

Determination of the yield of thermal mineral springs emerging into the Bečva River in the Teplice Spa

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Abstract: The mineral water in the Teplice Spa emerges into the Bečva River bed from the hypogenic karst formed by Palaeozoic limestones. Recently the focus on the hydrological and hydrogeological conditions of the mineral springs issues from the planning of the Skalička Dam whose reservoir is believed to be interconnected with the karstic formation and may influence the regime of mineral waters in the spa. One of the related particular problems is to determine the discharge of the mineral water which emerges into the Bečva River in the river reach along the Teplice Spa. The knowledge about the emerging mineral water discharge is crucial for further assessment of an impact of planned reservoir. The most challenging issue and novelty of the study was to determine a relatively small increment of the discharge in the Bečva river, when the magnitude of the error of determination was comparable to the determined discharge. Therefore, for the assessment of the discharge three methods were applied, namely measurements by the classical current meter, measurements using the Acoustic Doppler Current Profiler and evaluation of the measurements of electrical conductivity along the river reach. The analysis of obtained results and comparison of the obtained methods indicate the emerging discharge between 250 and 500 l/s with realistic value about 350 l/s. The study shows quite good agreement of results determined by individual methods which justifies the methodology used and is good guidance for similar studies.

Keywords: Karst; Mineral springs; Hydrometrical measurement; Electrical conductivity.

1 INTRODUCTION

The Hranice Karst is situated in the eastern region of the Czech Republic (N 49°32', E 17°45'), at the contact between the eastern Bohemian Massif and the Outer Western Carpathians and is classified as a hypogene karst.

The contact of the Bohemian Massif and the Outer Western Carpathians influenced the overall tectonic structure of the Hranice Karst. The stable isotopic composition of CO₂ together with the ratio of 3He/4He dissolved in water indicates the origin of the gases, which subsequently form thermal karst waters near the mantle/crust transition (Meyberg and Rinne, 1995; Šmejkal et al., 1976; Šrámek et al., 2019).

Discharges of groundwater into rivers and lakes often significantly alter surface water characteristics, such as temperature or contents of particular substances and minerals, and influences its quality. Monitoring of the discharges is important as the rivers are frequently a source of drinking water or are used in agriculture. Especially during dry periods, the groundwater continuously supplies a river and maintains its base flow. In this context determination of springing water quantity is essential.

At the same time, the springs that originate within karst areas belong generally to the least explored water sources. The karst aquifers are the most complex systems, and possibilities to explore them are considerably limited. In our study, we pay attention to Bohemian Karst, a region located in the Czech Republic, that belongs to the most significant karst areas worldwide.

The mineral water springs in the area of the Teplice Spa (the Czech Republic) origin in the karst structures formed by Palaeozoic limestones (Šrámek et al., 2019). The mineral water

emerges to the boreholes of the Teplice Spa and to the river bed of the Bečva River in the river reach passing along the spa. Higher mineralization was indicated also in karstic formations such as the Hranice Abyss and the Zbrašov Aragonite Caves.

The development of the territory from the end of the Miocene to the present is primarily controlled by the tectonic style of the prevailing Western Carpathians (Špaček et al., 2015). This fact influenced the tectonic structure of the karst and its current form. It is generally believed that due to the contact of the Bohemian Massif and the Western Carpathians, the formation of the hypogenic karst features and the surrounding mineral springs are related to the influx of carbon dioxide (CO₂) from deep parts of the karst (Špaček et al., 2015). The mineral water migrates from the depth along an undescribed network of fissures or channels. It is estimated that the water in the discussed karst retains in the system over 20 to 50 years (Šrámek et al., 2019) and discharges to the surface in the form of thermal springs.

The Skalička Dam with a lateral reservoir is planned about 3.5 km upstream of the spa and partly interferes the protection zone of the mineral waters. The dam locality is believed to be interconnected with the karstic formation and may influence the hydrogeological regime of the source of mineral waters (Geršl and Konečný, 2018). For further analysis, it is important to determine the rate of mineral water inflow into the Teplice Spa area. While mineral water captured in the spa is well monitored, springs emerging into the Bečva River are still unknown.

A common approach to estimating groundwater discharge is to develop a hydrologic model that incorporates several effective covariates, such as meteorological data, soil properties, or land surface parameters. These factors can be combined either in a simple water balance equation (Zacharias et al., 2003), or are merged in a more complex probabilistic model (e.g., see

Mirabbasi et al., 2024). Other usually used method is based on monitoring tracers, such as the isotopes ^{222}Rn , ^{226}Ra or ^3H . (Kong et al., 2025; Zill et al., 2023; Mirabbasi et al., 2024). Such methods are financially demanding and time consuming, and its accuracy may decrease under factors not incorporated into the model. Hence, these methods cannot be used in areas with complex hydrological regime (Zacharias et al., 2003).

In karstic formations it is usual that the geometry of groundwater flow system is not possible to be precisely identified and the connection between recharge area and spring area may not be clear (Milanovic, 2018).

The comprehensive hydrogeological studies (Řezníček, 1981; IlFaut, 2022) located the source of karstic water in the Bečva River about 4.5 km upstream from the Teplice Spa. The natural yield of thermal waters was also estimated by Bruthans et al. (2021) by the flow rate between 12 and 17 l/s. For the estimate the change of electrical conductivity (EC) in the Bečva River and data from pumping mineral water in the spa were used. However, the methodology described in the study by Bruthans et al. (2021) is considered to be misguided and the derived discharge as not reliable. Careful investigation of electrical conductivity in the locality was carried out by Koryčánková (2020), however without any estimate of the emerging discharge to the Bečva River. Valuable conductivity data obtained by Koryčánková (2020) were provided by the discharges in the Bečva River and analysed in this study. The average value of electrical conductivity upstream of the Teplice Spa, above the monitored area, was 398 $\mu\text{S}/\text{cm}$. The average value of electrical conductivity in the river reach with the mineral springs was 1172 $\mu\text{S}/\text{cm}$. The determined electrical conductivity of mineral water withdrawn from the wells in the Teplice Spa provided conductivity value of 2693 $\mu\text{S}/\text{cm}$.

