of 80–120 m as part of the project *"Rebilance zásob podzemních vod (Rebalancing of groundwater supplies)"*. The pelites are interpreted as a hydrogeological aquitard A/C [9]. In HGR 4522, the Bílá Hora Formation consists mainly of marlstone, in N calcareous siltstones to siltstones; it outcrops to the surface only in the Liběchovka valley in the NW of HGR 4522 [2].

The boundary between the Bílá Hora and overlying Jizera Formations is conventionally placed at the level of the first occurrence of calcareous sandstones with positions of concretionary limestones. The Jizera Formation (Middle to Upper Turonian, TUR3 to TUR6) is developed in the area of interest mainly in quartz sandstones and clayey-calcareous sandstones; it is the most widespread and represents a very important aquifer referred to as aquifer C. However, it is relatively split and forms several progradation cycles TUR3 to TUR6, divided into sub-aquifers Ca, Cb, Cc [8]. This splitting is more evident in the E, while on the W of HGR 4410, the Jizera Formation is formed throughout its thickness almost exclusively by quartz sandstones of aquifer C (*Fig. 2*). On the border with HGR 4521 (in the SW area), in the lower part of aquifer C (below TUR3), in HGR 4410, an anomalous development of two to three sharply limited layers of coarse-grained sandstones with a thickness of 10–30 m occurs, which increases the total thickness of the aquifer by up to 50 m. This is a unique phenomenon within the entire basin. The TUR5 base has elevated carbonate contents and forms a regional aquitard within aquifer C, with perched aquifers forming in places above the aquitard. The total thickness of the Jizera Formation in the SW part of HGR 4410 is around 200 m, it gradually decreases to the NNE. In HGR 4522, in the lower 80 m there is a Jizera Formation in aleuropelitic development referred to as aquitard A/C; towards the north, this thickness decreases to 10 m, and gradually the thickness of quartz sandstones increases. In the spring area of Liběchovka, the thickness of the Jizera Formation is 170 m [2].

The Teplice Formation (Upper Turonian to Coniacian) in isolated occurrences overlies the Jizera Formation in relics near Bukovno, Bezděz, and Bakov nad Jizerou. In HGR 4410, they form dark grey calcareous claystones up to 25 m thick. In the upper Pojizeří, no Rohatec Strata have been recorded; in the vicinity of Bezděz there are clayey sediments referred to as the Teplice and Březno Formations undivided. In HGR 4522, the Teplice Formation consists of very limited siltstone and calcareous siltstone relics.

Tectonic deformation of the area is minimal, with the exception of the N part near the Lusatian fault. In general, the Cretaceous layers are affected by by NW-SE, NNE-SSW to NE-SW fault systems. In the area south of Dubá and in the vicinity of Houska, there is probably a fault break into several separate blocks. The western part of HGR 4410 is deposited almost sub-horizontally, towards the E with a transition to a Cretaceous block slightly tilted to the E and SE. Isolated bodies of alkaline volcanics penetrate through the sediments, e.g. Malý and Velký Bezděz.

There are two important aquifers in the area of interest: aquifer A (Peruc–Korycany Formation) and aquifer C (Jizera Formation, divided into Ca, Cb, Cc). Locally, in the valley of the Strenický stream, there is also aquifer BC, passing laterally into the aquitard.

From a water management point of view, the most important aquifer is C, connected to the sandstone of the Jizera Formation, covering almost the entire area of HGR 4410, with the exception of its NW and S edges. The water-bearing capacity of aquifer C is highest in the W part (170–190 m) and decreases towards the edges of HGR 4410. The permeability of the aquifer is provided by both pores and fissures, and it generally decreases towards E [1].

However, based on current knowledge, the mere division into aquifer A and C and aquitard B may be too simplistic [8]. For example, in the eastern part of HGR 4410, aquifer C is actually divided by siltstones and limestones into at least two to three sub-aquifers (Ca, Cb, Cc [1, 8]), while the basal artesian sub-aquifer Ca is in contact with the surface only by boreholes or insignificant leaks in the confining layer, while the middle sub-aquifer Cb has an open surface and drains to surface watercourses. Sub-aquifer Cc has discontinuous water-bearing and is a perched aquifer. This rather complex situation is manifested, for example, by the fact that on the right bank of the Jizera there is a different groundwater level depending on the depth of the boreholes, although in all cases it is "aquifer C". Shallow boreholes (up to 50 m) up to the sequence TUR5 and TUR6 (sub-aquifer Cb) have levels close to the surface, connected to the Quaternary aquifer of the Jizera terraces. In contrast, deep boreholes (100–150 m) into TUR4 (sub-aquifer Ca) show levels 5–7 m above shallow boreholes. Although the majority of the groundwater circulation is probably linked to aquifer Cb, in the southern part of HGR 4410 the flow is significant only in TUR4 [1]. This considerable spatial variability must therefore be considered and distinguished when we speak of "aquifer C". In addition, the schematic geological sections in *Figs. 2* and *3* indicate that aquifer C is divided into 5–7 sandstone layers, so these sub-aquifers may often be even more than three.

According to archival tritium analyses [1–3], waters with low tritium activity can be found mainly in the southern part of HGR 4410 (south of Bělá), both in springs and in boreholes. Springs in the Strenický stream basin had values below 2 TU, with boreholes below 1 TU. In the Bělá basin, low values of tritium were detected in the vicinity of the Bělá paper mills (2.7 TU), Mukařov, and Mnichovo Hradiště (below 4 TU). Based on these values (considering the time of measurement around 2014 and the gradual decay of tritium), these objects of interest have a mixture of new water and water which infiltrated before 1950. In general, these objects of interest are mainly in the Strenický stream basin (total discharge about 150 l/s) and Bělá (about 50 l/s). Conversely, higher values of tritium activity (5–7 TU) are common for springs in the N and W parts of the district, but also occur in the Bělá basin.

In HGR 4522 in the Liběchovka basin, according to archival analyses, tritium activity was very variable (from 0.9 to 9.2 TU) but unrelated to the position in the basin. In the vicinity of Nedamov, on the upper Liběchovka, low tritium activity was detected in springs (below 4 TU). A spring with a lower value of tritium activity is also located in the lower Liběchovka in Liběchov (Boží voda). In the upper part of the Pšovka basin, tritium activity in springs was around 4–6 TU. However, Stříbrník spring had low tritium activity (> 10 l/s; 2.8 TU). Some collection boreholes in the upper part of Řepínský důl had lower activity as well [2, 3]. In this district, some objects of interest showed a considerable mean residence time, with the predominance of water which infiltrated before 1950. According to archival isolated analyses using other environmental tracers (radiocarbon, CFCs, SF_6), the average residence time of waters in the area of the upper Liběchovka and Pšovka ranges from tens of years to over 100 years. The total discharge of long-circulating water in the entire area of interest was estimated to be at least 250 l/s [2].

Measurement of physico-chemical parameters and sampling for tritium analyses

In order to verify discharge of the old waters, 11 samples were taken for tritium analysis in 2023 from the monitored profiles at the springs, Strenický stream, and from other springs. In 2024, the largest catchment areas were sampled. In cooperation with VaK Mladá Boleslav, all collection boreholes with a higher discharge in the Bělá basin (11 samples) were taken. These boreholes take in a total of about 140 l/s and at least part of the water is probably old water due to the low mineralization and exceptionally good quality. In cooperation with Kladno – Mělník Waterworks, all active boreholes in the Řepínský důl catchment area (41 samples) were sampled. Total discharge is around 300 l/s, and older studies show that in some objects of interest it could be old water [1, 2]. For all sampled objects of interest, physico-chemical parameters of the water were measured in the field in a flow cell without contact with the atmosphere – conductivity, temperature, pH, oxidation-reduction potential, and dissolved oxygen concentration. The chemical composition of part of the samples was analysed. Samples for tritium activity are currently being analysed. The monitored objects of interest are shown in *Fig. 4*.

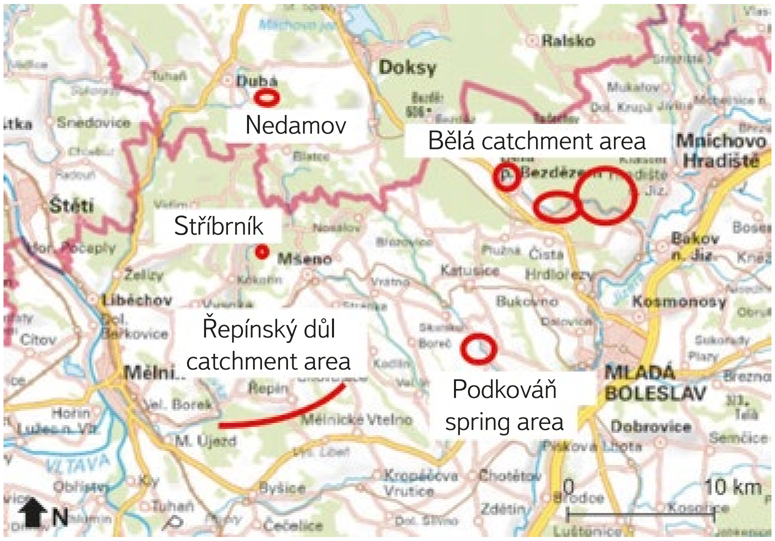

Fig. 4. Map of monitored sites (Based on cuzk.cz)

Discharge measurement

During the first six months of the project, ten locations for discharge monitoring were selected on the basis of archival data on tritium concentrations. These locations represent springs with low tritium activity, and are therefore older, and two profiles on the Strenický stream, which define an intermediate section recharged exclusively by springs with low tritium activity. Discharge was measured at roughly monthly intervals, either by the dilution method using NaCl with automatic recording of conductivity from the used WTW conductometers, or by calculation from the filling time of a vessel of a known volume. The first monitoring location is on the Strenický stream in Krnsko before the confluence with the Jizera. Strenický stream is mostly recharged by baseflow from the deeper zones of aquifer C, or B, and its flow is relatively constant over time. It is the main stream draining the area with springs with lengthy mean residence time based on older tritium activity analyses. During monitoring, discharge is measured using the dilution method with NaCl.

The second location is the Strenický stream near the village of Cetno, which is located above two springs with a low concentration of tritium. Here, discharge is measured using the dilution method. The third location is the outlet from the waterworks near the village of Cetno. According to previous analyses, this water also has low tritium activity. The flow here is measured by the dilution method. The fourth location is spring PP0230, currently monitored by CHMI in the village of Podkováň. This spring is one of the abundant sources at the Podkováň spring area with low tritium activity. Spring area discharge reaches 100 l/s at higher levels. Discharge here is calculated from the time it takes to fill a container of a known volume. The fifth location is the Strenický stream above Podkováň spring area. Knowing the flow of the Strenický stream above and below the spring areas (the difference in discharge from locations 1 and 5), it is possible to determine the total discharge of waters with a low concentration of tritium in the Strenický stream. Here, discharge is measured using the dilution method. The sixth location is Velký spring in Podkováň spring area. It is the most abundant resource in the spring area. There is a historical CHMI measuring weir (monitored in the past as PP00229) which, however, is no longer monitored by the CHMI. As part of the project, discharge here is measured using the dilution method.

The seventh site is located by the Rokytka watercourse near Bělá pod Bezdězem. It is an area with an abundance of springs, one of which – the Klokočka – has very low tritium activity. Discharge here is calculated from the time it takes to fill a container of a known volume. The eighth location is a small spring with a low tritium content near the village of Nedamov on the upper Liběchovka. Here, discharge is also calculated from the filling time of a vessel of a known volume. The ninth location is a spring watercourse with a low tritium content near the village of Nedamov, on the upper Liběchovka. The flow rate is measured by dilution method. The tenth site is Stříbrník spring near Vojtěchov in Kokořínský důl near the Pšovka, which is partly collected for drinking water. Here, discharge at the spring outflow is calculated from the time it takes to fill a container of a known volume; the amount of water collected must be added to it.

RESULTS

Research description of current groundwater flow

In this research section, we describe current groundwater flow in the area of interest, based on available information sources. Using new data, this conceptual model of flow will be critically evaluated within the project "Identification, quantification and protection of strategic deep-flow groundwater resources in the Bohemian Cretaceous Basin, in hydrogeological regions 4410 and 4522".

The investigated districts were described in detail within the projects *"Hydrogeologická syntéza české křídové pánve (Hydrogeological synthesis of the Czech Cretaceous Basin)"* [10] and *"Rebilance zásob podzemních vod (Rebalancing of groundwater supplies)" [1, 2]*. On their basis, areas of unconfined aquifers in the entire area of interest can be designated as areas of groundwater recharge. However, the highest groundwater recharge in HGR 4410 occurs in the upper parts of the basin in the N or NW part of the district, where baseflow is also higher than in the southern parts. The groundwater flow is subsequently determined by the flow of the Jizera with the influence of environmental inhomogeneities and groundwater collection. For aquifer A, infiltration is only in the N along the Lusatian fault; drainage occurs along the Elbe. Aquifer C drains into the river network (*Fig. 5*); only the area of the Jizera mainly to the south in the area of Sojovice and Čachovice can be considered as completely draining. Furthermore, drainage takes place in the valleys of the Zábrdka, Mohelka, Malá Mohelka, Rokytka, Bělá, and Strenický stream. Partial drainage is due to frequent and abundant fracture springs, especially at the intersection of faults in two directions or faults crossing the Jizera valley and its tributaries [11, 1].

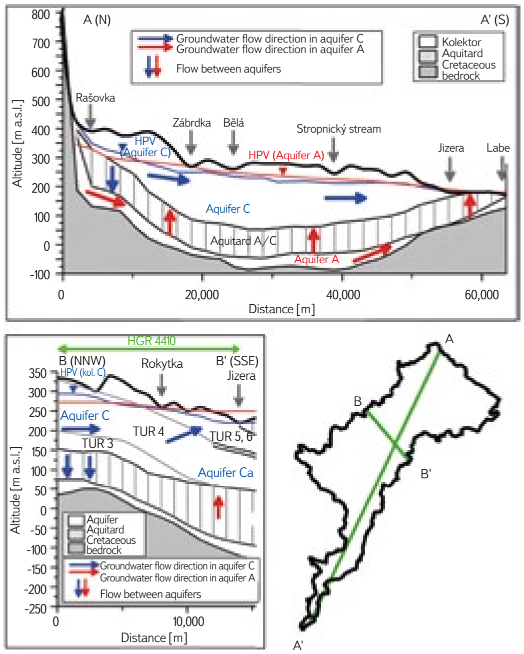

Fig. 5. Groundwater flow in region 4410; cross section N-S (top) and NNW-SSE (bottom left) with line markings of both cross sections (bottom right). Modified after [1]

In HGR 4522, there is a recharge of groundwater in the entire area; the dominant infiltration is in the N to NE of the district. Groundwater continues to flow towards the SW; in the eastern part of the district, groundwater flows from neighbouring region 4521 (169 l/s of groundwater flows in and 83 l/s flows out from region 4522 [2]). Groundwater drainage takes place in the lower part of the Pšovka, at the Liběchovka, and via the Elbe through Quaternary gravelly sands [2; *Fig. 6*]. From NE to SW, the thickness of aquifer C [2] is reduced in HGR 4522, which results in a large discharge increase in the lower parts of the Liběchovka stream and numerous springs. In various places of the upper reaches of the Pšovka and Liběchovka, important springs also occur. This indicates the inflow of old waters collected in Řepínský důl from the NE.

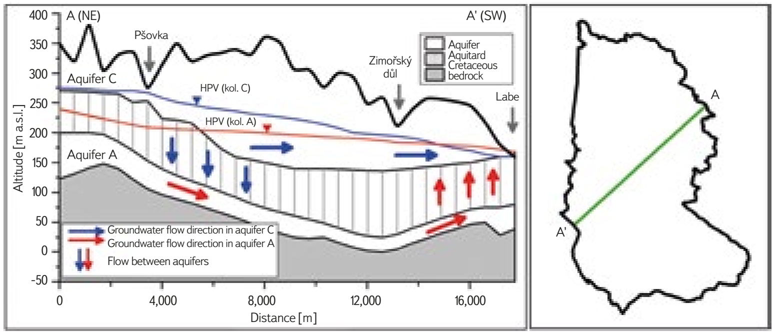

Fig. 6. Groundwater flow in region 4522; cross section NE-SW. Modified after [2]

The maximum permeability of the rocks in the area of the drainage bases, and the lowest is in the inter-river areas, where the aquifers are at their thickest. This indicates the important role of fracture systems in this area; permeability is most affected by the crossing of fracture belts in the NW-SE and NNE-SSW directions [1]. Springs often rise at these crossings, such as in the Bělá valley.

In the NW of HGR 4410, permeability provided dominantly by fractures prevails, however with a significant proportion of permeability given by pores; towards the S, the proportion of pores' permeability decreases due to the transition to calcareous claystone, marlstone, and calcareous sandstones.

Between Košátecký stream and Bělá pod Bezdězem, where aquifer C occurs with quartz sandstones up to 80 m thick, the permeability of aquifer C provided by pores and fractures. In areas without quartz sandstones, the permeability of aquifer C is almost exclusively provided by fractures, with high transmissivity (e.g., in the Bělá basin with the catchment area for Mladá Boleslav), indicating a large influence of fissures on the flow. In the higher areas between the Pšovka and Liběchovka, perched aquifers are formed [2], which are seen as springs and wells (e.g. Nedvězí).

Discharge measurement

The results of the measurements of the Strenický stream area are shown in *Fig. 7*. Although it is a relatively short monitored period, it can be seen that discharge is relatively constant over time (fluctuations less than 1 : 2), which means that the springs do not react to precipitation. This suggests a longer water cycle, which is consistent with the previous claim that these are old waters [1]. Monitoring spring discharge is essential for quantifying the dynamic resources of these old waters. So far, this discharge has not been monitored on most of the mentioned profiles.

Discharge at the first location on the Strenický stream in Krnsko ranges from 58 to 85 l/s. This is relatively low compared to archival measurements which show discharge of over 100 l/s. The Strenický stream near the village of Cetno has discharge ranging from 49 to 86 l/s. Discharge from the waterworks near the village of Cetno is 5 to 9 l/s. Kovánecký spring has a discharge from 6 to 8 l/s. The Strenický stream above Podkováň spring area has discharge of only between 2 and 5 l/s, while Velký spring is from 22 to 28 l/s. It is evident that most of the water in the Strenický stream comes from Podkováň spring area. Discharge of old water in this area is approximately 65 l/s.