To estimate emerging thermal water yield the discharge measurement along the river reach was used. Traditionally standard current metering using propellers was applied according to Boiten (2003), ISO 1088 (2007) and ISO 748 (2021). The horizontal distance of verticals was 1 m (about 30 verticals in a profile) with 3 velocity points at each vertical. In case of small yields of emerging thermal water, the uncertainty in point-velocity measurement and its integration over the profile may be governing the reliability of the results (Hasníková et al., 2015; González-Castro and Lee, 2020). So called "uncertainty budget" was used for the discharge estimation (Lee et al., 2014). The method was based on detailed statistical examination of seventeen sources of uncertainties. As the method is complicated and time consuming, in time varying conditions shift methods should be used to make correction in the discharge evaluation (Rainville et al., 2016).

For more rapid measurements Acoustic Doppler Current Profiler (ADCP) can be used (Rehmel, 2006; Turnipseed and Sauer, 2010; Laks et al., 2017). The application of the instrument for measurement of the discharge in open channels with mean depth less than 1 m is discussed by Fulford (1992). The ADCP instrument was applied with moving-float collecting data slowly traversing predefined profiles from one river bank to the other and back several times. This method was indicated as fast and efficient and applicable for measurement in shallow channel flow (Mueller et al., 2013). The uncertainty of this method was discussed by Despax et al. (2023). The uncertainty was validated by the authors using empirical uncertainty estimates from two large-scale repeated experiments with variable site and flow conditions. The mean and the 95% quantiles of the uncertainty differences were determined as -0.4% [-4.4% ; $+2.5\%$].

In case of mineral water springs the electrical conductivity measurements are frequently applied (Bruthans et al., 2021).

This geophysical method is frequently used to identify mineral waters leakages (Loisy et al., 2013), to detect mineral water flow in porous media (Schmidt-Hattenberger et al., 2011) or in carbonate rock (Cherubini et al., 2019).

A survey of available literature showed that methodology for determining of relatively small discharges, when the measurement error was comparable to the determined discharge was missing. In this study the upward flow of mineral water emerging in the Bečva River was determined using three independent methods, namely measurements by the classical current meter, using the ADCP and evaluation of the measurements of electrical conductivity along the river reach. The latter analysis concerns both data obtained in this study and older data measured by Koryčánková (2020). The results of this study provide an estimate of the emergence discharge of mineral water to the Bečva River in the Teplice Spa. The methodology presented may provide useful information for further studies elaborated in connection with the planned dam Skalička (e.g., multicriterial analysis of the variants of the scheme) and guidance for cases where an expected measured discharge has the same magnitude as the measurement error. This applies to river reaches with small inflows that cannot be directly measured, e.g., from groundwater aquifers.

2 STUDY AREA

2.1 Overview

The study area is located on the border of the Olomouc and Zlín regions in the Czech Republic and belongs to the administrative district of the Hranice Regional Municipality. The locality belongs to the Hranice Karst, particularly to the Teplice Spa on the Bečva River. The area is shown in Figure 1 where local municipalities with the Bečva River and the principal Karst formations are depicted with the planned Skalička Dam (Figure 1).

2.2 Geological and hydrogeological conditions

In the locality, the most prominent types of Devonian limestone are those that rise to the surface in the western part of the area between the Teplice Spa and the railway cut to the east from the village of Černotín. Their very easternmost outcrop is found in the locality of Kamenec in the area of the proposed reservoir (Figure 1). It is supposed that a certain amount of the surface water from the Bečva River and Kamenec sinks along the faults and then flows further on to a significant depth, where it becomes saturated with juvenile carbon dioxide (Šráček et al., 2019). After mineralization, the water proceeds upward and emerges into the Bečva River, the pumping wells at the Teplice Spa, to the Hranice Abyss and to the lakes in the Zbrašov Aragonite Caves. The thermal waters in the Teplice Spa have a temperature 22.5 °C, are of the Ca-HCO_3 type with a total mineralization of 2.9 g/l, with CO_2 content of 2.5 g/l and electrical conductivity about 2700 $\mu\text{S}/\text{cm}$. The carbon dioxide content and electrical conductivity of mineral water springs is generally highly variable depending on geological conditions, the depth of the spring, groundwater activity or seasonal fluctuations. CO_2 content of non-mineralized water in streams or springs may typically range from 0 to 15 mg/l with electrical conductivity up to 500 $\mu\text{S}/\text{cm}$.

The depressions of the post-Paleozoic relief are filled with the clays, claystones, sands, sandstones, gravels and siltstones that fill the Teplice Depression. The Hranice Karst is hypogenic karst at which confined karst water flow is upward (Klimchouk, 2009). The extent of the Hranice Karst and the spatial

distribution of its Devonian limestones has not been exactly specified. The karst layer is mostly overlaid by relatively impermeable Palaeozoic greywackes and tertiary claystones and by Quaternary layers of fluvial sediments of the Bečva River (sandy gravels and fluvial silts). Warm karst mineral waters spring up within the erosional base formed here by the Bečva River. Therefore, the springs are scattered, and it is not possible to search for a specific spring. For the protection of the Teplice

spa and valuable mineral springs the protection zone was declared (Fig. 1) based on the observed limestone outcrops and the results of historical drilling. The total thickness of the limestone forming the Hranice Karst has not yet been determined because its bedrock has not been reached by the drilling works; however, it is assumed to be in the order of thousands of meters (Geršl and Konečný, 2018).

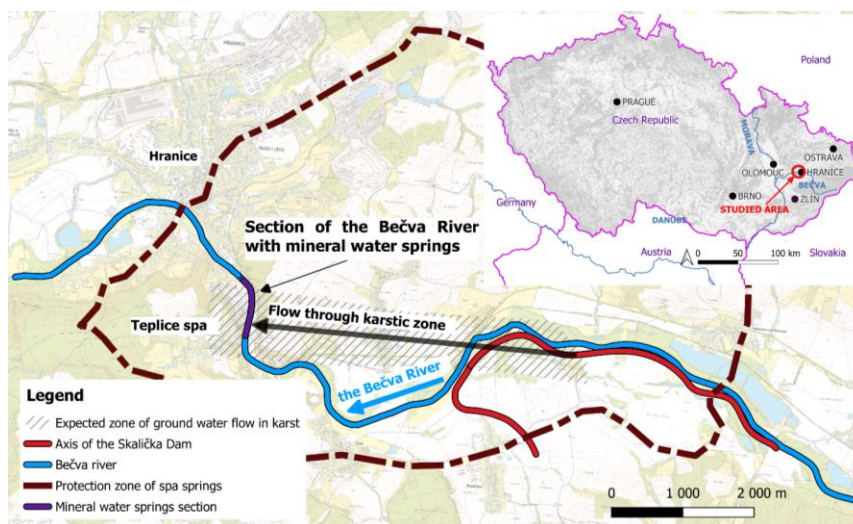


Fig. 1. The area of the Hranice Karst with the location of mineral water springs in the Teplice Spa

2.3 The Bečva River, emerging mineral water

The Bečva River is the principal stream in the area with the width about 35 m, with the maximum water depth of 0.85 m at average discharge 15.3 m³/s. During floods the water depth reaches several metres which in the past caused flooding the Teplice Spa and Zbrašov Aragonit Caves (CHMI 1997).

The discharges in the Bečva River are observed at the gauging station (GS) in the Teplice spa which is operated by the Czech Hydrometeorological Institute. However, experience and detailed measurements show that the discharges provided by the gauging station are not accurate due to certain influence of the backwater from the weir downstream of the spa. Therefore, these

data were not used directly for the spring discharges determination, but only to indicate non-stationarity in the water stages and the discharges in the Bečva River during the measurements.

Long term observation has indicated springs of mineral water in the river reach passing the Teplice Spa. The springs manifest themselves by abrupt outbursts of bubbles, increased water temperature and electrical conductivity and during winter by melting an ice on the water surface (Figure 2).

Irregularity of outbursts may be caused, except other causes, by riverbed aggradation (Bara et al., 2024) or trapped air in pores in quaternary sediments below the river bed (Dias et al., 2023).



Fig. 2. Mineral water springs into the Bečva River. Left - CO₂ bubbles, right - melting ice (Geršl 2020).

3. METHODS AND MATERIALS

3.1 General considerations

Preliminary investigations indicated springs of mineral water to the Bečva River bed in the river reach along the Teplice Spa. It was acknowledged that the emergencies are not continuous,

they occur in the form of outbursts at several places of the river reach. Therefore, the first step involved localization of principle springs and the proposal of measuring profiles (Section 3.3).

The discharge of emerging mineral water was determined from the differences of the discharges measured in specified profiles across the Bečva River located along the relevant river

reach. In advance it was expected that the size of the upward discharge of mineral water could be in the same order as the error of the measurement, therefore three different methods were used to analyse the yield of thermal water, namely:

- discharge measurements using traditional current meter - hydrometric propeller (HMP),
- discharge measurements using ADCP,
- measurements of electrical conductivity (EC).

At the predefined localities the data were measured in four campaigns (days). Unfortunately, some measurements could not be carried out on all days and profiles due to high water levels. Limiting factors were also complicated access to the channel and availability of measuring devices. The devices were rented from the Morava River agency only for this study. Based on measured data the discharge of mineral water was finally estimated. Due to the larger number of measurements by ADCP, the results were subjected to statistical analysis. Measurements using HMP were evaluated via interval analysis, so interval of expected values was determined (Jaulin et al., 2001). Observations of EC were evaluated deterministically and served for the comparison of the results, taking into account uncertainties associated with individual methods (ISO 1088, 2007).

3.2 Localization of mineral water springs

Previous studies documenting approximate locations of mineral water springs emerging into the Bečva River bed and in-

situ investigations were used to determine the river reach where the measurements have to be carried out. Koryčánková (2020) used electrical conductivity for the identification of the springs, she localized the springs to places with the most significant increase in electrical conductivity. Additional geophysical survey was carried out by IlFaut (2022), the geophysical profile was located just along the Bečva River on its right bank (Figure 3) to support identification of the mineral water spring zones. In the longitudinal profile (Figure 4) obtained by Electrical Resistivity Tomography (ERT) subvertical tectonic faults are marked which indicate probable places with the upward flow of thermal mineral water. These fractures can be assigned to the so-called Nysa-Morava Zone, which is oriented in the NW-SE direction and is characterized by CO₂ discharge. The surface of Devonian limestones was found in the depth of 3 to 42 m below the surface. Neogene sediments covered by clastic sediments occur at depth up to 67 m below the surface. It is obvious that the strongest outputs of mineral waters and gases are based on a combination of the occurrence of a fracture zone and limestones, which, however, may not have been detected by geophysics carried out to a depth of approximately 60 m. Based on all available studies, approximate river reaches with mineral water emergencies within the Bečva River stationing km 40.60 to 41.35 are marked in Figure 3. At the same time profiles for the hydrometric and conductivity measurements were established on the right bank.

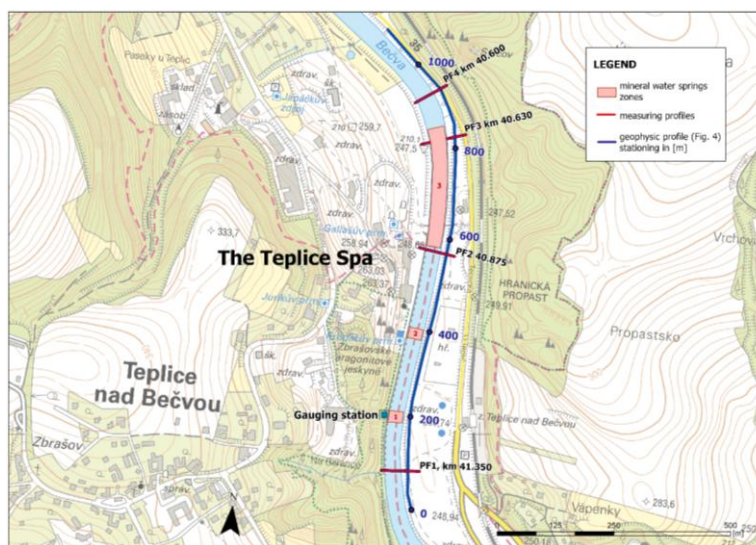


Fig. 3. Location of gauging profiles and profiles for electrical conductivity measurement.