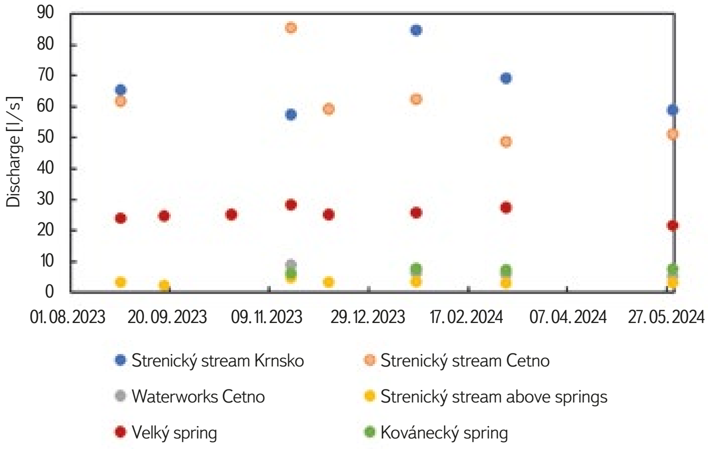

Fig. 7. Discharge measurement in the Strenický stream catchment

Results of discharge measurements from the surroundings of the Rokytka and Kokořínsko can be seen in *Fig. 8*: discharge from Klokočka spring is around 1.5 l/s; the spring watercourse near the village of Nedamov reaches 14 to 26 l/s; the spring in the village of Nedamov is from 0.5 to 2 l/s; and discharge from Stříbrník spring is around 1 l/s.

Tab. 1. Chemical properties of sampled sites. The order of the sites in each catchment area is arranged from lowermost to uppermost altitude. Q is abstraction from wells for water supply; for Klokočka spring it is average discharge

	Conductivity [µS/cm]	T [°C]	O_2 [mg/l]	pH	Redox [mV]	Q [l/s]
Bělá						
KL 4	480	10.3	0.6	7.2	-9	12
KL 1a	447	11.2	0.4	7.3	5	13
KL 16	425	10.8	1.4	7.3	182	20
KL 12	482	10.3	1.5	7.2	119	30
KL 11	507	9.9	1.1	7.2	200	30
KL 10	636	10.3	0.4	7.2	21	25
VMB1	477	9.4	3.1	7.3	293	
KL 7	439	10.5	2.1	7.3	52	28
KL 8	495	9.6	4.2	7.2	63	24
KL 3	579	9.3	2.7	7.2	49	~1
KL 9	477	10.9	2.1	7.2	21	~2
Klokočka spring	464	9.2	4.3	7.2	221	1.5
Řepínský důl						
PŠ2	728	10.5	2.1	7.2	87	16
PŠ3	778	10.7	0.2	7.2	-143	
PŠ3A	744	10.8	0.3	7.2	36	7
DV1	695	10.6	2.5	7.2	94	26
DV2	699	9.9	2.2	7.2	137	7
DV14	684	10.5	2.2	7.3	135	12
PŠ5	683	10.4	3.7	7.3	147	54
PŠ5A	687	10.5	3.0	7.3	151	11
DV13	754	9.7	1.3	7.2	292	
S9	686	9.2	0.3	7.2	29	
S10	680	10.3	2.6	7.1	104	12
S4	707	10.6	3.5	7.2	104	41
S1	708	10.5	5.4	7.2	102	20
Ř2 (west)	703	10.6	4.0	7.2	194	31
Ř2 (west)	694	10.5	1.8	7.2	134	14
S11	717	10.4	4.2	7.2	105	14
S13	759	10.2	3.2	7.2	70	12
S14	803	10.1	2.8	7.2	95	7
S15	837	10.3	2.6	7.1	70	9
S16	844	10.5	3.4	7.1	40	3
S25	769	10.5	1.7	7.2	48	3
S26	751	10.2	2.0	7.1	74	4
S27	728	10.7	0.5	7.2	2	2
DV15	710	11.1	0.1	7.2	-40	8
S28	685	10.7	0.1	7.2	5	5
S29	649	10.3	0.2	7.2	27	13
S30	640	10.4	0.5	7.1	5	8
Ř8A	550	10.4	0.1	7.2	-17	18
Ř8	643	10.7	1.3	7.1	69	3
S20	621	10.3	1.0	7.2	36	16
S21	620	10.2	2.0	7.2	26	
S22	599	10.1	1.2	7.2	40	5
S23	646	10.0	1.4	7.3	31	3
DV17	573	10.3	0.6	7.3	36	9
S7	571	10.3	0.4	7.2	-78	3
S19	498	11.0	0.1	7.2	-83	3
DV5	603	10.5	1.2	7.2	4	6
S8	551	10.6	1.0	7.3	-31	3
DV6	618	10.4	1.3	7.2	0	
Z2	875	11.0	4.0	7.2	88	1
DV7	593	10.6	0.9	7.3	-9	5

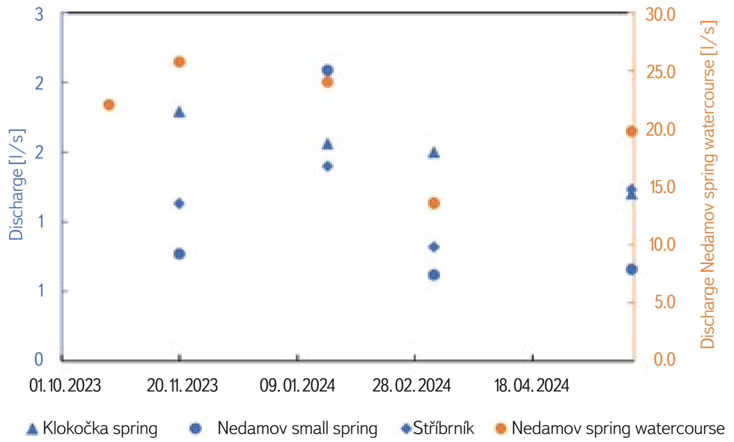

Fig. 8. Discharge measurement from Klokočka spring and the Pšovka and Liběchovka basins

Physico-chemical parameters

The measured physico-chemical parameters are shown in *Tab. 1*. Conductivity in the Bělá catchment area is lower than in Řepínský důl. While in the Bělá it ranges from 425 to 636 µS/cm, in Řepínský důl it is from 498 to 844 µS/cm. According to measurements by Kůrková [4], water originating purely from quartz sandstones has a conductivity of 100 to 300 µS/cm, while water from calcareous sandstones has a conductivity of 400 to 800 µS/cm. Therefore, the water in all measured objects of interest was probably in contact with calcareous sandstones for at least some time. Groundwater temperature is similar in both areas, from 9.2 to 11.2 °C. All monitored objects of interest have a neutral pH of approximately 7.2. Some monitored objects have a dissolved oxygen concentration < 1 mg/l, indicating an anoxic environment. The more frequent occurrence of these waters is in Řepínský důl. Oxidation-reduction potential measured with a calomel electrode ranges from -143 to +293 mV. The correlation between oxidation-reduction potential and dissolved oxygen was r = 0.57 (0.43 for Bělá and 0.62 for Řepínský důl), which indicates a medium degree of dependence. The range of the mentioned conductivities is within the values given for other objects of interest in the remaining parts of the studied districts [1, 2].

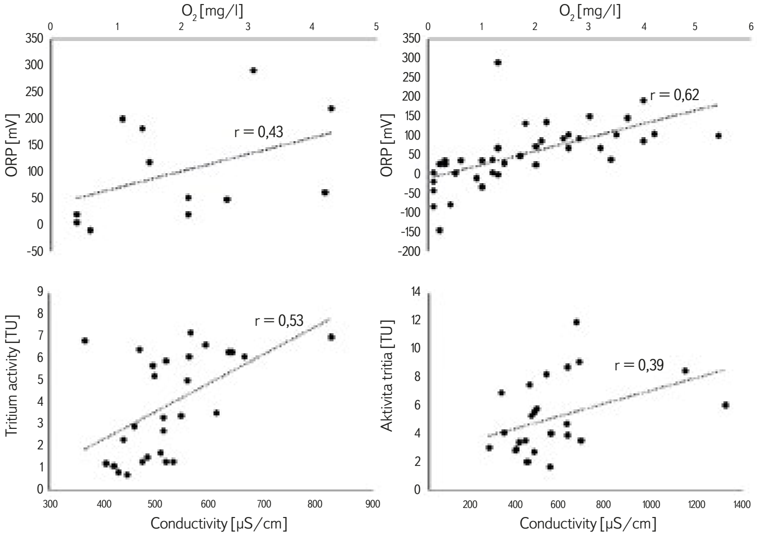

Fig. 9. Relationships between redox potential and amount of dissolved oxygen for Bělá (top left) and Řepínský důl (top right). Relationships between tritium activity and conductivity for springs in region 4410 (bottom left) and region 4522 (bottom right).

DISCUSSION

In the Results section, the current idea of groundwater flow in the area of interest was described as formulated in previous studies [especially 1, 2, 10] based on structural and hydrogeological data, supplemented with information from chemistry and fluctuations of groundwater levels. These are the basic results of the analysis of groundwater circulation in the area of interest, which significantly contributed to understanding of the hydrogeology in the region.

Nevertheless, in the context of low-tritium waters, there remain a number of questions that current models are unable to answer, and there are a number of inconsistencies as well as, in some cases, even contradictory information. Previous tritium analyses have come from only a limited number of objects of interest draining the structure of interest, which may be a mixture of both old and shallower, younger waters. There are also uncertainties regarding the usable amount of these waters and especially the area where these waters are formed (i.e. where their infiltration site is). It is therefore necessary to verify the existing conceptual model of the flow, supplement it and possibly modify it using new knowledge.

The infiltration site of these old waters is unknown. However, with an estimated discharge of 250–300 l/s (estimate of the total discharge of old waters according to [1, 2]) and infiltration before 1950, it is necessary to consider a pore volume of at least 6 × 10^8 m^3 to retain this water, which with the given porosity of sandstones (about 10–30 %) corresponds to a volume of 2–7 km^3 of Cretaceous rocks. The volume of Cretaceous rocks in the area of interest is higher, therefore the assumed volume of the current system of old waters and infiltration into the Cretaceous rocks are realistic.

In order to answer the questions described above, during the first year of the project, samples were taken from selected objects of interest for tritium analysis, which – with relatively low cost – will initially help to distinguish old water (with low to zero values of tritium activity) from young water (with higher tritium activity, indicating the origin of water infiltrated after 1950). Subsequently, on the basis of numerous tritium analyses, a smaller number of objects of interest (boreholes, springs) will be selected for more financially demanding, but more accurate dating methods, for example using radiocarbon, CFCs, SF$_6$, ^{85}Kr a ^{39}Ar.

Geological sections by Uličný et al. [8] made it possible for the first time to determine to which genetic sequences springs are bound and which rocks are highly permeable. Based on the positions of permeable rocks (especially sandstones), it is thus possible to verify hypotheses which lithologies form permeable aquifers, where water infiltration, etc. can occur. However, as Kůrková [4] points out, the aquifers defined according to these sections do not have to be formed of pure quartz sandstone; they may also contain calcareous layers. These layers of calcareous cement can be only the first few decimetres thick, while the vast majority of the aquifer thickness is made up of quartz sandstone [12]; however, even these thin layers can be sufficient to increase water conductivity.

Looking at previously measured data from springs [1, 2, 4], a weak trend can be observed where conductivity increases with increasing tritium activity (*Fig. 9*), i.e. water with a higher residence time tends to have lower conductivity. For HGR 4410, the correlation between tritium activity and conductivity is r = 0.53, with springs with tritium activity below 3 TU having a mean conductivity of 468 µS/cm (median 465 µs/cm), while springs with tritium activity above 3 TU having a mean conductivity of 564 µS /cm (median 558 µs/cm). For HGR 4522, the correlation is r = 0.39 and springs with tritium activity below 3 TU have a conductivity on average of 419 µS/cm (median 433 µS/cm), while springs above 3 TU have a conductivity on average of 596 µS/cm (median 535 µS/cm). For HGR 4410, according to Student's t-test (significance level 0.05), there is a statistically significant difference in conductivity between springs with tritium activity below 3 and above 3 TU.

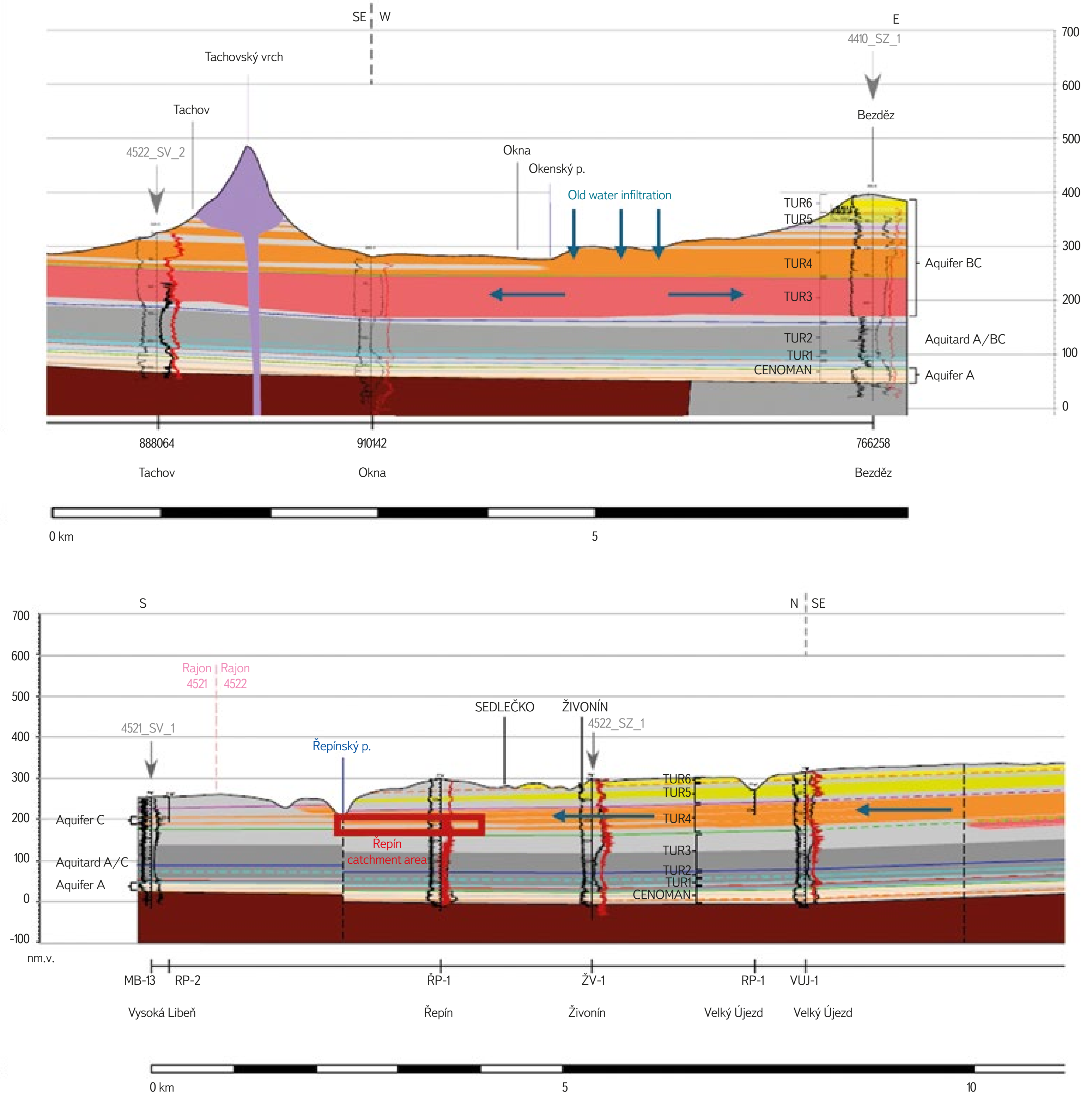

Fig. 10. Top – Geological cross section of the Bezděz area with continuous aquifers TUR4 and TUR3, indicating the possible directions of water flow (blue arrows); direction W-E. Bottom – Geological cross-section from Kokořínský důl to the Řepín catchment area (red rectangle) with an indication of possible water flow directions (blue arrows). Modified after [8]

In the Bělá basin there are springs with both low and high conductivity, indicating drainage of two different waters of different chemistry, and – according to different tritium activities – of different ages (J. Bruthans, unpublished). In this context, the values of tritium and conductivity will also be verified at the newly sampled collection boreholes in Bělá and Řepínský důl, as it is not entirely clear whether the water collected in these catchment areas is exclusively water originating in Turonian aquifer C, or whether it is an outflow from Cenomanian aquifer A, at least in part at some collection facilities. Water with low tritium activity, and thus a long circulation time, may also originate from aquifer BC (TUR3 and TUR4) near Strenický stream. In the following sections, we discuss the possible flow paths of the old waters.

Probable groundwater flow paths for HGR 4522

The old water in Řepínský důl has relatively lower conductivity, so it did not infiltrate through the unsaturated zone containing calcareous sandstones, but only through the quartz sandstones. The vicinity of Bezděz appears to be a probable area of infiltration, where there are outcrops of quartz sandstone of the continuous aquifer TUR3 and TUR4 [8; *Fig. 10*] and where, in addition (according to the groundwater level isolines), the infiltration area can be located because the groundwater level here is much higher than in the drainage areas of old waters [2; *Fig. 11*]. This water would subsequently flow from the east around the elevation of the base of aquifer C and the numerous faults between Dubá and Mšeno (fault failure system south of Dubá) and then turn SW towards Řepínský důl (*Fig. 11*). Towards Řepínský důl, quartz sandstones TUR3 and TUR4 gradually pass into calcareous sandstones. This can cause an increase in water conductivity in Řepínský důl to values from 400 to 800 µS/cm (*Tab. 1*), which indicates water from quartz sandstones that has passed through calcareous layers [4].

Another possible source is outflow from the Cenomanian aquifer. As shown in *Fig. 6*, in the area of Řepínský důl (especially in its lower parts), a change in the situation occurs even with unaffected water levels when Cenomanian water already flows from aquifer A through aquitard A/C to aquifer C. However, if outflow of Cenomanian water occurred in the lower parts of the catchment area, a change in physico-chemical parameters could be expected here, such as a decrease in the amount of dissolved oxygen and a decrease in the redox potential which, however, is not apparent from *Tab. 1*. The dating of the water from these collection boreholes can further support or disprove this assumption.