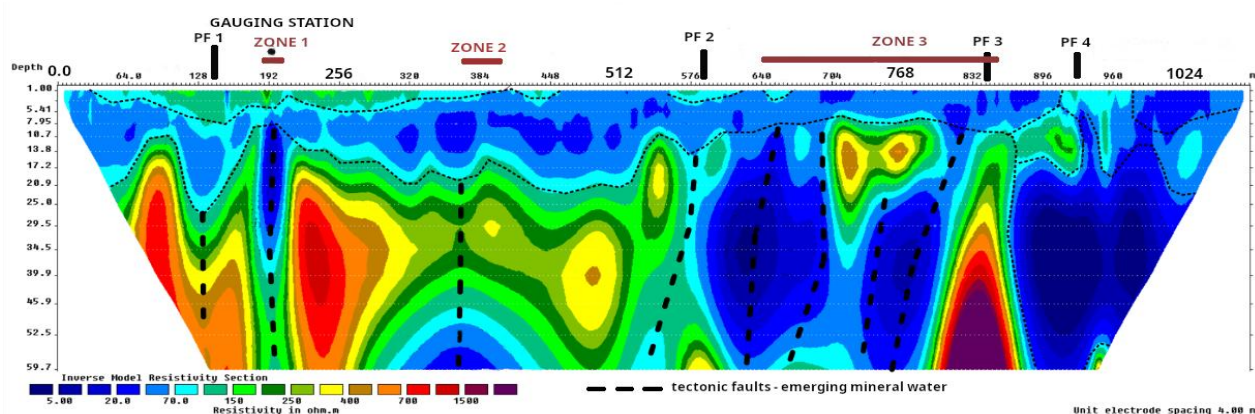


Fig. 4. Geophysical profile.

3.3 Hydrometric measurements by the propeller

The hydrometric measurements were carried out according to ISO 748 (2021). The distribution of verticals was carried out uniformly over the entire width of the river channel at an equidistant span of 1 m, close to the banks the span of verticals was 0.5 m. Water depth measurements were made by a propeller post with a support head at the lower end. The accuracy of the depth measurements was approximately 1 cm. The number of measurement points per vertical was determined according to ISO 748 (2021). Due to the different flow conditions (depth, velocity), three propellers with diameters of 30 mm, 45 mm and 50 mm were used.

Three campaigns were carried out from July to August 2020 at the profiles PF1 (upstream profile) and PF4 (downstream profile). Only two profiles were used due to rather poor access to the riverbed in other profiles. The measurements were carried out using 35 verticals and 3 measuring points along the vertical. Denote Q_H the discharge estimate obtained by the hydrometric measurements. The error ΔQ_H of the measurement according to Boiten (2003) and ISO 1088 (2007) for 35 equidistant verticals is about $\Delta Q_H = 0.016Q_H$ (i.e. relative standard error 1.6 %).

In steady state conditions the discharge of upward springs of mineral water was determined as the difference between discharges measured in profiles PF1 and PF4. In some cases, the flow conditions were a little variable during the measurement with differences in the water level up to 5 cm.

The influence of the non-stationarity of the flow in the Bečva River was taken into account by adjusting the difference in the measurements in the upper and lower profiles PF1 and PF4, respectively, using measurements at GS. The upward inflow Q_U to the Bečva River was determined as the difference of the discharges determined by hydrometric measurements in profiles PF4 and PF1 and was rectified by the difference of the discharges read at the gauging station at the time of the measurements in the respected profiles. The point estimate of Q_U was determined using the relation:

$$Q_U = (Q_{H4} - Q_{H1}) - (Q_{G4} - Q_{G1}), \quad (1)$$

where Q_{H1} and Q_{H4} are discharges measured in PF1 and PF4, Q_{G1} and Q_{G4} are the discharges recorded at GS at the time corresponding to measurements of Q_{H1} and Q_{H4} , respectively.

For the error in the gauging station, it holds approximately $Q_G \approx 0.03Q_G$ (relative standard error 3 %). Here the standard error ΔQ_U of Q_U can be determined as follows:

$$\Delta Q_U = \sqrt{(\Delta Q_{H4})^2 + (\Delta Q_{H1})^2 + (\Delta Q_{G4})^2 + (\Delta Q_{G1})^2}, \quad (2)$$

where ΔQ_{H4} , ΔQ_{H1} , ΔQ_{G4} and ΔQ_{G1} are the standard errors related to the observed quantities Q_{H4} , Q_{H1} , Q_{G4} and Q_{G1} , respectively. Due to the uncertainty in the measurements mentioned above, it is useful to determine also an interval estimate of Q_U , i.e., an interval that captures the variability of the upward discharge Q_U to the Bečva River. For this purpose, a simple statistical rule was used to evaluate the bounds $Q_U \pm \Delta Q_U$ within one standard error from the estimated value of Q_U . Notice that under additional normality assumption on Q_U , such interval captures the true value with the probability 0.68.

3.4 Acoustic Doppler Current Profiler

The ADCP contains piezoelectric transducers to transmit and receive sound signals. The traveling time of sound waves gives an estimate of the distance, i.e. the water depth. The frequency shift of the echo is proportional to the water velocity along the acoustic path. Further components of the ADCP are an electronic amplifier, receiver, clock to measure the traveling time, temperature sensor, positioning system, and in this study also conductivity sensor (Section 3.5). All devices were mounted on a plastic float that was pulled across the flow by a rope. Several measurements (three or four) were always successively carried out at one profile. The ADCP was used for the total water discharge measurements in profiles PF1, PF2, PF3 and PF4. The data about the measurements are shown in Table 2 together with information from the gauging station located in the Teplice Spa close to the profile PF1.

For the discharge data determined by ADCP method, a statistical analysis was carried out. The statistical inference on the mineral water inflow estimated from the ADCP measurements, its significance and quantity, is based on multivariate regression analysis. We could consider an ANOVA model (Devore et al., 2021) that accounts for the joint discharge in the river and possible differences at the particular measuring profiles. However, the measurements observed by ADCP may vary in time, particularly because of gradual change in hydrologic conditions at the site when moving to downstream profiles. For this reason, we incorporate in our model the observations made at stationary GS (Section 4.2) and obtain a model of Analysis of Covariance (ANCOVA) (Agresti, 2013). The model is of the following form:

$$Q_{Aij} = \mu + \alpha_i + \beta \cdot Q_{Gij} + \varepsilon_{ij}, \quad (3)$$

where Q_{Aij} stands for the j -th measurement obtained by ADCP at the i -th profile, and Q_{Gij} denotes the time-corresponding discharge measurement observed at GS. The aim of the statistical analysis is estimation of the parameters in the model and assessment of their significance in order to identify particular contribution of the upward mineral water inflow to the total flow in the Bečva River. Specifically, the member $\mu + \beta \cdot Q_{Gij}$ represents the common discharge in the river given by the observations at GS, while the particular contribution of the upward inflow at the i -th profile ($i = 1, \dots, 4$) is given by parameters α_i . The random errors ε_{ij} are considered to be independent zero-mean random variables for which we assume constant variance. The form of the model corresponds to a simple ANCOVA and estimates of the parameters can be obtained by the Ordinary Least Squares method as usual (Devore et al., 2021, Casella and Berger, 2002). Graphically, the dependency model can be interpreted as parallel regression lines corresponding to discharges at particular profiles with intercepts $\mu + \alpha_i$ where μ corresponds to the general river flow and α_i values describe the differences at the gauging station. In the absence of mineral water inflow, the regression lines representing flows at the gauging stations should be similar or slightly shifted, where the shift could be caused by measurement inaccuracy. However, a statistically significant change between the two gauging stations proves the existence of the mineral water inflow.

Hence, the differences between α_i correspond to differences between mean discharges at given profiles. It should be emphasized that the contributions α_i at particular profiles are expected to be constant and independent of the actual discharge. This simplified model could be modified in order to incorporate

the influence of the discharge on parameters α_i . However, this issue would require thorough analysis of local geological bedrock and processes therein which is not available at the time.

Possible mineral water inflow to the Bečva River is indicated by differences in values of α_i , causing a positive shift of parallel regression lines between each pair. Since the model (3) is over-parametrized, the parameters α_i are usually restricted by the additional condition $\sum_i \alpha_i = 0$ to ensure the model is of full rank. Hence, we have a model with $k = 5$ parameters to be estimated. This condition also causes some of the parameters α_i are negative, which however does not imply that the water vanishes between some measuring profiles. The difference in the discharges between profiles PF*i* and PF*j* is given by the difference $\alpha_i - \alpha_j$. Hence, increasing values of the parameters indicate increasing discharge observed at particular measuring profiles.

Of special interest is the difference $Q_U = \alpha_4 - \alpha_1$ that captures the total upward inflow within the whole monitored area. From

the covariance matrix of the model, it is possible to determine the standard error SE_U of Q_U . To find the lower bound of Q_U with a given confidence of $100(1-\alpha)\%$, the left-sided confidence interval based on asymptotic normality was evaluated. The lower bound is then given as follows:

$$\alpha_4 - \alpha_1 - SE_U \cdot t_{1-\alpha}(n-k), \quad (4)$$

where n is number of observations, k is number of parameters in the model, and $t_{1-\alpha}(n-k)$ is the $100(1-\alpha)\%$ quantile of Student's distribution.

3.5 Electrical conductivity measurement

Along with ADCP, the electrical conductivity was measured using a probe (Greisinger 5450 with LF 425 electrode) attached to the float.

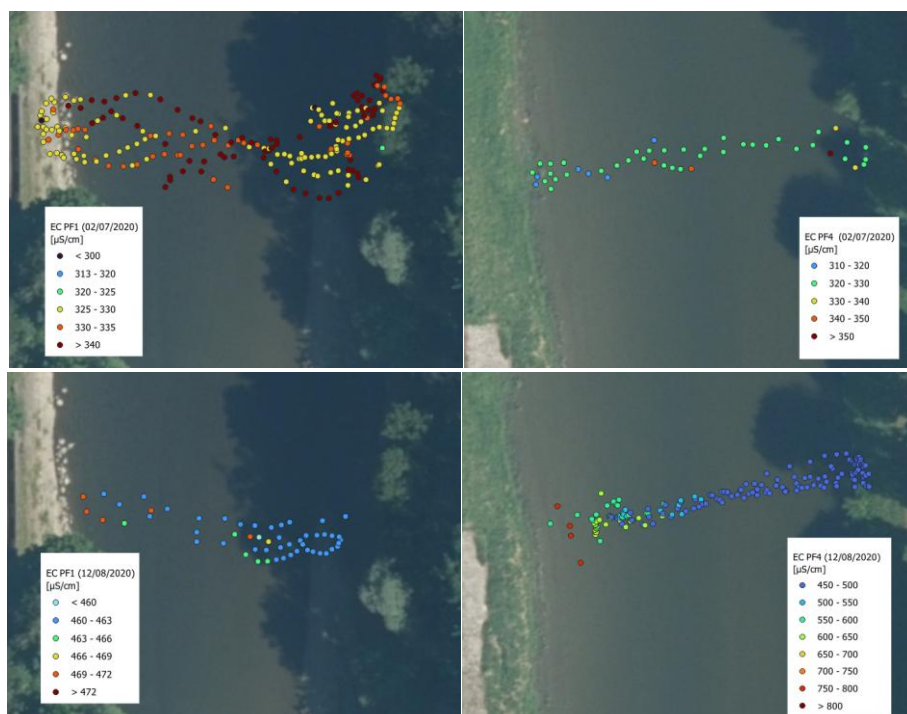


Fig. 5. Points of conductivity measurements in PF1 and PF4 during the campaigns on 2 July and 12 August 2020.