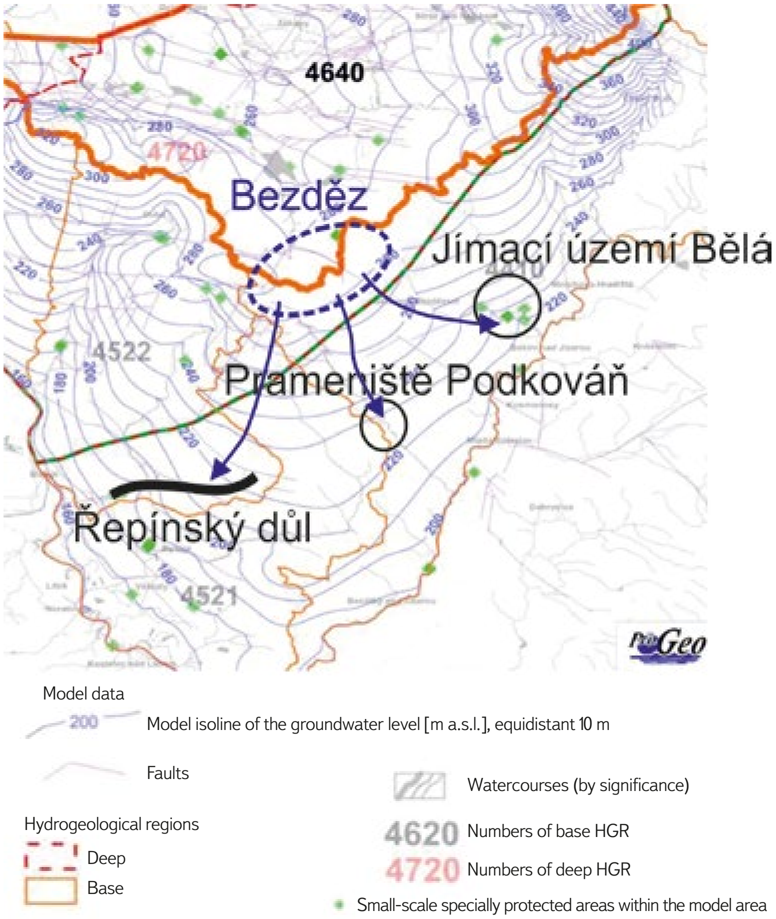

Fig. 11. Model isolines of the groundwater level from a model from PROGEO, s. r. o., with marking of the probable location of infiltration of low-tritium waters (blue oval) and the direction of water flow (blue arrows). Modified after [1]

Simultaneously, the question arises as to where the old water from Stříbrník spring and in the spring area near Nedamov comes from because, according to the known water levels in these areas, the level in aquifer A is lower than in aquifer C (*Fig. 6*, *Fig. 11*); therefore, there should not be outflow from the Cenomanian aquifer. At the same time, the isohypses of aquifer C (TUR4) in *Fig. 11* are not affected by tectonic disturbances, which is contrary to the spatial variability of rock permeability, which is most affected by the crossing of fracture belts, to which springs are often connected [1, 2]. It thus remains an open question whether, for

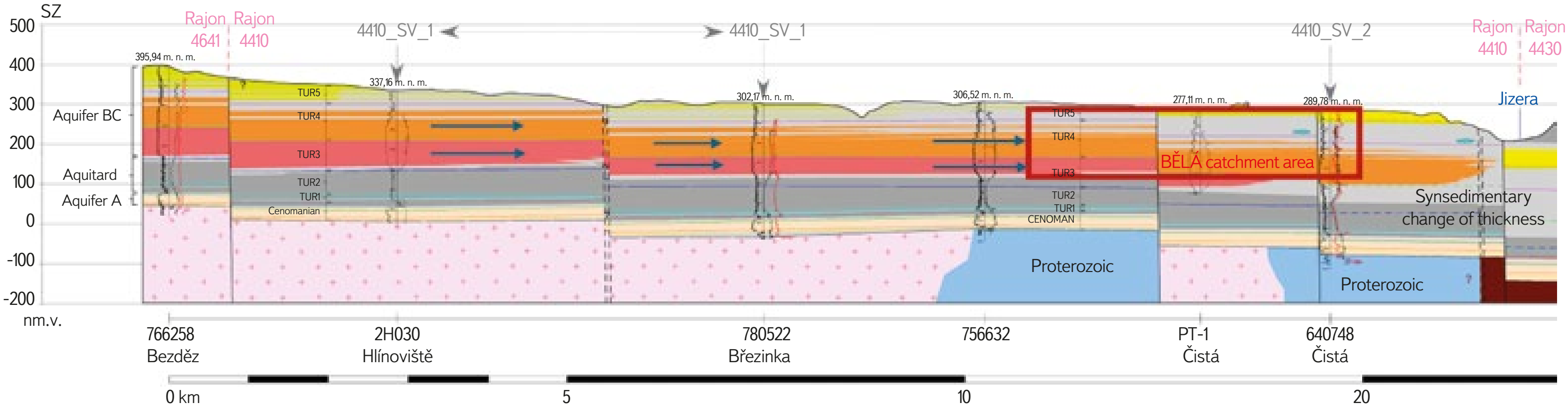

Fig. 12. Geological cross-section from Bezděz towards the Bělá catchment area (red rectangle), with indications of possible water flow directions (blue arrows). Modified after [8]

example, in the area of Stříbrník spring, outflow from the Cenomanian aquifer through fissures cannot occur locally.

Probable groundwater flow paths for HGR 4410

On the basis of contemporary knowledge, it is possible to assume that the old water springing from Strenický stream and collected in Bělá came into contact with limestones only for a limited time [4], i.e. it infiltrated in places of quartz sandstones. Again, the area of infiltration for the Bělá catchment may be in the vicinity of Bezděz, where outcrops of quartz sandstone TUR4 reach the surface. Infiltrated water would move further through the continuous aquifer TUR4 and TUR3 and reach the surface along the faults or at the places of gradual disappearance of these aquifers (*Fig. 12*). Another possibility is outflow from the Cenomanian aquifer which, according to *Fig. 5,* has a groundwater level in the Bělá catchment area at a very similar level to aquifer C, and according to [7] even higher.

CONCLUSION

The goal of the presented project is to specify and quantify water sources in HGR 4410 and 4522, which according to previous studies can have a residence time of at least 70 years (in some cases significantly more). The infiltration of this old water is probably in the vicinity of Bezděz, where there are sandstone outcrops without carbonate cement. This old water then flows through the continuous aquifer TUR3 and TUR4. Given the discharge of springs, sandstones occupy a sufficient volume for its accumulation and residence time. In order to quantify the dynamic sources of these waters, discharge monitoring is carried out on selected streams and springs with a low concentration of tritium. All monitored objects of interest show stability of discharge over time, which means longer circulation without the influence of local meteorological conditions. Selected objects of interest used for drinking water supply were sampled to determine the age of the water based on tritium activity. Based on the results, objects of interest will be selected for which the age will be refined based on the analysis of CFCs, SF$_6$, and other dating techniques. The project is currently entering its second year. The following actions include ongoing evaluation of newly acquired hydrochemical, water management, and hydrogeological data, creation of relevant maps, sections and design of water supply utilization of resources, and protection of hydrogeological structure. A detailed survey of the hydrogeology of the area will lead to an update of the conceptual model of water flow in both districts, especially with regard to the origin of long-circulation water.

Acknowledgements

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Methodology for creating a *Map of the Vulnerability of the Quantity of Natural Groundwater Resources to Drought for the Czech Republic*

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Keywords: groundwater — drought — vulnerability — groundwater resources — expert map

ABSTRACT

Groundwater drought affecting groundwater availability is still mostly understood as a subset of hydrological drought. The impact of hydrological drought on groundwater is manifested with a delay and depends on its duration. An expert interactive *Map of the Vulnerability of the Quantity of Dynamic Groundwater Resources to Drought* for the Czech Republic was created as part of the TA CR project SS01010208 – "*Controlled Groundwater Recharge as a Tool to Reduce the Impacts of Drought in the Czech Republic*". The presented vulnerability map is created on the basis of the use of precipitation normal and regression relationships between precipitation and total runoff and groundwater discharge (base flow) using the Base Flow Index (BFI) and ratio of base flow in the driest year of 2010–2019 to the long-term average of base flow (M index), which guarantees uniform processing for the entire Czech Republic at a scale of 1 : 50,000 and an objective comparison of the vulnerability of dynamic groundwater resources to drought throughout the country. It is also based on recorded groundwater abstraction and in the case of municipalities with individual supply, the abstraction is calculated from the number of inhabitants and the national average consumption of drinking water per capita. The Map is compiled based on the balance of dynamic groundwater resources and groundwater abstraction. It contains six categories and shows which regions and areas will struggle to have sufficient groundwater resources during periods of prolonged drought. It synthesizes all available flow logs and other data until 2020 and is designed so that the layers with variable information can be updated in the future.

This map is available at www.suchovkrajine.cz/zranitelnost-k-suchu and enables the preparation, design and implementation of measures that will ensure sufficient water resources, especially of drinking water, for the population even in periods of long-term drought.

INTRODUCTION

We are in a period of climate change, which is characterized by more frequent extreme weather fluctuations. In 2015–2020, there was an unusually long period of hydrological drought in the Czech Republic which, in a large part of the country, caused a drop in groundwater levels and a lack of water sources, especially in smaller settlements. Drought affects the state of groundwater with great persistence. Almost three-quarters of the Czech Republic is made up of rocks that have a low ability to accumulate larger reserves of groundwater for several years, and thus most of the water drains from the country. Groundwater resources in these areas are dependent on regular annual recharge from rainfall which, however, is highly variable in quantity. Among the main priorities of the country is the provision of sufficient groundwater resources to supply the Czech population, even during periods of prolonged drought.

One of the goals of the project ISTA TA CR SS01010208 *"Controlled Groundwater Recharge as a Tool to Reduce the Impacts of Drought in the Czech Republic"* was therefore the methodology and creation of a *Map of the Vulnerability of the Quantity of Dynamic Groundwater Resources to Drought* for the operational management system of the Ministry of the Environment.

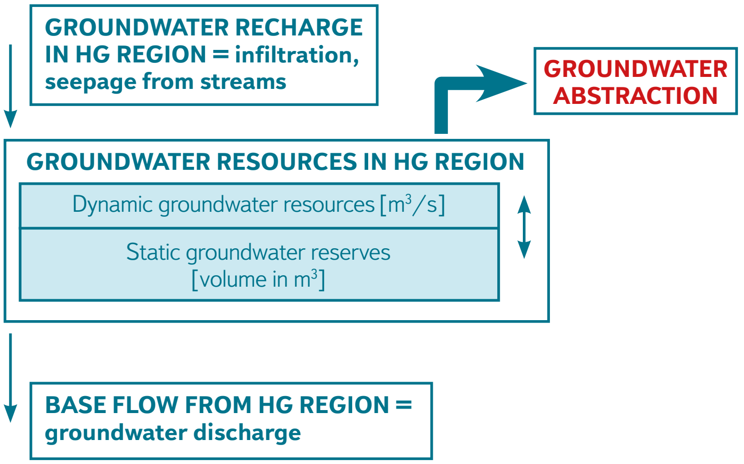

Fig. 1. Groundwater resources

Groundwater resources consist of the volume and flow of groundwater in the aquifer in accordance with Decree No. 369/2004 Coll., on the design, implementation and evaluation of geological activities, as amended.

Groundwater resources include:

- The amount of water flowing in a given time (month, year) through an aquifer, i.e. the dynamic resources of groundwater expressed in volume units per unit of time – usually l/s. The volume of these dynamic resources fluctuates depending on the recharge, mainly by groundwater recharge fed by precipitation, locally also by seepage from streams. Dynamic groundwater resources are usually considered equal to base flow in the longer-term average.
- The volume of water that fills the pores, cavities, and fractures in the aquifer (static groundwater reserves), i.e. the volume of water in the water-bearing part of the aquifer, expressed in volume units (m^3). However, static reserves are only the volume of water filling the rock environment. The only rejuvenating element are dynamic resources. The rate of decline of base flow in the dry season (of dynamic groundwater sources) also reflects part of the static storage to some extent, since the volume of the static reserves and the rate of water release from them determine the base flow in the period when potential evapotranspiration prevails over precipitation. The relationship between groundwater resources, recharge, and drainage is expressed in *Fig. 1.*

METHODOLOGY

Compilation of the *Map of the Vulnerability of the Quantity of Dynamic Groundwater Resources to Drought* (hereinafter referred to as *Map of Groundwater Drought Vulnerability*) is not sufficient with information on the size volume of groundwater resources; the Map must also contain information on the intensity of groundwater abstraction. In the Czech Republic, the hydrogeological regions (HGR) with the greatest groundwater resources are often largely used to supply the population with drinking water, so it is not true that the greater the groundwater resources, the lower the vulnerability of dynamic groundwater resources to drought. The opposite statement does not apply either. It always depends on the difference between the groundwater resources and the rate of their use, and different variability of groundwater resources recharge over time is also reflected, as well as the amount of groundwater in static reserves, which is reflected in the rate of decline of base flow in the dry season. The HEIS information system (https://heis.vuv.cz/data/webmap/), managed by TGM WRI, contains abstraction points (4,693 sites with groundwater abstraction and 941 with surface water abstraction) and water discharge (5,092 sites with surface water discharge and 28 with discharge into groundwater) that are subject to registration in the sense of Decree No. 252/2013 Coll. (data as of 2020). Furthermore, there are over 1,000 municipalities dependent on the individual supply of drinking water to the population, where groundwater abstraction is not subject to records; at the same time, it is these municipalities that often have problems with ensuring sufficient groundwater supply in dry periods. In order to use all this information effectively, it was necessary to compare the groundwater resources and their variability over time with groundwater abstraction from the same area. In the area outside the main aquifers and Quaternary aquifers, which is not expedient to divide into smaller units, the fourth order stream basins (of which there are 8,750 in the Czech Republic) were used as a basic unit.

The Map is a scale of 1 : 50,000. It is based on logs ofstream discharge and precipitation of the Czech Hydrometeorological Institute (CHMI), available at https://www.chmi.cz/historicka-data; data on recorded groundwater and surface water abstraction and discharge from the HEIS database; and information about municipalities and their parts that do not have a water supply connection according to the available Water Supply and Sewerage Development Plans (PRVKUK) for each region from the Ministry of Agriculture website (https://mze.gov.cz/public/portal/mze/water/waterworks-and-sewerage/plans-development-of-water-works-and-sewerage, from 2007); records of residents in municipalities, etc.

Basic environment types

For the purposes of the *Map of Groundwater Drought Vulnerability*, the Czech Republic was divided into four basic environments which have very different characteristics in terms of groundwater resources and recharge:

A. hydrogeological basins and Quaternary aquifers, i.e. aquifers with extensive groundwater flow systems usually not respecting orographic drainage divides,

B. hardrock environment, i.e. the environment of hard rocks and heavily cemented sediments, where the aquifer is mainly in the zone of near-surface fracturing and weathering of rocks, the groundwater flow corresponds to the surface topography (downslope flow),

C. floodplains of rivers and smaller streams, where there is possibility for induced recharge, i.e. groundwater sources derived from the surface streams, from extensive orographic basins higher upstream, or hinterland,

D. populated parts of municipalities with predominant individual groundwater supply, where there is relatively high abstraction of groundwater per unit of area for the needs of the inhabitants.

A) Hydrogeological basins and Quaternary aquifers (except valley floodplains) were taken into consideration. The basal Cretaceous aquifer A (Cenomanian sediments) was not evaluated as it is less sensitive to drought compared to the above lying aquifers in the base layer and, with exceptions, its use is low. Hydrogeology basin structures usually form an integrated flow systems, and therefore HGR were treated as elementary units, i.e. the calculation of the balance of groundwater resources was carried out for a whole unit; the whole zone has a uniform vulnerability. Environment A includes permeable parts of the Bohemian Cretaceous Basin, the South Bohemian Basin, and Quaternary regions.

B) The environment of near-surface hardrock aquifers and their equivalent includes all other areas. This includes areas of igneous, metamorphic, and folded sedimentary rocks and parts of the Bohemian Cretaceous basin where aquitards (permeable only in the near-surface zone) of the Tertiary Carboniferous to Permian rocks prevail, i.e. the vast majority of the Czech Republic. These are areas that have limited static groundwater reserves and are therefore dependent on an yearly recharge from rainfall. In contrast to environment A, there are usually no larger aquifers here, where the cone of depression would spread laterally to a distance of hundreds of metres or more. In these areas, the territory was divided into individual fourth order basins, e.g. to small units.

C) River floodplains differ from other environments in the fact that groundwater resources per unit area are generally orders of magnitude higher here than in the surrounding rocks. The environment is in hydraulic contact with a surface stream; at the same time, groundwater from surrounding rocks or sediments drains here via fluvial sediments into the stream, so it is usually possible to obtain an order of magnitude higher amount of groundwater in the floodplains than in the surrounding environment. For the above reason, a large number of water-collecting facilities are located in the area of river or stream floodplains.

Floodplain areas were extracted from geological maps "GeoČR50" from the Quaternary layer, namely polygons with the attribute in the genesis column fluvial undivided + reservoir sediments. The continuous floodplain area obtained in this way was divided into sections in which it is possible to calculate the hydrogeological balance. In each of the second order basins, there is a main stream that has tributaries from the right and left sides. The area of the floodplains of the right- and left-hand tributaries was manually separated from the floodplain of the main stream. The floodplains of the left- and right-hand tributaries were defined only if their length exceeded 9.5 km (the basins of shorter segments were very similar by size to the fourth order basins). Shorter tributaries were cut out with a buffer of 250 m. This was followed by unification of the individual floodplain areas according to the second order basins - the main stream within the second order basin and its right- and left-hand tributaries were separated (the main stream floodplains and the floodplains of each individual tributary form segments). Larger rivers flowing through several second order basins (e.g. the Sázava, the Vltava) have a continuous floodplain from the spring to the confluence with the larger stream. Smaller stream that do not exceed the second order basin are also formed by a single floodplain segment. After that, the area of all floodplain segments was determined, and for each floodplain segment, the total area of its orographic basin was determined. Two data are thus available for each defined floodplain segment: the area of the floodplain segment and the area of its orographic basin.