Two measurements were carried out in July and August 2020. Measurements were performed along the studied river reach with more detailed tracking in the predefined profiles PF1 to PF4 (see Figure 5).

The measurements were always started at the upstream end and then the float with the device was pulled downstream in an attempt to capture the increased conductivity of the water in selected profiles. For further processing EC values in PF1 and PF4 were used (Figure 5).

The discharge of the mineral water springs between the uppermost profile PF1 and lower profile PF4 was determined by the mixing equation. In the following Eq. (5) the non-stationarity of the Bečva River discharge was taken into account:

$$Q_U = \frac{(Q_1 + Q_{G4} - Q_{G1})EC_4 - Q_1EC_1}{(EC_{MW} - EC_4)} \quad (5)$$

where Q_U is the vertical upward flow of mineral water between profiles PF1 and PF4, Q_1 is the average discharge

measured by ADCP in the upper profile PF1, EC_1 and EC_4 are the average electrical conductivities in the profiles PF1 and PF4, EC_{MW} is the electrical conductivity of mineral water considered by the value $EC_{MW} = 2700 \mu\text{S/cm}$ taken from the long-term monitoring of the conductivity in wells in the spa. The average values of electrical conductivity in profiles were determined by averaging about 49 to 303 conductivity values obtained in single points (Figure 5) during measurements on 2 July and 12 August 2020 (when measuring device was available).

The electrical conductivity in PF1 and PF4 was also measured in the previous study carried out in the same location in 2019 by Koryčánková (2020) with a frequency of several point measurements per week in selected profiles, however without any quantification of the upward discharge. At the same time, the water level was recorded at the gauging station in the Teplice Spa. From the measurements by Koryčánková, (2020) the set of conductivity values corresponding to our ADCP measurements were selected according the water stage at the gauging station in

the spa. For the evaluation of the discharge of emerging mineral water Eq. (5) was also applied.

4. RESULTS AND DISCUSSION

4.1 Results from hydrometric measurements by the propeller

As mentioned above, the hydrometric measurements by the propeller were carried out in three campaigns in profiles PF1 and

PF4. The summary of measurements and obtained results are shown in Table 1.

From Table 1 it can be seen that in general the discharge increases along the river reach between profiles PF1 and PF4. Naturally, the interval of upward inflow increases with the discharge in the Bečva River. Therefore, the best accuracy can be expected for measurements during small discharges at steady state conditions on 23 July 2020. The upper limit for the upward inflow reaches here about 380 l/s.

Table 1. Discharges determined by hydrometric propeller.

Date	Time [h:min]	Profile	Regime	Q_H [m ³ /s]	Q_{GS} [m ³ /s]	Q_U Eq. (1) [m ³ /s]	$Q_U \pm \Delta Q_U$ Eq. (2) [m ³ /s] *)
8 July 2020	8:15 – 9:40	PF1	Unsteady	9.53	8.20	0.16	$\langle -0.247, 0.567 \rangle$
	10:40 – 11:40	PF4		9.56	8.07		
23 July 2020	8:25 – 9:25	PF 1	Steady	6.21	4.56	0.14	$\langle -0.100, 0.380 \rangle$
	10:20 – 11:20	PF4		6.35	4.56		
12 August 2020	8:10 – 9:10	PF1	Unsteady	3.92	2.99	0.08	$\langle -0.079, 0.239 \rangle$
	9:10 – 10:15	PF1		4.05	3.10	0.05	$\langle -0.114, 0.214 \rangle$
	10:50 – 11:50	PF4		4.15	3.14		
	12:00 – 13:00	PF4		4.22	3.22		

4.2 Results obtained by ADCP measurements

Measurements by the ADCP were carried out in four campaigns, in the first three sets (2, 8 and 23 July 2020) the measurements in all four profiles (PF1, PF2, PF3, PF4) were carried out while in the last one only PF1 and PF3 were measured. The summary of measurements (62 observations in total) and obtained results are shown in Table 2 (see Appendices). The data were completed by the reference discharges obtained from the gauging station.

Statistical analysis of the ADCP discharge data was carried out on the basis of ANCOVA model described in Section 3.4. The estimates of the regression parameters are shown in the Table 3.

Table 3. Parameter estimates of the ANCOVA model with standard errors given in parentheses.

Term	Estimate
Intercept μ	0.9883 (0.09196)
α_1	-0.1527 (0.08412)
α_2	-0.1495 (0.10175)
α_3	-0.018 (0.09520)
α_4	0.3202 (0.09871)
Slope β	1.0575 (0.00738)

Increasing values of parameters α_i indicate a change in the measured water discharge, implying the discharge in the river increases through the measuring profiles. The difference between parameters α_4 and α_1 , i.e. the total upward inflow is estimated to be $Q_U = \alpha_4 - \alpha_1 = 0.4729$ m³/s. It is statistically significant at all commonly considered significance levels as the left-sided p -value is 0.0011. The standard error obtained from the model covariance matrix is $SE_U = 0.1474$ m³/s, and quantile of Student's t -distribution $t_{0.95}(57) = 1.6720$. Assuming normal

distribution of the errors ε_{ij} , the left-sided confidence interval for the inflow Q_U can be evaluated using Eq. (4). Hereby, we obtain that contribution of the upward flow between PF1 and PF4 exceeds the value 0.2265 m³/s with 95% probability, or alternatively the value 0.1201 m³/s with 99% probability.

Graphical visualization of the measurements is shown in Figure 6 along with the corresponding estimated regression lines. Notice that the vertical shift between particular lines is controlled by the parameters α_i .

4.3 Results of electrical conductivity measurement

From the point values of measured electrical conductivities (Figure 5) average values were determined. The average electrical conductivities, discharges at the upstream profile (PF1) and discharges of the upward springs between profiles PF1 and PF4 are shown in Table 4.

From the Table 4 it can be seen that the discharge of mineral springs vary between 0.244 and 0.342 m³/s.