D) Municipalities with individual groundwater supply.

The build-up parts of municipalities with predominant individual supply were defined as follows. Based on the available PRVKUK plans and the digitized layer of the water supply pipelines, municipalities that do not have a water supply system were selected. According to the overlay of municipalities, those that did not cross the water supply pipelines were chosen. After that, the check of the obtained selection of municipalities was carried out according to PRVKUK tables and plans. As a result, a layer was created containing over 1,726 parts of municipalities without public supply of drinking water (out of a total of 1,035 municipalities). For these municipalities, the area of the built-up part was determined. Its basis is a map of building blocks (map of the Czech Republic 1 : 50,000) obtained using an orthophoto map with manual completion of built-up areas in selected municipalities using polygons in GIS. This was followed by a check and verification of the correctness of the range of polygons and their affiliation to individual municipalities. After that, the area of the built-up parts of the polygons was determined for each municipality. If the municipality consisted of several parts, all parts of the municipality were dealt with together. It is worth noting that the PRVKUK plans for individual regions (publicly available on the websites of the relevant regions, or the Ministry of Agriculture) at the time of processing the groundwater vulnerability layer to drought mainly date from 2007 and provide information on the existence of water mains with the outlook for 2015.

Computational planar elements in environments A to D:

- for environment A (Hydrogeological basin and Quaternary HG region), the element is the entire HGR, with the exception of floodplains,
- for environment B with a near-surface aquifer, the element is the fourth order basin, with the exception of floodplains,
- for environment C, i.e. the floodplains of smaller stream, the element is the entire floodplain,
- for environment D, i.e. municipalities, the element is a built-up area of a part of the municipality.

Individual GIS layers and determination of base flow

The basis for the *Map of Groundwater Drought Vulnerability* consists of the following GIS layers:

1. dynamic groundwater resources corresponding to the base flow in the dry season (l/s/km^2),
2. recorded groundwater and surface water abstraction (l/s).

For all types of planar elements except floodplains (i.e. A, B, D), the groundwater source is considered to be base flow. Only for floodplains that have the potential recharge from stream seepage, the groundwater source per floodplain area unit is higher (see below).

Layer of groundwater recharge from precipitation

Long-term base flow – dynamic resources of groundwater by hydrograph separation

Groundwater recharge corresponds to the precipitation total, minus evapotranspiration and water temporarily stored in the soil and unsaturated zone. Since neither the actual evapotranspiration nor the stored amount of water in the unsaturated zone can be effectively determined on larger areas, the average value of groundwater recharge is determined from base flow. All water that has become groundwater (recharge) must sooner or later leave the ground in the form of base flow. Thus, base flow is being considered which corresponds to groundwater recharge for a certain period of time. However, the equation between groundwater recharge and base flow is valid only for long-term averages (several years or more), when the change in storage becomes negligible compared to recharge and discharge.

A number of different methods are used in the Czech Republic to determine base flow. One of the main ones, which still remains a benchmark for comparison with the results of other methods, is Kille's method [1]. It is based on the lowest values of average daily discharge of streams in individual months from at least a ten-year time series. The advantage is easy determination, the disadvantage is getting a single average value of the base flow over a long period. This restriction is particularly inconvenient at present, when the base flow can change quite significantly due to climate change. Based on Kille method, the first map of groundwater recharge, or base flow from the Czech Republic was created [2].

In the past, the Kliner-Kněžek method was also used [3]. It derives base flow from measured pairs of the groundwater level in the borehole and the stream discharge plotted together. Its advantage is the consideration of fluctuations in the groundwater level, i.e. an indicator of the actual oscillation of groundwater resources. On the other hand, the disadvantage is significant sensitivity of the results to the selected pair of the borehole and stream profile. In many areas, a suitable borehole with logs of groundwater level measurements corresponding to the evaluated aquifer is not available.

At present, two approaches are most commonly used to determine base flow, both based on hydrograph separation. The first is separation using Eckhardt filter [4]. This approach is widely used abroad and is also used by the CHMI to determine dynamic groundwater resources in HGR and to determine base flow in basins and areas where hydrological balance has been calculated. The method is derived from the Boussinesq equation. Eckhardt's digital filter applied to total daily discharge has two parameters: recession coefficient of discharge decline over time, and Base Flow Index (the ratio of the average base flow to the average total runoff). The derivation of parameters is time-consuming and methodologically demanding.

The second approach is the separation of base flow by the moving minima method [5]. A moving 31-day minimum is applied to the daily step total discharge data, and the resulting series is then smoothed with a 31-day moving average. The only parameter in this case is the size of the moving window (31 days). This procedure is inspired by the method used in Great Britain (UKIH, see e.g. [6]). Its advantage is simplicity, and therefore it is less time-consuming.

Base flow obtained by the Eckhardt filter method represents on average 70–80 % of base flow obtained by the moving minima method.

For the purposes of the *Map of Groundwater Drought Vulnerability*, base flow was uniformly separated using the moving minima method from the available daily discharge data of 518 CHMI gauging stations in 1981–2019. Unlike the previously widely used Kille method [2], this method of separation allows determination of the variable value of base flow with a monthly resolution. This is especially valuable today, when base flow can change in time quite significantly due to climate change.

Base Flow Index

At each CHMI gauging station, Base Flow Index (BFI) was obtained as the ratio of the average base flow from the moving minima method to the average total runoff. BFI therefore shows what proportion of the total runoff constitutes base flow in long-term average.

Tab. 1 shows BFI for all HGR in the Czech Republic derived from the separation of the hydrograph on the CHMI gauging profiles. It is evident that the HGR in the flysch and Carpathian foreland have by far the lowest BFI (index 0.3, i.e. only 30 % of the total runoff is base flow on a long-term average, the rest is quick flow, i.e. surface and subsurface runoff). The vast majority of HGR in the Czech Republic have BFI values between 0.4 and 0.5, so base flow here makes up 40–50 % of total runoff. These are primarily rocks of crystalline rocks, culm, parts of the Carboniferous to Permian sediments, and those parts of the Cretaceous HG regions where aquitards predominate on the surface. This is followed by transitional areas with a BFI between 0.55–0.65 with Cretaceous, Carboniferous to Permian and, exceptionally, crystalline rocks. Several Cretaceous HG regions have a BFI of 0.7–0.75, documenting considerable storage capacity.

The highest BFI is represented by a belt of HGR along the Jizera and the Labe right-hand tributaries (basins of the Zábrdka, Bělá, Skalský stream, Košátecký stream, Pšovka, Liběchovka, Obrtka), formed by highly permeable Cretaceous calcareous sandstones and sandy limestones, in places with karst permeability [7]; they have an extreme storage capacity probably due to the alternation of porous and calcareous sandstones, where BFI reaches anomalously high values of 0.75–0.9. Here, base flow accounts for 75–90 % of total runoff, and quick flow is therefore insignificant.

Tab. 1. Base Flow Index (BFI) values derived from the separation of hydrographs on watercourses in different zones (HGR)

BFI	HGR (HG regions)	Lithology
0.3	2120-2132, 2211-2242, 2261-3224, 6531- 6532, 6620	Mainly flysch and fore-deep, Ore Mountain Basin, exceptionally crystalline rocks and culm
0.4	2250, 4222, 4320-4340, 4360, 4540-4620, 5221-6111, 6120-6133, 6222-6230, 6320- 6412, 6420, 6510, 6540-6550, 6611-6612	Mainly crystalline rocks, Permocarbon, culm and Bohemian Cretaceous Basin covered by aquitards
0.45	3230, 4430, 5151, 6112, 6213-6221, 6414, 6560-6570	Mainly crystalline rocks and Permocarbon
0.5	1420-1430, 1623, 2140-2160, 4210, 4231, 4240-4262, 4280-4310, 4350, 4420, 5110- 5120, 5132, 5152-5212, 6211-6212, 6240- 6250, 6413, 6520, 6630-6640	South Bohemian basins, Quaternary with loess*, Bohemian Cretaceous Basin, crystalline rocks, karst
0.55	4221, 5140, 6310, 6431-6432	Bohemian Cretaceous Basin, Permocarbon, crystalline rocks
0.6	4110, 4510, 4530, 4630, 4660, 5131	Mainly Bohemian Cretaceous Basin aquifers, exceptionally Permocarbon
0.65	4650	Bohemian Cretaceous Basin
0.7	1110-1410, 1510-1622, 1624-1652, 4232, 4270, 4640	Quaternary* and Bohemian Cretaceous Basin aquifers with high storage capacity
0.75	4522-4523	Bohemian Cretaceous Basin aquifers with high storage capacity
0.85	4410	Bohemian Cretaceous Basin aquifers with exceptionally high storage capacity
0.9	4521	Cretaceous aquifers with exceptionally high storage capacity

Notes: *estimation only, separation of the hydrograph in the Quaternary HG zones is not possible because groundwater inflows into rivers from the Quaternary HG zones are much lower than the error in determining river flow. HG zones(HGR) are sorted by number. Full names of the HG zones are in Decree No. 5/2011 Coll., on the definition of HG zones and groundwater bodies, the method of assessing groundwater status and the requirements of programmes for the detection and assessment of groundwater status, as amended.

For Quaternary fluvial aquifers, BFI was only tentatively estimated to be 0.7 for most Quaternary fluvial HG regions and 0.5 for loess-covered fluvial aquifers. This estimate is based on the fact that surface runoff does not occur from Quaternary fluvial aquifers. However, the course of the groundwater levels in the boreholes documenting the Quaternary fluvial aquifer indicate the presence of a quick flow as well. The actual BFI can be higher up to a value of about 0.9 there. However, with the value of 0.7 used, the data from the *Map of Groundwater Vulnerability to Drought* remains on the safe side of uncertainty, and a lower value is thus desirable.

HGR with the lowest BFI are, as follows from the above, formed by rocks with very low permeability. In contrast, HGR with the highest BFI represent rocks with high permeability and considerable storage capacity in the event of a deficit in groundwater recharge.

Independent treatment of BFI is presented in [8], where the average BFI values of for several groups of rocks and also BFI for gauging stations on the river network are given.

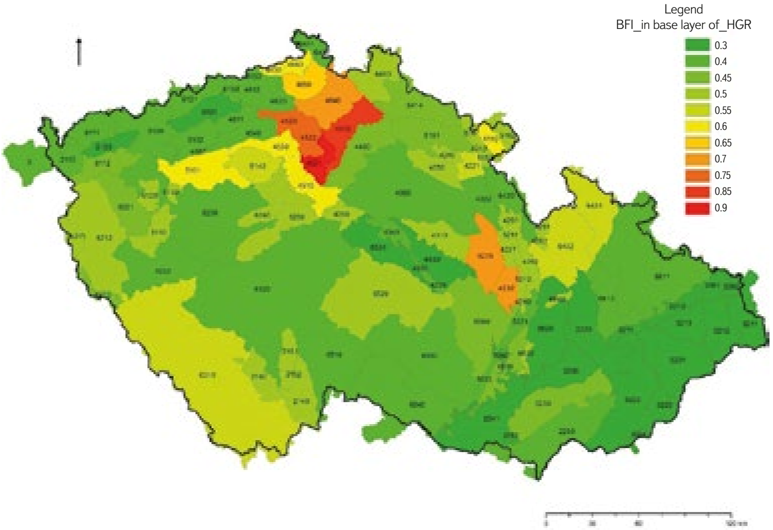

Fig. 2. Base Flow Index obtained by separating hydrographs from 518 streams in the Czech Republic monitored by the CHMI and assigned to individual HGR in the base layer *(Tab. 1)*

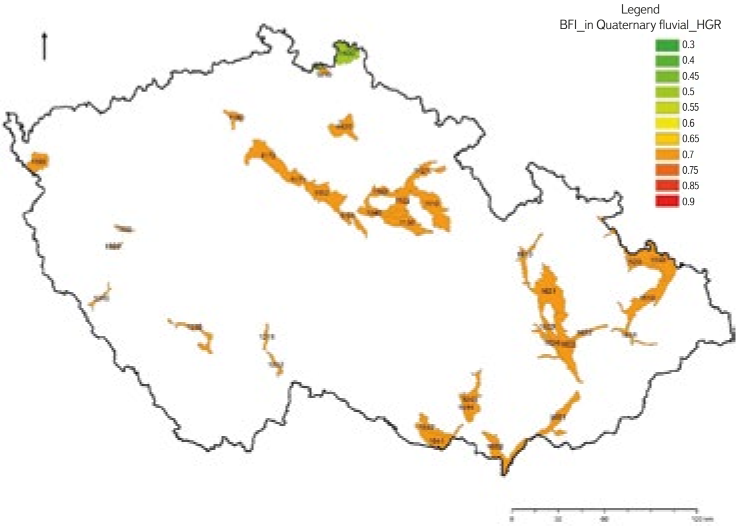

Fig. 3. Base Flow Index assigned to individual HGR in the upper layer (*Tab. 1*)

Base flow – dynamic sources of groundwater in the dry season

Dynamic groundwater resources for the dry season were determined as average annual base flow on the CHMI profile in the driest recorded year for 2010–2019 in given basin. Base flow obtained in this way may appear to be overestimated, as the flow rates of a number of surface streams sometimes decrease significantly in summer.

However, defining dynamic resources on the basis of minimum discharge from the summer season does not appear to be appropriate, as studies from recent years show that under hot summer temperatures a complete loss of stream flow can occur – not because of an extreme decrease in base flow, but because of extreme evapotranspiration of water from floodplain by vegetation and from water bodies [9].

At the same time, the loss of stream flow is manifested only in the summer and possibly lasting till autumn due to the drop of the water level below the riverbed. If this discharge strongly affected by evapotranspiration is taken as a value typical for drought, then there would be literally no groundwater reserves at a number of streams in lower altitudes (discharge e.g. only 0.07 l/s/km^2) and even the smallest groundwater abstraction from these large basins would lead to the distortion that the basins are extremely vulnerable and are over-exploited. However, it is obvious from spring discharge in these basins that even though surface stream discharge drops drastically during summer hot air temperatures, the spring discharge from the same basins does not decrease [10].

Fig. 4. Examples of extremely low flows on surface streams with catchments of about 100 km^2. Runoff was temporarily drastically reduced as a result of massive evapotranspiration of groundwater from the river floodplain in dry and hot summer periods: a) Brzina (Sedlčansko) 10 July 2019, flow rate 0 l/s, river basin 133 km^2; b) Žehrovka (Březina) 9 July 2019, measured flow 20 l/s, basin 90 km^2

As a result of ongoing climate change, the idea that evapotranspiration from the floodplains can be neglected because the floodplain area is very small compared to the river's catchment area is no longer valid for streams in the lower reaches of the Czech Republic. In the non-rainfall summer period, it is not true that the stream discharge on the CHMI profiles corresponds to the base flow. In contrast, on the Brzina, Loděnice, Bakovský stream, and Klenice, and apparently on many others, losses by evapotranspiration from the stream floodplain and water bodies are so significant (200–250 l/s per stream basin) that they exceed many times the residual measured discharge from the CHMI basins measured on the closing profiles of the Brzina, Loděnice, Bakovský stream, and Klenice (0–20 l/s). The vast majority of base flow thus evaporates and does not run off. In the dry summers of 2018 and 2019, total discharge on the CHMI profiles was thus up to two orders of magnitude lower than base flow from the same basins before it was consumed by evapotranspiration from floodplain vegetation [9] (*Fig. 4*). This phenomenon is well known from arid regions, where water from streams also massively disappears through evapotranspiration until the streams dry up completely. In a number of streams in the lower areas of the Czech Republic, even without water abstraction in the summer, residual discharge is below the legislative threshold, purely due to environmental phenomena (extreme temperatures, and thus extreme evapotranspiration). The summary updated report on the impact of climate change [11] confirms a significantly greater influence of evapotranspiration (greater water consumption by vegetation also due to the extension of the growing season) as a result of ongoing climate change.

In theory, discharge from wastewater treatment plants, which significantly increases stream discharge in conditions of long-term drought, could have a certain influence on the results [12]. However, a significant increase in discharge occurs during times of extreme evapotranspiration from the floodplain, when a large part of base flow is consumed by evapotranspiration in the floodplain which, on the contrary, leads to an extreme underestimation of base flow. The effect of these processes on base flow is thus opposite and the effect of reducing discharge by evapotranspiration in the floodplain is usually significantly higher than the contribution of discharge from wastewater treatment plants.

M index

For each CHMI gauging station, the M index was determined as the ratio of average base flow in the driest recorded year of 2010–2019 to average long-term base flow. The M index therefore indicates what part of average base flow forms the base flow in the driest year (*Tab. 2*).

Tab. 2. M index values

0.3	1651-1652, 2120-2132, 3110, 3224, 4350, 4530-4550, 5140, 6620	Ore Mountain Basin, low-lying flysch areas, Bohemian Cretaceous Basin, Permocarbon and culm
0.35	1623-1644, 2220-2250, 4611-4612, 6540	Low-lying flysch areas, Bohemian Cretaceous Basin and crystalline rocks, Quaternary*
0.4	1110-1622, 3230, 4231-4232, 4280, 4360, 4510, 6240, 6510	Low-lying areas in the Bohemian Cretaceous Basin, Quaternary*
0.45	2140-2160, 3222-3223, 4521, 4620, 5131-5132, 6230, 6320, 6550, 6630-6640	South Bohemian Cretaceous basin, low-lying parts of Bohemian Cretaceous Basin, Permocarbon and karst
0.5	2212, 2261-2262, 4270, 4310-4340, 4430, 4522-4523, 5221-5222, 6250, 6413, 6520-6531, 6560-6570	Lower and middle altitudes of the Bohemian Cretaceous Basin, Permocarbon and crystalline rocks
0.55	2211, 3112, 3221, 4110-4210, 4240-4250, 6222, 6411-6412, 6612	Flysh and middle altitudes of Bohemian Cretaceous Basin and crystalline rocks
0.6	2110, 3211, 4221-4222, 4261-4262, 4291-4292, 4410-4420, 4640, 5110, 5120, 5152, 5211-5212, 6211-6221, 6432, 6611	Middle altitudes of the Bohemian Cretaceous Basin, Permocarbon and crystalline rocks
0.65	3213, 5161-5162, 6111-6120, 6310, 6420-6431, 6532	Upper altitudes of the Permocarbon and crystalline rocks, exceptionally flysch
0.7	4630, 4650-4660, 5151, 6131-6133, 6414	Highest altitudes of Bohemian Cretaceous Basin, higher altitudes of Permocarbon and crystalline rocks

Notes: *only estimated, hydrograph separation in Quaternary HG zones is not possible; see *Tab. 1*. HG zones have been sorted by number; a hyphen between the numbers means the range of all districts between the numbers.

Tab. 2 shows the M index for all HGR in the Czech Republic derived from the separation of the hydrograph on the CHMI gauging stations. The lowest values of the M index are reached in the lowest altitudes of the Czech Republic, where significant groundwater recharge typically occurs after several dry years. This is also the reason why base flow in the dry season can drop, for example, to 30 % of average base flow at the same gauging station. Conversely, in the highest altitudes, where annual recharge prevails over multi-year oscillations, the drop in base flow in the dry season is naturally smaller, to 70 % of the value of average base flow. Unlike BFI, which is significantly related to lithology, the M index is mainly influenced by altitude. The influence of lithology should be assessed in future studies. The limited influence of lithology is evident, for example, at M = 0.45, which is valid both for very little permeable flysch rock and the most permeable Bohemian Cretaceous Basin aquifers with a strong storage capacity. It is obvious that the storage capacity of the rock environment has only a limited effect on M index; for example, at HGR 4521 Cretaceous rocks in the Košátecký stream basin, although the porosity is able to absorb almost all the quick flow and convert it into base flow (BFI 0.9), this porosity is however not capable to sustain the stable discharge for several years so that discharge would not fluctuate between dry and wet years.

Therefore, the regularity of groundwater recharge from rainfall has a much greater influence on the stability of runoff in multi-year cycles. At higher altitudes, the groundwater recharge is more regular, as the capillary water storage in the soil is recharged every year, and infiltration can thus proceed to greater depths and groundwater recharge is significant each year. In contrast, in the lowlands, the soil water deficit can last several years, and significant groundwater recharge occurs only after many years (e.g. after seven years in the case of Slánsko), when the base flow has already dropped to values significantly below average.

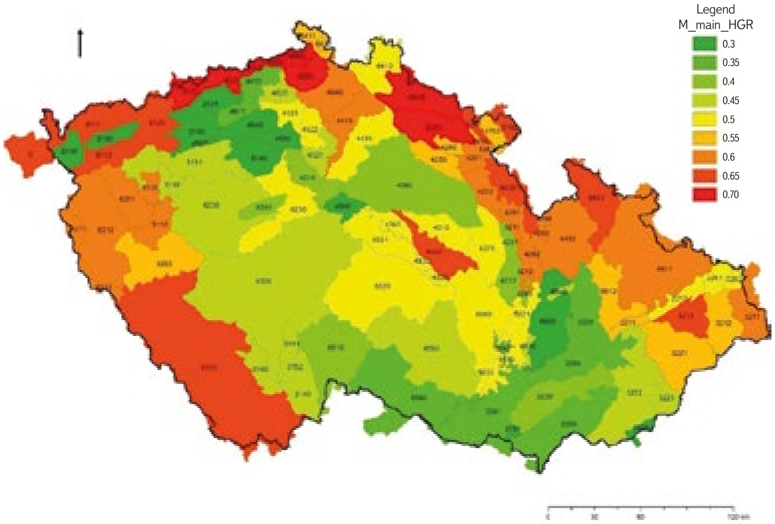

Fig. 5. Index M determined by hydrograph separation from 518 surface streams assigned to HGR in the base layer

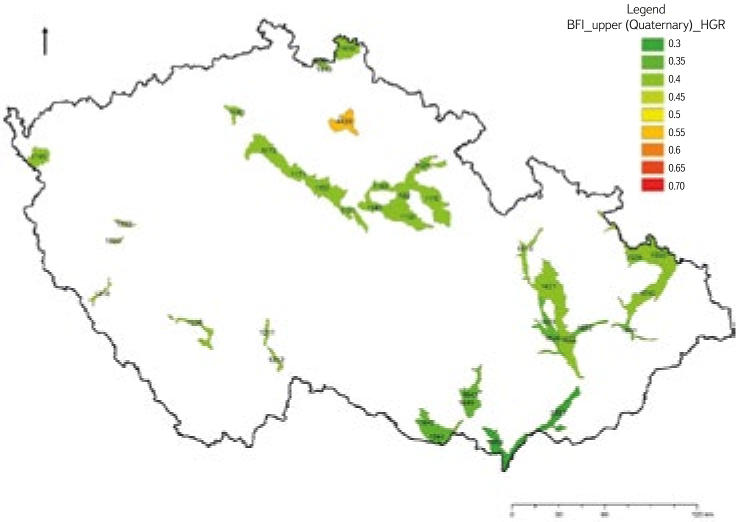

Fig. 6. Index M assigned to individual HGR in the upper layer (*Tab. 2*)

Derivation of base flow from longterm precipitation totals

In an ideal situation, every area in the Czech Republic would belong to a given basin with a gauging station. By separating the hydrograph on a given CHMI gauging profile, it would be possible to directly determine both the average base flow and the base flow in the dry season. In reality, however, this approach cannot be used in almost half of the Czech Republic, because:

1. many rivers originate in border mountain ranges, and the CHMI gauging profiles in the lowlands located on these rivers (e.g. the Labe) do not reflect the conditions of formation of base flow in the lowlands, but rather the conditions prevailing in the source area (significantly higher altitudes, and therefore higher discharge than the one in the inter-catchment area of a gauging station);
2. Quaternary fluvial aquifer, with some exceptions, drain into large streams. Base flow from Quaternary fluvial aquifers cannot be determined by measurement below and above aquifer because the increase in stream discharge due to inflow from aquifer is much lower than the measurement error of a large stream.

Therefore, for a significant part of the Czech Republic, base flow cannot be determined by separating the hydrograph on existing profiles. It was therefore necessary to determine base flow indirectly from parameters that are available in the entire Czech Republic. The most appropriate parameter is the long-term average precipitation total, available at a resolution of 1 km^2 (30-year precipitation normal, CHMI). Long-term average precipitation changes gradually in space without sharp changes. The relatively close relationship between long-term average precipitation and total runoff is well known [13].

The close relationship between average long-term rainfall and total runoff based on the analysis of 65 CHMI basins is described in [14]. Average total runoff can be calculated from average precipitation according to the following equation:

$$CO_{\text{prům}} = 0.000571 \times (\text{precipitation})^2 + 0.132 \times (\text{precipitation}) - 170.2 \qquad (1)$$

where:

$CO_{\text{prům}}$	is	total average runoff (mm/year)
(precipitation)		average rainfall (mm/year); in both cases it is a long-term average

The coefficient of determination was 0.97, the root mean square error 7.9 %.

The equation cannot be used for precipitation lower than 450 mm/year because the equation no longer correctly reflects the rainfall-runoff relationship.

After converting to other discharge units, the [14] equation has the following form:

$$CO_{\text{prům}} = 0.0000181 \times (\text{precipitation})^2 + 0.00419 \times (\text{precipitation}) - 5.397 \qquad (2)$$

where:

$CO_{\text{prům}}$	is	total average runoff (l/s/km^2)
(precipitation)		average rainfall (mm/year), again in a long-term average

In 2011, in cooperation with R. Vlnas, the influence of geology on total runoff and base flow was studied. Profiles that did not have one predominant geological unit, as well as those that had obvious in/out flow of water from/to other basins, were omitted from the monitored CHMI gauging profiles. The resulting 138 basins were divided into the following five groups according to geology: crystalline rocks, culm (Lower Carboniferous sediments in Moravia), Carboniferous to Permian, Bohemian Cretaceous Basin, flysch [15].

In the case of total runoff, it was found out that, with the exception of flysch, all basins have the same relationship to the long-term average total precipitation, which can thus be expressed by a single equation; only flysch rocks show lower discharge at the same precipitation total (*Fig. 7*). The reason for the difference in flysch is apparently climatic, not geological. Flysch rocks are found only in the Carpathians, on the border with Slovakia, while other rocks are found in the wider area of the Czech Republic, i.e. their average location differs by up to hundreds of kilometres. Flysch is in a geographically different area in more continental conditions than the average of the other basins. The analysis showed that, in order to determine total runoff, it is sufficient to divide basins in the Czech Republic into just two groups. For all HGR except flysch, average total runoff can be determined from average long-term precipitation from the relationship in *Fig. 8*, while for flysch HGR, the relationship is shown in *Fig. 9*. A comparison of these regression equations with equation [13] is shown in *Fig. 10*.

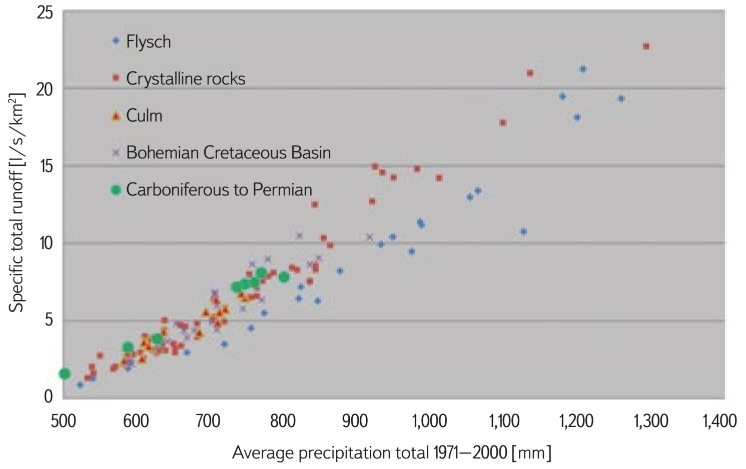

Fig. 7. Influence of precipitation and geology on total flow for catchments monitored by CHMI [15]

It is obvious that precipitation determines total runoff significantly. Geology does not matter with the exception of the flysch, whose basins show lower total runoff than other basins [15].

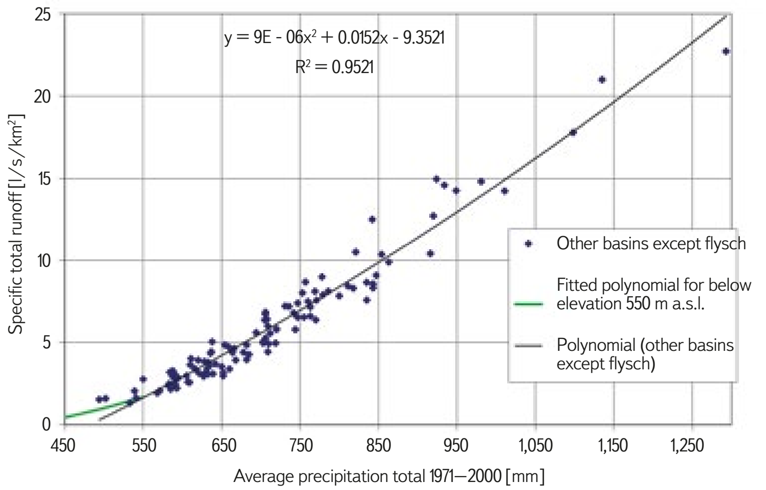

Fig. 8. Relationship between mean precipitation and total flow for all geological types of catchments other than flysch; the fitted polynomial underestimates flow for precipitation below 550 mm/year, and therefore for the lower precipitation total it is replaced by a polynomial for flysch (green line)

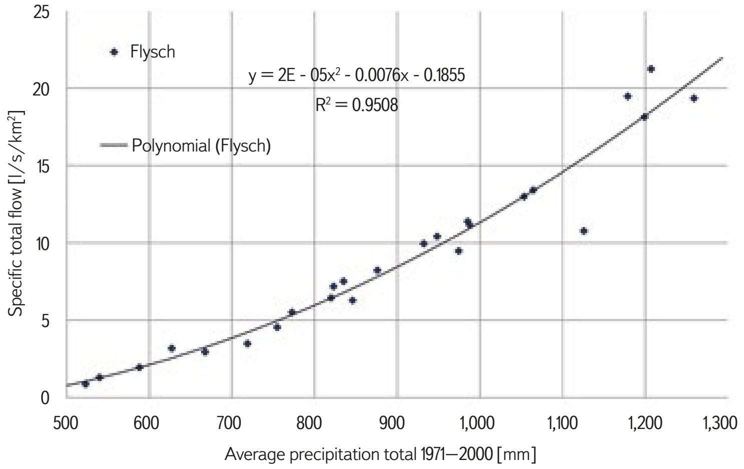

Fig. 9. Relationship between average precipitation and total flow for flysch

Average base flow was calculated from the following equation based on tight regression relationships with precipitation:

$$ZO_{prům} = (a \times (\text{precipitation})^2 + b \times (\text{precipitation}) - c) \times BFI \qquad (3)$$

where:

$ZO_{prům}$	is	average base flow (l/s/km²)
(precipitation)		long-term average total rainfall (mm/year)
BFI		Base Flow Index (dimensionless)
a, b, c		equation parameters (dimensionless) (*Figs. 8, 9*)

BFI for all HGR is listed in *Tab. 1* and parameters (a, b, c) are shown in *Figs. 8* and *9* in the form of regression equations. A similar procedure, i.e. obtaining total runoff from precipitation and then base flow by multiplying by BFI, was used by [16].

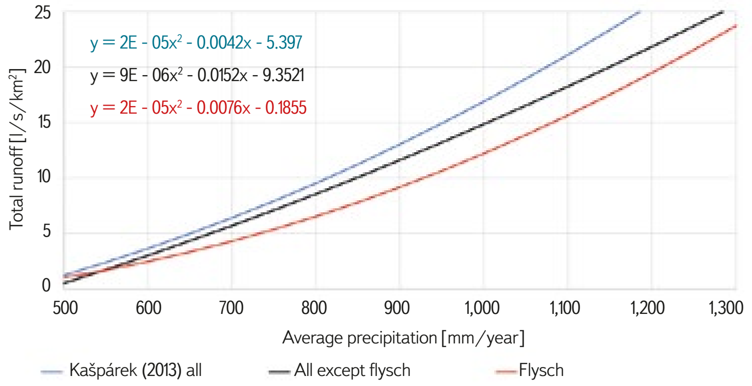

Fig. 10. Comparison of relationships for determination of total flow from precipitation. It is clear that the total flow from flysch catchments (red) is significantly lower than that of other catchments (black). In blue relationship according to formula [16]. The regression equation in *Fig. 10* shows the parameters a, b, c in the form $a \times x^2 + b \times x + c$

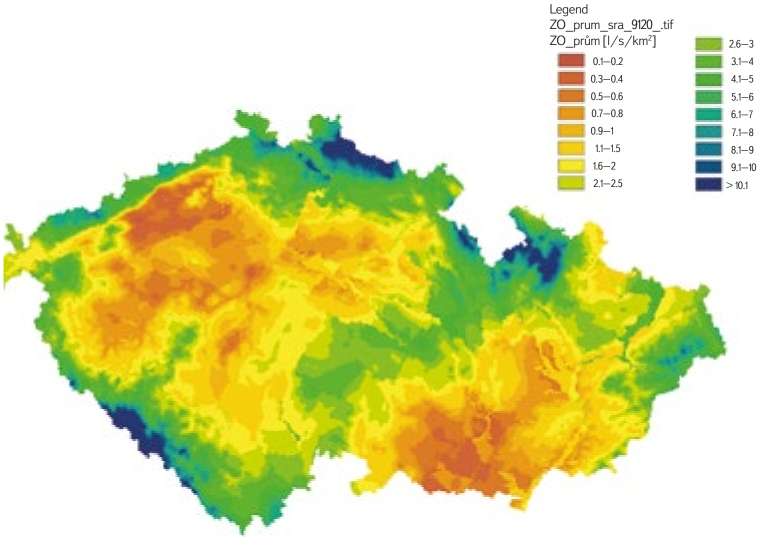

Fig. 11. Long-term average base flow (l/s/km^2) derived from precipitation normal 1991–2020 using regression relationships and BFI index for individual zones. Map is available at: https://mapy.geology.cz/hydro_rajony/

For flysch, the following equation is always used to calculate base flow:

$$ZO_{av} = (2.\,10^{-5} \times (\text{precipitation})^2 + 0.0076 \times (\text{precipitation}) - 0.1855) \times \text{BFI of a given HGR} \qquad (3a)$$

For other HGR in the area with a normal rainfall above 550 mm/year, the following equation is used to calculate base flow:

$$ZO_{\text{prům}} = (9.10^{-6} \times (\text{precipitation})^2 + 0.0152 \times (\text{precipitation}) - 9.3521) \times \text{BFI of a given HGR} \qquad (3b)$$

For other HGR in the area with normal precipitation below 550 mm/year, the following equation is used to calculate base flow:

$$ZO_{\text{prům}} = (2.10^{-5} \times (\text{precipitation})^2 + 0.0076 \times (\text{precipitation}) - 0.1855) \times \text{BFI of a given HGR} \qquad (3c)$$

The resulting map of base flow is shown in *Fig. 11*. The values are slightly lower than in the map of base flow by Krásný et al. [2], which was constructed from data from the 1960s and 1970s (10- to 12-year series from 250 gauging stations) even before the reduction of base flow due to climate change.

Long-term average base flow (*Fig. 11*) is calculated from the long-term average total precipitation from *Equation 3* (variants 3a, 3b, 3c) and the parameters from *Fig. 5* and *Tab. 1* (l/s/km^2). It is clearly visible that in the Quaternary HG regions, base flow is higher than in many of the surrounding HGR thanks to higher BFI.