The results of this study were compared to the results obtained by the analysis of measurements of Koryčánková (2020). Her measurements were carried out at five locations along the river reach in the Teplice Spa. For the comparison results from PF1 and PF4 (Figure 7) were selected taking into account only values corresponding to water stages in the Bečva River during our ADCP measurements (Figure 8). This enabled to determine discharges related to measured electrical conductivities. The average values of the measured electrical conductivity by Koryčánková (2020) and derived discharges of the mineral water between PF1 and PF4 are shown in Table 5.

It must be noted that the sampling was in some cases performed directly at points where mineral water suddenly outbursts to the river. This resulted in higher local values of EC and consequently higher resulting values of Q_U .

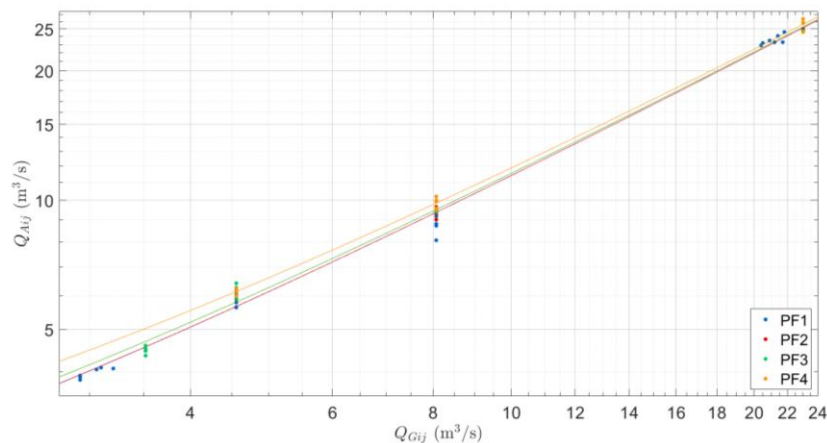


Fig. 6. Estimated regression dependencies between measurements observed at GS (Q_{Gij}) and by ADCP (Q_{Aij}). Particular profiles are visualized separately.

Table 4. Average conductivities in profiles and calculated Q_U .

Date	Profile	Conductivity	Q_1	Q_G	Q_U
		[$\mu\text{S}/\text{cm}$]	[m^3/s]	[m^3/s]	[m^3/s]
02 July 2020	PF1	322	23.475	21.8	0.244
	PF4	333		23.0	
12 August 2020	PF1	463	3.965	3.05	0.342
	PF4	622		3.18	

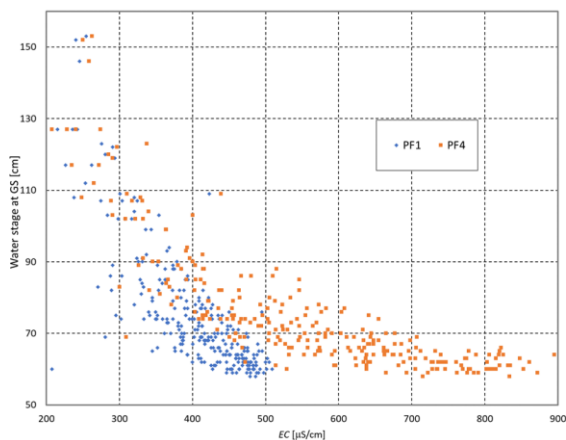


Fig. 7. Electrical conductivity measured by Koryčánková (2020) in PF1 and PF4.

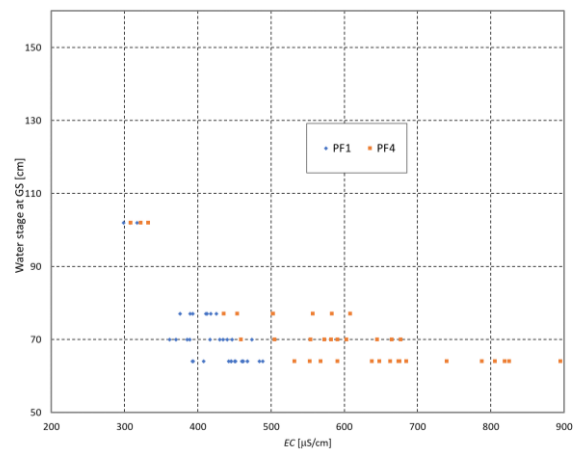


Fig. 8. Selected EC measured by Koryčánková (2020) in PF1 and PF4 at water stages according to Table 5.

Table 5. Analysis of the measurements by Koryčánková (2020).

Water stage at GS [cm]	Q_1 [m^3/s]	Conductivity [$\mu\text{S}/\text{cm}$]		Q_U [m^3/s]
		PF1	PF4	
102	23.475	308	321	0.128
77	8.695	403	520	0.467
70	5.770	415	585	0.464
64	3.965	448	694	0.486

From Table 5 it can be seen that for smaller discharges in the Bečva River the upward discharges vary approximately between 0.45 and 0.50 m³/s. The values measured at higher discharges suffer from significant errors in the determined discharge in the Bečva River and in the EC measurements

4.5 Summary and discussion

The results obtained by three methods mentioned above together with the analysis of measurements performed by Koryčánková (2020) are summarized in Table 6.

Table 6. Comparison of estimated upward flow obtained by different approaches.

Date	Upward flow Q_U [m ³ /s]			
	Hydrometry		Electrical conductivity	
	HMP	ADCP	EC during ADCP	Koryčánková (2020) *)
2 July 2020	-		0.244	0.128
8 July 2020	< 0.567	0.4729 (Table 3)	-	0.467
23 July 2020	< 0.380	> 0.2265 with 95% probability	-	0.464
12 August 2020	< 0.239	> 0.1201 with 99% probability	0.342	0.486
	< 0.214			

*) calculated for values of EC selected for discharge conditions equivalent to these during measuring campaigns

It is obvious that methods used suffer from numerous uncertainties, namely in the measurement of the individual components, such as depth, width, flow velocity, electric conductivity. Another uncertainty lies in the computational method used (Boiten, 2003; ISO 1008, 2007). In general and with respect to all uncertainties the results show reasonable agreement in the derived flow rates in the order of single hundreds of l/s. At higher flow rates the differences in obtained values of Q_U increase due to the limited accuracy of the methods, therefore the interval of the resulting Q_U becomes unrealistically wide, the measurement error may exceed the values of the upward discharge. Therefore, it is reasonable to focus on the values obtained during lower discharges in the Bečva River. Moreover, at significantly high flow rates, it was not possible to carry out HMP measurement (2 July 2020). The error may also increase due to changes in hydrodynamic conditions during the measurement. This uncertainty was attenuated by the corrections of the discharge using the data from the gauging station.