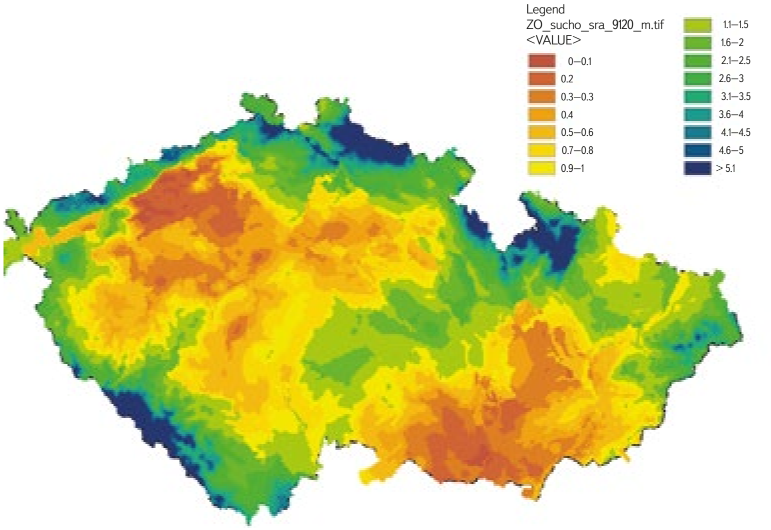

Fig. 12. Base flow in the dry season (l/s/km^2) generated from precipitation normal 1991–2020 using regression relationships and BFI and M indices for individual zones. Map is available at: https://mapy.geology.cz/hydro_rajony/

Derivation of base flow in the dry season from precipitation

Base flow in the dry season was calculated according to the following formula:

$$ZO_{\text{sucho}} = ZO_{\text{prům}} \times M \qquad (4)$$

where:

M is the minimum Base Flow Index (dimensionless) and is listed for all HGR in *Tab. 2* (*Figs. 5* and *6*).

The boundaries of the colour scale categories are different in the ZO$_{\text{sucho}}$ map than in the ZO$_{\text{prům}}$ map due to optimal resolution of values. The maps thus looks like similar. However, the displayed values in both maps differ considerably (cf. *Figs. 11* and *12*). Base flow values in the dry season are significantly lower than average base flow, especially at lower elevations.

BFI and M indices are multiplied together and their multiplication with total runoff gives base flow in the dry season. Therefore, the lowest base flow can be expected during drought in rocks with low permeability at the lowest altitudes (e.g. flysch). Here, base flow in the dry season can reach as little as 10 % of average total runoff of a given area.

Groundwater abstraction and treated wastewater discharge of groundwater and surface water

Recorded groudwater abstraction and discharge of treated wastewater to surface water and groundwater (annual average) was taken from the HEIS point database and subsequently converted to l/s. Each point data is assigned to a given area unit. For example, under individual fourth order basins or floodplains, and for each such unit, the amount of water abstracted from or discharged into a given unit was calculated as a differential of the sums of water abstraction and discharge back to environment.

While for environments A and B (HGR and fourth order basins) only groundwater abstraction and discharge were considered, for environment C (floodplain) surface water abstraction and discharge were also considered. For environment D (build-up parts of municipalities with predominant individual drinking water supply), only groundwater abstraction at the level of the number of inhabitants and average consumption per capita in the Czech Republic was considered. Individual groundwater abstraction and discharge was displayed in the resulting vulnerability map as point objects with different point diameters according to the volume of water abstraction, so that it is clear where exactly in a given unit the recorded water abstraction or discharge occurs.

Vulnerability of groundwater resources to drought

The resulting *Map of Groundwater Vulnerability to Drought* was generated by overlaying and combining several separate GIS layers. The main advantage of this procedure is the fact that a given existing network of units allows updating data, for example, on a change in recharge or, conversely, on a change in water abstraction and discharge, which leads to a change in the values of the units in the vulnerability map. In the future, it will be possible to update the map. For individual environment types, available groundwater resources after subtracting groundwater abstraction were determined in the following ways:

Determining vulnerability for fourth order basins and hydrogeological regions

For environments A and B (fourth order basins and HGR), vulnerability was determined according to the following formula:

$$\mathrm{Bp}\ (\mathrm{l/s/km^2}) = (\mathrm{ZO_{sucho}}{*}\mathrm{Sp} - \mathrm{Op} + \mathrm{Vp})\ /\mathrm{Sp} \qquad (5)$$

where:

$\mathrm{ZO_{sucho}}$	is	base flow in the dry season (l/s/km^2)
Op		groundwater abstraction (l/s)
Vp		discharge of treated wastewater to groundwater (l/s) (very rare)
Sp		area of the fourth order basin or HG region (km^2)
Bp		symbol for the vulnerability of the fourth order basin area and the HG region

Base flow in the dry season ($\mathrm{ZO_{sucho}}$) was calculated from *Equation 4* at a resolution of 1 km^2. Where the groundwater flow in HGR forms a unified flow system (highly permeable aquifers, e.g. Bohemian Cretaceous Basin and South Bohemian Basin, Javoříčsko-Mladečský Karst), the hydrological balance was calculated for the entire HGR as the division into parts of the HGR would be highly subjective. Everywhere else, the balance was calculated in the fourth order basin, thus much smaller area.

Determining vulnerability of floodplains

For environment C (floodplains), vulnerability was determined according to the following formula:

$$\mathrm{Bn}\ (\mathrm{l/s/km^2}) = (\mathrm{ZO_{sucho}}{*}\mathrm{Sp}{*}\mathrm{K} - \mathrm{O} + \mathrm{V})\ /\mathrm{Sn} \qquad (6)$$

where:

$\mathrm{ZO_{sucho}}$	is	base flow in the dry season (l/s/km^2)
K		utilization factor (dimensionless), which was set to 0.5
O		abstraction of both surface water and groundwater (l/s)
V		discharge of treated wastewater to surface water and groundwater (l/s);
Sn		area of floodplain segment (km^2)
Sp		area of the entire orographic basin whose water flows through the floodplain segment (km^2)
Bn		symbol for the vulnerability of a floodplain environment

Base flow was calculated as the average value of base flow from the fourth order basin and HGR in a floodplain orographic basin. Since the floodplain is in contact with the stream, in this case not only groundwater abstraction is considered, but also surface water abstraction and discharge of wastewater. Water abstraction and discharge were considered from the entire floodplain area and also in a strip of 250 m further (use of buffer).

The calculation therefore considers that 50 % (utilization factor) of all base flow in the dry season, formed in the entire area of the orographic basin of a given stream, is available for induced groundwater resources. Since a floodplain typically makes up only a few per cent of the stream orographic basin (about 2–5 % on average), potential induced groundwater resources from the entire basin per unit area of the floodplain are about 20 times higher than for other units. The category boundaries are therefore set differently for the floodplains. If the utilization factor K was 100 %, then the consumption of all base flow from the entire orographic basin would be considered only in a given floodplain segment. However, the orographic basin also accounts for floodplain segments further downstream, which are calculated separately, and such a procedure could lead to an overestimation of groundwater resources.

Determination of vulnerability for municipalities with predominant individual drinking water supply

Groundwater abstraction for individual household wells is not recorded; however, it can be derived from the number of inhabitants of a given municipality because, according to available data, daily average water consumption in the Czech Republic is around 100 l/person/day. Based on the experience of 2015–2020 (hydrological drought), individual groundwater abstraction in municipalities is also one of the most threatened by drought. Individual household wells are very often shallow and use the upper part of a near-surface aquifer where groundwater can only be obtained from the relatively close vicinity of a well. This especially applies to built-up areas, where individual plots are directly adjacent to each other and population density is so high that a sufficient supply of groundwater from precipitation per unit area cannot be guaranteed. This can be demonstrated by a simple calculation using the example of water consumption. The typical base flow in lower altitudes of the Czech Republic, where the majority of population lives and the majority of municipalities are located, does not exceed 1–2 l/s/km^2 [2]. At the same time, base flow corresponds to average groundwater recharge. On 1,000 m^2 of land, the recharge does not exceed 1–2 ml/s, which corresponds to 90–180 l/day. The average consumption is 100 l/person/day, so a relatively large plot of land with an area of 1,000 m^2 is able to supply water to 1–2 people. At the same time, it is obvious that the plots are often significantly smaller and usually more than 1–2 people live on them. The above calculation is based on average long-term recharge from precipitation, not on the recharge in the dry season, when it decreases to half the average value or less at lower altitudes. From the above calculation, it is quite obvious that the drying up of wells in the summer period is inevitable in a number of municipalities as a result of ongoing climate change.

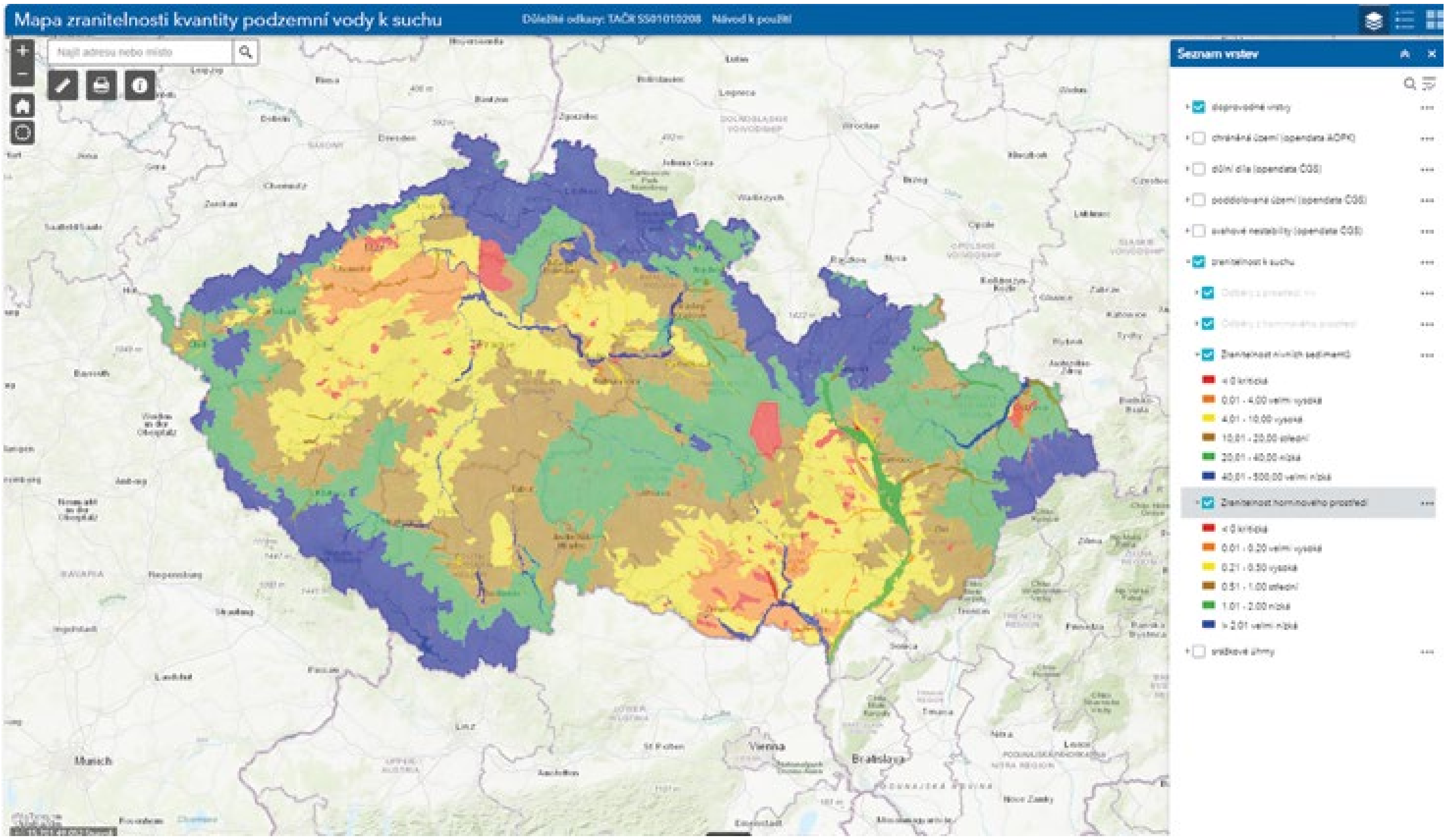

Fig. 13. *Map of the Vulnerability of Natural Groundwater Resources to Drought*. Vulnerability categories are determined from the numerical value of remaining groundwater resources in the dry season after subtraction of groundwater abstraction (l/s/km^2). For floodplains, these are the values of potential remaining recharge from streams (l/s/km^2)

For environment D (municipality with predominantly individual drinking supply), vulnerability was determined according to the following formula:

$$Bo\ (l/s/km^2) = (ZO_{sucho} * So - O * N)/So \qquad (7)$$

where:

ZO_{sucho} is base flow in the dry season obtained from the fourth order basin or from the HGR in which the village is located (l/s/km^2)
So area of the built-up part of the village (km^2)
O average water consumption per inhabitant (0.0011 l/s, which corresponds to 100 l/person/day, and thus the average water consumption per inhabitant in the Czech Republic)
N number of inhabitants of a given municipality
Bo symbol for the vulnerability of the area of the municipality

The number of inhabitants of the municipality was taken from the layer https://csu.gov.cz/vysledky (2020 population census). Alternatively, data was found on the Czech Statistical Office website.

In the hydrological balance, it is therefore assumed that the groundwater source for a given municipality is only water that falls in the built-up part of a municipality, and that no water flows into the municipality from the wider surroundings. Furthermore, it is assumed that the amount of groundwater that is formed in the municipality is the same as the amount of groundwater that is formed in the average landscape around the municipality. Both of these assumptions are basically the worst possible scenario; a number of municipalities have infiltration facilities in the wider area as well, and groundwater flows into them from a larger area. However, there are also municipalities where the orographic basin coincides with the built-up area. In municipalities, more groundwater is clearly formed than in the surrounding landscape, thanks to a much lower density of vegetation and a higher proportion of impermeable surfaces, which are largely drained underground (in residential areas, there is an obligation to infiltrate rainwater on the land and water from a significant part of impermeable surfaces is infiltrated). The resulting hydrological balance therefore represents the worst-case scenario, and the actual result is on the safety side. The actual groundwater recharge in urban areas has not been measured and it is one of the most important unknowns that requires further study.

RESULTS – MAP OF GROUNDWATER VULNERABILITY TO DROUGHT

Vulnerability map categories

The resulting *Map of Groundwater Drought Vulnerability (Fig. 13)* is available at www.suchovkrajine.cz/zranitelnost-k-suchu, maps of average base flow and base flow in the dry season are available at: https://mapy.geology.cz/ hydro_rajony/

The above-mentioned Map is divided into areas in six categories, quantitatively according to the balance (groundwater sources-abstraction/area), i.e. the balance normalized per unit of area:

— critical (red)
— very high (orange)

- high (yellow)
- medium (brown)
- low (green)
- very low (blue)

The following category boundaries apply to fourth order basins, HGR, and built-up parts of municipalities:

- Critical vulnerability (red) has a negative balance, which means that in a given area unit, more groundwater is consumed during the dry season than replenished by groundwater recharge. Natural resources are thus over-exploited in the dry season.
- Very high vulnerability (orange) applies to areas where, after subtracting groundwater abstraction during the dry season, very low base flow remains below 0.2 l/s/km^2.
- High vulnerability (yellow) is for areas where low base flow remains between 0.21–0.5 l/s/km^2 after subtracting groundwater abstraction in dry season.
- Medium vulnerability (brown) applies to areas where base flow remains between 0.51–1 l/s/km^2 after subtracting abstraction in dry season.
- Low vulnerability (green) is for areas where 1.01–2 l/s/km^2 remains after subtracting groundwater abstraction in dry season.
- Very low vulnerability (blue) applies to areas where, after subtracting groundwater abstraction in dry season, there is over 2 l/s/km^2 left.

For floodplains whose small area is contributed by inflowing groundwater from vast orographic basin by stream seepage (induced groundwater resources), the category boundaries are 20 times higher.

Representation of individual categories of vulnerability

Finally, the representation of critical and high vulnerability categories was calculated. For fourth order basins and HGR, the representation is expressed as the ratio of the area of a given unit falling into a given category to the area of the Czech Republic (78,870 km^2).

HGR occupy 16.7 % of the area. In the case of floodplains, it is the area of floodplains in a given category to their total area (5,584 km^2). In the case of municipalities, it is the number of municipalities in a given category to the number of municipalities with a predominant individual drinking water supply (a total of 1,726 municipalities).

For HGR and fourth order basins, 2 % of the territory falls into critical vulnerability, 5 % into very high vulnerability, and 22 % of the Czech Republic into high vulnerability (*Tab. 3*).

For floodplains, 3 % of the floodplain area is critically vulnerable, 13 % is very vulnerable, and another 17 % is highly vulnerable.

The situation is worst in municipalities with predominantly individual drinking water supply, where 93 % of the municipality's territory falls under critical vulnerability, another 5 % under very high vulnerability, and 2 % under high vulnerability.

Tab. 3. Representation of categories from Map of Drought Vulnerability of Groundwater Resources in the Czech Republic

Vulnerability	HG zones (HGR) and fourth order basins area [%]	Floodplain area [%]	Municipalities number [%]
Critical	2	3	93
Very high	5	13	5
High	22	17	2
Medium	27	25	0
Low	25	19	0
Very low	19	23	0
	100	100	100

SUMMARY AND DISCUSSION

The vulnerability of groundwater resources to drought determines not only the volume of dynamic groundwater resources, but also the degree of their current use, since the HGR with the largest groundwater resources often also has the largest groundwater abstraction. The purpose of the *Map of Groundwater Vulnerability to Drought* is an objective comparison of vulnerability of dynamic groundwater resources within the entire Czech Republic. This map is compiled in the form of a hydrologic balance of dynamic groundwater resources and groundwater abstraction based on base flow, base flow in the driest year of 2010–2019, HEIS data, PRVKUK for 2019, population, precipitation totals for 1991–2020, etc. The Map authors are aware that some information from publicly available sources may not correspond to the contemporary situation, for example from PRVKUK, which are updated over a multi-year time horizon and according to the needs of the respective region. The Map is designed so that GIS layers with variable information can be updated in the future.

For large aquifers, where the balance in the entire area is interconnected and the area cannot be meaningfully divided, HGR were the basic units. In hard rock and similar aquifers, the basic unit was the fourth order basin (much smaller areas). River and stream floodplains are assessed individually; here, the groundwater resource is also the water seeping of from streams from large orographic basins.

Total long-term average runoff in the Czech Republic closely correlates with long-term average total precipitation. From the long-term average total rainfall, average total runoff can therefore be fairly accurately determined for any place in the Czech Republic. The influence of geology on total runoff shows to be negligible.

On the other hand, for determining the base flow, the influence of geology is very important and it is necessary to consider different BFI values for individual HGR (see *Tab. 1*). Then, the average base flow was multiplied by the M index – that is, the ratio of the base flow in the driest year of 2010–2019 to the long-term average base flow, which was determined for all HGR (*Tab. 2*). In this way, base flow during the dry season was obtained (dynamic groundwater resources during the dry season). Based on the hydrologic balance, groundwater abstraction was subtracted from base flow during the dry season, and vulnerability of dynamic groundwater resources to drought was quantitatively determined based on the resulting remaining base flow. This procedure also considers the release of water from static reservoirs since base flow from areas with higher storage capacity tends to be more balanced, and thus discharge decreases less in dry periods.

Newly the information on groundwater resources on induced groundwater resources were obtained, which has not yet been recorded in the Czech Republic. The calculations also determined vulnerability of dynamic groundwater resources in built-up parts of municipalities with individual household wells, based on the number of inhabitants and the size of built-up area of the municipality.

The *Map of Groundwater Vulnerability to Drought* is a uniformly processed document that does not coverthe details and specifics of individual locations which could not be determined from the currently available documents. It should therefore be used for obtaining information with the knowledge that a detailed study specifying the groundwater resources for a specific location is needed, including the necessary field measurements.

In 2022, the article *Balance of Groundwater Resources and Needs for Drinking Purposes in Conditions of Climate Change* [17] was presented, which states the probable impact of climate change on the possibilities of abstracting groundwater for drinking purposes in 2041–2060 and processing the balance of the amount of groundwater of the current status, or for the third cycle of river basin plans, i.e. based on data for 2013–2018 (https://www.vtei.cz/2022/10/bilance-zdroju-podzemni-vody-a-potreb-pro-pitne-ucely-v-podminkach-klimaticke-zmeny/). The methodology is based on procedures of water management balance and assessment of the quantitative status of groundwater bodies in accordance with Decree No. 5/2011 Coll., as amended, considering the fact that the article contains three categories – compliant, conditionally compliant, and non-compliant.

When comparing *Fig. 1* in document [16] with the *Map of Groundwater Vulnerability to Drought*, some areas of the corresponding HGR or their parts fall into the category of critical to high vulnerability of the rock environment to drought. The different methodological procedure in the evaluation of floodplain sediments is particularly evident in the upper HGR 1510 Quaternary of the Odra River, 1622 Plio-Pleistocene of the Upper Moravian Graben – southern part, 1623 Plio-Pleistocene of the Blata River, and 1652 Quaternary of the Morava and Dyje Rivers confluence area, which, compared to document [16], are a part of the low vulnerability of floodplain sediments.

The methodology for the creation of an interactive *Map of Groundwater Vulnerability to Drought*, in comparison with paper [16], does not use the methodology for evaluating the quantitative state of groundwater bodies, nor predicting the amount of dynamic groundwater resources in the Czech Republic. It calculates long-term base flow from precipitation for 1991–2020, considers BFI in the driest year of 2010–2019, fourth order basins, abstraction for individual drinking water supply in locations where there are no water works, and presents the values of the remaining specific dynamic groundwater resources in l/s/ km^2 in the driest year of the five-year hydrological drought. The rating scale has six levels. Overall, it can be stated that the newly created *Map of Groundwater Vulnerability to Drought* provides a more detailed assessment of the current status and specific data on residual dynamic groundwater resources compared to document [17].

CONCLUSIONS

- The *Map of Groundwater Drought Vulnerability* is based on data available from the CHMI monitoring network, valid PRVKUK for individual regions as of 2020, from the HEIS database, and population records.
- The vulnerability of dynamic groundwater resources to drought was divided into six categories. The most fundamental is critical vulnerability, which means temporary over-exploitation of dynamic groundwater resources in the dry season, when the groundwater recharge is lower than the currently used amount of groundwater in a given area unit. Areas with this type of vulnerability should be given increased attention. The categories of very high and high vulnerability define areas with only small reserves of base flow, where problems may arise when climate change worsens, or in a period of multi-year hydrological drought.
- The Map shows that areas most at risk of drought are built-up areas of municipalities with individual groundwater supply; 93 % of these municipalities fall under critical vulnerability and another 5 % under very high vulnerability. In floodplain areas, critical vulnerability is only in 3 % of areas and very high in 13 % of areas. For HGR and fourth order basins, the areas of critical vulnerability reach 2 % of the area and high vulnerability 5 % of the area of the Czech Republic, and thus affect a small part of the country so far.
- The Map is designed so that layers with variable information can be updated in the future.
- The Map provides essential information for planning in the area of supplying the population with drinking water, targeting recharge programmes securing resources, and other elimination measures.
- This Map is available at www.suchovkrajine.cz/zranitelnost-k-suchu

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Zambia, a dried-up arm of the Luangwa
River on the border with Malawi, 2022

Interview with doc. RNDr. Zbyněk Hrkal, CSc., hydrogeologist, writer, and populariser of water management

The October issue of the VTEI journal deals mainly with groundwater and its management. We therefore discussed the promotion of this topic with a colleague who is engaged in research in groundwater, has been lecturing on hydrogeology for a long time at the Faculty of Science, Charles University in Prague, and deals with the topic of water management in his publications. "The main problem in the world is not a physical lack of water, but poverty, illiteracy, and economic backwardness," says Zbyněk Hrkal.

Mr. Hrkal, you have been popularizing hydrogeology and water management for a long time. Why this topic?

I will start with a little detour. The aphorism "publish or perish" has been used since 1928. For this reason, among others, scientists have recently been under increasing pressure to publish the results of their research. The quantity and, above all, the quality of the articles becomes a criterion not only for the quality of their work, but also for the professional status of their institution.

I will give one classic example. Almost everyone in the world knows Robert Koch, a German doctor and microbiologist, winner of the Nobel Prize for Physiology and Medicine. After all, he was the one who discovered the cholera bacterium. However, it is not entirely true. Indeed, Koch was the first to publish the results of the origin of this deadly bacterium, thus gaining immortal fame. However, in 1854, 30 years before him, the causative agent of cholera – *Vibrio cholerae* – was isolated by the Italian anatomist Filippo Pacini. But he remained in the laboratory with his discovery and died in poverty and oblivion. He got some recognition only recently.

An important conclusion can be drawn from this: even if they are brilliant, scientists who keep their results "in a drawer" are almost worthless for their institutions, as well as for society in general.

Indeed, but you are talking about professional publications; I rather had in mind the popular-scientific ones, intended for the widest readership. Is it difficult to move from the professional position of a researcher to a level understandable to the common layperson?

Not every top expert – and now I am speaking in general, no matter the field – is able to present their results in a comprehensible manner. They may have dozens of publications in the most prestigious professional journals on their list, but when it comes to conveying the results of their work to ordinary people, no one understands them. It is extremely difficult to find a compromise between professional language and expression understandable to the layperson. The so-called vulgarization of professional text must not occur, which unfortunately we often witness in our media. Journalists read a professional article and, without understanding it, translate it, in their opinion, into the so-called vernacular. The result is "packaged" for the reader in an attractive graphic form, and the popular article is also given a provocative title. The result is a very bad example of how professional literature should be handled. But the opposite example is also bad, when a renowned expert takes up the pen and overwhelms the readers with a whirlwind of professional, often completely unnecessary terms. Although the result is different from the first example, the effect is similar; being able to write a professional text so that it is not only comprehensible, but above all readable and interesting for a layperson unfamiliar with a field is extremely challenging. With a bit of exaggeration, I would say that it is a separate, completely specific literary discipline. It is all the more challenging in the case of hydrogeology, because the subject of our research – groundwater – is not (with rare exceptions) visible.

But you have been dealing with it for many years…

So far, I have published ten books, while the most read ones are from the scientific-popular category. In them, I try to disprove a number of old myths that journalists keep reviving, such as scaring the population that the planet will run out of water. Sometimes it feels like a battle with windmills. I can emphasize endlessly that water on Earth never runs out, it just moves from one corner to another, or changes its state. The next day, however, I open the newspaper and again read a headline with a similarly catastrophic title.

This is why I find popularizing the results of our scientific work enjoyable and fulfilling. I have had a very good response from readers of my books and listeners of my media appearances. I have already received various prestigious literary awards for three books, all of them are selling well, and their dramatizations by the expert in his field, actor Tomáš Töpfer, have had over 200,000 listeners in the Meteor programme on Czech Radio.

What are you working on at the moment?

As far as my popularization activities are concerned, the highlight so far is probably the film project *Water Stories*. Based on my books, I wrote a script for a film documentary that presents water as one of the most important phenomena shaping human civilization. The film will be made by the Twinstars studio of filmmaker Steve Lichtag, who is world famous for his documentaries about marine life. In eight parts, the Water Stories documentary takes the viewer to various places on the planet (China, Sahara, Nepal, Dubai, Israel, etc.). The series presenter will be Taťána Kuchařová, ambassador of the UN Sustainable Development Goals programme. National Geographic became the general partner, which will also distribute the film on its network.

Namibia, with Herero women, 2017

What was your starting point, your career path?

I started my professional career at the then Central Institute of Geology in Prague. Then I moved to France, where I worked for two years at BRGM in Orléans and later at ANTEA. After returning to the Czech Republic, I started working at my alma mater, the Faculty of Science of Charles University, teaching hydrogeology and water management. However, teaching activities did not prevent me from participating in foreign projects. For my former French employer, I led projects in Kazakhstan and Siberia. For my job, I visited India, Nepal, Kyrgyzstan, Israel, and a number of other, mainly developing countries. I am still at Charles University; however, my main job is currently at the Water Research Institute.

In terms of water management, which other countries could we take an example from?

Israel should definitely inspire us. The speed with which new water management technologies are developed and put into practice is admirable. Thanks to them, Israel became the first country to stop depending on atmospheric precipitation. Even if it hypothetically stopped raining, Israelis can be incredibly economical with water, they know how to recycle water almost endlessly, and in the worst case they can produce it cheaply from the inexhaustible source, which is the sea. So, when my Israeli colleagues visit the Czech Republic and I talk about our issues with drought, they usually smile indulgently. Israel demonstrates my long-presented idea that all issues related to water scarcity are currently technically solvable. The main problem is not the physical lack of water, but poverty, illiteracy, and economic backwardness.

What about the topic of artificial and bank infiltration, which you have been dealing with for a long time?

This is one of the topics that is related to the previous question. It is a technology that simulates and intensifies the natural process of transforming surface water into better quality groundwater. At the beginning of the twentieth century, we were already worldwide pioneers of this water management process in the Káraný area. In 1968, we supplemented the original process of bank infiltration with today's perfectly functioning artificial infiltration system. At that time, our water management was at the top of the world. Since then, however, only repetitive preparatory studies have been created, but no similar project has yet been implemented.

You also study the occurrence of micropollutants in groundwater, such as pharmaceuticals and microplastics. What are the latest findings in this issue?

It is true, the issue of the presence of pharmaceuticals and recently also microplastics, especially in drinking water, has recently become my main activity. After a long time, it is a new water management challenge, because thanks to the leap in development of analytical chemistry, the door to a completely unknown world has opened before us. A few years ago, we had no idea that specific substances could be present in the aquatic environment in concentrations of tens of nanograms per litre, which, in rough comparison, represents a drop in a swimming pool. We now know about dozens of pharmaceuticals that are quite commonly present in all European rivers and represent a kind of "natural" background. These substances penetrate into groundwater and are also found in drinking water. The problem is that this is an interdisciplinary question. A water manager can describe in detail the behaviour of these substances in aquatic and rock environments, characterize their transformations into subsidiary products, but in the end, they always encounter the limits of their own knowledge. We ask ourselves a question that we cannot answer. The question is: are the concentrations of substances that we have described in such detail dangerous for human health? We have hundreds of scientific studies on negative impacts on fish stocks and water-bound ecosystems. However, we still know very little about how these specific micropollutants affect the human body.

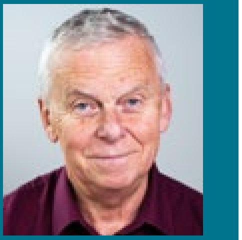
Where do you see the future of your field?

Definitely in interdisciplinarity. We have before us a number of questions, in many cases of a very fundamental nature, the solution of which will require a change in established scientific procedures. It will be necessary to connect scientific disciplines whose cooperation was considered unlikely until recently. The scientist will have to place the achieved results in the widest possible context, including the often neglected economic one. I am personally convinced that a completely new world can open before us, for example, by connecting medicine and hydrogeology. As an inspiration, I can mention studies from Japan and the USA, where collaboration between hydrogeologists and doctors demonstrated a statistically significant impact of increased lithium contents in drinking water on crime reduction. This metal, commonly used in psychiatric practice, reduces aggression. We can build on the long-term successful cooperation with doctors in the field of mineral waters. However, in my opinion, there are a lot of discoveries hidden in the issue of micropollutants, which can move human knowledge in perhaps unexpected directions.

Mr. Hrkal, thank you very much for the interview.

Mgr. Pavel Eckhardt

Doc. RNDr. Zbyněk Hrkal, CSc.



Doc. RNDr. Zbyněk Hrkal, CSc., born on 1st March 1957 in Prague, studied hydrogeology at the Faculty of Science, Charles University in Prague, and Francophone culture at the Faculty of Education of Charles University. After graduating in 1981, he joined the Central Institute of Geology in Prague, where he dealt with the hydrogeological issues of nuclear waste repositories. In 1991, he moved to France, where he worked first in the French geological survey BRGM, based in Orléans, and later in its privatized branch, ANTEA. The main goal of his work was the application of GIS in dealing with hydrogeological issues. After returning in 1992, he joined the Department of Hydrogeology of the Faculty of Science, Charles University in Prague as a teacher and researcher, where he completed his habilitation in 2003. In parallel with his academic work, he continued to cooperate with ANTEA on foreign contracts, ecological audits on the Irtysh River in Kazakhstan in the Ust Kamenogorsk region and Semipalatinsk, and later also in Russia in the vicinity of Omsk. Later, he led projects focused on the issue of Borjomi mineral waters in Georgia and for the international group IDS in Ukraine. As part of development aid projects, he worked in Nepal, India, Saudi Arabia, the Palestinian Territory on the West Bank, and other countries. In 2003, he came to the Water Research Institute as a researcher, where he led the Department of Hydrogeology. However, he has maintained his teaching activity at Charles University, as well as at French universities, to this day. His professional long-term focus is on two areas – artificial infiltration and micropollutants in surface and groundwater, especially pharmaceuticals and microplastics. In this context, he led a number of domestic projects (TA CR) as well as foreign ones (Horizon and Interreg).

Photo: J. Unucka

Photo: 123RF.com

Danube Regional Water Lighthouse Action

Accessible and high-quality water is a natural resource essential for life, well-being, and social prosperity. After decades of intensive exploitation, pollution and socio-economic pressure, Europe's freshwaters and seas are at risk of degradation. This has to be seen not only as a potential dramatic loss from an economic point of view, but also it means unpredictable ecological, social, and cultural damage.

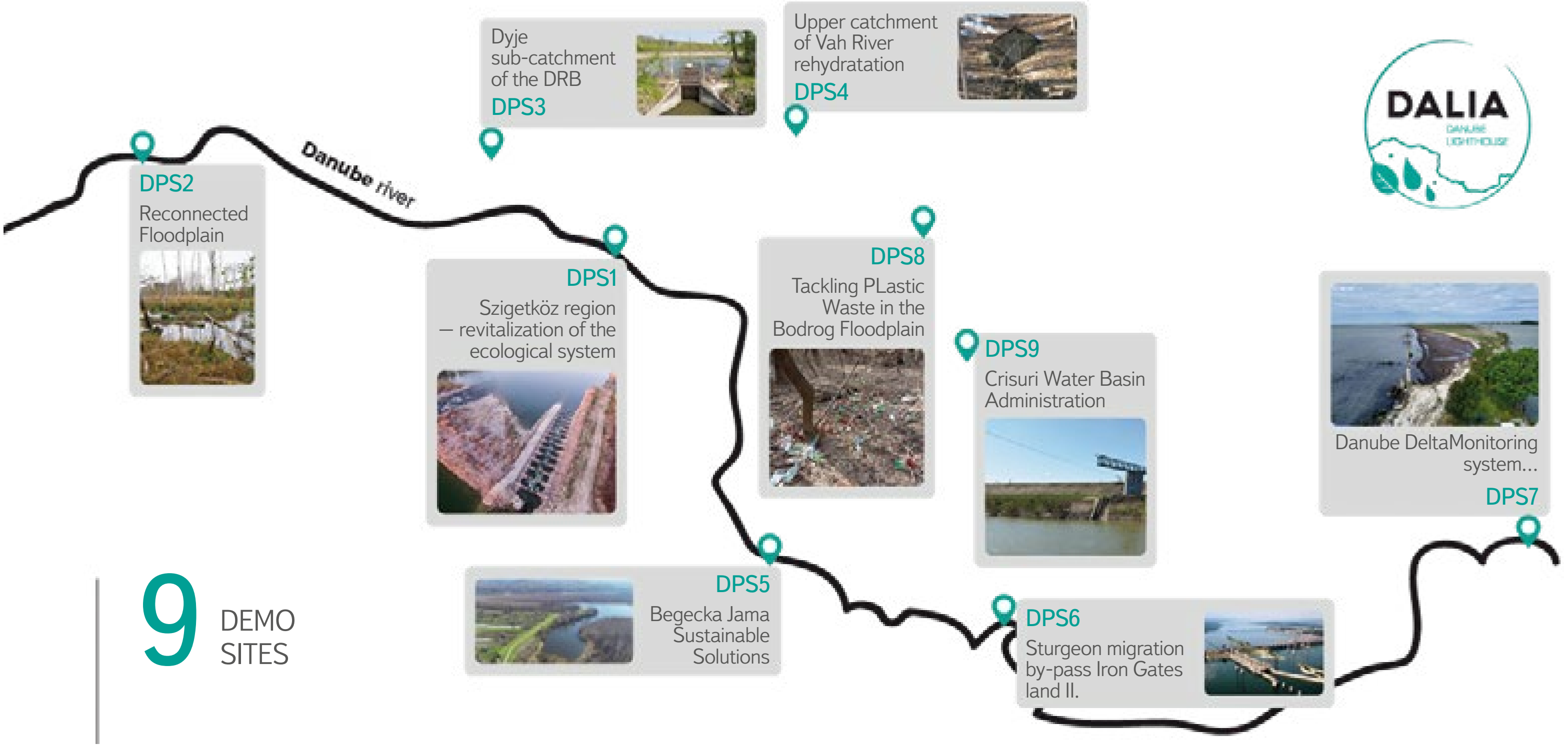
The European Commission has responded to this challenge by creating the research and innovation mission *Restore our oceans and waters*; with a 2030 target, the aim is to provide a systemic approach for the restoration, protection and conservation of oceans and freshwater. In 2022–2025, a development and pilot phase has been underway, during which four so-called *Mission Lighthouses* were launched. "*The Danube Regional Water Lighthouse Action*" (DALIA) aims to significantly contribute to the improvement of the state of the Danube basin; it is financed by the European Union under the Horizon Europe programme with a total subsidy of € 8,499,236. The basin is home to almost 80 million people and extends over 19 European countries, which is exceptional even on a global scale.