In the case of conductivity measurements, higher discharges in the Bečva River result in higher dilution of incoming mineral water, which leads to a significant reduction in conductivity in the river. One must note that upward effluent is not steady permanent flow but unsteady sudden "eruptions" changing in time and also in space along the specified river reach.

When taking into account the above-mentioned factors, the expected upward flow can be in an interval (0.12, 0.57) m³/s with realistic value between 0.22 and 0.38 m³/s. The estimated discharge considerably differs from the one determined in the study of Bruthans et al. (2021), who estimated the upward flow to be 12 to 17 l/s at six single points of expected mineral water outbursts. Thus, the methodology applied by Bruthans et al. (2021) does not represent the total inflow of mineral water along the entire river reach in the Teplice Spa (Figure 3) so the discharge is probably considerably underestimated.

Unfortunately, the comparison with other localities is not possible, as the authors do not know any locality with a similar situation. The Hranice Karst is a specific area with a complex geological condition including Palaeozoic karst and non-karst rocks, Tertiary sediments and Quaternary cover with thermal springs outbursts to the Bečva River in the Teplice Spa.

5. CONCLUSIONS

In the presented study the discharge of the mineral water springs emerging into the Bečva River in the Teplice Spa was assessed. As expected, upward discharge Q_U of mineral water would be in the same order as an error of the measurement, the comparison of three different methods was used for the estimate of Q_U , namely traditional hydrometric measurements, measurements using ADCP and electrical conductivity.

Each of the methods used is subject to a degree of uncertainty. These include uncertainties in the hydrometric measurements (Boiten, 2003) and in electrical conductivity observation in the river. The upward springs into the Bečva River are rather random sudden bursts than permanent continuous flow which significantly influence instant local electrical conductivity which may significantly vary even at constant discharges in the Bečva River (Figures 7, 8). Therefore, averages of measured EC values were used in the analysis. In such uncertain conditions, the authors consider it a success that the individual methods provide Q_U values of the same order of magnitude, that is, in single hundreds of litres per second.

It can be concluded that expected upward flow of mineral water may vary between 0.12 and 0.57 m³/s with realistic value between 0.22 and 0.35 m³/s and is not influenced by the discharge in the Bečva River.

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Appendices

Table 2. Discharges determined by ADCP and at the gauging station (GS).

Date	Time [h:min]		Profile	Discharge - ADCP [m ³ /s]	Discharge - GS [m ³ /s]
2 July 2020	9:10	9:13	PF1	22.9	20.5
	9:10	9:13		22.9	20.5
	9:13	9:16		23.2	20.5
	9:16	9:19		23.5	20.5
	9:35	9:38		23.3	21.2
	9:38	9:41		24.1	21.2
	9:41	9:45		23.3	21.8
	9:45	9:48		24.6	21.8
	10:36	10:38	PF2	25.0	23.0
	10:38	10:40		24.8	23.0
	10:41	10:43		24.7	23.0
	10:43	10:45	PF3	24.6	23.0
	10:53	10:56		24.8	23.0
	11:15	11:17	PF4	25.9	23.0
	11:19	11:21		25.8	23.0
	11:23	11:24		24.6	23.0
	11:24	11:26		26.4	23.0
8 July 2020	10:01	10:04	PF1	8.72	8.07
	10:04	10:07		8.07	8.07
	10:10	10:13		8.81	8.07
	10:13	10:16		9.18	8.07
	11:04	11:07	PF2	9.39	8.07
	11:09	11:12		9.31	8.07
	11:12	11:14		9.65	8.07
	11:14	11:17		9.01	8.07
	11:34	11:36	PF3	9.51	8.07
	11:36	11:39		9.48	8.07
	11:39	11:42		9.49	8.07
	11:42	11:45		9.46	8.07
	11:45	11:48		9.39	8.07
	12:07	12:09		9.50	8.07
	12:09	12:11	PF4	10.0	8.07
	12:11	12:13		10.2	8.07
	12:14	12:15		9.92	8.07
	12:16	12:18		9.58	8.07
23 July 2020	10:14	10:16	PF1	5.78	4.56
	10:16	10:19		5.64	4.56
	10:20	10:22		6.03	4.56
	10:22	10:24		5.63	4.56
	11:11	11:13	PF2	6.16	4.56
	11:15	11:17		5.89	4.56
	11:17	11:19		6.13	4.56
	11:19	11:20		6.14	4.56
	11:49	11:51	PF3	6.13	4.56
	11:53	11:54		6.26	4.56
	11:55	11:56		6.41	4.56
	11:56	11:58		5.99	4.56
	11:58	12:00		5.91	4.56
	12:20	12:21	PF4	6.23	4.56
	12:21	12:23		6.00	4.56
	12:23	12:24		5.99	4.56
	12:24	12:26		6.14	4.56
12 August 2020	10:33	10:35	PF1	4.08	3.21
	10:37	10:38		3.91	2.92
	10:38	10:40		3.82	2.92
	10:40	10:42		3.88	2.92

Determination of the yield of thermal mineral springs emerging into the Bečva River in the Teplice Spa

10:42	10:44		4.04	3.21
10:46	10:48		4.06	3.21
13:08	13:10		4.49	3.52
13:10	13:12		4.35	3.52
13:14	13:15	PF3	4.52	3.52
13:16	13:19		4.46	3.52
13:19	13:20		4.59	3.52