The project consortium is coordinated by the Hungarian General Directorate of Water Management (OVF) and consists of 22 institutions from nine European countries (eight from the EU). The consortium is developing an integrated tool to improve decision-making mechanisms and to more effectively restore freshwater and transitional ecosystems in the Danube basin. It also participates in cooperation with a wider network of related national and EU-funded missions and projects. As part of the work packages, there are nine pilot sites addressing various issues of the Danube and its tributaries. These include, for example, pollution by the introduction of micropollutants, municipal waste, a change in the natural physical parameters of the watercourse (e.g. temperature), and the maintenance of a minimum residual flow.

The integrated web-based tool will benefit from the knowledge and experience transferred from individual pilot sites, located along the watercourse up to the delta on the Romanian-Ukrainian border. In this area, which is a UNESCO biosphere reserve, research is focused on sediment transport and accumulation and reducing municipal waste inputs, especially plastics. A pilot area on the Bodrog River in Hungary is facing a similar problem; here, the contamination of micro and macro plastics is also compounded by the legacy of toxic load from former mining activity.

In Slovakia, the Danube hydrology is influenced by rainwater management practices in rural areas. The underestimated impact of erosion leads to reduction of water resources in the upper parts. The drying up of spring areas and small watercourses during recurring long-lasting drought affects the overall river flows in the area.

In the lower part of the Danube, the focus is on river connectivity enabling sturgeon migration. As part of the project, a strategy will be proposed to help



sturgeons pass upstream through Iron Gates I and II. This includes a special solution for each hydroelectric power station and tracking the movement and behaviour of sturgeon using ultrasound. Monitoring will be carried out by three fixed gates and ships on more than 700 river kilometres.

Another demonstration site on the Danube left bank includes Begečka Jama Nature Park and the Begeč-Gložan drainage system. Pollutants from agriculture and wastewater threaten the local ecosystem stability. For secondary wastewater treatment, a constructed wetland system is used here, which acts as a biofilter to remove pollutants and pathogens. This, along with careful monitoring, aims to improve the area's environmental health.

The research team of the TGM WRI Department of Hydrology (Ing. Adam Vizina, Ph.D., Ing. Adam Beran, Ph.D., and Ing. Petr Pavlík) is participating in the project mainly via research in the Dyje pilot basin with special emphasis on the Soutok site. In this area, a comprehensive restoration measure is currently underway – *Obnova přirozeného vodního režimu revitalizační soustavy v EVL Soutok-Podluží* (*Restoration of natural water regime of the revitalization system in Soutok-Podluží SAC*); its purpose is to improve the water regime in Soutok-Podluží SAC. It includes 14 actions; the most significant is the construction of a transverse object – a flap gate weir, which will enable a substantial increase in the amount of water released into the alluvial forest through existing infiltration structures. The pilot site is studied within the proposed modifications and its character is evaluated with a view to simulated climate change scenarios.

The project team is developing a robust online tool for calculating and comparing the minimum residual flow (MRF) and is involved in hydrological modelling tasks in the context of future climate scenarios. It is also coordinating the creation of a summary report on implemented technical measures in pilot sites and links the activities of related projects.

At the time of writing the article (June 2024), DALIA Rivers Revived call was taking place. It was an open call for associated regions within the "*Danube Regional Water Lighthouse Action*" project. Detailed information about the project can be found at https://dalia-danube.eu/.

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Hydrogeological aspects of boreholes for heat pumps

In recent years, there have been significant legislative and methodological changes in the construction and use of geothermal heat pumps (GHP), also known as ground-source heat pumps (GSHPs). The use of GHP has become a widespread solution for heating buildings of all kinds, from family homes to industrial buildings. This article concerns GHP (ground-to-water and water-to-water types) that use shallow geothermal energy, obtained mainly through boreholes.

A GHP removes heat from the geological environment (rocks or groundwater) and converts it to a higher temperature usable for central heating and hot water. The primary GHP circuit of the ground-to-water type most often consists of a borehole, but it can also be surface collectors placed a short distance under the surface (or other solutions); in the case of water-to-water GHP, it is a system of collection and injection wells (one or more).

Methodological instruction of the Ministry for Regional Development

In 2023, the Energy Act No. 458/2000 Coll. was amended by Act No. 19/2023 Coll. The result of these changes is, among other things, a significant simplification and acceleration of the process of permitting ground-to-water GHPs. In July 2023, a methodological instruction was published by the Ministry for Regional Development entitled *Location, permission, and use of heat pumps* [1].

According to this instruction, a borehole for the ground-to-water system does not meet the definition of a structure according to the Building Act No. 283/2021 Coll.; therefore, according to this Act, boreholes do not require any permit. The GHP itself is considered a product, and its installation is not subject to planning or building regulations.

Drilling these boreholes (with an average depth of 100–200 m) means a considerable risk of affecting the natural conditions of groundwater in the area (such a deep borehole usually passes through several aquifers) and a large number of these boreholes are drilled every year throughout the Czech Republic. Therefore, from a hydrogeological point of view, it is very problematic that these boreholes are not subject to any approval and documentation process.

However, drilling these (mostly deep) boreholes still requires a permit according to the Water Act, i.e. obtaining consent from the relevant water authority according to Section 17, paragraph 1, letter g, of the Water Act No. 254/2001 Coll. The main basis for them is the expert statement from the holder of the certificate of professional competence for hydrogeology (Act No. 62/1988 Coll.) [2] and the opinion of the basin manager. Currently, the Water Authority is the only body that comments on the plan of a borehole for a ground-to-water GHP. Its role in the protection of natural water conditions in an area is therefore absolutely crucial.

New handbook of the Ministry of the Environment and the Czech Association of Hydrogeologists

In response to this new situation, the Ministry of the Environment (MoE) and the Czech Association of Hydrogeologists (ČAH) published a *Handbook for the design, permission, and drilling boreholes for "ground-to-water" and "water-to-water" heat pumps* [3], which is intended to help to better design and construction of boreholes for GHP. The material is intended for water law, construction and other authorities assessing and authorizing these boreholes, and borehole and exploration companies. The issue is also dealt with in detail by Semíková et al. [4], however, this older methodology reflects the legislative status of that time.

The MoE and ČAH handbook has two basic parts:

- design, permission, and drilling boreholes for ground-to-water GHP;
- design, permission, and construction of collection and injection wells for water-to-water GHP.

Both parts discuss the design and placement of boreholes, their design parameters and specific conditions for their construction, the procedure for permitting boreholes, and risks for surface and groundwater bodies, and ways to prevent these risks. The handbook also addresses issues of assessing the impact of these plans on the environment pursuant to Act No. 100/2001 Coll. (EIA).

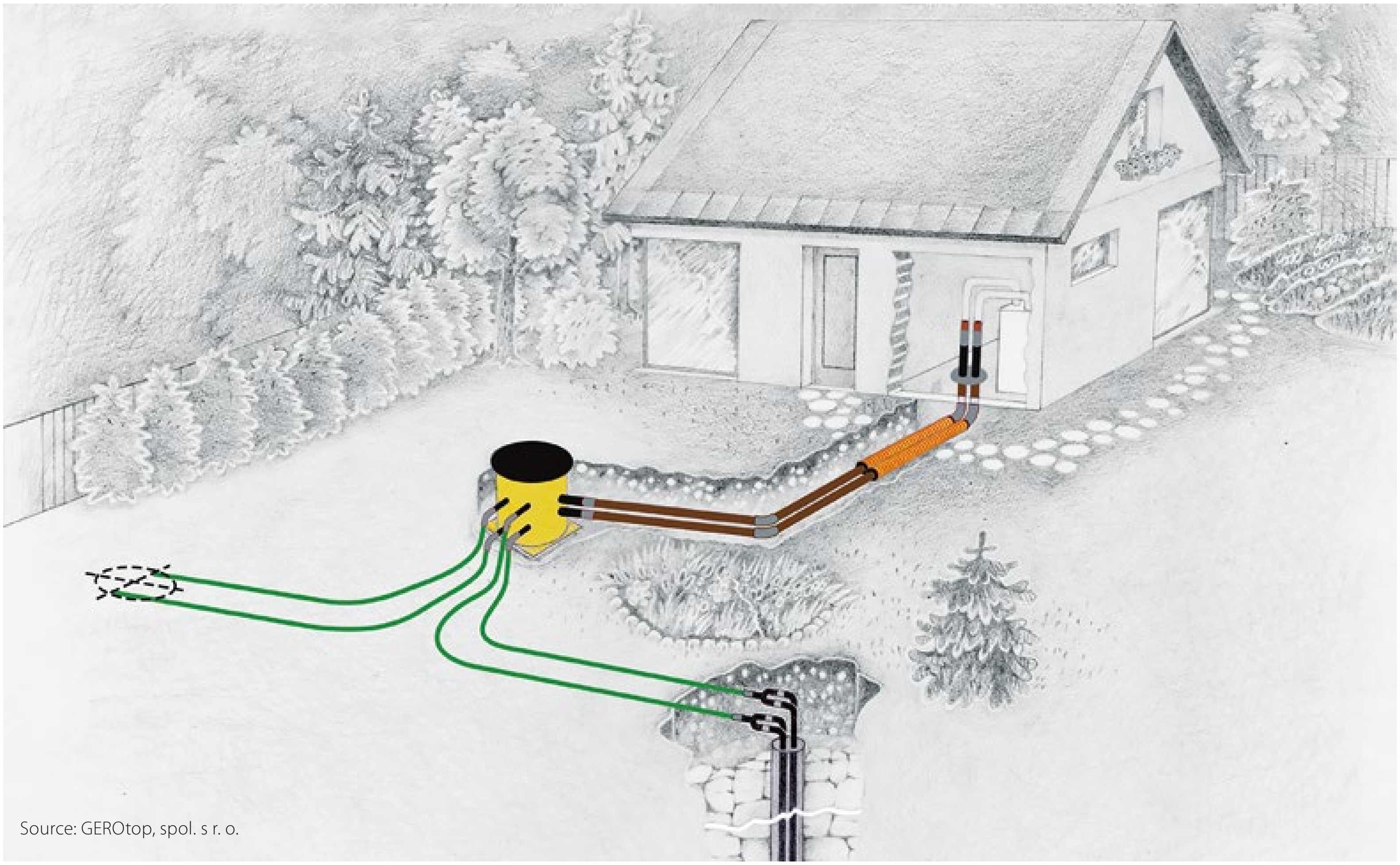
Ground-to-water heat pumps

The risk of boreholes for ground-to-water GHP lies primarily in the danger of disrupting the natural hydrogeological stratification of the rock environment, i.e. in connecting several aquifers, which are often used as sources of water for human needs. Their incorrect drilling therefore risks the reduction of natural groundwater resources and an impact on surrounding water collection facilities. A fundamental requirement is therefore an expert assessment of the impact of boreholes on the water regime of an area (see Annexes No. 7 and No. 11 of Decree No. 183/20218 Coll.). It is recommended that a hydrogeological cross-section of the area is created with the designation of aquifers and aquitards, as well as a proposal for the parameters of the borehole seal, so that GHP boreholes are as detached as possible from their surroundings and, above all, do not connect naturally separated aquifers. This often happens in practice, either due to an inappropriately designed borehole structure or poor-quality construction of the borehole seal. The problem is often an insufficient drilling diameter; the loops of the vertical probe of the primary circuit fill the borehole and there is insufficient space for a functional pressure seal of the borehole.

Water-to-water heat pumps

The second part of the handbook refers to water-to-water GHPs, which serve for groundwater abstraction, the removal of its heat, and the return of the cooled water back to the rock environment. The system therefore usually consists of a collection and injection well (drilled or dug). There have been no fundamental changes to these GHPs; wells or boreholes are waterworks and are built within the framework of Building Act No. 283/2021 Coll., like so-called other structures. The collection and injection of water falls within groundwater treatment, which is permitted by the relevant water authority on the basis of the statement of a person with professional competence in hydrogeology (Section 9, paragraph 1 of the Water Act), the opinion of the basin manager, and other documents.

During the drilling of wells, it is possible to proceed even through the intermediate stage of exploratory hydrogeological boreholes according to



Source: GEROtop, spol. s r. o.

Act No. 62/1988 Coll. (Geology Act), in cases where there is a lack of sufficient documents for proper design and engineering of the waterworks. However, they also require the prior consent of the water authority according to Section 17 paragraph 1 letter i) of the Water Act.

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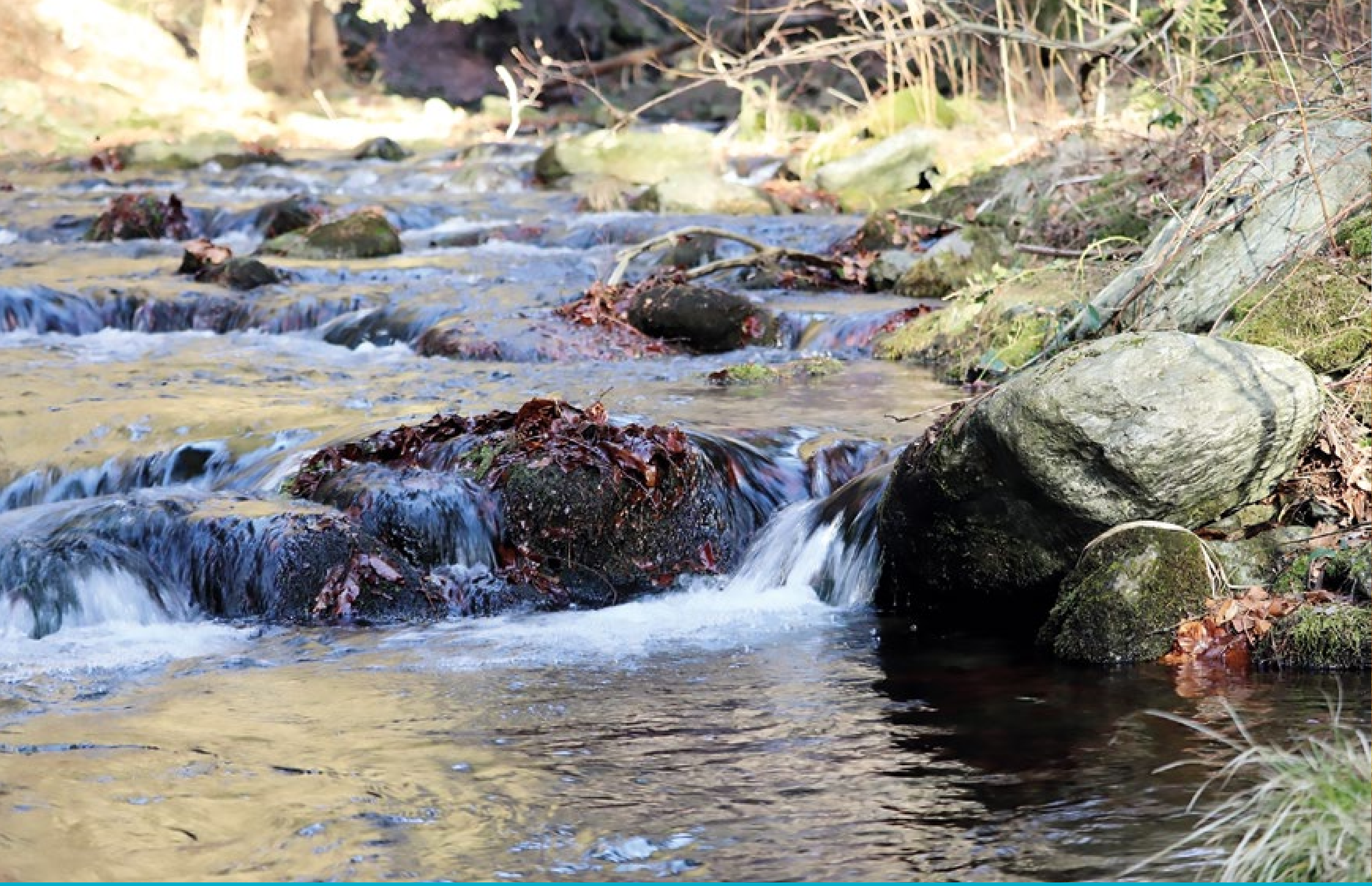

BŘEZNÁ

The Březná river is the most important tributary of the Moravská Sázava. Its headstream with a spring is located in Hanušovická vrchovina in the Jeřáb massif (1,103 m above sea level), in the mountain pass towards Bouda hill (956 m above sea level). One of the springs is the so-called Rudolf's spring, which is also named Leopold Grabner's spring. The length of the stream is less than 32 km and the catchment area is 130 km^2. The Březná flows into the Moravská Sázava as its left-hand tributary on the edge of the village of Hoštejn, near the railway corridor, and roughly follows the historical land border between Bohemia and Moravia. It flows through the villages of Moravský Karlov, Štíty, and Drozdovská Pila, among others. Mill races are typical for its valley, which are mainly concentrated in the section between Drozdovská Pila and Hoštejn. In the village of Drozdovská Pila itself, mills and races were established as early as the 17th century, soon after the establishment of the village (the first records of it date from 1633). Other preserved mills include Karlovský mill and, further downstream, Panský and Kuhnův mills. In contrast, only modest remains and ruins have survived from Valentův and Felzmanův mills. In the village of Hoštejn, on a prominent deforested hill, we can find the ruins of a medieval castle (first mentioned in 1267) and a monument to the completion of the Prague-Olomouc railway (1845). Březná valley is one of the most beautiful in the Morava basin. The area's natural attractions include serpentine forests with the occurrence of dwarf forms of plants. Silver fir (*Abies alba*) can be seen quite often in the coniferous forests of the basin. Rare and interesting representatives of the local fauna include black stork (*Ciconia nigra*), common crane (*Grus grus*), and Eurasian lynx (*Lynx lynx*).

Text and photo by doc. RNDr. Jan Unucka, Ph.D.

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